Climatic Change (2012) 113:499–524
DOI 10.1007/s10584-011-0326-z

Climate change effects on stream and river temperatures across the northwest U.S. from 1980–2009 and implications for salmonid fishes

D. J. Isaak · S. Wollrab · D. Horan · G. Chandler

Received: 27 November 2010 / Accepted: 9 October 2011 / Published online: 4 November 2011

Abstract Thermal regimes in rivers and streams are fundamentally important to aquatic ecosystems and are expected to change in response to climate forcing as the Earth's temperature warms. Description and attribution of stream temperature changes are key to understanding how these ecosystems may be affected by climate change, but difficult given the rarity of long-term monitoring data. We assembled 18 temperature time-series from sites on regulated and unregulated streams in the northwest U.S. to describe historical trends from 1980–2009 and assess thermal consistency between these stream categories. Statistically significant temperature trends were detected across seven sites on unregulated streams during all seasons of the year, with a cooling trend apparent during the spring and warming trends during the summer, fall, and winter. The amount of warming more than compensated for spring cooling to cause a net temperature increase, and rates of warming were highest during the summer (raw trend = 0.17°C/decade; reconstructed trend = 0.22°C/decade). Air temperature was the dominant factor explaining long-term stream temperature trends (82–94% of trends) and inter-annual variability (48–86% of variability), except during the summer when discharge accounted for approximately half (52%) of the inter-annual variation in stream temperatures. Seasonal temperature trends at eleven sites on regulated streams were qualitatively similar to those at unregulated sites if two sites managed to reduce summer and fall temperatures were excluded from the analysis. However, these trends were never statistically significant due to greater variation among sites that resulted from local water management policies and effects of upstream reservoirs. Despite serious deficiencies in the stream temperature monitoring record, our results suggest many streams in the northwest U.S. are exhibiting a regionally coherent response to climate forcing. More extensive monitoring efforts are needed as are techniques for short-term sensitivity analysis and reconstructing historical temperature trends so that spatial and temporal patterns of warming can be better understood. Continuation of warming trends this century will increasingly stress important regional salmon and trout resources and hamper efforts to recover these species, so comprehensive vulnerability assessments are needed to provide strategic frameworks for prioritizing conservation efforts.

D. J. Isaak (✉) · S. Wollrab · D. Horan · G. Chandler
U.S. Forest Service, Rocky Mountain Research Station, Air, Water, and Aquatics Program—Boise Aquatic Sciences Lab, 322 E. Front St., Suite 401, Boise, ID 83702, USA
e-mail: disaak@fs.fed.us

1 Introduction

Thermal regimes in river and stream ecosystems are fundamentally important to fish and other aquatic organisms because most are ectotherms with physiologic processes directly controlled by temperatures of the ambient environment (Neuheimer and Taggart 2007; Buisson et al. 2008; Pörtner and Farrell 2008; Durance and Ormerod 2009). As a result, temperature strongly dictates the distribution and abundance of individual species across many spatial and temporal scales (Brannon et al. 2004; Rieman et al. 2007; Wenger et al. 2011a). As anthropogenic climate change progresses and the Earth's temperatures warm this century, aquatic communities in rivers and streams will have to shift to track thermally suitable habitat, but could encounter difficulties in linear stream networks that are often heavily fragmented by water resource development (Daufresne and Boet 2007; Heino et al. 2009). Moreover, populations of many recreationally and economically important cold-water fishes like trout and salmon are already constrained by unsuitably warm temperatures and additional warming may simply result in net losses of habitat (Mohseni et al. 2003; Rieman et al. 2007; Isaak et al. 2010a; Wenger et al. 2011b). A critical step to understanding potential climate change impacts on aquatic resources, therefore, is describing the rates at which streams may be warming and the factors that contribute to warming so that potential biological responses may be better understood and predicted.

Thermal regimes in streams reflect the balance of numerous physical processes that cause heating or cooling with short- (e.g., hourly, daily) or long-term (e.g., annual, decadal) temperature trends due simply to changes in the relative importance of these processes through time. Short-wave solar radiation is the dominant warming factor in stream heat budgets (Webb and Zhang 1997; Johnson 2003) but warming also occurs from long-wave atmospheric radiation, sensible heat transfer between air and water, direct conduction from the stream bed, friction created by water flow over the bed, and advective heat gains from precipitation and groundwater inputs (Brown 1969; Webb and Zhang 1997; Caissie 2006; Webb et al. 2008). Stream heat budgets are frequently altered by human activities that increase solar gains through removal of riparian vegetation (Moore et al. 2005), diversion of water out of streams (Meier et al. 2003), thermal effluents from powerplants, warm runoff from paved surfaces in urban environments, (Nelson and Palmer 2007), and storage of water in reservoirs (Olden and Naiman 2009; Poff et al. 2010). These factors, however, alter stream thermal regimes at relatively restricted spatial and temporal scales in comparison to the pervasive effects of climate change across the broad extents of regional river networks that often encompass 100,000's stream kilometers. Air temperatures affect stream temperatures everywhere throughout these networks via several mechanisms that include direct sensible heat transfer, long-wave atmospheric radiation (Brown 1969; Webb and Zhang 1997; Webb et al. 2008), and heating of groundwater that warms streams through advection (Taylor and Heinz 2009; Gunawardhana and Kazama 2011). Moreover, additional indirect effects may occur as air temperatures warm in association with anthropogenic climate change and cause stream discharge regimes to change in ways that could alter stream sensitivity to warming (Hockey et al. 1982; Meier et al. 2003). Across much of the western U. S., for example, warming air temperatures have been linked to increasing precipitation rainfall fractions (Knowles et al. 2006), decreasing snow accumulations (Mote et al. 2005, Knowles et al. 2006), and earlier snowmelt (Hamlet et al. 2005; Mote et al. 2005). As a result, the timing of spring stream freshets driven by snowmelt has advanced 2–3 weeks in the last 50 years (Regonda et al. 2005; Stewart et al. 2005). Because streams discharge more water earlier in the year, less remains in the summer when flows have been trending lower for many decades (Stewart et al. 2005; Rood et al. 2008; Luce and Holden 2009; Leppi et al. 2011).

In contrast to the extensive long-term meteorological and flow gaging records that have been valuable for documenting many trends in climate-related parameters (e.g., Mote et al. 2005; Stewart et al. 2005; Leppi et al. 2011), few long-term stream temperature records exist. The best long-term records in the U.S. are typically associated with municipal water supplies, U.S. Geological Survey stream gages, or hydroelectric facilities on larger rivers that are often subject to varying degrees of local thermal alterations (Olden and Naiman 2009; Kaushal et al. 2010). Not surprisingly, therefore, studies based on observational records of sufficient length to address potential climate effects are rare, often include only a single site (Langan et al. 2001, Petersen and Kitchell 2001; Patterson et al. 2007), or have been done to assess shorter-term climate cycles like the Pacific Decadal Oscillation (PDO) or El Niño Southern Oscillation (ENSO; Kiffney et al. 2002; Mote et al. 2003). Only two studies (Hari et al. 2006; Kaushal et al. 2010) have looked at multiple streams contemporaneously across multiple decades to discern long-term warming trends. In each instance, such trends were commonly detected, but a variety of factors related to urbanization, climate cycles, and reservoir management also affected the results. No observational study, to our knowledge, has attempted to describe background rates of stream temperature warming associated with climate change or to examine seasonal patterns that could be driven by concurrent trends in climate forcing variables like air temperature and stream discharge.

Here, we examine 18 temperature time-series from sites on unregulated and regulated northwest U.S. streams that span the period from 1980–2009 to assess historical trends. Our objectives were to: 1) determine whether regionally coherent stream temperature trends were apparent, 2) determine whether trends differed between sites on free-flowing streams and those downstream of reservoirs, 3) describe seasonal variation in temperature trends, and 4) assess the relative influence of variation in air temperature and discharge on stream temperature trends. Lastly, we discuss the implications of our findings for conservation of salmon and trout in the northwest U.S.

2 Climate in the northwest U.S.

The climate in the northwest U.S. has been well studied, initially because of the dominance of climate cycles like the PDO and ENSO in regional weather patterns. These phenomena reflect periodicity in ocean conditions at different temporal scales (PDO~20–30 years, ENSO~2–5 years) that result in phases of conditions in the Pacific Northwest that are generally wetter and cooler or warmer and drier conditions than average (Mantua and Hare 2002). These phases may have strong, sometimes dominant effects on temporal variation in stream flows and temperatures (Kiffney et al. 2002; Mote et al. 2003).

More recently, the region's climate has been extensively studied in association with anthropogenic climate change (Mote 2003, Mote et al. 2005, Hamlet et al. 2007). Important motivations for this work include above average rates of past warming (Mote 2003, Saunders et al. 2008), projected future warming (Mote et al. 2008), and the region's heavy reliance on water supplies associated with seasonal snowpacks that are showing sensitivity to a warming climate (Mote et al. 2005; Knowles et al. 2006; Hamlet et al. 2007; Barnett et al. 2008). Warming rates have varied during the 20th century, but a consistent warming trend believed to be associated with climate change emerged in the late 1970's/early1980's and persists to the present (Mote 2003, Hamlet et al. 2007).

3 Methods

3.1 Stream temperature data

Data for this assessment were queried out of the U.S. Geological Survey National Water Information System (NWIS; http://waterdata.usgs.gov/nwis), which hosts historical and real-time records for a variety of stream discharge, temperature, and other water quality attributes measured at gage sites across the United States. Our query included only sites in the states of Oregon, Montana, Idaho, and Washington that had multiple years of stream temperature measurements and only those years of site data were retained that had at least 300 daily observations. This excluded years that could have omitted entire seasons (temperature sensor malfunctions often occur over consecutive days) and potentially biased annual temperature summaries. The time-series of remaining years with data were then examined and only those sites having at least 20 of the 30 years in the period from 1980–2009 were retained (average number of years was 26). These criteria represented a compromise that provided a contemporaneous view of the largest number of stream sites over the longest period and yielded 18 sites for the analysis (Fig. 1; Table 1). Extending the record prior to 1980 was impossible for many sites because most time-series were initiated in the late 1970's.

The 18 sites used in this assessment encompassed a wide range of stream sizes, elevations, and climatic conditions, but most drained mountainous watersheds and forested landscapes with various landuse histories and limited impacts from urbanization (Table 1). Many of the sites were located in the Oregon coast range and were subject to a moderate maritime climate with annual precipitation of 100–300 cm falling mostly as rain (some snow at higher elevations) during fall, winter, and spring months. Peak flows in these streams typically occurs during the winter and early spring. Sites further inland in Idaho and Montana were generally higher elevation and drier (30–150 cm), with most precipitation

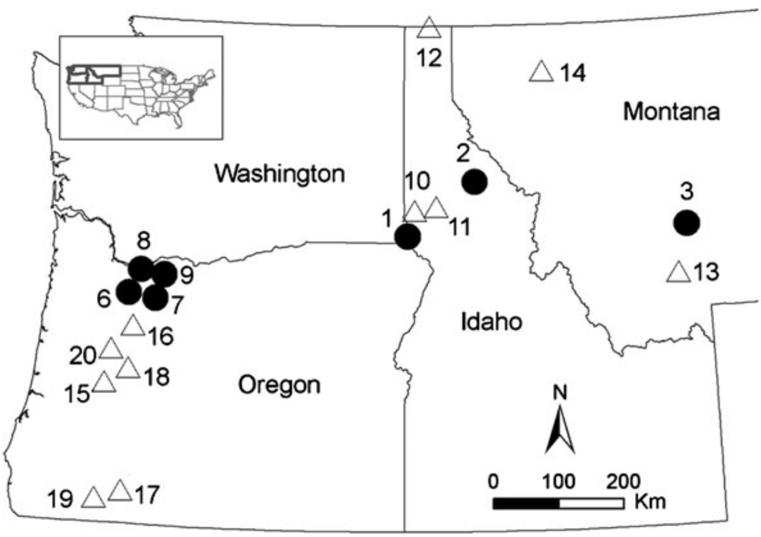

Fig. 1 Locations of 18 river and stream monitoring sites used to assess temperature trends in the northwest U.S. from 1980–2009. Circles denote sites in the unregulated thermal category; whereas triangles denote sites in the regulated category

Table 1 U.S. Geological Survey gage sites for rivers and streams in the northwest U.S. with long-term temperature records that were used to assess trends from 1980–2009. Values in parentheses are the temperature standard deviations and number of years used in the analysis after screening for missing data

Site	Gage number	Gage elevation (m)	Watershed area (km^2)	Landcover	Thermal category	Upstream reservoir distance (km)	Average stream temperature (°C)			
							Spring	Summer	Fall	Winter
1. Snake River Near Anatone, WA	13334300	256	240765	Grassland, desert	Unregulated	160	9.4 (0.67, 27)	19.5 (0.89, 28)	14.2 (0.54, 27)	3.9 (0.55, 27)
2. North Fork Clearwater River, ID	13340600	506	3356	Forest	Unregulated	–	5.7 (0.71, 24)	15.5 (1.42, 26)	8.2 (0.62, 23)	1.1 (0.59, 25)
3. Missouri River, MT	6054500	1191	37992	Grassland, forest	Unregulated	–	8.9 (0.91, 30)	18.8 (1.17, 30)	8.7 (0.83, 28)	0.5 (0.32, 28)
6. South Fork Bull Run River, OR	14139800	302	39	Forest	Unregulated	–	6.3 (0.85, 29)	12.2 (0.86, 29)	8.6 (0.51, 30)	4.1 (0.56, 30)
7. Fir Creek, OR	14138870	439	14	Forest	Unregulated	–	5.5 (0.77, 27)	10.7 (0.82, 30)	8.1 (0.48, 29)	4.0 (0.47, 28)
8. North Fork Bull Run River, OR	14138900	323	21	Forest	Unregulated	–	5.9 (0.84, 29)	10.3 (0.36, 27)	7.8 (0.47, 30)	3.7 (0.53, 29)
9. Bull Run River, OR	14138850	329	124	Forest	Unregulated	–	5.8 (0.79, 28)	12.0 (0.82, 28)	8.4 (0.50, 26)	3.6 (0.53, 27)
10. Clearwater River at Spaulding, ID	13342500	235	24042	Forest	Regulated	30	7.8 (0.90, 27)	14.7 (2.06, 28)	10.2 (0.91, 27)	3.5 (0.44, 23)
11. Clearwater River Near Peck, ID	13341050	283	20657	Forest	Regulated	5	6.7 (0.60, 29)	13.4 (1.56, 29)	9.6 (0.55, 26)	3.2 (0.46, 26)
12. Kootenai River, ID	12322000	518	35482	Forest	Regulated	25	7.3 (0.88, 24)	15.4 (1.27, 25)	11.0 (0.63, 26)	3.8 (0.80, 21)
13. Madison River, MT	6041000	1429	5661	Grassland, forest	Regulated	1	7.3 (1.16, 27)	18.1 (0.98, 28)	8.5 (0.86, 26)	1.4 (0.33, 26)
14. Flathead River, MT	12363000	908	11561	Forest	Regulated	15	5.1 (0.52, 29)	12.2 (1.30, 28)	7.1 (1.25, 29)	2.6 (0.44, 30)
15. Fall Creek, OR	14151000	194	481	Forest	Regulated	1	8.7 (0.76, 23)	12.8 (1.47, 24)	11.9 (0.79, 24)	6.2 (0.79, 22)
16. North Santiam River, OR	14181500	333	1173	Forest	Regulated	1	5.8 (0.40, 26)	9.1 (0.97, 26)	11.5 (0.64, 26)	5.1 (0.60, 27)
17. Rogue River Near McLeod, OR	14337600	454	2429	Forest	Regulated	2	7.6 (0.56, 28)	11.8 (0.59, 29)	8.5 (0.59, 28)	5.5 (0.45, 28)
18. Blue River, OR	14162200	322	227	Forest	Regulated	1	6.4 (0.46, 23)	9.1 (1.30, 26)	12.6 (1.31, 25)	5.2 (0.59, 26)
19. Rogue River at Dodge Bridge, OR	14339000	388	3146	Forest	Regulated	16	8.5 (0.74, 27)	13.2 (0.76, 27)	9.0 (0.44, 28)	5.4 (0.48, 27)
20. South Santiam River, OR	14187200	162	1442	Forest	Regulated	1	8.4 (0.73, 22)	12.1 (0.55, 22)	11.0 (0.64, 22)	6.5 (0.59, 25)

falling as snow during the winter and spring periods. Peak runoff at these sites occurs in late spring and early summer as air temperatures warm enough to melt accumulated snowpacks.

3.2 Stream temperature metrics

Mean daily stream temperatures were obtained (or calculated as the average of the daily maxima and minima) for each year in a temperature time-series that met the 300 day criterion described above. The calendar year average of these values was used as the estimate of annual stream temperature. Similar summaries were constructed for each year's seasonal periods; Spring (March, April, May), Summer (June, July, August), Fall (September, October, November), and Winter (December, January, February). As a minimum threshold, we required temperature measurements from 75 of the days in a seasonal period for that season to be included in the analysis. Because of a general concern that climatic extremes will change faster than mean conditions (Jentsch et al. 2007; IPCC 2007), we also summarized each year's Minimum Weekly Average Temperature (MinWAT) and the Maximum Weekly Average Temperature (MaxWAT) from the seven-day rolling averages of daily means.

3.3 Air temperature and discharge data

To assess linkages between stream temperature and air temperature and discharge, we summarized the latter variables from climate stations associated with each of the 18 monitoring sites. Air temperature data were not available at the 18 stream temperature sites so were obtained from the nearest three weather stations in the U.S. Historical Climatology Network (Menne et al. 2009; http://cdiac.ornl.gov/epubs/ndp/ushcn/background.html) that had the most complete daily records from 1980–2009. The air monitoring stations were located 26–168 km away from the stream temperature sites, but strong regional and landscape level correlations among air temperatures (Beever et al. 2010; Holden et al. 2011) suggest these remote locations provided sufficiently precise information for our purposes. Moreover, Mohseni et al. (1998) demonstrated that separation distances up to 244 km had no discernable effect on the accuracy of stream temperature models developed using air temperature data from remote stations. To minimize the possibility that anomalous readings from one air temperature station could adversely affect our results, we averaged daily measurements from the three weather stations associated with each stream temperature site to make a composite air temperature record (Pearson correlations among the air temperature time-series averaged 0.96).

Daily discharge measurements were available from the stream gage at the same site as the stream temperature measurements and were downloaded from the U.S. Geological Survey National Water Information System (NWIS; http://waterdata.usgs.gov/nwis). Given the periodicity in discharge data associated with PDO cycles (Hamlet and Lettenmaier 1999; Mote et al. 2003), a longer period of record than 1980–2009 was necessary to accurately represent trends associated with long-term climate change. A standard period often considered in many hydrologic assessments of climate change in the western U.S. is 50–60 years because it encompasses two recent opposing PDO phases (Luce and Holden 2009; Stewart et al. 2005; Hamlet et al. 2007). Time-series for the discharge data, therefore, were obtained back to 1954 to examine a 56 year period because that was also a consistent start date for most of the stream gages. Daily mean discharge and air temperature values were summarized for each year and the same seasonal and annual periods as those described above for stream temperatures. Table 2 summarizes the trends observed in these data during recent decades.

Table 2 Decadal trends by season in air temperatures and stream flows associated with 18 temperature monitoring sites on rivers and streams in the northwest U.S. (SD in parentheses). Discharge data were obtained from the USGS gage co-located with the water temperature sensor and air temperature data were averages from the nearest three NOAA Cooperative observer weather stations

Climate variable	Thermal category	Spring	Summer	Fall	Winter	Annual
30 year air temperature trend (°C/decade)	Unregulated	−0.13 (0.08)	0.36 (0.10)	0.17 (0.10)	0.12 (0.12)	0.13 (0.018)
	Regulated	−0.12 (0.14)	0.35 (0.082)	0.16 (0.086)	0.13 (0.11)	0.12 (0.036)
56 year discharge trend (% change/decade)	Unregulated	−1.1% (2.4%)	−3.5% (1.2%)	−0.8% (3.4%)	−3.5% (2.2%)	−2.1% (1.1%)
	Regulated	−5.5% (6.2%)	−1.7% (6.7%)	−0.22% (5.1%)	−3.82% (6.7%)	−2.8% (1.0%)

[a] Percentages calculated relative to the average discharge at individual gages from 1980–2009.

3.4 Data analysis

Data associated with the 18 sites were stratified into two categories for subsequent analyses; sites with stream temperature data measured downstream of reservoirs that could alter thermal trends (hereafter "regulated sites") and those with measurements taken on free-flowing rivers and streams (hereafter "unregulated sites"). One exception was the Snake River site, which was included in the unregulated category because the nearest reservoir was 160 km upstream. The spatial lags over which stream temperatures are correlated are generally much less than this (Isaak et al. 2010a), so it was assumed that river temperatures would equilibrate to local climatic conditions before reaching the temperature site. Moreover, two large unregulated tributaries, the Salmon River and the Grande Ronde River enter the Snake River and double its size upstream of the Anatone temperature site to further dilute any remaining reservoir effects.

Patterns of regional coherence in stream temperatures were described by calculating Pearson correlations among all pairwise combinations of sites for each of the seasonal periods. We tested whether the correlations among sites within the two stream classes differed statistically using two-sample *t*-tests (α=0.05). Trends from raw data at individual sites were estimated from simple linear regressions of each temperature metric versus year over the 1980–2009 period (Fig. 2). The slope parameter for year was multiplied by 10 to convert annual rates to decadal rates. The average rate was then calculated across all the streams in a thermal category (annually or within

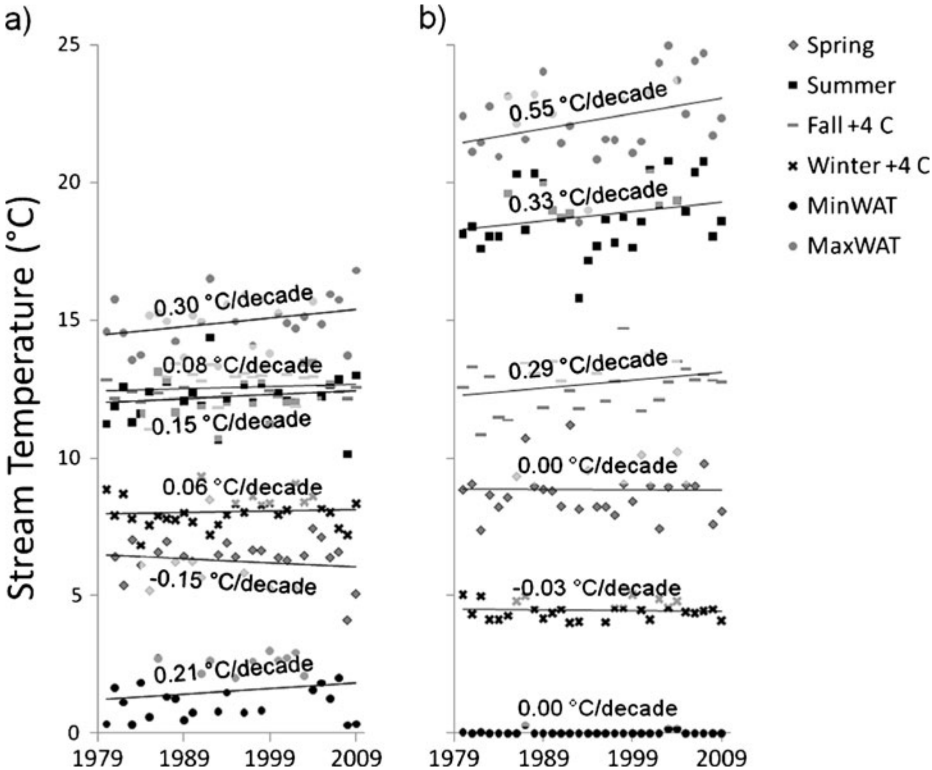

Fig. 2 Examples of raw seasonal temperature trends at two unregulated sites; the South Fork Bull Run River, OR (**a**) and the Missouri River near Toston, MT (**b**) from 1980–2009. Trend lines represent simple linear regressions of the raw time series and trend estimates are the slope parameters converted to decadal rates. Fall and winter temperatures were offset for better visibility by adding 4°C to all values

a seasonal period) and tested for statistical difference from zero using a one sample *t*-test. We tested the group as a whole rather than the significance of trends at individual sites because of our interest in ascertaining broad, regional patterns that were anticipated with climate change.

Trend estimates from raw data suffer two potential deficiencies, however. These include bias that may result from missing years of observations and could be important given the relatively short length of available time-series (Table 1). This short length also means that trend estimates could be unduly influenced by regional climate cycles because the PDO, in particular, has a periodicity approximating the length of stream temperature time series in the northwest U.S. (Mantua and Hare 2002). We therefore derived a complimentary set of reconstructed trend estimates using multiple regression models to overcome these deficiencies. This linear modeling approach was chosen over the nonlinear approaches often employed in similar reconstructions (e.g., Mohseni et al. 1998; Webb et al. 2003; Van Vliet et al. 2010) because temperatures in the streams we studied were rarely warm enough for the nonlinear behavior of atmospheric heat exchange processes to be relevant (Mohseni and Stefan 1999). Multiple regressions have also worked well in previous stream temperature reconstructions (Moatar and Gailhard 2006; Isaak et al. 2010a) and pilot analyses we conducted yielded more accurate results than the nonlinear approaches.

Reconstructed trend estimates were obtained by first developing a multiple regression that predicted stream temperature from the air temperature and discharge values associated with a monitoring site. Once this link was established and parameter estimate existed for air temperature and discharge, the trends in the predictors at a site were used to describe the total amount of stream temperature change from 1980–2009. This approach was not affected by missing data because monitoring records for air temperatures and discharge data were nearly continuous or were made so through adjustments based on inter-station correlations in climate station data (Menne et al. 2009). Parameters in the regression models also provided flexibility in terms of the climate scenarios considered. Rather than having to rely exclusively on changes that occurred during the last 30 years, for example, it was possible to consider trends that occurred over longer time periods, so we used 56 year discharge trends to offset the effects of opposing PDO phases in the reconstructed trend estimates. We retained the air temperature trend rates for the 30-year period from 1980–2009 in the reconstructions because of the globally coherent warming signal that emerged approximately 30 years ago and because air temperature increases have been accelerating (IPCC 2007; Meehl et al. 2009).

The final advantage to the multiple regression approach for reconstructing trends was that the parameter estimates for discharge and air temperature provided insights regarding how stream temperatures were responding to regional climate forcing. To determine whether discharge and air temperature effects were additive or multiplicative, we tested for significant interactions between these predictors. Standardized regression coefficients were also calculated to determine the relative importance of the predictors in causing inter-annual variation in the raw stream temperature time-series. Finally, the reconstructed stream temperature trends from 1980–2009 were decomposed and associated with each predictor to assess the relative influence of each on long-term stream temperature trends.

4 Results

Pairwise correlations among stream temperatures at the 18 sites varied by season and thermal class (Table 3), with correlations among unregulated sites being significantly stronger than those among regulated sites (annual period: $r_{\mathrm{unregulated}} = 0.74$ versus $r_{\mathrm{regulated}}$ 0.41; Table 3). The one seasonal exception was the winter period when streams were coldest and least thermally

Table 3 Pairwise correlations between summer stream temperatures from 1980–2009 for 18 rivers and streams in the northwest U.S. Values in bold are for streams in the unregulated thermal category; numbers correspond to the same streams in Table 1. Table inset shows average pairwise correlations among all sites by season; asterisks indicate seasons when the correlations differed statistically between thermal categories ($\alpha \leq 0.05$)

	1	2	3	6	7	8	9	10	11	12	13	14	15	16	17	18	19
2	**0.80**																
3	**0.67**	**0.52**															
6	**0.61**	**0.61**	**0.50**														
7	**0.58**	**0.64**	**0.47**	**0.96**													
8	**0.45**	**0.56**	**0.26**	**0.73**	**0.71**												
9	**0.69**	**0.77**	**0.50**	**0.89**	**0.92**	**0.77**											
10	0.17	0.31	−0.04	0.14	0.09	0.17	0.19										
11	0.10	0.30	−0.13	0.03	0.01	0.11	0.15	0.95									
12	0.29	0.43	0.19	0.15	0.25	0.34	0.25	0.43	0.47								
13	0.73	0.54	0.88	0.48	0.44	0.21	0.40	−0.25	−0.30	0.12							
14	0.41	0.39	0.28	0.17	0.25	0.24	0.28	−0.65	−0.63	0.00	0.46						
15	0.15	−0.25	0.06	−0.04	−0.09	−0.06	−0.08	−0.26	−0.34	−0.09	0.18	0.08					
16	0.20	0.15	0.27	0.01	0.03	0.26	0.01	−0.37	−0.36	0.13	0.29	0.49	0.11				
17	0.75	0.60	0.38	0.42	0.42	0.35	0.47	−0.08	−0.21	0.15	0.58	0.34	0.05	0.39			
18	0.32	0.45	0.02	0.41	0.41	0.35	0.46	0.63	0.52	0.45	−0.05	−0.34	−0.39	0.02	0.38		
19	0.68	0.54	0.44	0.56	0.51	0.43	0.55	−0.15	−0.29	0.02	0.62	0.31	0.13	0.33	0.88	0.42	
20	−0.18	0.03	−0.34	−0.12	−0.12	0.29	0.02	0.73	0.64	0.05	−0.54	−0.36	−0.48	−0.23	−0.23	0.44	−0.32

Thermal category	Spring*	Summer*	Fall*	Winter	Annual*
Unregulated	0.81	0.65	0.59	0.61	0.74
Regulated	0.58	0.20	0.28	0.49	0.41

variable. The discrepancy between stream classes was also apparent in efforts to develop multiple regression models for the trend reconstructions. These regressions performed well at unregulated sites (R^2~0.70; RMSE~0.33°C) but poorly at regulated sites (R^2~0.34; RMSE~ 0.68°C), where the parameter estimates were also inconsistent. This suggested thermal patterns at regulated sites were effectively decoupled from the local climates by the reservoir effects and local water management policies. As a result, temperature trend estimates at regulated sites were based only on the raw trend estimates.

Temperature trends across the seven unregulated sites were significantly different from zero during many seasons of the year (Figs. 3 and 4; Appendix A). A cooling trend was apparent during the spring and warming trends during other seasons, with warming rates highest during the summer (raw trend = 0.17°C/decade; reconstructed trend = 0.22°C/ decade). Estimates based on the raw data were usually smaller and less precise than reconstructed estimates, suggesting that missing data and short-term discharge trends were influencing the estimates. Comparison of trends in annual temperature extremes (MinWAT raw trend = 0.21°C/decade, $p<0.01$; MaxWAT raw trend = 0.28°C/decade, $p<0.01$) to the summer and winter periods in which they occurred (Fig. 3) suggested more rapid warming of the year's highest and lowest weekly temperatures.

In contrast to the unregulated sites, statistically significant trends across the 11 regulated sites were never detected. This remained true even after estimates were excluded from two sites on the Clearwater River where cold-water releases from an upstream reservoir had caused dramatic cooling trends (Fig. 3; Appendix A). Seasonal averages at the remaining 9

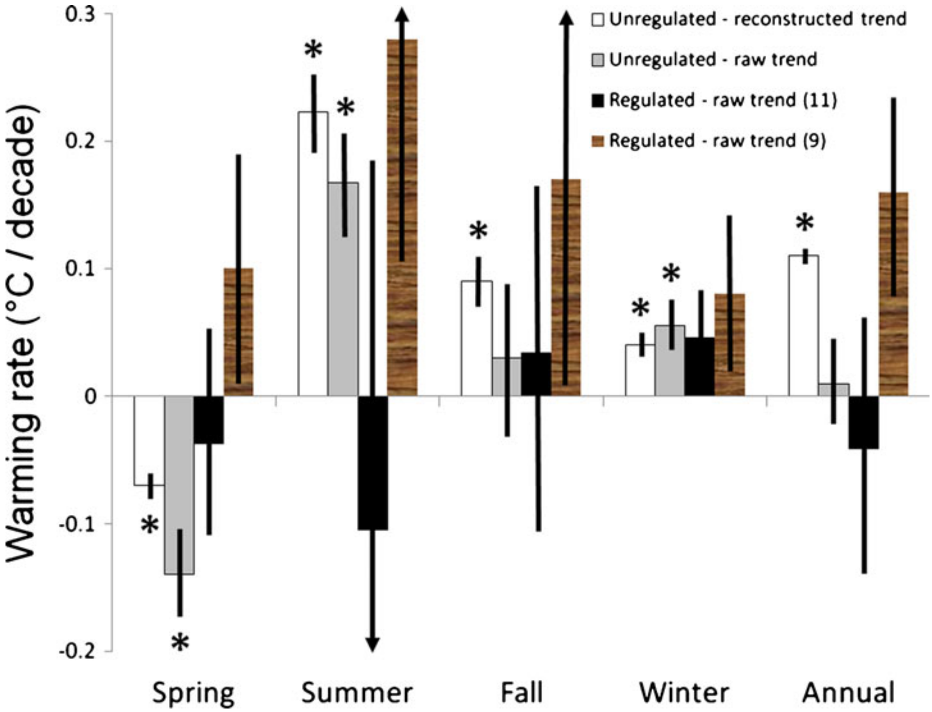

Fig. 3 Seasonal temperature trend estimates across 18 stream sites in the northwest U.S. Error bars denote ± 1 SE; asterisks denote trends that are significantly different from zero at $\alpha \leq 0.05$. Arrows indicate SE values that extend beyond the Y-axis scale

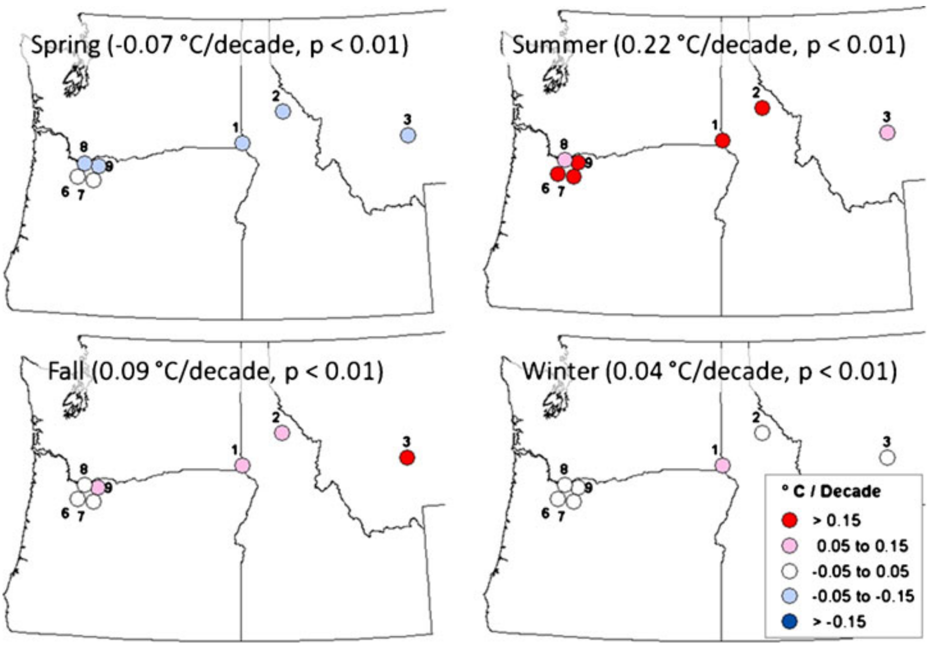

Fig. 4 Spatial variation in seasonal temperature trends from 1980–2009 based on reconstructed historical trends for seven unregulated river and stream sites across the northwest U.S.

sites were indicative of warming, but considerable variation among sites precluded ascribing statistical significance.

Multiple regressions at the seven unregulated sites indicated a consistent relationship between air temperature and stream temperature, with the air temperature parameter being statistically significant and positively related to stream temperature in all 35 of the seasonal and annual regressions calculated (Appendix B). The discharge relationship was less consistent, with this parameter negatively related to stream temperature in 28 of 35 regressions but statistically significant only in half (17 of 35). Significant interactions between air temperature and discharge occurred in only 2 of the 35 regressions, suggesting that these effects were additive and could be considered separately. Comparison of the standardized regression coefficients for air temperature and discharge indicated air temperature was the dominant factor accounting for inter-annual variation in stream temperatures (48–86% of variation), except during the summer when discharge accounted for half the inter-annual variation (Fig. 5; Appendix C). Trend decomposition suggested air temperature trends consistently accounted for the majority of stream temperature trends (82–94%) observed from 1980–2009 (Fig. 5; Appendix C).

5 Discussion

A sample of 18 stream sites with long-term temperature monitoring records is a small one from which to generalize, especially when the majority of these sites was affected by upstream reservoirs and did not provide useful trend data for assessing responses to climate forcing. Moreover, none of the unregulated sites was likely to have "pristine" thermal conditions, given more than a century of anthropogenic land uses, forest management, water abstractions, and degradation of riparian ecosystems in this region (McIntosh et al. 2000; Hessburg and Agee

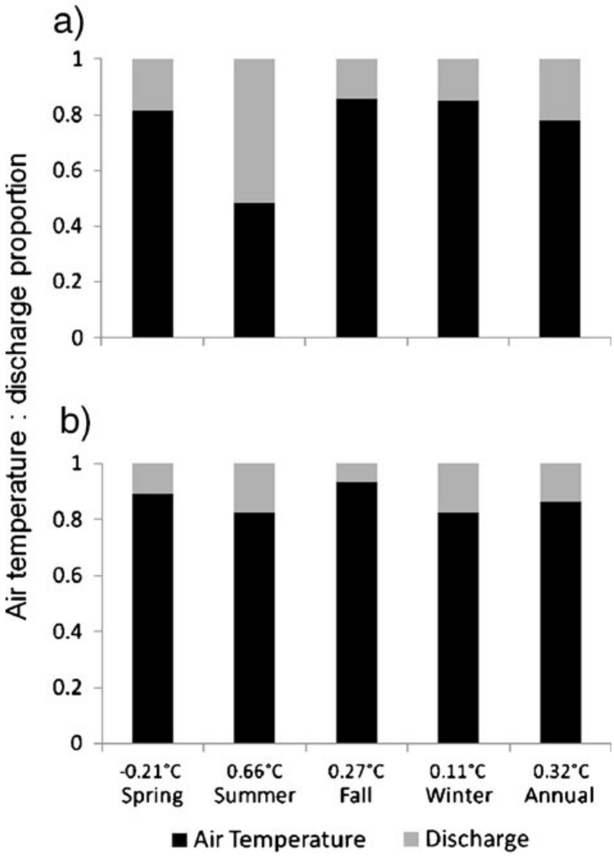

Fig. 5 Relative contributions of air temperature and discharge to inter-annual variation in raw stream temperature time-series (**a**) and long-term temperature trends based on decomposition of reconstructed historical trends (**b**) at seven unregulated river and stream sites in the northwest U.S. Temperature values under bars are the total stream temperature changes that occurred from 1980–2009 based on the reconstructed trends

2003). The temperature data at these seven sites, however, are some of the few long-term monitoring records that have not been significantly altered by the proximity of upstream reservoirs or urbanization and it is unlikely that factors other than climate would have occurred systematically across these sites to cause the patterns we observed. The consistency of the temperature responses at these sites, which included important diversity (i.e., coastal and inland sites, large and small streams, high and low elevation sites), suggests that many streams in this region are responding similarly to regional climate forcing. Significant warming during many seasons of the year has more than offset a spring cooling trend in recent decades to cause a net temperature increase that generally tracks regional air temperature increases (Mote et al. 2003; Mote et al. 2005, Hamlet et al. 2007). As a result, this study adds to the growing list that documents warming of the Earth's rivers and streams (Petersen and Kitchell 2001; Morrison et al. 2002; Bartholow 2005; Hari et al. 2006; Webb and Nobilis 2007; Moatar and Gailhard 2006; Durance and Ormerod 2009; Kaushal et al. 2010), and makes a useful contribution by providing trend estimates that are not potentially confounded by short-term climate cycles, urbanization, or reservoir development.

Current projections for air temperature increases across the northwest U.S. (IPCC 2007; Mote et al. 2008) suggest stream temperatures will continue to warm this century. Moreover, these projections suggest air temperature increases during the next several decades will occur at rates 50–100% faster than in recent decades (Mote et al. 2008; Mantua et al. 2010). Air temperature increases of this magnitude during the summer would imply stream temperature warming rates of 0.3°C/decade–0.45°C/decade. Total thermal gains of 1.2°C–1.8°C could be expected by midcentury (assuming the ~60% ratio for stream:air warming rates we observed), which supports recent estimates Mantua et al. (2010) made for rivers across the state of Washington. Air temperature increases during non-summer seasons are projected to occur more slowly (Mote et al. 2008), and periods of cooling as we observed in the spring may even persist for decades at a time (Easterling and Wehner 2009), but it appears that fish and other aquatic organisms will ultimately have to adjust to warmer stream temperatures.

5.1 Seasonal trends and attribution

Air temperature was a much stronger predictor of stream temperatures than discharge in our models as others have found when these factors are considered simultaneously (Hockey et al. 1982; Webb et al. 2003; Moatar & Gailhard 2006; Isaak et al. 2010a; Van Vliet et al. 2010). Moreover, seasonal stream temperature trends (both warming and cooling) tracked air temperature trends during the same season and sometimes ran counter to the consistent warming effect otherwise expected from the general decline in discharge observed during all seasons at the monitoring sites (Table 2). Statistical interactions between air temperature and discharge were rare in the regression models, however, suggesting that stream temperature sensitivity to air temperature forcing was not contingent on discharge level. Rather, the two effects appear to be additive and the seasonal variation in stream warming rates is drawn from how the two predictors operate in concert or opposition over a period of time. So, for example, the largest warming trend during the summer resulted from the effects of the largest air temperature increases added to the largest discharge decreases, rather than smaller discharges being more easily warmed by air temperature increases.

Mechanistic explanations regarding how air temperatures affect stream temperatures have been treated in detail on numerous occasions (Mohseni and Stefan 1999; Caissie 2006; Webb et al. 2008), so are not addressed at length here. It suffices to say that air temperature affects more than one physical process in stream heat budgets and warms streams directly through sensible heat transfer, indirectly by increasing groundwater temperatures and advective heat gains (Taylor and Heinz 2009; Gunawardhana and Kazama 2011), and by radiating more long-wave radiation into streams (Webb and Zhang 1997; Webb et al. 2008). Less understood are mechanistic relationships between discharge and stream temperatures because it has often been assumed that this effect operated indirectly by increasing the sensitivity of streams to air temperature increases (e.g., Smith and Lavis 1975). The lack of a significant interaction in our regression models, however, suggests a different explanation. Discharge may in reality be a surrogate for water velocity such that higher discharges are indicative of decreased travel time through a reach and less opportunity for streams to equilibrate to local microclimatic conditions (Meier et al. 2003). This could explain why stream slope is often negatively related to stream temperature in river-network scale models (Sloat et al. 2005; Wehrly et al. 2009; Isaak et al. 2010a). An alternative mechanism may be that discharge equates to the relative influence of the snowpack and the amount of cold groundwater inputs along stream courses since many of the streams we studied are snowmelt dominated systems. In years with smaller snow accumulations, these groundwater inputs may be diminished and initial temperatures in headwater source areas warmer. Regardless, studies clarifying the mechanistic role of discharge in regulating stream temperatures would be useful.

5.2 Temperature monitoring needs

One of the strongest conclusions from this study is that long-term and representative monitoring of river and stream temperatures has been inadequate. Most monitoring records exist at sites that are near reservoirs or in urban environments (Kaushal et al. 2010), which largely compromises their utility for understanding a phenomenon such as climate change. Moreover, there are hundreds of thousands of unregulated stream kilometers that support fish and other aquatic organisms in the northwest U.S., yet perhaps only seven sites with more than a few decades of full year data to provide some indication of long-term temperature trends. In recent years, natural resource agencies have begun to deploy thousands of temperature sensors in streams across the region (Isaak et al. 2010b; Isaak and Horan 2011) but these efforts are poorly coordinated, often redundant, and typically limited to summer data collections due to concerns about instrument losses during annual floods. Implementation of an extensive monitoring network that generated full-year data would be invaluable and could be accomplished at a fraction of current costs if properly coordinated. Spatial databases, reliable and inexpensive sensor technology, and improved methods for establishing permanent sites in streams should make this easier in the future (Dunham et al. 2005; Isaak et al. 2010b; Isaak and Horan 2011).

Better monitoring efforts are important, but actions in the near-term to mitigate the threats posed by climate change will require information soon regarding how temperatures are changing across a broad array of streams. Historical reconstructions like those employed here or in previous studies (Moatar and Gailhard 2006; Isaak et al. 2010a; Van Vliet et al. 2010) could provide a powerful means of leveraging useful information from existing databases without waiting decades for monitoring data to accumulate. Another useful technique may be sensitivity analyses (Mohseni et al. 1999; Trumbo et al. 2010) wherein inter-annual changes in stream temperatures are examined across many monitoring sites spread along important environmental gradients (Post et al. 2009 provide a biological example). In the span of a few years, a monitoring network could generate the data necessary to disentangle the relative roles of spatial variation in local climate forcing (i.e., changes in air temperature and stream flow; Daly et al. 2009; Holden et al. 2011) and stream responsiveness due to geomorphic or other considerations (i.e., glaciation, elevation, ground water buffering; Hari et al. 2006; Brown and Hannah 2008; Tague et al. 2008) in effecting stream temperature change. To the extent that non-climate factors matter, they might then be used to develop geographic classification schemes for mapping the relative vulnerabilities of streams to climate change (e.g., Wolock et al. 2004; Santhi et al. 2008). These data would also contribute to a more general understanding of how temporal variation in stream thermal regimes is spatially structured and facilitate attribution of this variability to appropriate mechanisms at regional, landscape, and stream scales.

5.3 Implications for salmonid fishes

As streams and rivers across the northwest U.S. warm this century, it will have significant biological implications for both the quality and quantity of habitats available to species of regional importance like salmon and trout. Several anadromous salmon species that return to spawn each year in this region do so during the summer period when average temperatures and seasonal extremes (i.e., MaxWATs) are warming most rapidly. In some instances, these migrations are now periodically disrupted during especially warm periods as the fish pause to congregate near cold-water sources (Goneia et al. 2006; Sutton et al. 2007; Keefer et al. 2009) and fish that migrate during the year's warmest temperatures often return less successfully to their spawning areas (Cooke et al. 2004; Keefer et al. 2008). Thermal "events" wherein hundreds or thousands of adult salmon die simultaneously because thermal tolerances are exceeded have been documented in recent years (Lynch and Risley 2003, Doremus and Tarlock 2008; Keefer et al. 2010) and important recreational fisheries are now sometimes suspended during warm periods to minimize additional fish stress (Brick et al. 2008). The frequency of these thermal impacts to populations during warm summer periods appears likely to increase in the future

(Jentsch et al. 2007; Mantua et al. 2010), so understanding where thermal tolerances are close to being exceeded for key fisheries resources is an important priority.

Warming temperatures are also expected to have less dramatic, but wide-ranging population effects. Zones of species sympatry and thermal boundaries at the edges of species distributions are expected to gradually shift upstream (Parmesan and Yohe 2003; Root et al. 2003; Rieman and Isaak 2010) as the outcomes of competitive interactions are increasingly skewed towards species with warmer temperature tolerances (DeStaso and Rahel 1994; McMahon et al. 2007) and physiologic limits are exceeded (Pörtner and Farrell 2008). Such shifts will reduce habitats available to native trouts like cutthroat trout and bull trout that often persist in the colder waters upstream of encroaching non-native fishes (Peterson and Fausch 2003; Rieman et al. 2006; Fausch et al. 2006). Warmer cold season temperatures and annual minima also mean that biological processes will proceed at slightly faster rates during the winter period. Although this is a relatively quiescent time for the adults of many species in temperate streams, many salmon and trout species spawn in the fall and eggs incubate in stream substrates before hatching late in the winter or early spring. Egg development and hatching dates are strongly regulated by rates of degree-day accumulation (Crisp 1988; Beacham and Murray 1990), suggesting that warming trends will reduce the time between spawning and juvenile hatching. Accelerated egg development could benefit populations in high elevation streams that are currently too cold and unproductive to support populations (Bystrom et al. 2006; Coleman and Fausch 2007) but in other streams could desynchronize juvenile hatching and emergence dates from optimal periods dictated by annual floods and food availability (Brannon et al. 2004). In a few instances, migration dates of salmon past hydroelectric dams in northwest U.S. rivers appear already to be shifting in response to warming temperatures (Keefer et al. 2008; Crozier et al. 2008) but data to describe long-term biological responses during other life-stages or across spatial distributions are rare.

5.4 Management implications

Ongoing temperature increases will profoundly influence the ecology of salmonids as described above, but the summer period, in particular, may become a key bottleneck for many species. Not only are temperatures warming most rapidly during this period, but the volume of available habitat is shrinking as summer stream discharges across the region continue multi-decadal declines that have also been partially linked to climate change (Stewart et al. 2005; Luce and Holden 2009; Leppi et al. 2011). Many things can be done to ameliorate stresses on salmonids during this period (Rieman and Isaak 2010). On large rivers where cold-water storage is available behind reservoirs, water releases could be timed to decrease temperatures during critical biological periods as has been the case on the Clearwater River for migrating salmon in northern Idaho the last two decades. On smaller streams, maintaining or restoring instream flows and improving riparian communities to increase stream shading could offset significant amounts of future warming where degradation is severe (Meier et al. 2003; Moore et al. 2005; Cristea and Burges 2009). Removal of barriers to fish movement could decrease fragmentation and provide populations the flexibility to shift their distributions and track thermal habitat as needed (Fausch et al. 2006; Daufresne and Boet 2007; Isaak et al. 2010a). Basic fish distribution monitoring programs are also needed (Rieman et al. 2006; Isaak et al. 2009) so that anticipated shifts in species distributions can be accurately described in future decades to provide a clearer understanding of how salmonids integrate and respond to changes in thermal conditions (McCullough et al. 2009).

Tactical responses are key, but needed conservation projects are likely to greatly exceed available resources, so strategic prioritization schemes are essential. Improving regional monitoring networks and new models capable of accurately downscaling climate change effects on stream thermal regimes and other attributes across broad areas can provide the information necessary to implement such schemes (e.g., Rieman et al. 2007; Isaak et al. 2010a; Wenger et al. 2010; Wenger et al. 2011b). This information, however, needs to be integrated into detailed aquatic vulnerability assessments so that it provides "actionable intelligence" regarding priorities for specific projects at both regional and local scales. If these vulnerability assessments were used by consortiums of collaborating agencies with sets of common goals, available conservation resources could be leveraged across agencies and redundancies minimized (Rieman et al. 2010).

6 Conclusion

A growing number of studies predict substantial disruptions to aquatic ecosystems from climate change within the northwest U.S. (Battin et al. 2007; Rieman et al. 2007; Crozier et al. 2008; Schindler et al. 2008; Isaak et al. 2010a; Mantua et al. 2010; Wenger et al. 2011a) and more broadly (Eaton and Schaller 1996; Keleher and Rahel 1996; Mohseni et al. 2003; Hari et al. 2006; Heino et al. 2009). The trends in river and stream temperatures we document, in combination with increasing evidence of thermal constraints on some populations (Cooke et al. 2004; Goneia et al. 2006; Sutton et al. 2007; Keefer et al. 2007; Doremus and Tarlock 2008; Keefer et al. 2009), suggest these predictions are being realized. Although most species have persisted through greater climatic perturbations in past millennia, modern climate change is happening especially rapidly, at the end of an already warm period, and is being imposed on populations that are often already depressed and fragmented from a century of intense human development (McIntosh et al. 2000; Hessburg and Agee 2003). To minimize the losses of biodiversity that could occur in the next half century, much needs to be learned in a relatively short period of time about changing stream and river thermal regimes and aquatic ecological responses (McCullough et al. 2009).

The task is substantial, but the resources to create the necessary infrastructure for improved stream temperature monitoring, modeling, and strategic assessments would represent a tiny portion of those typically available for aquatic conservation purposes. In the northwest U.S., almost $4 billion U.S. dollars have been spent in recent decades to monitor and restore salmon and trout habitats (McDonald et al. 2007). These efforts have met with some success, but mainly have helped minimize declines in many species and stream habitats (McDonald et al. 2007; Al-Chokhachy et al. 2010). In a warmer, less predictable future, past investments and future project successes could be vulnerable to rising stream temperatures that gradually or catastrophically shift habitat suitability away from target species (Lawler et al. 2009). The apparent shift in recent years to cooler PDO conditions across the northwest U.S. may provide a brief respite before a warming trend is resumed that will become increasingly stressful for many salmonid fishes in the northwest U.S. This opportunity should be used to gain important information about stream temperature regimes and develop better tools, knowledge, and prioritization schemes for what may lie ahead.

Acknowledgements We thank the U.S. Geological Survey for making the stream temperature and discharge data available. This project was supported by the Rocky Mountain Research Station—Air, Water, and Aquatic Environments Program. An earlier draft of this manuscript was improved by comments from Bruce Rieman and Frank McCormick.

Appendix A

Table 4 Seasonal temperature trends at individual sites on 18 rivers and streams in two thermal classes across the northwest U.S. from 1980–2009. Trend rates from raw data were estimated as the slope parameter of simple linear regressions (multiplied by 10 to convert to decadal rate) of stream temperature versus year. Subscripts denote the r^2 of the simple linear regressions. Values in parentheses are decadal rates based on trends reconstructed using multiple regressions with air temperature and discharge as predictors

Site	Thermal category	Spring period (°C/decade)	Summer period (°C/decade)	Fall period (°C/decade)	Winter period (°C/decade)	Annual period (°C/decade)
1. Snake River Near Anatone, WA	Unregulated	$-0.18_{6\%}$ (−0.11)	$0.27_{7\%}$ (0.20)	$-0.15_{6\%}$ (0.12)	$0.09_{2\%}$ (0.08)	$-0.08_{2\%}$ (0.13)
2. North Fork Clearwater River, ID	Unregulated	$-0.31_{15\%}$ (−0.12)	$0.05_{0\%}$ (0.33)	$-0.10_{2\%}$ (0.13)	$0.01_{0\%}$ (0.05)	$-0.10_{2\%}$ (0.11)
3. Missouri River, MT	Unregulated	$-0.01_{0\%}$ (−0.05)	$0.33_{6\%}$ (0.14)	$0.29_{10\%}$ (0.18)	$-0.03_{1\%}$ (0.01)	$0.16_{6\%}$ (0.08)
6. South Fork Bull Run River, OR	Unregulated	$-0.15_{2\%}$ (−0.05)	$0.15_{2\%}$ (0.29)	$0.08_{2\%}$ (0.05)	$0.06_{1\%}$ (0.02)	$0.04_{0\%}$ (0.11)
7. Fir Creek, OR	Unregulated	$-0.08_{1\%}$ (−0.05)	$0.21_{5\%}$ (0.27)	$0.01_{0\%}$ (0.05)	$0.09_{3\%}$ (0.03)	$0.07_{1\%}$ (0.11)
8. North Fork Bull Run River, OR	Unregulated	$-0.15_{2\%}$ (−0.05)	$0.07_{3\%}$ (0.10)	$0.13_{6\%}$ (0.04)	$0.05_{1\%}$ (0.04)	$0.02_{0\%}$ (0.09)
9. Bull Run River, OR	Unregulated	$-0.10_{1\%}$ (−0.06)	$0.09_{1\%}$ (0.23)	$-0.08_{2\%}$ (0.05)	$0.10_{3\%}$ (0.03)	$-0.01_{0\%}$ (0.12)
	Average =	−0.14[a] (−0.07[a])	0.17[a] (0.22[a])	0.03 (0.09[a])	0.05[a] (0.04[a])	0.01 (0.11[a])
10. Clearwater River at Spaulding, ID	Regulated	$-0.22_{5\%}$	$-1.84_{63\%}$	$-0.33_{11\%}$	$-0.01_{0\%}$	$-0.71_{55\%}$
11. Clearwater River Near Peck, ID	Regulated	$0.06_{1\%}$	$-1.47_{68\%}$	$-0.34_{32\%}$	$0.17_{10\%}$	$-0.40_{37\%}$
12. Kootenai River, ID	Regulated	$-0.44_{18\%}$	$-0.25_{3\%}$	$-0.02_{0\%}$	$-0.19_{4\%}$	$-0.09_{2\%}$
13. Madison River, MT	Regulated	$0.20_{2\%}$	$0.45_{16\%}$	$0.22_{5\%}$	$0.03_{1\%}$	$0.17_{6\%}$
14. Flathead River, MT	Regulated	$-0.06_{1\%}$	$1.05_{53\%}$	$1.00_{51\%}$	$-0.16_{10\%}$	$0.44_{45\%}$
15. Fall Creek, OR	Regulated	$-0.25_{10\%}$	$0.59_{14\%}$	$0.07_{1\%}$	$0.16_{4\%}$	$0.05_{1\%}$
16. North Santiam River, OR	Regulated	$0.05_{1\%}$	$0.52_{21\%}$	$-0.11_{3\%}$	$0.19_{8\%}$	$0.16_{13\%}$
17. Rogue River Near McLeod, OR	Regulated	$0.41_{40\%}$	$0.27_{15\%}$	$0.17_{7\%}$	$0.01_{0\%}$	$0.25_{25\%}$
18. Blue River, OR	Regulated	$-0.19_{14\%}$	$-0.48_{11\%}$	$-0.77_{28\%}$	$0.05_{0\%}$	$-0.38_{27\%}$
19. Rogue River at Dodge Bridge, OR	Regulated	$0.30_{13\%}$	$0.33_{14\%}$	$0.24_{21\%}$	$0.19_{11\%}$	$0.17_{10\%}$
20. South Santiam River, OR	Regulated	$-0.31_{15\%}$	$-0.33_{32\%}$	$0.24_{13\%}$	$0.06_{1\%}$	$-0.11_{4\%}$
	Average =	−0.04	−0.11	0.03	0.05	−0.04

[a] Statistically significant at $\alpha \leq 0.05$

Appendix B

Table 5 Multiple regression relationships predicting stream temperatures from air temperature and discharge from 1980–2009 for seven unregulated river and stream sites in the northwest U.S. Discharge data were obtained from the USGS gage co-located with the water temperature sensor and air temperature data were averages from the nearest three NOAA Cooperative Observer weather stations

Site	Regression equations[a]	R^2	RMSE(°C)	Significant air temperature-discharge interaction?	COOP stations
Spring period					
1. Snake River Near Anatone, WA	$y=3.43+0.588^{a}(\text{air °C}) - 0.00013(\text{m}^3/\text{s})$	0.68	0.37	No	102845, 457059, 355593
2. North Fork Clearwater River, ID	$y=1.48+0.548^{a}(\text{air °C}) - 0.00373(\text{m}^3/\text{s})$	0.79	0.32	No	102845, 457938, 245745
3. Missouri River, MT	$y=7.05+0.583^{a}(\text{air °C}) - 0.00499^{a}(\text{m}^3/\text{s})$	0.85	0.35	Yes	248597, 241318, 249023
6. South Fork Bull Run River, OR	$y=1.01+0.716^{a}(\text{air °C}) - 0.183^{a}(\text{m}^3/\text{s})$	0.85	0.32	No	353402, 354003, 357500
7. Fir Creek, OR	$y=0.0139+0.701^{a}(\text{air °C}) - 0.313(\text{m}^3/\text{s})$	0.89	0.26	No	353402, 354003, 357500
8. North Fork Bull Run River, OR	$y=0.768+0.710^{a}(\text{air °C}) - 0.307^{a}(\text{m}^3/\text{s})$	0.84	0.33	No	353402, 354003, 357500
9. Bull Run River, OR	$y=-0.276+0.810^{a}(\text{air °C}) - 0.0392(\text{m}^3/\text{s})$	0.83	0.32	No	353402, 354003, 357500
	Average =	0.82	0.32		
Summer period					
1. Snake River Near Anatone, WA	$y=9.02+0.559^{a}(\text{air °C}) - 0.00116^{a}(\text{m}^3/\text{s})$	0.81	0.39	No	Same as above
2. North Fork Clearwater River, ID	$y=5.44+0.650^{a}(\text{air °C}) - 0.0256^{a}(\text{m}^3/\text{s})$	0.96	0.28	No	
3. Missouri River, MT	$y=9.00+0.670^{a}(\text{air °C}) - 0.00521^{a}(\text{m}^3/\text{s})$	0.62	0.71	No	
6. South Fork Bull Run River, OR	$y=3.17+0.595^{a}(\text{air °C}) - 0.803^{a}(\text{m}^3/\text{s})$	0.85	0.33	No	
7. Fir Creek, OR	$y=2.78+0.527^{a}(\text{air °C}) - 2.73^{a}(\text{m}^3/\text{s})$	0.85	0.31	Yes	
8. North Fork Bull Run River, OR	$y=6.89+0.217^{a}(\text{air °C}) - 0.319^{a}(\text{m}^3/\text{s})$	0.45	0.26	No	
9. Bull Run River, OR	$y=5.69+0.445^{a}(\text{air °C}) - 0.272^{a}(\text{m}^3/\text{s})$	0.79	0.37	No	
	Average =	0.76	0.38		
Fall period					
1. Snake River Near Anatone, WA	$y=9.42+0.438^{a}(\text{air °C}) - 0.00011(\text{m}^3/\text{s})$	0.51	0.37	No	
2. North Fork Clearwater River, ID	$y=2.47+0.607^{a}(\text{air °C})+0.00349(\text{m}^3/\text{s})$	0.41	0.47	No	
3. Missouri River, MT	$y=6.64+0.453^{a}(\text{air °C}) - 0.00387(\text{m}^3/\text{s})$	0.67	0.46	No	

Table 5 (continued)

Site	Regression equations[a]	R^2	RMSE(°C)	Significant air temperature-discharge interaction?	COOP stations
6. South Fork Bull Run River, OR	$y=4.04+0.417^{a}(\text{air °C})+0.161^{a}(m^3/s)$	0.60	0.32	No	
7. Fir Creek, OR	$y=3.27+0.482^{a}(\text{air °C})+0.0864(m^3/s)$	0.59	0.30	No	
8. North Fork Bull Run River, OR	$y=3.72+0.378^{a}(\text{air °C})+0.215^{a}(m^3/s)$	0.57	0.30	No	
9. Bull Run River, OR	$y=3.19+0.518^{a}(\text{air °C})+0.00844(m^3/s)$	0.56	0.33	No	
	Average =	0.56	0.36		
Winter period					
1. Snake River Near Anatone, WA	$y=3.48+0.309^{a}(\text{air °C}) - 0.000015(m^3/s)$	0.59	0.35	No	
2. North Fork Clearwater River, ID	$y=0.806+0.211^{a}(\text{air °C})+0.0087^{a}(m^3/s)$	0.53	0.40	No	
3. Missouri River, MT	$y=1.10+0.113^{a}(\text{air °C}) - 0.00061(m^3/s)$	0.34	0.26	No	
6. South Fork Bull Run River, OR	$y=2.78+0.490^{a}(\text{air °C})+0.0232(m^3/s)$	0.72	0.29	No	
7. Fir Creek, OR	$y=3.25+0.407^{a}(\text{air °C}) - 0.118(m^3/s)$	0.73	0.24	No	
8. North Fork Bull Run River, OR	$y=3.09+0.489^{a}(\text{air °C}) - 0.160^{a}(m^3/s)$	0.78	0.24	No	
9. Bull Run River, OR	$y=2.57+0.448^{a}(\text{air °C}) - 0.00431(m^3/s)$	0.70	0.28	No	
	Average =	0.63	0.29		
Annual period					
1. Snake River Near Anatone, WA	$y=3.94+0.731^{a}(\text{air °C}) - 0.000141(m^3/s)$	0.66	0.32	No	
2. North Fork Clearwater River, ID	$y=1.31+0.743^{a}(\text{air °C}) - 0.00439(m^3/s)$	0.47	0.50	No	
3. Missouri River, MT	$y=7.86+0.423^{a}(\text{air °C}) - 0.00677^{a}(m^3/s)$	0.64	0.38	No	
6. South Fork Bull Run River, OR	$y=0.316+0.839^{a}(\text{air °C}) - 0.116(m^3/s)$	0.76	0.27	No	
7. Fir Creek, OR	$y=1.15+0.713^{a}(\text{air °C}) - 0.720^{a}(m^3/s)$	0.74	0.26	No	
8. North Fork Bull Run River, OR	$y=1.77+0.603^{a}(\text{air °C}) - 0.241(m^3/s)$	0.71	0.23	No	
9. Bull Run River, OR	$y=0.827+0.811^{a}(\text{air °C}) - 0.0812^{a}(m^3/s)$	0.75	0.28	No	
	Average =	0.68	0.32		

[a] Statistically significant at $\alpha \le 0.05$

Appendix C

Table 6 Relative contributions of air temperature and discharge to reconstructed seasonal stream temperature trends and inter-annual variation in raw time series (standardized regression coefficients) from 1980–2009 at seven unregulated river and stream sites in the northwest U.S

Site	Reconstructed trends		
	Total stream temperature change (°C)	Air temperature, discharge contributions (°C)[a]	Standardized b_x's (air temperature, discharge)[b]
Spring Period			
1. Snake River Near Anatone, WA	−0.325	−0.307, −0.018	0.78, −0.12
2. North Fork Clearwater River, ID	−0.346	−0.453, 0.107	0.80, −0.20
3. Missouri River, MT	−0.155	−0.198, 0.043	0.81, −0.25
6. South Fork Bull Run River, OR	−0.143	−0.168, 0.024	0.81, −0.20
7. Fir Creek, OR	−0.147	−0.164, 0.017	0.88, −0.14
8. North Fork Bull Run River, OR	−0.150	−0.166, 0.017	0.80, −0.22
9. Bull Run River, OR	−0.181	−0.189, 0.009	0.85, −0.17
Average =	−0.207		
Summer Period			
1. Snake River Near Anatone, WA	0.600	0.564, 0.036	0.55, −0.57
2. North Fork Clearwater River, ID	0.978	0.604, 0.374	0.41, −0.83
3. Missouri River, MT	0.409	0.316, 0.093	0.57, −0.39
6. South Fork Bull Run River, OR	0.868	0.759, 0.108	0.56, −0.50
7. Fir Creek, OR	0.795	0.672, 0.123	0.51, −0.57
8. North Fork Bull Run River, OR	0.308	0.277, 0.032	0.47, −0.35
9. Bull Run River, OR	0.684	0.567, 0.118	0.40, −0.64
Average =	0.663		
Fall Period			
1. Snake River Near Anatone, WA	0.358	0.348, 0.010	0.70, −0.03
2. North Fork Clearwater River, ID	0.388	0.390, −0.002	0.62, 0.08
3. Missouri River, MT	0.528	0.452, 0.076	0.77, −0.15
6. South Fork Bull Run River, OR	0.148	0.128, 0.021	0.77, 0.30
7. Fir Creek, OR	0.150	0.148, 0.003	0.76, 0.06
8. North Fork Bull Run River, OR	0.129	0.116, 0.014	0.76, 0.26
9. Bull Run River, OR	0.161	0.158, 0.003	0.74, 0.06
Average =	0.266		
Winter Period			
1. Snake River Near Anatone, WA	0.251	0.248, 0.003	0.77, −0.01
2. North Fork Clearwater River, ID	0.140	0.192, −0.052	0.47, 0.51
3. Missouri River, MT	0.015	0.011, 0.004	0.58, −0.03
6. South Fork Bull Run River, OR	0.072	0.076, −0.004	0.84, 0.06
7. Fir Creek, OR	0.077	0.064, 0.013	0.86, −0.12
8. North Fork Bull Run River, OR	0.127	0.076, 0.051	0.91, −0.28
9. Bull Run River, OR	0.077	0.070, 0.008	0.85, −0.04
Average =	0.109		

Table 6 (continued)

Site	Reconstructed trends		
	Total stream temperature change (°C)	Air temperature, discharge contributions (°C)[a]	Standardized b_x's (air temperature, discharge)[b]
Annual Period			
1. Snake River Near Anatone, WA	0.384	0.381, 0.003	0.78, −0.08
2. North Fork Clearwater River, ID	0.342	0.296, 0.046	0.60, −0.15
3. Missouri River, MT	0.247	0.157, 0.090	0.52, −0.45
6. South Fork Bull Run River, OR	0.334	0.322, 0.011	0.84, −0.11
7. Fir Creek, OR	0.323	0.274, 0.050	0.77, −0.25
8. North Fork Bull Run River, OR	0.260	0.232, 0.028	0.77, −0.18
9. Bull Run River, OR	0.365	0.311, 0.054	0.78, −0.26
Average =	0.322		

[a] Stream temperature change at a site from 1980–2009 associated with 30 year trend in air temperature and 56 year trend in discharge.

[b] Standardized coefficients were derived from multiple regressions in Appendix A.

References

Al-Chokhachy R, Roper BB, Archer EK (2010) Evaluating the status and trends of physical stream habitat in headwater streams within the interior Columbia River and upper Missouri River basins using an index approach. Trans Am Fish Soc 139:1041–1059

Barnett TP, Pierce DW, Hidalgo HG, Bonfils C, Santer BD, Das T, Bala G, Wood AW, Nozawa T, Mirin AA, Cayan DR, Dettinger MD (2008) Human induced changes in the hydrology of the western United States. Sci 319:1080–1083

Bartholow JM (2005) Recent water temperature trends in the lower Klamath River, California. North Am J Fish Manag 25:152–162

Battin J, Wiley MW, Ruckelshaus MH, Palmer RN, Korb E, Bartz KK, Imaki H (2007) Projected impacts of climate change on salmon habitat restoration. Proc Nat Acad Sci (USA) 104:6720–6725

Beacham TD, Murray CB (1990) Temperature, egg size, and development of embryos and alevins of five species of Pacific salmon: a comparative analysis. Trans Am Fish Soc 119:927–945

Beever EA, Ray C, Mote PW, Wilkening JL (2010) Testing alternative models of climate-mediated extirpations. Ecol Appl 20:164–178

Brannon EL, Powell MS, Quinn TP, Talbot A (2004) Population structure of Columbia River basin Chinook salmon and steelhead trout. Rev Fish Sci 12:99–232

Brick C, Randall B, Oberbillig D (2008) Low flows, hot trout: climate change in the Clark Fork watershed. Clark Fork Coalition, Missoula

Brown GW (1969) Predicting temperatures of small streams. Water Resour Res 5:68–75

Brown LE, Hannah DM (2008) Spatial heterogeneity of water temperature across an alpine river basin. Hydrol Proc 22:954–967

Buisson LL, Blanc GG, Grenouillet G (2008) Modelling stream fish species distribution in a river network: the relative effects of temperature versus physical factors. Ecol Freshw Fish 17:244–257

Bystrom P, Andersson J, Kiessling A, Eriksson LO (2006) Size and temperature dependent foraging capacities and metabolism: consequences for winter starvation mortality in fish. Oikos 115:43–52

Caissie D (2006) The thermal regime of rivers: a review. Freshw Biol 51:1389–1406

Coleman MA, Fausch KD (2007) Cold summer temperature limits recruitment of age-0 cutthroat trout in high elevation Colorado streams. Trans Am Fish Soc 136:1231–1244

Cooke SJ, Hinch SG, Farrell AP, Lapointe MF, Jones SMR, Macdonald JS, Patterson DA, Healey MC, Van Der Kraak G (2004) Abnormal migration timing and high en route mortality of sockeye salmon in the Fraser River, British Columbia. Fisheries 29:22–33
Crisp DT (1988) Prediction, from temperature, of eyeing, hatching and 'swim-up' times for salmonid embryos. Freshw Biol 19:41–48
Cristea NC, Burges SJ (2009) An assessment of the current and future thermal regimes of three streams located in the Wenatchee River basin, Washington State: some implications for regional river basin systems. Clim Change 102:493–520
Crozier LG, Hendry AP, Lawson PW, Quinn TP, Mantua NJ, Battin J, Shaw RG, Huey RB (2008) Potential responses to climate change in organisms with complex life histories: evolution and plasticity in Pacific salmon. Evol Appl 1:252–270
Daly C, Conklin DR, Unsworth MH (2009) Local atmospheric decoupling in complex topography alters climate change impacts. Int J Climatol. doi:10.1002/joc.2007
Daufresne MD, Boet P (2007) Climate change impacts on structure and diversity of fish communities in rivers. Global Change Biol 13:2467–2478
DeStaso J, Rahel FJ (1994) Influence of water temperature on interactions between juvenile Colorado River cutthroat trout and brook trout in a laboratory stream. Trans Am Fish Soc 123: 289–297
Doremus H, Tarlock AD (2008) Water war in the Klamath Basin. Macho Law, Combat Biology, and Dirty Politics. Island Press, Washington
Dunham JB, Chandler G, Rieman BE, Martin D (2005) Measuring stream temperature with digital dataloggers: a user's guide. General Technical Report RMRSGTR-150WWW. U.S. Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado, USA.
Durance I, Ormerod SJ (2009) Trends in water quality and discharge confound long-term warming effects on river macroinvertebrates. Freshw Ecol 54:388–405
Easterling DR, Wehner MF (2009) Is the climate warming or coolings? Geophys Res Lett 36:L08706. doi:10.1029/2009GL037810
Eaton GJ, Schaller RM (1996) Effects of climate warming on fish thermal habitat in streams of the United States. Limnol Oceanogr 41:1109–1115
Fausch K, Rieman B, Young M, Dunham J (2006) Strategies for conserving native salmonid populations at risk from nonnative invasions: tradeoffs in using barriers to upstream movement. Gen. Tech. Rep. RMRS-GTR-174. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 44 p.
Goneia TM, Keefer ML, Bjornn TC, Peery CA, Bennett DH, Stuehrenberg LC (2006) Behavioral thermoregulation and slowed migration by adult fall Chinook salmon in response to high Columbia River water temperatures. Trans Am Fish Soc 135:408–419
Gunawardhana LN, Kazama S (2011) Climate change impacts on groundwater temperature change in the Sendai plain, Japan. Hydrol Proc 25:2665–2678
Hamlet AF, Lettenmaier DP (1999) Columbia River streamflow forecasting based on ENSO and PDO climate signals. J Water Resour Plan Manag 125:333–341
Hamlet AF, Mote PW, Clark MP, Lettenmaier DP (2005) Effects of temperature and precipitation variability on snowpack trends in the western United States. J Clim 18:4545–4561
Hamlet AF, Mote PW, Clark MP, Lettenmaier DP (2007) Twentieth-century trends in runoff, evapotranspiration, and soil moisture in the western United States. J Clim 20:1468–1486
Hari RE, Livingstone DM, Siber R, Burkhardt-Holm P, Guttinger H (2006) Consequences of climatic change for water temperature and brown trout populations in alpine rivers and streams. Glob Change Biol 12:10–26
Heino J, Virkkala R, Toivonen H (2009) Climate change and freshwater biodiversity: detected patterns, future trends and adaptations in northern regions. Biol Rev 84:39–54
Hessburg PF, Agee JK (2003) An environmental narrative on inland northwest United States forests, 1800–2000. Forest Ecol Manag 178:23–59
Hockey JB, Owens IF, Tapper NJ (1982) Empirical and theoretical models to isolate the effect of discharge on summer water temperatures in the Hurunui River. J Hydrol (New Zealand) 21:1–12
Holden ZA, Crimmins MC, Cushman SA, Littell JS (2011) Empirical modeling of temporal and spatial variation in nocturnal warm season temperature across two North Idaho Mountain ranges, USA. Agri Forest Meteorol 151:261–269
Intergovernmental Panel on Climate Change (IPCC) (2007) Climate change 2007: the physical science basis. [Online]. Available: http://www.ipcc.ch/ [January 21, 2009].
Isaak DJ, Horan DL (2011) An evaluation of underwater epoxies to permanently install temperature sensors in mountain streams. North Am J Fish Manag 31:134–137

Isaak DJ, Rieman BE, Horan D (2009) A watershed-scale monitoring protocol for bull trout. Gen. Tech. Rep. GTR-RMRS-224. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 25 p

Isaak DJ, Luce CH, Rieman BE, Nagel DE, Peterson EE, Horan DL, Parkes S, Chandler GL (2010a) Effects of climate change and recent wildfires on stream temperature and thermal habitat for two salmonids in a mountain river network. Ecol Appl 20:1350–1371

Isaak DJ, Holden Z, Roper B, Luce C (2010b) Complimentary and dense sensor networks to understand climate variability in mountainous terrain. Abstract GC51D-0771 presented at 2010 Fall Meeting, American Geophysical Union, San Francisco, CA, Dec 13–17.

Jentsch A, Kreyling J, Beierkuhnlein C (2007) A new generation of climate-change experiments: events, not trends. Frontiers Ecol Environ 5:365–374

Johnson SL (2003) Stream temperature: scaling of observations and issue for modeling. Hydrol Proc 17:497–499

Kaushal SS, Likens GE, Jaworski NA, Pace ML, Sides AM, Seekell D, Belt KT, Secor DH, Wingate RL (2010) Rising stream and river temperatures in the US. Frontiers Ecol Environ. doi:10.1890/090037

Keefer ML, Peery CA, Heinrich MJ (2008) Temperature mediated en route migration mortality and travel rates of endangered Snake River sockeye salmon. Ecol Freshw Fish 17:136–145

Keefer ML, Peery CA, High B (2009) Behavioral thermoregulation and associated mortality trade-offs in migrating adult steelhead (*Oncorhynchus mykiss*): variability among sympatric populations. Can J Fish Aquat Sci 66:1734–1747

Keefer ML, Taylor GA, Garletts DF, Gauthier GA, Pierce TM, Caudill CC (2010) Prespawn mortality in adult spring Chinook salmon outplanted above barrier dams. Ecol Freshw Fish 19:361–372

Keleher CJ, Rahel FJ (1996) Thermal limits to salmonid distributions in the Rocky Mountain region and potential habitat loss due to global warming: a geographic information system (GIS) approach. Trans Am Fish Soc 125:1–13

Kiffney PM, Bull JP, Feller MC (2002) Climatic and hydrologic variability in a coastal watershed of southwestern British Columbia. J Am Water Resour Ass 38:1437–1451

Knowles N, Dettinger MD, Cayan DR (2006) Trends in snowfall versus rainfall in the Western United States. J Clim 19:4545–4559

Langan SJ, Johnston UL, Donaghy MJ, Youngson AF, Hay DW, Soulsby C (2001) Variation in river water temperatures in an upland stream over a 30-year period. Sci Total Environ 265:195–207

Lawler JJ, Tear TH, Pyke C, Shaw MR, Gonzalez P, Kareiva P, Hansen L, Hannah L, Klausmeyer K, Aldous A, Bienz C, Pearsall S (2009) Resource management in a changing and uncertain climate. Frontiers Ecol Environ. doi:10.1890/070146

Leppi JC, DeLuca TH, Harrar SW, Running SW (2011) Impacts of climate change on August stream discharge in the Central-Rocky Mountains Climatic Change. doi:10.1007/s10584-011-0235-1

Lynch DD, Risley JC (2003) Klamath River Basin hydrologic conditions prior to the September 2002 die-off of Salmon and Steelhead. U.S. Geological Survey Water-Resources Investigations Report 03–4099.

Luce CH, Holden ZA (2009) Declining annual streamflow distributions in the Pacific Northwest United States. Geophys Res Lett 36:L16401. doi:10.1029/2009GL039407

Mantua NJ, Hare SR (2002) The Pacific decadal oscillation. J Oceanogr 58:35–44

Mantua NJ, Tohver I, Hamlet A (2010) Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington state. Clim Change 102:187–223

McCullough DA, Bartholow JM, Jager HI, Beschta RL, Cheslak EF, Deas ML, Ebersole JL, Foott JS, Johnson SL, Marine KR, Mesa MG, Petersen JH, Souchon Y, Tiffan KF, Wurtsbaugh WA (2009) Research in thermal biology: burning questions for coldwater stream fishes. Rev Fisheries Sci 17:90–115

McDonald LL et al (2007) Research, monitoring, and evaluation of fish and wildlife restoration projects in the Columbia River Basin: lessons learned and suggestions for large-scale monitoring programs. Fisheries 32:582–590

McIntosh BA, Sedell JR, Thurow RF, Clarke SE, Chandler GL (2000) Historical changes in pool habitats in the Columbia River basin. Ecol Appl 10:1478–1496

McMahon TE, Zale AV, Barrows FT, Selong JH, Danehy RJ (2007) Temperature and competition between bull trout and brook trout: a test of the elevation refuge hypothesis. Trans Am Fish Soc 136:1313–1326

Meehl GA, Tebaldi C, Walton G, Easterling D, McDaniel L (2009) Relative increase of record high maximum temperatures compared to record low minimum temperatures in the U.S. Geophys Res Lett 36:L23701. doi:10.1029/2009GL040736

Meier W, Bonjour C, Wüest A, Reichert P (2003) Modeling the effect of water diversion on the temperature of mountain streams. J Environ Eng 129:755–764

Menne MJ, Williams CN, Vose RS (2009) The United States historical climatology network monthly temperature data version 2. Bull Amer Meteor Soc 90:993–1007
Moatar F, Gailhard J (2006) Water temperature behaviour in the River Loire since 1976 and 1881. Comptes Rendus Geosci 338:319–328
Mohseni O, Stefan HG (1999) Stream temperature/air temperature relationship: a physical interpretation. J Hydrol 218:128–141
Mohseni O, Stefan HG, Erickson TR (1998) A nonlinear regression model for weekly stream temperatures. Water Resour Res 34:2685–2692
Mohseni O, Erickson TR, Stefan HG (1999) Sensitivity of stream temperatures in the United States to air temperatures projected under a global warming scenario. Water Resour Res 35:3723–3733
Mohseni O, Stefan HG, Eaton JG (2003) Global warming and potential changes in fish habitat in U.S. streams. Clim Change 59:389–409
Moore RD, Spittlehouse DL, Story A (2005) Riparian microclimate and stream temperature response to forest harvesting: a review. J Am Water Resour Ass 41:813–834
Morrison J, Quick MC, Foreman MGG (2002) Climate change in the Fraser River watershed: flow and temperature projections. J Hydrol 263:230–244
Mote PW (2003) Trends in temperature and precipitation in the Pacific Northwest during the twentieth century. Northwest Sci 77:271–282
Mote PW, Parson EA, Hamlet AF, Keeton WS, Lettenmaier D, Mantua N, Miles EL, Peterson DW, Peterson DL, Slaughter R, Snover AK (2003) Preparing for climatic change: the water, salmon, and forests of the Pacific Northwest. Clim Change 61:45–88
Mote PW, Hamlet AF, Clark MP, Lettenmaier DP (2005) Declining mountain snowpack in western North America. Bull Am Meteorol Soc 86:39–49
Mote PW, Salathé E, Dulière V, Jump E (2008) Scenarios of future climate for the Pacific Northwest. Seattle, WA: University of Washington, Climate Impacts Group. Report prepared by the Climate Impacts Group, Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Oceans
Nelson KC, Palmer MA (2007) Stream temperature surges under urbanization and climate change: data, models, and responses. J Amer Water Resources Ass 43:440–452
Neuheimer AB, Taggart CT (2007) The growing degree-day and fish size-at-age: the overlooked metric. Can J Fish Aquat Sci 64:375–385
Olden JD, Naiman RJ (2009) Incorporating thermal regimes into environmental assessments: modifying dam operations to restore freshwater ecosystem integrity. Freshw Biol. doi:10.1111/j.1365-2427.2009.02179.x
Parmesan C, Yohe G (2003) A globally coherent fingerprint of climate change impacts across natural systems. Nature 421:37–42
Petersen JH, Kitchell JF (2001) Climate regimes and water temperature changes in the Columbia River: bioenergetic implications for predators of juvenile salmon. Can J Fish Aquat Sci 58:1831–1841
Peterson DP, Fausch KD (2003) Upstream movement by nonnative brook trout (*Salvelinus fontinalis*) promotes invasion of native cutthroat trout (*Oncorhynchus clarki*) habitat. Can J Fish Aquat Sci 60:1502–1516
Patterson DA, Macdonald JS, Skibo KM, Barnes D, Guthrie I, Hills J (2007) Reconstructing the summer thermal history for the lower Fraser River 1941 to 2006, and implications for adult sockeye salmon (*Oncorhynchus nerka*) spawning migration. Can Tech Rep Fish Aquat Sci 2724:1–43
Poff NL, Richter BD, Arthington AH, Bunn SE, Naiman RJ, Kendy E, Acreman M, Apse C, Bledsoe B, Freeman MC, Henriksen J, Jacobson RB, Kennen JG, Merritt DM, O'Keeffe JH, Olden J, Rogers K, Tharme RE, Warner A (2010) The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. Freshw Biol 55:147–170
Pörtner HO, Farrell AP (2008) Physiology and climate change. Sci 322:690–692
Post E, Brodie J, Hebblewhite M, Anders AD, Maier JAK, Wilmers CC (2009) Global population dynamics and hot spots of response to climate change. Biosci 59:489–497
Regonda SK, Rajagopalan B, Clark M, Pitlick J (2005) Seasonal cycle shifts in hydroclimatology over the Western United States. J Clim 18:372–384
Rieman BE, Isaak DJ (2010) Climate change, aquatic ecosystems and fishes in the Rocky Mountain West: implications and alternatives for management. USDA Forest Service, Rocky Mountain Research Station, GTR-RMRS-250, Fort Collins, CO
Rieman BE, Peterson JT, Myers DL (2006) Have brook trout *Salvelinus fontinalis* displaced bull trout *Salvelinus confluentus* along longitudinal gradients in central Idaho streams? Can J Fish Aquat Sci 63:63–78
Rieman BE, Isaak DJ, Adams S, Horan D, Nagel D, Luce C, Myers D (2007) Anticipated climate warming effects on bull trout habitats and populations across the Interior Columbia River Basin. Trans Am Fish Soc 136:1552–1565

Rieman BE, Hessburg PF, Luce C, Dare MR (2010) Wildfire and management of forests and native fishes: conflict or opportunity for convergent solutions? BioScience 60:460–468
Rood SB, Pan J, Gill KM, Franks CG, Samuelson GM, Shepherd A (2008) Declining summer flows of Rocky Mountain rivers: changing seasonal hydrology and probably impacts on floodplain forests. J Hydrol 349:397–410
Root TL, Price JT, Hall KR, Schneider SH, Rosenweig C, Pounds JA (2003) Fingerprints of global warming on wild animals and plants. Nature 421:57–60
Santhi C, Allen PM, Muttiah RS, Arnold JG, Tuppan P (2008) Regional estimation of base flow for the conterminous United States by hydrologic landscape regions. J Hydrol 351:139–153
Saunders S, Montgomery C, Easley T, Spencer T (2008) Hotter and drier: the West's changed climate. [Online]. The Rocky Mountain Climate Organization. Available: http://www.rockymountainclimate.org/ [March, 2008].
Schindler DE, Augerot X, Fleishman E, Mantua NJ, Riddell B, Ruckelshaus M, Seeb J, Webster M (2008) Climate change, ecosystem impacts, and management for Pacific Salmon. Fisheries 33:502–506
Sloat MR, Shepard BB, White RG, Carson S (2005) Influence of stream temperature on the spatial distribution of westslope cutthroat trout growth potential within the Madison River basin, Montana. North Am J Fish Manag 25:225–237
Smith K, Lavis ME (1975) Environmental influences on the temperature of a small upland stream. Oikos 26:228–236
Stewart IT, Cayan DR, Dettinger MD (2005) Changes toward earlier streamflow timing across western North America. J Clim 18:1136–1155
Sutton RJ, Deas ML, Tanaka SK, Soto T, Corum RA (2007) Salmonid observations at a Klamath River thermal refuge under various hydrological and meteorological conditions. River Res Appl 23:775–785
Tague C, Grant G, Farrell M, Choate J, Jefferson A (2008) Deep groundwater mediates streamflow response to climate warming in the Oregon Cascades. Clim Change 86:189–210
Taylor CA, Heinz SG (2009) Shallow groundwater temperature response to climate change and urbanization. J Hydrol 375:601–612
Trumbo B, Hudy M, Smith EP, Kim DY, Wiggins BA, Nislow KH, Dolloff CA (2010) Sensitivity and vulnerability of brook trout populations to climate change. Proc 10th Annu Wild Trout Symp, West Yellowstone, MT.
van Vliet MTH, Ludwig F, Zwolsman JJG, Weedon GP, Kabat P (2010) Global river temperatures and sensitivity to atmospheric warming and changes in river flow. Water Resour Res 47:W02544. doi:10.1029/2010WR009198
Webb BW, Nobilis F (2007) Long-term changes in river temperature and the influence of climatic and hydrological factors. Hydrol Sci J 52:74–85
Webb BW, Clack PD, Walling DE (2003) Water-air temperature relationships in a Devon river system and the role of flow. Hydrol Proc 17:3069–3084
Webb BW, Hannah DM, Moore RD, Brown LE, Nobilis F (2008) Recent advances in stream and river temperature research. Hydrol Proc 22:902–918
Webb BW, Zhang Y (1997) Spatial and seasonal variability in the components of the river heat budget. Hydrol Proc 11:79–101
Wehrly KE, Brenden TO, Wang L (2009) A comparison of statistical approaches for predicting stream temperatures across heterogeneous landscapes. J Am Wat Res Assoc 45:986–997
Wenger SJ, Luce CH, Hamlet AF, Isaak DJ, Neville HM (2010) Macroscale hydrologic modeling of ecologically relevant flow metrics. Water Resour Res 46:W09513. doi:10.1029/2009WR008839
Wenger SJ, Isaak DJ, Dunham JB, Fausch KD, Luce CH, Neville HM, Rieman BE, Young MK, Nagel DE, Horan DL, Chandler GL (2011a) Role of climate and invasive species in structuring trout distributions in the Interior Columbia Basin, USA. Can J Fish Aqua Sci 68:988–1008
Wenger SJ, Isaak DJ, Luce CH, Neville HM, Fausch KD, Dunham JD, Dauwalter DC, Young MK, Elsner MM, Rieman BE, Hamlet AF, and Williams JE (2011b) Flow regime, temperature, and biotic interactions drive differential declines of trout species under climate change. Proc Nat Acad Sci doi:10.1073/pnas.1103097108.
Wolock DM, Winter TC, McMohan G (2004) Delineation and evaluation of hydrologic-landscape regions in the United States using geographic information system tools and multivariate statistical analyses. Environ Manage 34:71–88