Comparing headwater stream thermal sensitivity across two contrasting lithologies in Northern California

Running title: Regional thermal sensitivity comparison

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Abstract

Understanding drivers of thermal regimes in headwater streams is critical for a comprehensive understanding of freshwater ecological condition and habitat resilience to disturbance, and to inform sustainable forest management policies and decisions. However, stream temperatures may vary depending on characteristics of the stream, catchment, or region. To improve our knowledge of the key drivers of stream thermal regime, we collected stream and air temperature data along eight headwater streams in two regions with distinct lithology, climate, and riparian vegetation. Five streams were in the Northern California Coast Range at the Caspar Creek Experimental Watershed Study, which is characterized by permeable sandstone lithology. Three streams were in the Cascade Range at the LaTour Demonstration State Forest, which is characterized by fractured and resistant basalt lithology. We instrumented each stream with 12 stream temperature and four air temperature sensors during summer 2018. Our objectives were to compare stream thermal regimes and thermal sensitivity—slope of the linear regression relationship between daily stream and air temperature—within and between both study regions. Mean daily stream temperatures were ~4.7 °C warmer in the Coast Range but were less variable (SD = 0.7 °C) compared to the Cascade Range (SD = 2.3 °C). Median thermal sensitivity was 0.33 °C $°C^{-1}$ in the Coast Range and 0.23 °C $°C^{-1}$ in the Cascade Range. We posit that the volcanic lithology underlying the Cascade streams likely supported discrete groundwater discharge locations, which dampened thermal sensitivity. At locations of apparent groundwater discharge in these streams, median stream temperatures rapidly decreased by 2.0 °C, 3.6 °C, and 7.0 °C relative to adjacent locations, approximately 70–90 meters upstream. In contrast, thin friable soils in the Coast Range likely contributed baseflow from shallow subsurface sources, which was more sensitive to air temperature and generally warmed downstream (up to 2.1 °C km^{-1}). Our study revealed distinct longitudinal thermal regimes in streams draining contrasting lithology, suggesting that streams in these different regions may respond differentially to forest disturbances or climate change.

Keywords:

lithology, stream temperature, thermal sensitivity, thermal heterogeneity, groundwater, climate change

1 | INTRODUCTION

Stream temperature (T_s) is a critical water quality parameter that drives dissolved oxygen solubility (Loperfido, Just, & Schnoor, 2009; Ozaki et al., 2003), nutrient cycling (Morin, Lamoureux, & Busnarda, 1999; Neres-Lima et al., 2017), in-stream primary productivity (Bernhardt et al., 2018), and habitat provision (Brewitt, Danner, & Moore, 2017). When stream temperature warms, it can negatively impact sensitive cold water aquatic species, such as salmonid fishes and amphibians, by reducing habitat suitability for spawning and rearing life stages, and influencing individual metabolism and behavior (Dallas & Ross-Gillespie, 2015; Eaton & Scheller, 1996; Hester & Doyle, 2011; Railsback & Rose, 1999). Recent studies have illustrated that climate change and shifts in forest disturbance regimes have the potential to intensify thermal pollution and increase the risks to anadromous fish and other aquatic vertebrate populations (Benjamin, Connolly, Romine, & Perry, 2013; Ford et al., 2011; Thomas et al., 2004). In Mediterranean climates, the threat to aquatic species is particularly important during the summer low flow period, when precipitation inputs are low and both thermal inputs from solar radiation and convective heat exchange between the warm air and cooler streams are at their maximum (Arismendi, Safeeq, Johnson, Dunham, & Haggerty, 2013; Larsen & Woelfle-Erskine, 2018; Xu, Letcher, & Nislow, 2010).

However, research on longitudinal thermal regimes of streams has revealed substantial complexity and variability in the dominant processes driving the spatial patterns in stream temperature (Fullerton et al., 2015, 2018; Hofmeister, Cianfrani, & Hession, 2015). For many years, the conventional perspective was that stream temperature increased progressively from headwaters to larger downstream river systems (Caissie, 2006; Vannote, Minshall, Cummins, Sedell, & Cushing, 1980). Other studies have quantified decreasing stream temperature moving downstream in some headwaters (Dent, Vick, Abraham, Schoenholtz, & Johnson, 2008; Leach & Moore, 2011; Moore, Sutherland, Gomi, & Dhakal, 2005b; Story, Moore, & Macdonald, 2003) and larger streams (O'Sullivan, Devito, & Curry, 2019). Additionally, recent advances in remote sensing technology and larger scale observations have revealed that many streams cannot be characterized by a simple longitudinal profile pattern in stream temperature (Briggs, Dawson, Holmquist-Johnson, Williams, & Lane, 2018a; Dugdale, Bergeron, & St-Hilaire, 2015; Ebersole, Wigington, Leibowitz, Comeleo, & Van Sickle, 2015; Fullerton et al., 2015). This is especially true for non-fish bearing headwaters, where complex geomorphology and discrete groundwater inputs can produce distinct patterns of flow permanence and network connectivity (Gendaszek et al., 2020; Pate, Segura, & Bladon, 2020) that influence stream temperature.

Despite recent advances in our knowledge, there is still much uncertainty about the longitudinal patterns in stream temperature due to numerous local and regional controls. One dominant local control on stream temperature is groundwater discharge, which in some systems can provide a stable supply of cool water and promote refugia for sensitive aquatic species during summer (Arscott, Tockner, & Ward, 2001; Briggs et al., 2018b; Griebler & Avramov, 2015; Snyder, Hitt, & Young, 2015). Groundwater contributions are, in part, controlled by regional lithology and are typically greater in more permeable geology (Hale & McDonnell, 2016). The magnitude of groundwater contributions may also be influenced by channel morphology (Johnson, Wilby, & Toone, 2014; Kasahara & Wondzell, 2003; Moore et al., 2005b; Story et al., 2003), the direction of subsurface hydraulic gradients (Peterson & Sickbert, 2006), the available alluvial hydraulic storage (Kelson & Wells, 1989), and the catchment hydraulic conductivity (Morrice, Valett, Dahm, & Campana, 1997). In headwater streams with a predominance of groundwater discharge, stream temperature is often cooler and less variable

(Brown & Hannah, 2008; Danehy, Colson, & Duke, 2010; Johnson, 2004). Localized springs (Leach & Moore, 2011) and zones of concentrated upwelling (Moore et al., 2005b) can cause downstream cooling and reduce stream temperature variation, even during the winter (Danehy et al., 2010; Westhoff & Paukert, 2014). As such, streams with substantial groundwater discharge may be less responsive to reductions in canopy cover and subsequent increases in radiative loading (Janisch, Wondzell, & Ehinger, 2012; Larson, Larson, & Larson, 2002) compared to streams with lesser groundwater contributions (Bladon, Segura, Cook, Bywater-Reyes, & Reiter, 2018; Dent et al., 2008; Moore, Spittlehouse, & Story, 2005a; Story et al., 2003).

Many studies have also used air temperature as a predictor of stream temperature (Jackson, Fryer, Hannah, Millar, & Malcolm, 2018; Kelleher et al., 2012; Mayer, 2012; Mohseni & Stefan, 1999; Segura, Caldwell, Sun, Mcnulty, & Zhang, 2015; Snyder et al., 2015; Stefan & Preud'homme, 1993), although convective heat exchange at the water surface often represents a minor portion of the overall stream heat budget (Johnson, 2003). Regardless, air temperature has been used successfully to develop simple, empirical models that predict changes in stream temperature due to climate change (Caldwell et al., 2015) or to identify locations of groundwater discharge (Fullerton et al., 2018; Mayer, 2012; Snyder et al., 2015). Air temperature has often been an effective predictor of stream temperature at coarse temporal scales (e.g., daily, weekly, monthly; Segura et al., 2015) and can act as a surrogate for total heat flux to the stream surface (Arismendi, Safeeq, Dunham, & Johnson, 2014; Gomi, Moore, & Dhakal, 2006; Gu, Anderson, Colby, & Coffey, 2015; Mohseni & Stefan, 1999; Tague, Farrell, Grant, Lewis, & Rey, 2007).

The relationship between air and stream temperature is often described with a linear regression model in which the slope provides an indicator of the thermal sensitivity of the stream (Lisi, Schindler, Cline, Scheuerell, & Walsh, 2015; Segura et al., 2015; Snyder et al., 2015). This relationship can also be used to elucidate the spatial extent of different streamflow contributions (Kelleher et al., 2012; Mayer, 2012; Snyder et al., 2015). For example, stream segments dominated by groundwater discharge or substantial hyporheic exchange may be identified by stable stream temperatures or lower thermal sensitivity to diel and seasonal variations in air temperature. Comparatively, stream segments with greater channelized flow, less groundwater or hyporheic contributions may be characterized by greater fluctuations in stream temperature due to greater coupling with atmospheric controls. This observational tool has been used in many broad applications to assess contributions of groundwater and hyporheic flow (Briggs et al., 2018b; Johnson et al., 2014; Mayer, 2012; Selker, van de Giesen, Westhoff, Luxemburg, & Parlange, 2006; Snyder et al., 2015). However, the longitudinal variability in thermal sensitivity along headwater streams remains poorly characterized and the potential implications for headwater stream management in contrasting regions are not known.

In our study, we quantified both stream temperature and air temperature in eight headwater streams draining contrasting lithologies in Northern California. Specifically, we deployed 128 thermistors longitudinally down streams draining volcanic basalt (Cascade Range) and friable sandstone (Coast Range) lithology to characterize local and longitudinal trends in stream warming or cooling. We also sought to quantify the degree of atmospheric control on stream temperature, or thermal sensitivity, to improve our understanding of the processes driving longitudinal stream temperature variability in headwater streams. Thus, our primary objectives were to: (a) compare stream and air temperatures during the summer low flow period in streams draining contrasting lithology, (b) quantify the reach-scale longitudinal variability in stream and air temperatures in streams draining contrasting lithology, and (c) quantify inter- and intra-regional thermal sensitivity in streams draining contrasting lithology. Our results revealed differences in the processes governing the stream thermal regimes across our two study regions. We observed greater longitudinal thermal heterogeneity in streams underlain by basalt than sandstone, which we posit was driven primarily by the presence of discrete groundwater discharge locations that dominated over atmospheric control on stream temperature at these locations. Understanding the dominant controls on the thermal regime of small headwater streams is critical to make informed management decisions in headwater catchments across diverse regions.

2 | METHODS

2.1 | Study locations

Our study occurred in two distinct geological regions of Northern California: the Southern Cascade Range (LaTour Demonstration State Forest) and the North Coast Range (Caspar Creek Experimental Watershed in Jackson Demonstration State Forest) (Figure 1). The two regions were selected to represent strongly different climates, geologies, and dominant forest types (Table 1).

Our study included three streams in the Cascade Range: Beaver Creek, (BEA), Bullhock Creek (BUL), and Sugar Creek (SUG). All three streams are step-pool systems (Montgomery & Buffington, 1997) with few large cascades—they all have similar slope, canopy cover, and elevation (Table 2). Soils are coarse, fast draining loams with depths < 2 meters (McDonald, 1995). The stream channel substrate was coarse gravel (D_{50}: 46–60 mm) except in locations behind debris jams where finer substrate accumulated (Pate et al., 2020). Valleys in the Cascade Range are U-shaped carved by glaciation processes with stream channels typically unconfined, except in some locations along Sugar Creek. The geology in the Cascade Range contains resistant, fractured basalt and andesite (MacDonald, 1963) characterized by rapid drainage to deep groundwater aquifers with long residence times (Tague et al., 2007; Tague, Grant, Farrell, Choate, & Jefferson, 2008) typical of volcanic geology (Jaeger et al., 2007). The climate is semi-arid, with hot, dry summers, and snowy, cold winters (CAL FIRE, 2013) (Table 1). Precipitation is snow dominated with snowpack persisting often into early May (CAL FIRE, 1995; PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, accessed April 10, 2020), with a snow water equivalent depth on April 1, 2018 of 384 mm (Snow Mountain, CA station, 18 km from study location; NRCS, 2020). The forests in our study catchments were dominated by 10 to 17 m tall sugar pine (*Pinus lambertiana*), lodgepole pine (*Pinus contorta*), and ponderosa pine (*Pinus ponderosa*), with some Douglas-fir (*Pseudotsuga menziesii*) and mountain hemlock (*Tsuga mertensiana*), with a comparatively low to moderate density canopy cover (Oregon State LEMMA Database, 2020) (Table 1).

Study streams in the North Coast Range were located in the Caspar Creek Experimental Watershed Study, where research has been ongoing since 1961 addressing questions about forest management effects on forest hydrology and water quality (Cafferata & Reid, 2013; Keppeler, Ziemer, & Cafferata, 1994). We included five streams in the Coast Range: Henningson (HEN), Iverson (IVE), Richards (RIC), Williams (WIL), and Xray (XRA) Creeks, which are step-pool systems (Montgomery & Buffington, 1997) with a few small cascades and similar slope, canopy cover, and elevation (Table 2). The channel substrate for all streams was medium gravel (D_{50}: 13–24 mm). Valleys are steep and V-shaped with considerable channel incision, resulting in strong confinement and coupling between the streams and hillslopes. Soils were 1 to 1.5 meters deep, well drained loams underlain by a restrictive clay layer, which results in substantial pipeflow that rapidly transfers shallow subsurface flow laterally to the channel (Amatya et al., 2016; Keppeler & Brown, 1998). Geology of the region is dominated by friable sandstone and mudstone lithology of the Franciscan complex (Amatya et al., 2016). Winter climate is characterized as mild, cool, and wet, with temperatures rarely below 0 °C, while summers are warm and dry (Keppeler et al., 1994) (Table 1). Precipitation is rain dominated, with >1,200 mm falling annually (PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, accessed April 10, 2020). Riparian vegetation consists of 20 to 30 m tall, dense (canopy cover between 78 to 91 %; Oregon State LEMMA Database, 2020) coast redwood (*Sequoia sempervirens*) forest, with Douglas-fir (*Pseudotsuga menziesii*), grand fir (*Abies grandis*), and western hemlock (*Tsuga heterophylla*) occurring at lower densities (Cafferata & Reid, 2013).

2.2 | Data collection

In each of the eight study streams, we installed 16 HOBO TidbiT v2 sensors (Onset, Bourne, MA; accuracy ± 0.21 °C) to measure both air and stream temperature (128 total sensors). Specifically, we installed 12 stream temperature sensors and four air temperature sensors along each stream to collect continuous data (15-minute intervals). The four air temperature sensors were co-located with stream temperature sensors near the top, bottom, and two midpoints of each stream (Figure 1, inset). In-stream sensors were placed along the thalweg and secured with rebar driven through the channel bottom. Air temperature sensors were placed adjacent to the channel and suspended from tree branches approximately one meter above the ground. All sensors were enclosed in sections of white PVC tubing with drilled holes to allow fluid exchange and to minimize solar influences. Stream temperature sensors were positioned approximately every 80 m in the Cascade Range streams and every 30 to 60 m in the Coast

Range streams (Table 2). Sensor spacing was regular and dictated by the available stream length from the point of channel head initiation to the confluence with a higher order stream.

2.3 | Data Analysis

Temperature data was first visually explored to remove periods when sensors were not submerged or behaving abnormally. To do this, we visually assessed and compared the diel temperature range of stream temperature and adjacent air temperature sensors to discern periods when sensors were dry (Campbell et al., 2013; Sowder & Steel, 2012). If sensors were lost during the study, we assumed that any sensor that went dry prior to being lost remained dry throughout the remainder of the monitoring period. Similarly to previous research (Arismendi, Dunham, Heck, Schultz, & Hockman-Wert, 2017), we made this decision by considering data for sensors with complete records, which indicated that once the stream sections went dry, they remained dry for the rest of the summer. We did not make assumptions for sensors that were submerged prior to being lost. As a result, from the total available stream temperature data in the Cascade Range we were able to use 44 % in SUG, 49 % in BUL, and 91 % in BEA. Comparatively, in the Coast Range we were able to use 28 % of the data in HEN, 47 % in IVE, 48 % in WIL, 42 % in XRA, and 69 % in RIC. Data exploration, quality control, and statistical analysis were conducted in R version 3.6.1 (R Core Team, 2020).

We focused our analysis on the summer low flow period (June 1–September 30, 2018), when the warmest stream temperatures are typically recorded in the northern hemisphere (Dent et al., 2008; Groom, Johnson, Seeds, & Ice, 2017; Macdonald, Boon, Byrne, & Silins, 2014). Specifically, we quantified the diel range and daily maximum, minimum, median, and mean temperatures. Statistically, we used one factor ANOVA with Tukey's *post hoc* tests to assess differences in daily mean air temperatures recorded among and within streams in both regions, and among streams in each region. Welch's two-sample *t*-test was used to assess differences in daily stream and air temperature metrics among regions.

2.3.1 | Assessing longitudinal stream temperature trends

We quantified the rate of downstream warming or cooling for each stream by fitting a linear regression equation with upstream distance (m) as the independent variable and average daily mean stream temperatures at each sensor location (°C) as the dependent variable (Figure S1). Regression slopes greater than zero indicated net downstream warming, while slopes less than zero indicated net downstream cooling.

We quantified the average incremental temperature difference (AITD) as the absolute value of the difference in the average mean daily stream temperatures between adjacent sensors within each individual stream. Specifically, we calculated AITD to provide an indicator of the site-level variability in stream temperature as:

$$AITD = \frac{\sum_{i=1}^{n-1} \left| ADM_i - ADM_{i+1} \right|}{n-1} \tag{1}$$

where ADM_i was the average daily mean stream temperature measured at an upstream location, ADM_{i+1} was the average daily mean stream temperature measured at the nearest location downstream, and *n* was the number of stream temperature monitoring locations in each stream (8–12). Large values of AITD, were indicative of high variability in stream temperature magnitude from site to site. Alternatively, low values of AITD, were indicative of comparatively low site-level variability in stream temperature magnitude. Although the AITD metric captured variability in the central tendency of stream temperature at each monitoring location (average daily mean), it did not consider the variability in stream temperature at each monitoring location. For that reason, we also calculated the average incremental standard deviation difference (AISDD) as the absolute value of the difference between the average daily standard deviation in stream temperatures at each in-stream sensor and the one immediately downstream, using:

$$AISDD = \frac{\sum_{i=1}^{n-1} \left| ADSD_i - ADSD_{i+1} \right|}{n-1} \tag{2}$$

where $ADSD_i$ was the average of the standard deviation of daily stream temperature at an upstream location, $ADSD_{i+1}$ was the average of the standard deviation of daily stream temperature at the location immediately downstream, and *n* was the number of stream temperature monitoring locations in each stream (8–12). One value of AITD and AISDD was calculated for each stream to assess site-level thermal heterogeneity.

2.3.2 | Stream thermal sensitivity analysis

To assess relative differences in atmospheric control on stream temperature between and within streams in the Coast and Cascade Ranges, we used the linear relationship between mean daily stream and air temperatures (equation 3). Mean daily stream temperatures (T_s) for each in-stream sensor were regressed against mean daily air temperature (T_a) values from the nearest sensor as:

$$T_s = mT_a + b \tag{3}$$

where *m* is the regression slope (hence forth referred to as the thermal sensitivity) and *b* is the intercept. Thus, our analysis provided up to 12 linear regression equations and corresponding thermal sensitivity values per stream. Prior to analysis, we removed temperature data below 0 °C as linear regression relationships between stream and air temperature were only valid for temperatures above freezing (Mayer, 2012; Morrill, Bales, & Conklin, 2005; Segura et al., 2015). Additionally, we also removed daily mean temperature values derived from less than a complete day of data (i.e., $n < 96$, 15-minute interval data points) prior to fitting linear regression models —this resulted in removal of ~0.2 % of the data (23 days) across all sites. Regression equations where T_a was not significantly correlated with T_s ($p > 0.05$) were not included in the final analysis. Out of 96 stream temperature sensors, 14 were dry at the beginning of monitoring and one was lost during high flows. Four of the remaining 81 models were excluded due to a lack of correlation between T_a and T_s, and were assumed to contain substantial sources of unexplained variation, which was likely due to additional factors that provided greater control on stream temperature than atmospheric conditions. Therefore, 77 model fits were used in the final analysis. The coefficient of determination (R^2) was used to assess individual model fits. Median thermal sensitivity values measured in each region were compared using the non-parametric Wilcoxon Rank Sum test as it was determined that the distribution of thermal sensitivity values measured in the Cascade Range streams were not normally distributed (Shapiro-Wilk test, $p < 0.05$).

3 | RESULTS

3.1 | Summer air and stream temperatures

Overall, our data indicated that during summer 2018 air temperatures were warmer and exhibited greater diurnal variability in the Cascade Range than in the Coast Range of California (Table 3). Specifically, daily mean air temperatures were 1.63 °C (95 % confidence interval (CI): 1.49–1.75 °C) warmer in the Cascade Range than in the Coast Range ($t = -24.67$, $p < 0.01$;

Figure 2). Air temperatures were also more variable in the Cascade Range—the average diel air temperature range in the Cascade Range was ~2.3-times greater than in the Coast Range (Table 3). Daily maximum air temperatures in the Cascade Range (average: 26.2 °C) were also higher than in the Coast Range (average: 17.6 °C; $t = -74.52$, $p < 0.01$). Alternatively, daily minimum air temperatures were on average 1.45 °C (95 % CI: 1.33–1.59 °C) warmer in the Coast Range (9.95 °C) than in the Cascade Range (8.48 °C; $t = 21.78$, $p < 0.01$).

There was strong evidence ($F(2, 2620) = 2.11$, $p < 0.01$) that average daily mean air temperatures were different between streams in the Cascade Range. For example, the air temperature at BUL was ~0.31 °C warmer than at BEA and 0.70 °C warmer than at SUG (Figure 2). Comparatively, there was suggestive evidence ($F(4, 3399) = 2.11$, $p = 0.08$) that average daily mean air temperatures were different between streams in the Coast Range (Figure 2). However, there was strong evidence that both the average daily minimum ($F(4, 3399) = 16.64$, $p < 0.01$) and maximum ($F(4, 3399) = 89.73$, $p < 0.01$) air temperatures were different across streams in the Coast Range (Table S1). Longitudinally, the average daily mean air temperatures differed between proximate air temperature sensors in the Coast Range by 0.10–0.75 °C and in the Cascade Range by 0.42–2.2 °C (Figure S1). Similarly, in the Coast Range the average daily minimum temperatures between proximate sensors varied by 0.08–1.45 °C, while the maximum temperatures varied by 0.02–4.0 °C. In the Cascade Range, the average daily minimum temperatures between proximate sensors varied by 0.10–2.95 °C, while the maximum temperatures varied by 0.90–11.15 °C. Thus, there was greater within-region air temperature variation in Cascade Range streams than in Coast Range streams.

Overall, our data indicated that summer stream temperatures were substantially cooler, but more variable in the Cascade Range streams compared to streams in the Coast Range (Figure

2). The average daily mean stream temperature in the Cascade Range streams (7.3 °C) was significantly cooler than in the Coast Range (12.0 °C; $t = 112.4$, $p < 0.01$; Table 3). While the streams were cooler, the average diel stream temperature range in the Cascade Range (2.2 °C day^{-1}) was ~2.5-times greater than in the Coast Range (0.9 °C day^{-1}; $t = -45.79$, $p < 0.01$). We also found strong evidence that average daily maximum stream temperatures in the Cascade Range streams (8.8 °C) were less than in the Coast Range streams (12.5 °C; $t = 72.3$, $p < 0.01$). Average daily minimum stream temperatures were also cooler in the Cascade Range streams (6.5 °C) compared to the Coast Range streams (11.6 °C, $t = 134.0$, $p < 0.01$). Site-level stream temperature statistics are available in Table S2.

3.2 | Longitudinal stream temperatures

Longitudinally down the entire length of our study streams in the Cascade Range, stream temperature generally cooled (-0.66 to -3.9 °C km^{-1}) (Table 4). In contrast, four of the five streams in the Coast Range warmed (0.18 to 2.1 °C km^{-1}) in the downstream direction, while HEN displayed moderate cooling (-1.1 °C km^{-1}) (Table 4 and Figure 3). The average incremental temperature difference (AITD) between each stream temperature sensor and the one immediately downstream was greater in the Cascade streams (1.0 °C) compared to the Coast Range streams (0.29 °C; $t = 3.8$, $p = 0.03$), indicating greater longitudinal variability in stream temperature magnitude in the Cascade Range streams (Table 4). AITD values ranged from 0.66 to 1.3 °C in Cascade Range steams and from 0.17 to 0.42 °C in Coast Ranges streams (Table 4). The average incremental difference in daily stream temperature standard deviation (AISDD) in the Cascade Range streams was 0.41 °C, ranging from 0.19 °C (BEA) to 0.61 °C (SUG). Comparatively, the AISDD in the Coast Range streams was 0.19 °C, ranging from 0.15 °C (RIC) to 0.31 °C (HEN).

Despite these differences, statistically, we did not find evidence that AISDD values were greater in Cascade Range streams compared to Coast Range streams ($t = 1.73$, $p = 0.11$).

The three streams in the Cascade Range (underlain by volcanic lithology) exhibited substantial longitudinal variability in stream temperature (Figure 3). Overall, the site-level average daily standard deviation (SD) in stream temperature ranged from 0.19–1.84 °C (mean = 0.68 °C). Much of the variability could be attributed to distinct locations where stream temperature decreased markedly in each of the three streams in this region. For example, we observed abrupt declines in average daily mean stream temperatures between two adjacent sensors of 2.0 °C in SUG, 3.5 °C in BEA, and 7.0 °C in BUL (Figure 3). Interestingly, stream temperatures generally warmed slightly between stream segments upstream from the locations of dramatic cooling. For example, the average daily mean summer stream temperature at BEA increased from 5.4 to 8.2 °C between the first (furthest upstream sensor) and sixth temperature sensor (0.55 fractional distance upstream), which represented ~50 % of the monitored distance (~400 m). However, the average daily mean summer stream temperatures abruptly decreased to 4.7 °C (a loss of ~3.5 °C) over the next ~80 meters, between the sixth and seventh stream temperature sensors (between 0.55 and 0.45 fractional distance upstream) (Figure 3). We also noted that the variability in daily mean stream temperatures in BEA was generally greater (SD: 1.3 °C) in the upper 400 m of the stream (i.e., above the segment where temperatures cooled rapidly), relative to the lower 480 to 880 m of stream (SD: 0.39 °C). We observed similar patterns in summer stream temperatures in BUL and SUG, although both streams had ephemeral sections, which went dry during portions of the summer.

Comparatively, in the Coast Range, stream temperatures were more stable with no strongly discernible downstream warming or cooling trends (Figure 3). Site-level average daily standard deviations in stream temperature in the Coast Range ranged from 0.02–0.95 °C (mean = 0.28 °C). Generally, average daily mean stream temperatures increased moving downstream (Table 4), with the exception of the steam temperature at HEN, which cooled by 1.1 °C km^{-1} (Figure S2). There were some sections of localized cooling and reduced stream temperature variability present in HEN, IVE, WIL, and XRA approximately mid-stream. For example, the average daily mean stream temperature decreased 0.67 °C over 38 m between the fifth and sixth sensor location (from 0.64 to 0.55 fractional distance upstream) in HEN with a corresponding decrease in average daily standard deviation of stream temperature of 0.34 °C (Figure 3). However, the largest change in average daily mean stream temperatures observed moving downstream between any two adjacent sites along the Coast Range streams was 0.91 °C in XRA (between sensors 9 and 10, from 0.27 to 0.18 fractional distance upstream), which was 13 % of the maximum change observed in the Cascade Range streams (Figure 3). The largest observed reductions in average daily mean stream temperature in the remaining three streams in the Coast Range were 0.31 °C in IVE, 0.19 °C in RIC, and 0.64 °C in WIL (Figure 3).

3.3 | Stream thermal sensitivity

Our site-level linear regression models between air and stream temperature revealed fine-scale spatial variability in stream thermal sensitivity to air temperature in both study regions (Figure 4). In the Cascade Range streams, the median site-level thermal sensitivity was 0.23 °C $°C^{-1}$, ranging between 0.04–0.63 °C $°C^{-1}$ (R^2 = 0.11–0.85) (Table 5). Interestingly, in BUL, the thermal sensitivity increased consistently from 0.27 °C $°C^{-1}$ at the uppermost sensor to a maximum of 0.63 °C $°C^{-1}$ at the eighth sensor (0.36 fractional distance upstream). However, the thermal sensitivity dramatically decreased to 0.04 °C $°C^{-1}$ at the next sensor downstream and stream temperature generally remained decoupled from atmospheric controls across the bottom ~20 % (starting at 0.27 fractional distance upstream) of the stream reach (Figure 4).

Similarly, in BEA the thermal sensitivity increased from 0.05 °C °C^{-1} at the uppermost sensor to 0.31 °C °C^{-1} at the sixth sensor (0.55 fractional distance upstream), before also decreasing dramatically to 0.06 °C °C^{-1} at the seventh sensor (0.45 fractional distance upstream) (Figure 4). The stream temperature in BEA also generally remained decoupled from air temperature for the remainder of the monitored stream length, which was similar to BUL.

In SUG, site-level thermal sensitivity decreased from 0.32 °C °C^{-1} to 0.10 °C °C^{-1} over the first 328 m (to 0.64 fractional distance upstream). Thermal sensitivity in SUG then increased from 0.10 °C °C^{-1} to 0.59 °C °C^{-1} over 150 m from the fifth to sixth sensor (from 0.64 to 0.45 fractional distance upstream) before alternately decreasing to 0.28 °C °C^{-1} at 0.27 fractional distance upstream then increasing to 0.45 °C °C^{-1} at 0.18 fractional distance upstream.

Despite the variability in thermal sensitivity in the Cascade Range, the distribution of thermal sensitivity values was skewed to values less than 0.2 (Figure 5A), and these locations generally had the coolest stream temperatures. For instance, across the three Cascade Range streams, there was a strong, positive linear relationship between site-level thermal sensitivity values and the average daily mean stream temperature (R^2 = 0.79). Positive relationships also existed between site-level thermal sensitivities and average daily maximum stream temperatures (R^2 = 0.63), and average diel stream temperature range (R^2 = 0.59) (Figure S3). In other words, warmer stream segments were generally more coupled to air temperature, while cooler stream segments were less coupled with air temperature.

In the Coast Range, the median site-level thermal sensitivity was 0.33 °C °C^{-1} and ranged between 0.10–0.77 °C °C^{-1} (R^2 = 0.11–0.93) (Table 5). Statistically, the median thermal sensitivity in the Coast Range was greater than in the Cascade Range streams (Wilcoxon Rank Sum test, $p < 0.01$, 95% CI: 0.039 – 0.171) (Table 5). Longitudinal patterns in thermal sensitivity varied by stream, but generally increased moving downstream in RIC and XRA (Figure 4). For instance, thermal sensitivity increased from 0.20 to 0.53 °C $°C^{-1}$ over 300 meters from mid-reach (0.55 fractional distance upstream) to the bottom of RIC and from 0.26 to 0.49 °C $°C^{-1}$ over 210 m in XRA (from 0.27 fractional distance upstream to the bottom of XRA). Alternatively, longitudinal trends in thermal sensitivity for streams HEN, IVE, and WIL did not show strong increasing or decreasing trends. However, there were some stream segments in those three streams where thermal sensitivity between proximate temperature sensors changed rapidly. For instance, in WIL the thermal sensitivity increased from 0.10 to 0.37 °C $°C^{-1}$ over 28 m (from 0.45 to 0.36 fractional distance upstream), then decreased again to 0.10 °C $°C^{-1}$ over 56 m moving downstream starting at 0.18 fractional distance upstream. The largest change in thermal sensitivity observed in the Coast Range streams occurred mid-reach (0.45 fractional distance upstream) in HEN, where thermal sensitivity increased from 0.18 to 0.77 °C $°C^{-1}$ over 38 m and then decreased to 0.33 °C $°C^{-1}$; however, this particular stream segment went dry 17 days after the start of monitoring (June 18, 2018). Contrary to results in the Cascade Range, variability in site-level thermal sensitivity values in Coast Range streams was not well explained by the average daily mean stream temperature ($R^2 = 0.06$), indicating that the most thermally insensitive locations along Coast Range streams were not necessarily the coolest (Figure S3).

4 | DISCUSSION

Our study in Northern California provided evidence that stream temperatures during the summer low flow period were generally warmer, but exhibited less diel variation, in Coast Range headwater streams compared to the Cascade Range. Specifically, mean daily stream temperatures were ~4.7 °C warmer in the Coast Range despite greater riparian canopy closure and air temperatures that were ~1.6 °C cooler than in the Cascade Range (Table 3). Although stream temperatures were warmer in the Coast Range relative to the Cascades, temperatures remained well within the range found to be tolerable for many anadromous salmonids or amphibians, which inhabit the region (Sloat & Osterback, 2013; Welsh, Hodgson, Harvey, & Roche, 2001).

Our observations in the Coast Range catchments, which occurred in the Caspar Creek Experimental Watershed Study, were also consistent with stream temperature measurements collected over eight years, between 1965–1990, from catchments in the same region (Cafferata, 1990). For example, while we observed summer maximum stream temperatures of 12.5 °C and diel variation of 0.9 °C, Cafferata (1990) reported summer maximums of ~13.3–15.6 °C and diurnal fluctuations of 0.8 °C. Cool summer stream temperatures in Coast Range streams have previously been attributed to the insulating effect of the dense riparian canopy, high humidity, and coastal fog due to the proximity to the Pacific Ocean (Cafferata & Reid, 2013; Lewis et al., 2000; Moore et al., 2005a). In particular, a dense forest canopy cover, as observed in the Coast Range (85 %), has been found to limit energy exchange across the stream-air interface and thus, act as a first order control on the magnitude of stream temperature and thermal sensitivity (Chang & Psaris, 2013; Simmons et al., 2014; Winfree et al., 2018).

Our measurements of the longitudinal variability in stream temperature also indicated that the streams in both the Coast Range and the Cascade Range exhibited complex thermal profiles (Fullerton et al., 2015). In other words, the longitudinal stream temperature profiles across all our study streams included multiple discontinuities, with sections of increasing and decreasing temperatures (Figure 3). However, there was greater longitudinal thermal heterogeneity in streams underlain by volcanic lithology (Cascade Range) than in streams underlain by sedimentary lithology (Coast Range). In the Cascade Range, stream temperatures appeared to warm slightly moving downstream but cooled dramatically—dropping by as much as 2.0 to 7.0 °C, at discrete locations. Overall, this resulted in cooler average stream temperatures, despite warmer air temperatures, in the Cascade streams compared to the Coast Range streams. Similar discontinuities have previously been related to discrete groundwater discharge locations, which can thermally buffer streams against daily and seasonal temperature fluctuations (Snyder et al., 2015; Webb, Hannah, Moore, Brown, & Nobilis, 2008). Reduced diel stream temperature variation in the Cascade Range streams was also suggestive of the presence of concentrated groundwater discharge (Harrington, Hayashi, & Kurylyk, 2017; Surfleet & Louen, 2018). In part, this was expected, as the Cascade Range is underlain by highly fractured basalt bedrock, which has previously been shown in the Oregon Cascades to have high water holding capacity and high permeability, resulting in the majority of precipitation draining to groundwater and reemerging as cool springs (Jefferson, Grant, & Rose, 2006; Tague et al., 2007, 2008).

While the thermal buffering from these apparent locations of cool groundwater discharge extended several hundred meters downstream in two of our study streams in the Cascade Range (BEA and BUL), they were less pronounced in our other study stream (SUG). Thus, further research could provide valuable insights into how far downstream the influence of discrete groundwater discharge locations may persist, providing important cold-water refugia (Torgersen, Price, Li, & McIntosh, 1999). For example, in the Shasta River, a tributary to the Klamath in Northern California, Nichols, Willis, Jeffres, and Deas (2014) found that the thermal influence of spring discharge persisted downstream for 23 km, and suggested that understanding similar patterns was critical for managing cold-water fish habitat. Downstream cooling has been observed in other spring dominated systems (Harrington et al., 2017; Leach & Moore, 2011; Story et al., 2003; Surfleet & Louen, 2018), and has often been associated with the location of fractures or faults along underlying bedrock. Depending on the volume of groundwater discharge at these locations, stream temperatures may be modified for long distances downstream, with potentially important implications for aquatic habitat.

While the thermal profiles in the Coast Range streams were also complex, the downstream temperature variability was less dramatic than in the Cascade streams. The comparatively thin, friable soils in the Coast Range likely contributed to summer baseflow from spatially continuous shallow subsurface sources or perched areas of saturated soil on most of the streams (Keppeler & Brown, 1998), rather than discrete discharge from deep aquifers. Lateral inflow from a shallow layer at the base of the soil profile has previously been observed as the primary source of baseflow and a dominant control on stream temperature in a Coast Range watershed in the PNW (Moore et al., 2005b). Additionally, the step-pool geomorphology in the Coast Range streams may have contributed to hyporheic down-welling or sub-surface inter-gravel flow, which can contribute to greater thermal stability (Kasahara & Wondzell, 2003; Peterson & Sickbert, 2006).

Our results also highlighted the spatial variability in atmospheric control on stream temperature between the Coast Range and Cascade Range streams. Given the regional differences in climate and forest cover, we expected the influence of air temperature on stream temperature (i.e., thermal sensitivity) would be greater in the Cascade Range streams. However, streams were less thermally sensitive in the Cascade Range by 0.039–0.171°C $°C^{-1}$ compared to the Coast Range streams. Indeed, many stream segments along the Cascade Range streams were insensitive to changing air temperatures, despite large diel variability in air temperature. These low thermal sensitivities indicated a decoupling of atmospheric control on stream temperature that was likely due to the concentrated groundwater discharge from deep aquifers. Site level thermal sensitivity values in Cascade Range streams revealed that values less than 0.2 °C $°C^{-1}$ generally corresponded to locations with the coolest and least variable stream temperatures and likely, this threshold separated groundwater dominated versus surface flow dominated portions of the streams (Kelleher et al., 2012; O'Driscoll & DeWalle, 2006).

The importance of lithology as a first order control of groundwater contributions and stream thermal sensitivity was previously illustrated by Tague et al. (2007), who compared stream thermal sensitivities between spring dominated streams draining resistant volcanic lithology in the high Cascades and shallow sub-surface flow dominated streams draining less resistant lithology in the mid-Cascades of Oregon. They determined that spring dominated systems draining resistant lithology were less thermally sensitive than lower elevation shallow sub-surface flow systems due to differences in the magnitude of streamflow sourced from the subsurface. Indeed, headwater streams draining volcanic lithology and deep soils typically have a large proportion of summer baseflow generated from groundwater (Segura et al., 2019) that is derived from prior snowmelt or heavy rains (Tague et al., 2008). These inputs can dampen atmospheric sensitivity at discrete groundwater discharge locations, where the response to atmospheric warming may lag or mute air temperature signals (Briggs et al., 2018b). Briggs et al. (2018c) also determined that the magnitude of groundwater discharge varied longitudinally along a stream with the soil depth to bedrock and influenced the attenuation of stream temperature signals by groundwater. The authors also determined that shallow aquifer sourced groundwater displayed considerable sensitivity to the downward propagation of heat derived from surficial advective and conductive sources. We posit that we observed similar drivers in our study. It is likely that the Cascade Range streams, characterized by comparatively deeper soils than the Coast Range, were more thermally buffered from atmospheric controls on stream temperature. Alternatively, the stream and air temperature signals were more closely coupled in the Coast Range.

There have been many previous studies that have assessed stream thermal sensitivity; however, the majority have occurred at a regional or larger scale across multiple river basins, rather than a headwater scale (Table 6). Despite differences in scale, several of these previous studies have illustrated low thermal sensitivity in groundwater dominated systems (Kanno, Vokoun, & Letcher, 2014; Kelleher et al., 2012; Segura et al., 2015; Tague et al., 2007), similar to our study. Previous studies also found a similar strength (R^2) in their linear regression relationships between stream temperatures and air temperatures (Hilderbrand, Kashiwagi, & Prochaska, 2014; Segura et al., 2015; Snyder et al., 2015), as we found in our study, which was indicative that air temperature was only one controlling factor of stream temperature in headwater streams. For instance, baseflow index, a measure of groundwater contributions to flow, and stream size were two variables found to control stream thermal sensitivity in Pennsylvania streams (Kelleher et al., 2012), while drainage area and channel slope exerted the strongest control in regional thermal sensitivity studies (Segura et al., 2015; Winfree et al., 2018). Lisi et al. (2015) observed thermal sensitivity 5–8-times greater in low elevation, low gradient, rain dominated streams compared to high elevation, steep, snowmelt dominated streams due mainly to differences in slope and snowmelt contributions. Others have used measures of accumulated degree days above mean summer air temperature to act as a proxy of groundwater influence with success in stream temperature prediction to generate thermal sensitivity values (Snyder et al., 2015). Similarly, spatially variable groundwater inputs controlled thermal sensitivity magnitude (Kanno et al., 2014; O'Driscoll & DeWalle, 2006) and variability (Trumbo et al., 2014) elsewhere. In the present study, it is likely that site-level differences in riparian vegetation, discharge, and precipitation inputs explain majority of the remaining variation in stream temperature, but our monitoring did not allow us to consider these factors at a site-level resolution.

5 | CONCLUSIONS

We compared the longitudinal thermal regimes and thermal sensitivity of eight headwater streams across two distinct regions of Northern California. In general, stream and air temperatures were less coupled in streams underlain by volcanic lithology compared to streams underlain by sedimentary lithology. We posit that the decoupling of stream temperature from air temperature control in the Cascade Range streams was due to cool groundwater discharge, which occurred predominantly streams underlain by volcanic lithology. Interestingly, we also observed less variability in longitudinal stream temperatures in the Coast Range streams— underlain by sedimentary lithology—despite a slight warming in the downstream direction. This was likely due to greater sensitivity of the comparatively warmer, shallower subsurface sources in the Coast Range, resulting in a greater coupling to atmospheric temperatures. Our study revealed the complexities in thermal regimes in headwater streams and the potential importance of lithology. Improved understanding of the dominant controls on thermal regimes of small headwater streams will become increasingly critical in the future. This knowledge is necessary to improve projections of aquatic habitat resiliency or vulnerability to pressures from climate change or shifting disturbance regimes, where land management decisions may become increasingly complex. As such, future research should continue to quantify the comparative roles of streamflow, groundwater, and streamside vegetation on fine-scale temperature dynamics and aquatic habitat viability in headwater streams across diverse regions. Additional research is also needed on downstream thermal propagation from spring dominated and shallow subsurface dominated headwater catchments.

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TABLE 1. Climatic and physical characteristics of the study areas.

Characteristic	Cascade Range	Coast Range	Reference
Mean T_a (°C, range)	10.9 (-6.0–29.2)	13.5 (1.6–28)	Measured herein
Precipitation (mm, Oct 2017–Sept 2018)	1,018	956	PRISM Climate Group, 2020
30-year mean precipitation (mm)	1,350	1,262	PRISM Climate Group, 2020
Mean stream elevation (m, range)	1,741 (1,576–1,912)	124 (52–189)	Measured herein
Mean watershed slope (%)	28	33	Measured herein
Mean canopy cover (%, range)	61 (54–66)	85 (78–91)	Oregon State LEMMA Database, 2020
Dominant forest cover	Sugar, ponderosa, and lodgepole pine	Coast redwood, Douglas-fir, and western hemlock	Observed herein
Dominant lithology	andesite, basalt	sandstone, mudstone	MacDonald, 1963; Amatya et al., 2016

TABLE 2. Individual stream physical characteristics.

Characteristic	Cascade Range			Coast Range				
	BEA	**BUL**	**SUG**	**HEN**	**IVE**	**RIC**	**WIL**	**XRA**
Mean stream slope (%)†	19	17	24	21	23	27	19	25
Stream length (m)	880	1,078	902	418	418	550	308	770
Drainage area (km^2)†	1.07	3.13	0.58	0.38	0.23	0.47	0.26	0.62
Canopy cover (%)‡	66	54	62	92	78	88	80	87
T_s sensor spacing (m)	73	90	75	35	35	45	25	64
D_{50} (mm)§	60	51	46	24	13	17	16	21
Stream aspect†	S	S	NW	W	SE	SW	NW	SE
Elevation range (m)†	1,663–1,777	1,640–1,772	1,637–1,837	104–155	104–164	52–110	135–189	71–178

†Derived using ArcMap version 10.7 (ESRI, Redlands, CA)

‡Oregon State LEMMA Database (2020)

§From Pate et al. (2020)

TABLE 3. Stream (T_s) and air (T_a) temperature statistics during summer 2018 (June 1 to September 30) for streams in the Coast and Cascade Ranges. Avg. = Average, SD = standard deviation.

Type	Region	Avg. Daily Mean (°C)	Avg. Daily SD (°C)	Avg. Daily Max (°C)	Avg. Daily Min (°C)	Avg. diel range (°C)
T_a	Cascade Range	14.73	5.48	26.22	8.49	17.73
	Coast Range	13.11	2.44	17.60	9.95	7.66
T_s	Cascade Range	7.30	0.68	8.77	6.53	2.24
	Coast Range	12.00	0.28	12.46	11.59	0.90

TABLE 4. Longitudinal linear regression modeling results to assess downstream warming or cooling, and longitudinal heterogeneity in stream temperature in each stream. AITD = average difference in average daily mean stream temperature between each stream temperature sensor and the sensor immediately downstream. AISDD = average difference in average daily stream temperature standard deviation between each stream temperature sensor and the sensor immediately downstream.

Region	**Stream**	**Intercept (°C)**	**Slope (°C km^{-1})**	**AITD (°C)**	**AISDD (°C)**
Cascade Range	BEA	5.08	-2.74	0.66	0.19
	BUL	6.15	-3.88	1.26	0.44
	SUG	8.42	-0.66	1.16	0.61
	Average	6.55	-2.43	1.03	0.41
Coast Range	HEN	11.79	-1.07	0.30	0.31
	IVE	11.93	0.18	0.21	0.15
	RIC	12.10	0.91	0.17	0.15
	WIL	12.42	2.12	0.36	0.21
	XRA	12.26	0.79	0.42	0.16
	Average	12.10	0.59	0.29	0.19

TABLE 5. Thermal sensitivity descriptive statistics for each stream and region.

Region	Stream	# of T_s sensors	Mean R^2 (range)	Mean (°C °C^{-1})	Median (°C °C^{-1})	SD (°C °C^{-1})	Minimum (°C °C^{-1})	Max (°C °C^{-1})
Cascade Range	BEA	12	0.55 (0.11–0.85)	0.13	0.09	0.09	0.05	0.31
	BUL	11	0.64 (0.48–0.84)	0.26	0.23	0.18	0.04	0.63
	SUG	10	0.55 (0.30–0.71)	0.33	0.31	0.13	0.10	0.59
	Sub-totals	33	0.58 (0.11–0.85)	0.24	0.23	0.16	0.04	0.63
Coast Range	HEN	8	0.60 (0.44–0.93)	0.36	0.32	0.19	0.18	0.77
	IVE	10	0.60 (0.32–0.78)	0.27	0.25	0.10	0.15	0.44
	RIC	9	0.55 (0.28–0.75)	0.39	0.37	0.14	0.20	0.59
	WIL	9	0.48 (0.11–0.65)	0.28	0.33	0.11	0.10	0.37
	XRA	8	0.66 (0.35–0.78)	0.37	0.35	0.09	0.27	0.50
	Sub-totals	44	0.58 (0.11–0.93)	0.33	0.33	0.13	0.10	0.77

TABLE 6. Results from our study and other studies that have quantified stream thermal sensitivity to air temperature at a range of spatial scales.

Thermal Sensitivity Range (°C °C^{-1})	Location	Temporal Resolution	Reference
0.04–0.77	8 streams in Northern California, US	Daily	Present study
0.19–0.67	12 sites in a Pennsylvania watershed	Weekly	O'Driscoll & DeWalle, 2006
0.39–0.61	6 sites across northern latitudes of the US	Daily	Simmons et al., 2014
0.35–1.09	43 streams internationally	Daily, Weekly	Morrill et al., 2005
0.20–0.65	80 boreal streams in SW Alaska	Daily	Lisi et al., 2015
0.02–0.93	57 sites across Pennsylvania	Daily, Weekly	Kelleher et al., 2012
0.10–0.82	78 sites in Shenandoah National Park, Virginia, US	Daily	Snyder et al., 2015
0.10–0.81	74 sites in the Columbia River Basin, US	Daily, Weekly	Chang & Psaris, 2013
0.13–1.25	157 sites across US, Air Temp > 0 °C	Weekly, Monthly	Segura et al., 2015
0.20–1.14	104 sites across US PNW	Weekly	Mayer, 2012
0.02–1.09	43 sites across the Oregon Cascades	Daily	Tague et al., 2007
0.13–0.79	46 sites across Maryland, US	Daily	Hilderbrand et al., 2014
0.01–0.58	43 coastal streams in SW Alaska	Daily	Winfree et al., 2018
0.49–1.08	61 sites across the Southeast US	Monthly	Caldwell et al., 2015

Figure Legends:

FIGURE 1. Field site locations within California in the LaTour State Forest (Cascade Range) and Caspar Creek (Coast Range). Inset on the right: Schematic of temperature data collection for all 8 study reaches. Spacing between stream temperature sensors varied between streams and study regions (30–80 m).

FIGURE 2. Comparison of air and stream temperature distributions among streams in the Coast and Cascade Ranges. Data were pooled from all temperature sensors within each stream. The boxplot central tendency line is the median, shaded boxes represent the interquartile range (IQR), whiskers represent the largest value up to 1.5-times the IQR, and the black dots indicate outliers beyond 1.5-times the IQR.

FIGURE 3. Longitudinal distribution of stream temperatures measured along Coast Range and Cascade Range streams during summer, 2018. Upstream distance is normalized on the x-axis for comparison. The direction of flow is from left to right. Red arrows indicate likely spring locations in the Cascade Streams. Locations shown without data were either dry (D) throughout the summer or the sensor was missing during data collection (M). Measured stream lengths vary from 300 to 1000 m.

FIGURE 4. Longitudinal trends in thermal sensitivity (linear regression slope, Equation 3) along Cascade Range (BEA, BUL, SUG) and Coast Range (HEN, IVE, RIC, WIL, XRA) streams. Missing data points indicate sensors that went dry or regression models that were not included in the final analysis. The largest value in HEN is characterized by a sensor that went dry after 17 days. The x-axis is normalized for ease of comparison; stream lengths are in Table 2.

FIGURE 5. (A) Violin plot showing the distribution of thermal sensitivities of streams in the Cascade Range and the Coast Range. (B) The relationship between site-level thermal sensitivity values and model R^2 values. The red circle in (A) indicates likely locations of spring discharge and concentrated groundwater inflow.