

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

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[1] Temperature is a fundamentally important driver of ecosystem processes in streams. Recent warming of terrestrial climates around the globe has motivated concern about consequent increases in stream temperature. More specifically, observed trends of increasing air temperature and declining stream flow are widely believed to result in corresponding increases in stream temperature. Here, we examined the evidence for this using long-term stream temperature data from minimally and highly human-impacted sites located across the Pacific continental United States. Based on hypothesized climate impacts, we predicted that we should find warming trends in the maximum, mean and minimum temperatures, as well as increasing variability over time. These predictions were not fully realized. Warming trends were most prevalent in a small subset of locations with longer time series beginning in the 1950s. More recent series of observations (1987–2009) exhibited fewer warming trends and more cooling trends in both minimally and highly human-influenced systems. Trends in variability were much less evident, regardless of the length of time series. Based on these findings, we conclude that our perspective of climate impacts on stream temperatures is clouded considerably by a lack of long-term data on minimally impacted streams, and biased spatio-temporal representation of existing time series. Overall our results highlight the need to develop more mechanistic, process-based understanding of linkages between climate change, other human impacts and stream temperature, and to deploy sensor networks that will provide better information on trends in stream temperatures in the future. **Citation:** Arismendi, I., S. L. Johnson, J. B. Dunham, R. Haggerty, and D. Hockman-Wert (2012), 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, *Geophys. Res. Lett.*, 39, L10401, doi:10.1029/2012GL051448.

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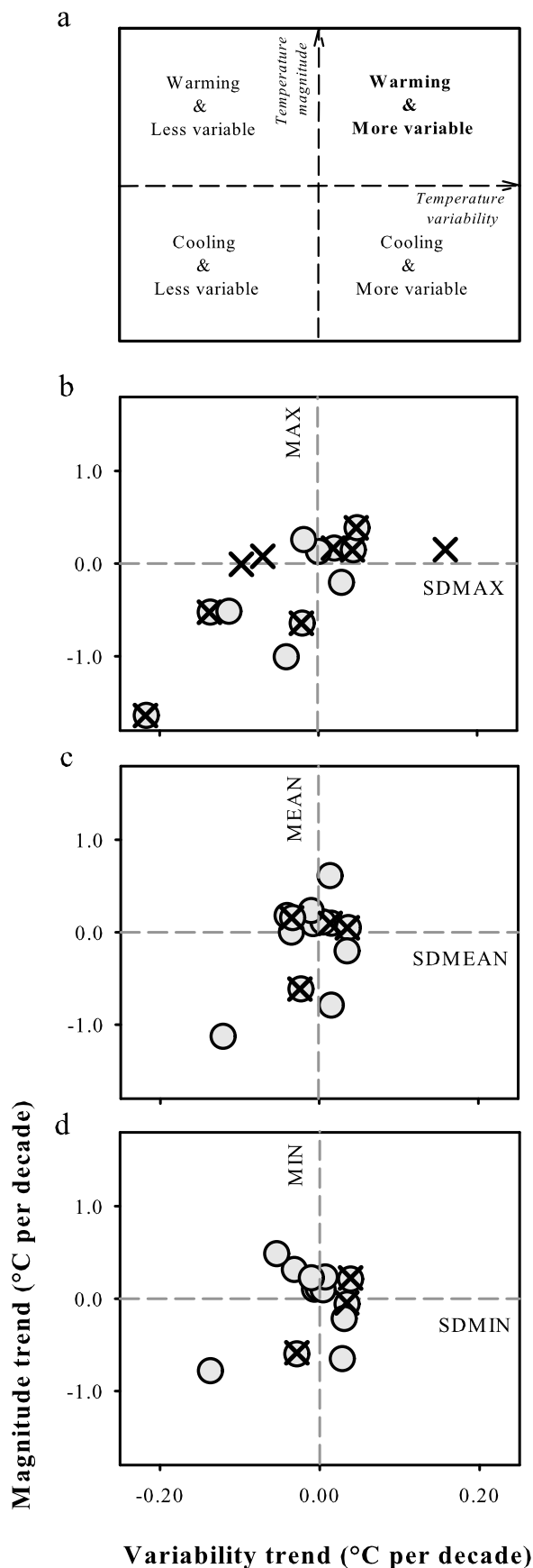
1. Introduction

[2] Temperature is a fundamental driver of processes affecting aquatic ecosystems [Magnuson *et al.*, 1979]; therefore, the implications of climate impacts on stream temperature are of increasing concern [Intergovernmental Panel on Climate Change, 2007; Webb *et al.*, 2008; Schneider and Hook, 2010]. In recent decades, studies of responses to climate change in western North America have shown increases in air temperature [Hamlet *et al.*, 2005; Mote *et al.*, 2005; Regonda *et al.*, 2005; Hansen *et al.*, 2006], declines in snowpack [Mote *et al.*, 2005; Regonda *et al.*, 2005; Nolin and Daly, 2006] and increasing variability in precipitation [Hamlet *et al.*, 2005; Regonda *et al.*, 2005]. Concurrently, stream discharges have shown changes in timing and magnitude related to earlier peak flow in spring [Regonda *et al.*, 2005; Barnett *et al.*, 2008] as well as declines and increasing variability of low flow [Luce and Holden, 2009]. Moreover, the increases in air temperature and an earlier spring snowmelt have been associated with increased frequency of large wildfires [Westerling *et al.*, 2006], which can lead to loss of riparian shade and increased heating of streams by short-wave radiation [Dunham *et al.*, 2007].

[3] Observed warming in air temperature (between 0.8 to 2.1°C for the first half-decade of the 21st century relative to the period 1950–1980) [Hansen *et al.*, 2006] and changes in streamflow timing and magnitude [Mote *et al.*, 2005; Regonda *et al.*, 2005; Luce and Holden, 2009] have been hypothesized to lead to increases in the magnitude and variability of stream temperature (Figure 1a). Several studies have noted increasing temperature of streams. However, these have been based on data from streams that include those altered by human influences, including impoundments and water withdrawals [Kaushal *et al.*, 2010; Mantua *et al.*, 2010], or through inferences and correlations derived from air-water relationships [Mantua *et al.*, 2010; Isaak *et al.*, 2011].

[4] Here, we conduct a comprehensive evaluation of historical trends in stream temperatures, contrasting trends in both highly impacted and minimally human influenced streams to evaluate temperature responses to hypothesized climate impacts. We analyzed stream temperature time series at 63 sites in the Pacific continental United States (Figure S1 and Tables S1 and S2 in the auxiliary material).¹ Eighteen of these sites represented forested watersheds with minimal human influence [Falcone *et al.*, 2010], which allowed us to evaluate trends in the absence of confounding impacts

¹Auxiliary materials are available in the HTML. doi:10.1029/2012GL051448.



of land use change or hydrologic modifications (Table S1). We also evaluated trends in 45 sites in streams representing potentially combined influences of human and climatic drivers [Falcone *et al.*, 2010] (Figure S1 and Table S2). We calculated six monthly metrics to describe trends in magnitude and variability of stream temperature over time, based on time series of daily minimum, mean, maximum values and their respective standard deviations. Given the observed trends of decreasing summer streamflow and increasing air temperature in this region, we expected most sites to exhibit trends in warming and increasing variability over time (Figure 1a, upper right quadrant), as observed for discharge [Luce and Holden, 2009], and predicted for streams with shifts from snowmelt to more flashy rain-dominated discharges [Regonda *et al.*, 2005].

2. Methods

2.1. Study Sites

[5] We selected long-term stream gage records (US Geological Survey and US Forest Service) where stream temperature has been monitored year-round in the Pacific continental United States (California, Nevada, Oregon, Idaho, Washington, and Alaska). Stream temperature was measured at 15-min to hourly intervals and summarized as daily minimum, maximum and mean. We first searched for data from least-disturbed watersheds, based on a recent classification of human impacts [Falcone *et al.*, 2010]. From the total number of potential sites that had year-round daily stream temperature records ($n = 601$) we selected those that met the following criteria: (1) had records for at least 13 years; (2) had information for at least 60% of the months in their period of record; and (3) were located in least-disturbed watersheds. From the total number of potential sites, 76 sites met criteria (1) and (2) and only 18 of those were considered minimally affected by humans and appropriate for examining climate change trends over time without human impacts (Figure S1). With the same criteria of selection, except for 'least disturbed', we selected 45 sites located in highly human-influenced watersheds [Falcone *et al.*, 2010] (more details in Figure S1 and Tables S1 and S2).

[6] We collected time series of air temperature from minimally human-influenced watersheds by using historical information from gridded meteorological data (1/8-degree resolution) of the Surface Water Modeling group at the University of Washington [Maurer *et al.*, 2002]. We estimated the daily minimum, mean and maximum air temperature

Figure 1. Expected and observed trends for stream temperature in 18 minimally human-influenced sites of western North America (entire period of record of each site). (a) We predicted that stream temperature trends influenced by recent warming climate would show higher magnitude (y-axis) and increased variability (standard deviation, x-axis; upper-right quadrant). Sites with significant trends (evaluated using the seasonal Mann-Kendall test, $P < 0.05$) in stream temperature magnitude (gray circle) and variability ("X" symbol). Estimates of slope of stream temperature trend calculated using Sen slope for (b) monthly mean of daily maximum (MAX), (c) mean (MEAN), and (d) minimum (MIN). See auxiliary material for specific results about each site (Table S3).

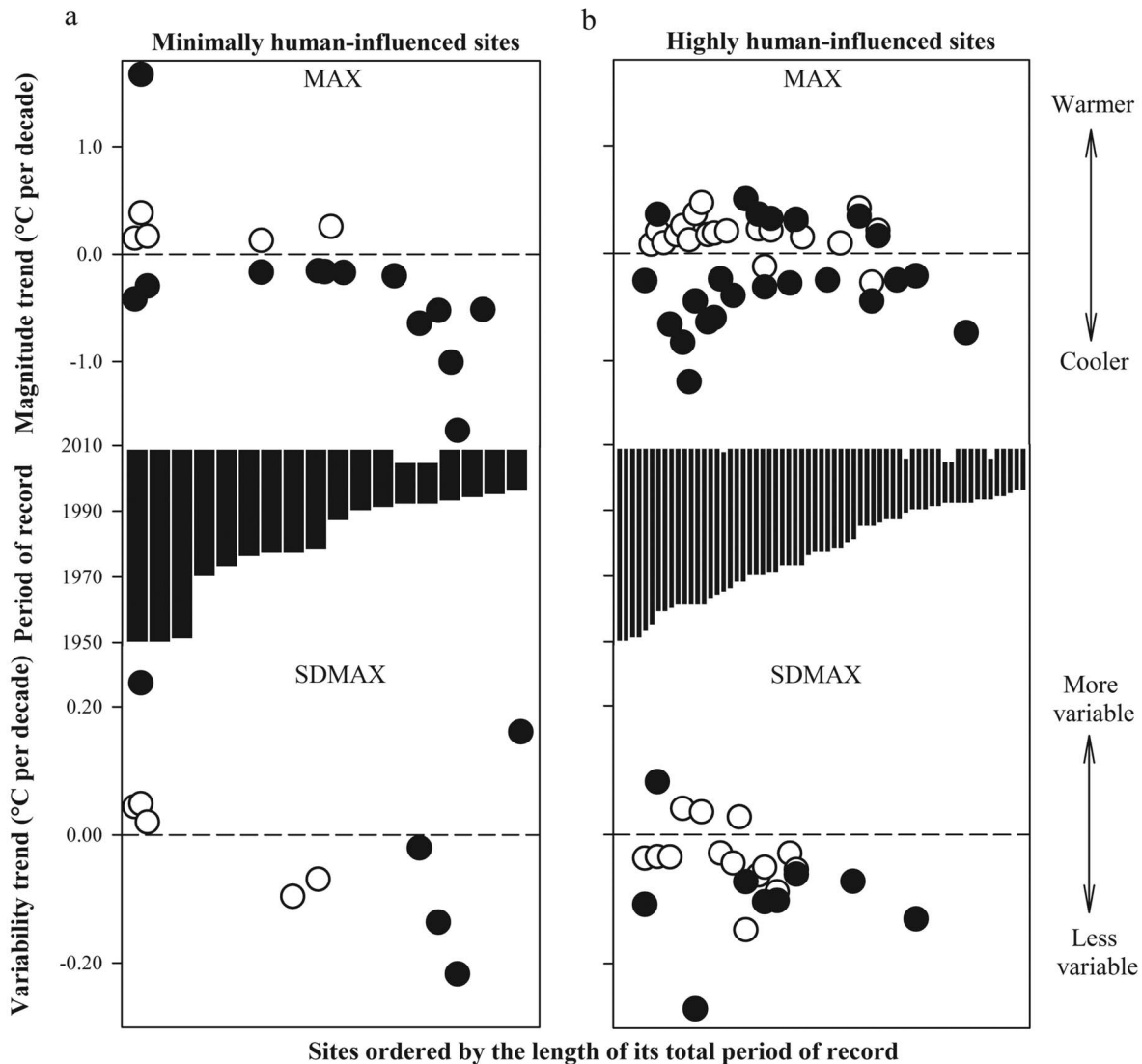


Figure 2. Significant trends for stream temperature magnitude and variability (SD = standard deviation) in both (a) minimally and (b) highly human-influenced sites using the seasonal Mann-Kendall test for the period 1987–2009 and the entire period of record. For each site, black circles show significant trend ($P < 0.05$) for the period 1987–2009; sites with data pre-1987 also have open circles showing significant trend for the entire period of record. Positive trends (Sen slope values of the trend per decade) are shown above the dotted line of the x-axis and negative trends are below. Vertical bar charts show lengths of records available for each site. See auxiliary material for similar results for MIN, MEAN, SDMIN, and SDMEAN (Tables S3–S8).

averaged over all the grid cells located in the area of the watershed above each stream gage.

2.2. Statistical Analyses

[7] Each time series was inspected to ensure there were no artifacts or processing errors (e.g., non-numerical values and those out of the range between less than -10°C and over 40°C). We did not fill missing values (Tables S1 and S2) in order to maintain the natural variability in magnitude and dispersion of the stream temperature records. Thus, all the analyses here were conducted using measured values. To obtain the magnitude and variability of stream temperature in each site, we calculated monthly mean values of minimum, maximum and mean (termed: MIN, MAX, MEAN)

from daily values of minimum, maximum and mean, respectively, and calculated a monthly standard deviation for each descriptor (termed SDMIN, SDMAX, SDMEAN).

[8] We determined the significance of temporal trends for each of the six monthly temperature metrics at each site using a non-parametric seasonal modification of the Mann-Kendall test for monotonic series [Mann, 1945; Hirsch *et al.*, 1982]. We also used the Mann-Kendall test to detect trends for a particular month. The advantages of this rank-based test are that it is robust to non-normal data, to series with outliers, missing values, and to non-linear trends [Hirsch *et al.*, 1982; Helsel and Hirsch, 1992; Esterby, 1996]. We estimated the magnitude of the trend using the Sen slope estimator, which represents the median slope of all possible

pairs in the data set [Sen, 1968; Helsel and Hirsch, 1992; Hipel and McLeod, 2005]. The seasonal Mann-Kendall test and the Sen slope estimator have previously been described as particularly useful for the detection of trends when applied to seasonal water quality time series [Webb, 1996; Hipel and McLeod, 2005]. Statistical tests used here assume statistical independence of the data through time. It is possible however, that stream temperature data could be auto-correlated, especially at shorter timescales such as daily, but also seasonal, or inter-annual. To account for potential serial correlation effects, we used monthly rather than daily values and used the seasonal Mann-Kendall test, which eliminates the effect of seasonality. To minimize the potential inter-annual serial correlations, we used a block-bootstrap method [Yue and Pilon, 2004].

[9] For our first retrospective analysis of stream temperature trends, we used information from the entire period of data record at each site (Tables S1 and S2). For our second analysis, we truncated the time series from sites with longest period of records and analyzed trends starting since 1987. Our third analysis evaluated the extent to which trends in time series can be strongly influenced by their duration (e.g., number of years in a record), as well as the timing of observation (e.g., specific years in the record). We performed a cumulative analysis showing year by year trends over the full time series for each site. We calculated significance of trends for MIN, MAX and MEAN starting with 10 years of data (2000–2009), and added one additional prior year of data and calculated trends again, until the entire record for each site was analyzed. This cumulative procedure allowed us to incrementally evaluate temporal variability in trends for each available time series.

[10] We tested the association between observed trends in MIN, MAX and MEAN stream temperature and climate trends using Spearman rank order correlation analysis. We calculated trends in monthly minimum, maximum and mean air temperatures (i.e., MIN, MAX AND MEAN air temperature) using similar procedures described for stream temperatures. Correlations between trends in air and stream temperatures used identical time periods. Lastly, we examined the association between observed trends in MIN, MAX and MEAN stream temperature and selected watershed characteristics (see auxiliary material) using Spearman rank order correlation analysis. These watershed characteristics represented those influencing hydrology, geomorphology, stream flow alteration, and land use, and were obtained from the literature [Falcone et al., 2010]. They represented summarized descriptions of static site conditions that have been suggested to influence the sensitivity of stream temperature to climate [Webb et al., 2008]. All the statistical analyses were performed using the software R ver. 2.11.1 [R Development Core Team, 2005].

3. Results and Discussion

[11] Using the entire period of record for each minimally human-influenced site, we detected significant warming trends for MIN (44% of the sites), MEAN (44% of the sites), and MAX values (28% of the sites; Figures 1b–1d and S2 and Table S3). We also detected cooling trends for MIN (27% of the sites), MEAN (22% of the sites), and MAX (33% of the sites). In evaluating stream temperature variability, we found most sites did not show significant trends

(83%, 78%, and 50% of the sites for SDMIN, SDMEAN, and SDMAX respectively). Few sites conformed to predictions from our initial hypothesis of both warming and increased variability of temperature over time for minimum, mean and maximum values (Figure 1).

[12] When we analyzed only more recent data (since 1987) at minimally human-influenced sites, we found fewer sites with warming trends and twice as many with cooling trends for MAX values (Figures 2a and S3 and Table S4). We detected cooling trends at 33% of the sites for MIN and MEAN and again little evidence of change in temperature variability, with the exception of decreasing variability at many sites for SDMAX. Analysis of trends in individual months for the entire period of record revealed a number of sites (up to 33.3%) with warming trends in summer months (Figure S4). But, monthly trends since 1987 again showed a different pattern than seen for the entire period of record; less than 16.7% showed warming during summer months, and an increased number showed cooling trends during spring and fall months (up to 27.7%).

[13] When we examined the entire period of record for the highly human-influenced sites, which included sites affected by dams, water diversion, and land-use changes (Table S2), we detected significant warming trends for MIN (44% of the sites), MEAN (36% of the sites), and MAX (40% of the sites) (Figures 2b and S2 and Table S5). When we truncated the time frame to consider more recent years (1987–2009), we found fewer warming trends (MIN 29%, MEAN 18%, and MAX 16% of the sites) and more cooling trends (MIN 29%, MEAN 27%, and MAX 36% of the sites; Figures 2b and S3 and Table S6). Furthermore, a higher proportion of sites showed significant and decreasing trends in temperature variability during the two periods of records (27%, 22%, and 27% during the entire period of records and 13%, 11%, and 18% since 1987 for SDMIN, SDMEAN, and SDMAX respectively; Figure 2b and Tables S7 and S8).

[14] The historical trends in stream temperature for minimally human-influenced sites do not simply parallel trends in air temperature (Figure 3). Rather, the direction and significance of trends in stream temperature were strongly dependent on the length of available time series. Consistent warming trends in the magnitude of stream temperature were more likely to be observed in sites with the longest records, whereas trends of variability were less prevalent and less consistent. Warming trends were partially attributed to the longer length of a few records as well as the time period over which they were recorded. These records also represented streams from only a small spatial extent within the range of sites we examined. For minimally human-influenced streams, the longest time series (>40 years of record; beginning prior to 1969) were only represented by three adjacent sites from the west slope of the Oregon Cascades (Figure S5). For sites with records of 30 years in length, warming trends were prevalent for MEAN, MAX, and MIN temperatures, but these sites represented only half ($n = 9$) of the total number of minimally human-influenced sites we were able to locate and use (Figure S5). For trends since 1987, there were more sites with available data, but we observed more non-significant trends as expected with shorter time series. Where significant trends were detected, cooling of temperatures predominated (Figures 2 and 3). Collectively, these results highlight the importance of the duration and timing of time series, as well as the limited spatial representation of available sites with

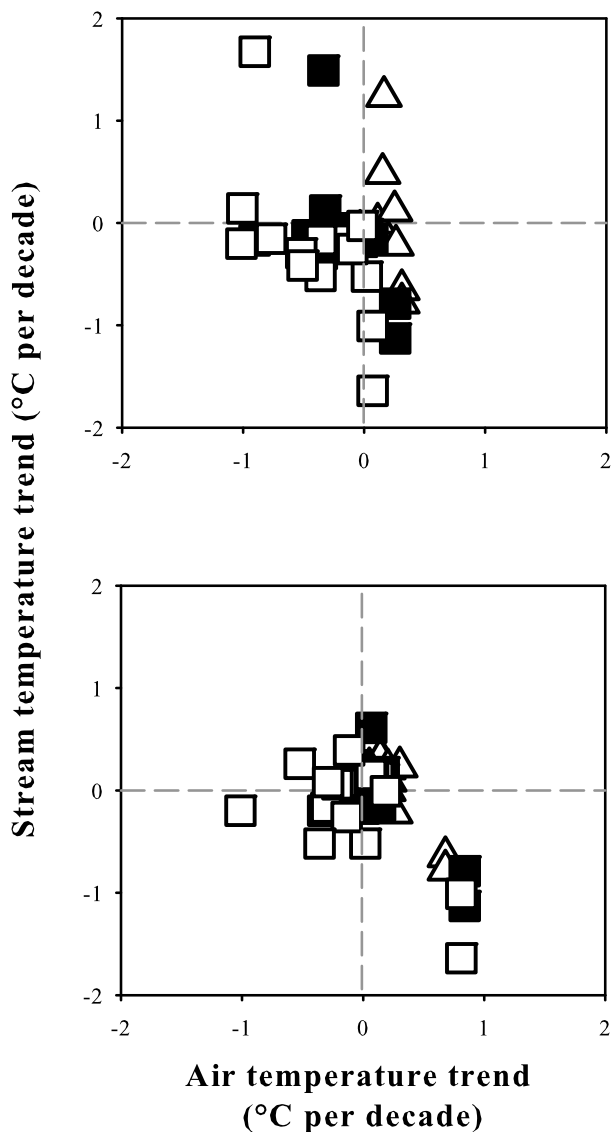


Figure 3. Scatter plots for MIN, MEAN and MAX air temperature trends versus MIN, MEAN and MAX stream temperature trends for minimally human-influenced sites for (a) the period 1987–2009 and (b) total period of record. In Figure 3a the correlation analysis resulted in non-significant association for MIN air temperature versus MIN stream temperature trends (open triangle; $\rho = 0.05$, $P = 0.84$); MEAN air versus MEAN stream temperature trends (black square; $\rho = -0.26$, $P = 0.33$); and MAX air versus MAX stream temperature trends (open square; $\rho = -0.53$, $P = 0.06$). In Figure 3b the correlation analysis similarly resulted in non-significant association for MIN versus MIN (open triangle; $\rho = -0.22$, $P = 0.40$); MEAN versus MEAN (black square; $\rho = -0.11$, $P = 0.68$); and MAX versus MAX (open square; $\rho = -0.17$, $P = 0.53$). In Figure 3b the identical periods of record for air and stream temperatures were used to avoid record-length effects at each site.

minimal-human impacts [Falcone *et al.*, 2010] for evaluating effects of climate change on stream temperature.

[15] Trends in MIN, MEAN, and MAX temperatures at highly human-influenced sites were similar to those observed

a with minimal human influences (Figures 2 and S5), but trends in the variability of temperature for human-influenced sites clearly decreased over time. This general finding contrasted with our expectation of increasing variability over time, based on climate impacts (Figure 1a), but was likely a function of the ways that rivers have been modified and managed. The homogenization of temperature caused by flow regulation and influences of reservoir storage can explain much of the observed decrease in trends of temperature variability [Rounds, 2007; Webb *et al.*, 2008]. Patterns

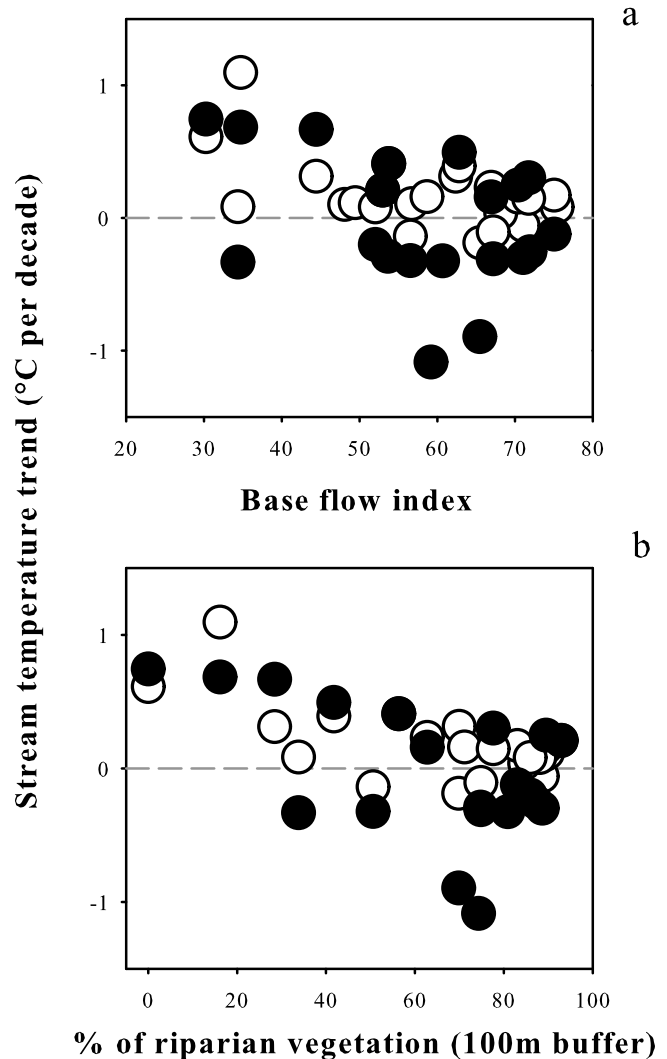


Figure 4. Scatter plot for significant trends in MIN stream temperature versus (a) base flow index, and (b) riparian vegetation buffer for each site. In Figure 4a Spearman rank order correlation for the total period of record (open circle) $\rho = -0.35$, $P = 0.07$ and for the period 1987–2009 (black circle) $\rho = -0.22$, $P = 0.34$. In Figure 4b Spearman rank order correlation for the total period of record (open circle) $\rho = -0.40$, $P = 0.049$ and for the period 1987–2009 (black circle) $\rho = -0.28$, $P = 0.22$. Riparian buffer and baseflow index are site characteristics defined in Falcone *et al.* [2010]. See auxiliary material for relationships using MEAN, MAX and other potential non-climatic drivers (Tables S9 and Table S10).

in these trends suggest that human influences can dominate or confound the effects of climate change.

[16] In addition to the categories of human, land and water use impacts used to classify streams as having minimal human influences [Falcone *et al.*, 2010], there are a variety of local factors that could be important in driving trends in stream temperatures. Shade from riparian vegetation and localized inputs from groundwater are most often cited as major components of the heat budgets of streams [Johnson, 2003; Moore *et al.*, 2005; Webb *et al.*, 2008] (Figure 4 and Tables S9 and S10). Temporal variability in these influences may partially account for the more recent cooling trends we observed (Figure 2). However, stream heat budgets are quite complex [Webb *et al.*, 2008] and other factors could be at play. Further, we do not wish to suggest that static baseflow and riparian vegetation indices correlated with stream temperature trends (Figure 4) might resolve questions about processes at an appropriate level of resolution. It is interesting to note, however, that streams with greater riparian vegetation and higher baseflow indices were less likely to show warming trends and more likely to show cooling over time (Figure 4). Riparian vegetation along streams prevents direct solar radiation reaching the water and modifies near-stream microclimate, influencing stream temperature dynamics, whereas groundwater can have a variety of impacts, depending on the timing and volume of inputs, and groundwater residence times [Moore *et al.*, 2005; Johnson, 2004]. Additionally, we find little association between air and stream temperature trends (Figure 3), which further highlights the importance of non-climatic local factors as drivers.

[17] In addition to uncertainties regarding the importance of local drivers that heat streams, our understanding of trends in the temperature of streams in relation to climate is constrained by the data themselves. These constraints include lack of data from additional sites with minimal human influences, the paucity of longer (>30 yr) time series, and limited spatial and temporal representation among available sites and periods of record for recorded stream temperatures. Our findings suggest the extent to which trends from such locations can be generalized spatially or temporally is unclear because of the shifts in trends related to the duration and timing of the observations. In summary, our consideration of available data within the expansive domain of this study suggests the existing network of sites with long-term information on stream temperatures is not adequate for a broad understanding historical climate impacts on stream temperatures. To better understand and predict future changes, a network of monitoring locations that provides better representation of spatial and temporal variability in streams with respect to the underlying processes hypothesized to influence their temperatures, is needed.

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