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Stream temperature response to variable glacier coverage in coastal watersheds of Southeast Alaska

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Abstract:

We measured stream temperature continuously during the 2011 summer run-off season (May through October) in nine watersheds of Southeast Alaska that provide spawning habitat for Pacific salmon. The nine watersheds have glacier coverage ranging from 0% to 63%. Our goal was to determine how air temperature and watershed land cover, particularly glacier coverage, influence stream temperature across the seasonal glacial meltwater hydrograph. Multiple linear regression models identified mean watershed elevation (related to glacier extent) and watershed lake coverage (%) as the strongest landscape controls on mean monthly stream temperature, with the weakest (May) and strongest (July) models explaining 86% and 97% of the temperature variability, respectively. Mean weekly stream temperature was significantly correlated with mean weekly air temperature in seven streams; however, the relationships were weak to non-significant in the streams influenced by glacial run-off. Streams with >30% glacier coverage showed decreasing stream temperatures with rising summer air temperatures, whereas those with <30% glacier coverage exhibited summertime warming. Glaciers also had a cooling effect on monthly mean stream temperature during the summer (July through September) equivalent to a decrease of 1.1 °C for each 10% increase in glacier coverage. The maximum weekly average temperature (an index of thermal suitability for salmon) in the six glacial streams was substantially below the lower threshold for optimum salmon growth. This finding suggests that although glaciers are important for moderating summer stream temperatures, future reductions in glacier run-off may actually improve the thermal suitability of some glacially dominated streams in Southeast Alaska for salmon. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS stream temperature; glacier; thermal sensitivity; hydrology; climate change; Pacific salmon

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INTRODUCTION

Glaciers cover an estimated 10% (approximately 525 000 km^2) of the earth's surface and store 75% of the world's freshwater (NSIDC, 2008). Glacial environments are sensitive to changes in climate because of linkages between atmospheric conditions, glacier mass balance and run-off, water quality, and ecology (e.g. Smith *et al*., 2001; Milner *et al*., 2009; Moore *et al*., 2009). Studies have shown an overall decrease in glacier area (i.e. thinning and retreating) over the last century in many regions worldwide (Dyurgerov and Meier, 2000; Barry, 2006). Hydrological models predict that glacial retreat may result in an initial increase in streamflow, but prolonged glacier retreat will cause a hydrological regime shift to that of a non-glacial stream, where streams warm and flow decreases as glacier and snowpack sources diminish (Fleming and Clarke, 2005; Stahl and Moore, 2006; Stahl *et al*., 2008). Changes in glacier volume that result in declining summer flows could therefore have substantial hydroecological effects, especially for stream temperature (Hood and Berner, 2009) and the distribution of aquatic species, such as salmonids (Hrachowitz *et al*., 2010; Isaak *et al*., 2010).

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Water temperature is a fundamental physical property of aquatic environments affecting the solubility of gases, such as carbon dioxide and oxygen, nutrient cycling and speciation, and the physiology and development of aquatic species (Caissie, 2006; Webb *et al*., 2008). Water temperature is not only a key indicator of overall ecosystem health, but it is important economically through its influence on fisheries and water requirements for industry, aquaculture and recreation (North, 1980; Dorava and Milner, 2000). Given the projected increases in atmospheric temperature and the current trend of rising stream temperature in many regions worldwide (e.g. Webb and Nobilis, 2007), identifying the main factors controlling stream temperature is necessary for improved comprehension and prediction at local to regional scales.

Stream temperature is a function of the combined effect of controlling factors generally related to atmospheric conditions, streamflow, topography and streambed processes (Caissie, 2006; Webb *et al*., 2008). Water temperature also varies temporally and spatially in watersheds, and its measurement from any one point in the stream incorporates both reach (e.g. riparian forest shading; Mellina *et al*., 2002) and watershed-scale (e.g. glacier area; Moore, 2006) influences from some distance upstream. For instance, water temperature near a glacial source will be close to 0 °C and will increase along the stream network depending on climate, distance downstream and non-glacial water flux to the stream (Brown *et al*., 2006; Moore, 2006). Therefore, assessing the contribution of glacial meltwater to streamflow is essential to our understanding of how glaciers influence the thermal behaviour of recipient streams. Stable isotopes of water (δ^{18}O) are commonly used in watershed-scale studies to indicate the relative contribution of glacier run-off to streamflow (Mark and McKenzie, 2007; Hood and Berner, 2009). This is because meltwater is typically depleted in δ^{18}O compared with other sources of water, such as groundwater or rainfall (Rietti-Shati *et al*., 2000; Mark and McKenzie, 2007). Thus, streamwater δ^{18}O values become more depleted (negative) with increasing glacier meltwater contributions to streamflow (Hood and Berner, 2009).

Glacial meltwater is an especially important control on stream temperature because glacier discharge peaks in summer and acts as a moderating influence on stream temperature (Moore, 2006). Glacial meltwater also helps to maintain favourable habitat for aquatic species such as salmonids (Dorava and Milner, 2000) and invertebrates (Milner and Petts, 1994; Brown *et al*., 2007; Jacobson *et al*., 2012). Climate warming is expected to increase discharge from heavily glaciated basins (Fleming and Clarke, 2003; Birsan *et al*., 2005; Hodgkins, 2009), with the most pronounced impacts in regions with high rates of glacier volume loss. Southeast Alaska is currently experiencing some of the highest rates of glacier volume loss on Earth (Larsen *et al*., 2007), and total glacier run-off in this region accounts for approximately 30% of the total land-to-ocean flux of freshwater (Neal *et al*., 2010). In this context, continued glacier volume loss has the potential to change watershed land cover and alter stream thermal patterns in a region where many glacier-fed streams currently provide favourable habitat for anadromous Pacific salmon.

In this study, we examine how air temperature and watershed land cover, especially glacier coverage, relate to stream temperature across the seasonal glacial meltwater hydrograph (typically June through September). We measured stream temperature from May through October 2011 in nine watersheds of coastal Southeast Alaska that provide spawning habitat for Pacific salmon. Six of the nine watersheds have glacier coverage ranging from 2% to 63%, whereas three are non-glacial. We also measured δ^{18}O of streamwater in three watersheds of varying glacial coverage to identify sources of water and their potential influence on stream temperature. Our results provide insight into how variable glacier coverage influences the timing and magnitude of seasonal stream temperature patterns as well as the streams' thermal suitability for salmon. Air temperature and landscape cover are commonly used in regression models to predict stream temperature (Webb, 1996; Kelleher *et al*., 2012), but few studies asses these relationships in glacial streams where they may be especially useful for predicting the stream temperature response to glacial retreat.

METHODS

Study area

The study watersheds are located in the northern region of coastal Southeast Alaska, near Juneau (Figure 1). The region is characterised by mild winters, cool wet summers, and persistent cloud cover. Juneau has a mean annual temperature of 4.7 °C and a mean annual precipitation of 1400 mm at sea level. Glacier recession has modified the region leaving steep sloping watersheds that support a mosaic of landscape features including glaciers, high alpine, waterlogged peatlands and forested mineral accumulations composed of alluvial and colluvial material over a residual bedrock and glacial till (D'Amore *et al*., 2012). Streams within each watershed reflect the variation in landcover across the watersheds. For example, Peterson Creek is a brownwater stream that drains a watershed with over 34% wetland cover in contrast to the adjacent Herbert River (49% glacier cover), which is a glacial river (Figure 1).

The nine study watersheds range in area from 11 to 231 km^2 and are typical of the many coastal temperate watersheds draining west to the Pacific Ocean in British Columbia and Southeastern Alaska (Table I). Six of the nine watersheds contain glaciers, which range in watershed coverage from 2% to 63%. Lake coverage ranges from 0% to 6.8% of watershed area and includes two large proglacial lakes (Mendenhall and Eagle). Glacier volume loss is pronounced in the study watersheds with low elevation ice thinning rates estimated at 2–8 m yr^{-1} (Motyka *et al*., 2002; Larsen *et al*., 2007). The glaciated watersheds contain extensive high elevation reaches of alpine tundra and have successional attributes typical of recently deglaciated terrain, such as exposed bedrock, poorly developed soils and sparse vegetation dominated by *Alnus sinuata*, *Salix* spp. and nitrogen fixing forbs (e.g. *Dryas drummondii*, Chapin *et al*., 1994; Milner *et al*., 2007). In the lower reaches of these watersheds, the landscape is older consisting of mixed coniferous forest of *Picea sitchensis* and *Tsuga heterophylla*. The glacial rivers are low gradient (<5%) downstream of the glacier terminus with few braided side channels. River wetted widths generally range from 15 to 45 m. Although riparian forest occupies almost the entire length of the stream channels (except recently deglaciated reaches near the glacier terminus), the main channels are not heavily shaded, because of the wide channels in these watersheds.

The Montana and Fish Creek watersheds consist mainly of spruce–hemlock forest interspersed with small areas of peatland but also have high elevation reaches of alpine tundra that seasonally accumulate large snowpacks. In particular, Montana Creek contains some semi-permanent snowfields and residual glacier ice (approximately 2% watershed glacier coverage) at high elevation. Montana and Fish Creeks have higher gradients than the glacial watersheds and contain few braided side channels. River wetted widths generally range from 15 to 25 m in the lower reaches of these watersheds, and well developed riparian forests provide partial shading of the stream channels.

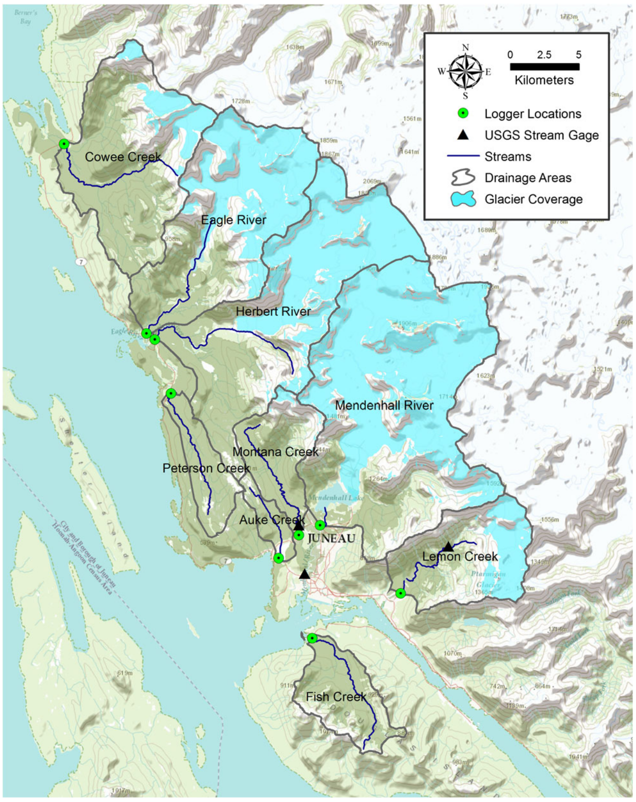

Figure 1. Map of nine study watersheds near Juneau, Alaska.

Auke and Peterson Creeks are low gradient watersheds that contain lakes, and the landscape is mainly spruce–hemlock forest with large areas of peatland. Stream channels are low gradient (<5%) and are characterised by a sequence of riffles and pools. River wetted-widths generally range from 5 to 10 m in the lower reaches of the watersheds, and well developed riparian forests provide almost complete shading of the channel along some reaches.

Alaska is currently the largest wild salmon-producing region on earth (salmon biomass in metric tonnes; Knapp *et al*., 2007), and all nine watersheds in this study have anadromous Pacific salmon runs (*Oncorhynchus* spp.) throughout the summer and early autumn (June through September). However, spawning density and species vary among streams. Discharge is measured continuously by the US Geologic Survey (USGS) in three of the study watersheds – Mendenhall River, Montana Creek and Lemon Creek.

Stream temperature measurement

Stream temperature at all sites was measured at 15-min intervals during the period of 1 May through 31 October 2011. Temperature monitoring stations were all <50 m above sea level and within 5 km from the coast. Two temperature data loggers (Onset Computer Corporation, HOBO Water Temp Pro V2, precision ±0.2 °C) were placed in the main stem of each watershed approximately

Table I. Watershed characteristics for the nine study watersheds

Variable	Auke Creek	Peterson Creek	Fish Creek	Montana Creek	Cowee Creek	Lemon Creek	Eagle River	Herbert River	Mendenhall River
Watershed area (km^2)	11	24	36	37	110	61	124	152	222
Mean watershed elevation (m)	251	309	487	481	648	804	894	860	994
Mean watershed aspect (deg)	163	190	164	178	204	196	195	196	200
Mean watershed slope (deg)	11	12	20	21	23	22	21	18	18
Mean stream elevation (m)	223	175	253	127	166	182	46	180	17
Mean stream slope (deg)	9	6	7	11	10	13	7	9	2.6
Mean stream aspect (deg)	112	126	165	116	200	213	183	176	177
Wetland coverage (%)	22	34	13	6	5	1	2	5	1
Lake coverage (%)	6.8	1.0	0.2	0	0.2	0.4	0.9	0.5	1.8
Glacier coverage (%)	0	0	0	2	13	29	48	49	63
Forest coverage (%)	82	92	72	66	57	22	23	25	8

2 m from the stream bank. Loggers were anchored both at the stream bank and from the streambed so that they were consistently submerged 10–20 cm above the streambed. Temperature loggers were placed in perforated white PVC pipes to prevent direct exposure to sunlight but to allow constant water throughflow. All data loggers were cross-calibrated before and after the study and found to be within 0.3 °C of each other with a standard deviation of 0.1 °C. Data logger failure and loss occurred at several sites during the study period, although each stream (except Herbert River) always had one logger recording measurements. For Herbert River, both loggers were buried with glacial outwash sediment for several weeks during August through October. Invalid data in Herbert were replaced using regression equations for stream temperature data from the adjacent Peterson Creek and Eagle River watersheds.

Discharge in Montana Creek during the 1 May through 31 October 2011 study period accounted for 88% of total annual flow from the watershed. This is well above the long term average (34-year period of record) of 74% for the May–October period. Similarly, discharge in Mendenhall River during the 6-month study period accounted for 95% of total 2011 discharge from the watershed, which is slightly above the long term average (46-year period of record) of 93% for Mendenhall River. Mean air temperature in Juneau during the measurement period was 10.3 °C, which is slightly below the long term May–October average of 10.6 °C. Rainfall for the study period (946 mm) was above the long term average of 870 mm at the Juneau airport. This observed increase largely occurred in August, when the 2011 August rainfall (272 mm) was nearly twofold greater than the long term average of 146 mm.

Streamwater δ^2H and $\delta^{18}O$ analysis

A 25 ml water sample was collected for δ^{18}O analysis in the three USGS gauged watersheds (Mendenhall River, Montana Creek and Lemon Creek). Water isotope samples were collected every 1–2 weeks and stored in glass bottles with zero headspace at room temperature until analysis on a Picarro L2120-*i* analyzer at Virginia Tech. Values for δ^{18}O are reported in per mil (‰) after normalisation to Vienna Standard Mean Ocean Water.

Watershed characterization and stream temperature models

We derived stream drainage boundaries for the study watersheds from a USGS (http://www.nrcs.usda.gov/) watershed boundary feature mapped at a level of 12-digit hydrological unit code or ‘sub-watersheds’. Stream gauge coordinates over a stream data set were derived from a regional hydrological geodatabase (SEAKHydro, http://seakgis.uas.alaska.edu). We reviewed topographic data and contours mapped at a 1 : 24 000 scale and then used ‘heads-up’ digitising to modify drainage boundaries to include only drainage area upstream of each stream gauge location. Using GIS, the area of each drainage was calculated as well as ten other compositional variables (Table I) derived from the following original sources: topographic variables at the watershed and stream scales were derived from 30-m resolution digital elevation data from the Shuttle Radar Topographic Mission (http://www2.jpl.nasa.gov/srtm/); wetland coverage, which we defined as any palustrine, lacustrine and riverine wetland body, originated from the National Wetland Inventory (http://alaska.fws.gov/fisheries/nwi/index.htm); forest coverage from the Nature Conservancy’s Terrestrial Ecological Systems landcover database (http://home.gci.net/~tnc/HTML/GIS_Database.html) and glacial extent from the 2010 Global Land Ice Measurements from Space data set (http://nsidc.org/).

We used multiple linear regression (MLR) of mean monthly stream temperature (i.e. mean of daily temperature from two data loggers on 15-min sample intervals averaged over 1 month) to assess the influence of landscape controls on seasonal variation in stream temperature. Stepwise regression analysis using SPSS software (Sigmastat, 2012) was used for each monthly model, and only those variables significant at $p < 0.05$ were retained. Adjusted R^2 values (R^2_{adj}) were used in MLR models because they account for the number of predictor variables in each model. Variance inflation factors were calculated to assess for multicollinearity among retained predictor variables. In some cases, predictor variables were highly correlated (e.g. watershed glacier coverage and watershed elevation), and only the strongest variable was retained in the model.

Linear regression was used to assess the relationship between mean weekly air and mean weekly stream temperatures. Weekly linear regression models for air and water temperatures typically provide a better fit than daily models because averaging daily values to a weekly time step often reduces scatter by moderating both high and low temperature extremes (Kelleher *et al*., 2012). Non-linear regression was also used to relate air and water temperature (Mohseni *et al*., 1998; Kelleher *et al*., 2012), but these models did not improve the fit due to the narrow temperature range of our study streams. In addition, we used the slope of the regression of mean weekly air temperature against mean weekly water temperature to assess how sensitive water temperature is to a given change in air temperature (Kelleher *et al*., 2012).

Thermal suitability metrics

We used the maximum weekly average temperature (MWAT) to assess stream thermal suitability for Pacific salmon (Eaton *et al*., 1995). The MWAT is a commonly used temperature criterion for risk assessments in salmonid streams because it correlates well with growth metrics for salmonids at different life stages (Sullivan *et al*., 2000; Nelitz *et al*., 2007). Here, we use 12.8–14.8 °C as the optimum range in MWAT for salmon growth, which is based on models used to predict salmonid growth in natural streams (Sullivan *et al*., 2000). We also used 6-month temperature-duration curves to assess stream thermal suitability for Pacific salmon because unlike temperature indices (e.g. MWAT), they summarise all data for a given period. For temperature duration curves, we use a water temperature range of 5–17 °C with a physiological optimum of 15 °C (Brett *et al.*, 1969; Brett, 1971) to assess stream thermal suitability for salmon.

RESULTS

Watershed hydrology and isotope chemistry

Discharge and $\delta^{18}O$ values in the three watersheds gauged by the USGS were used to identify sources of water and their potential influence on stream temperature. Mean daily run-off in Montana Creek ranged from 0.14 to 3.16 mm hr^{-1} and generally decreased from late May to its summer minimum in mid-August before rebounding during the fall rainy season (Figure 2a). The more heavily glaciated watersheds Lemon Creek and Mendenhall River showed more variability in run-off relative to Montana Creek, ranging from 0.06 to 5.69 mm hr^{-1}. Run-off in Lemon Creek and Mendenhall River was lowest for the 6-month study period on 1 May followed by an overall increase through mid-August. Run-off in the three watersheds showed numerous rainfall spikes during the study period, especially during a large storm in mid-August when run-off in all three rivers increased more than fourfold over a 24-h period. Mendenhall River also showed a large run-off peak on 21 July due to a glacial lake outburst flood that caused run-off to increase from 1.50 to nearly 5.64 mm hr^{-1} over a 2-day period.

Mean streamwater $\delta^{18}O$ values were −14.5‰ for Montana Creek, −15.3‰ for Lemon Creek and −15.6‰ for Mendenhall River despite similar values during the initial mid-May sampling (Figure 2b). The two heavily glaciated rivers showed an overall decrease in $\delta^{18}O$ concurrent with snowmelt that lasted from mid-May through June in Lemon Creek and through mid-July in Mendenhall River. In contrast, $\delta^{18}O$ values in Montana Creek showed an overall increase from mid-May through late July indicating the seasonal winter snowpack had mostly melted by the initial monitoring in May. All three streams showed a substantial decrease in $\delta^{18}O$ during the large storm in mid-August followed by an increase in values during the autumn rainy season months of September and October.

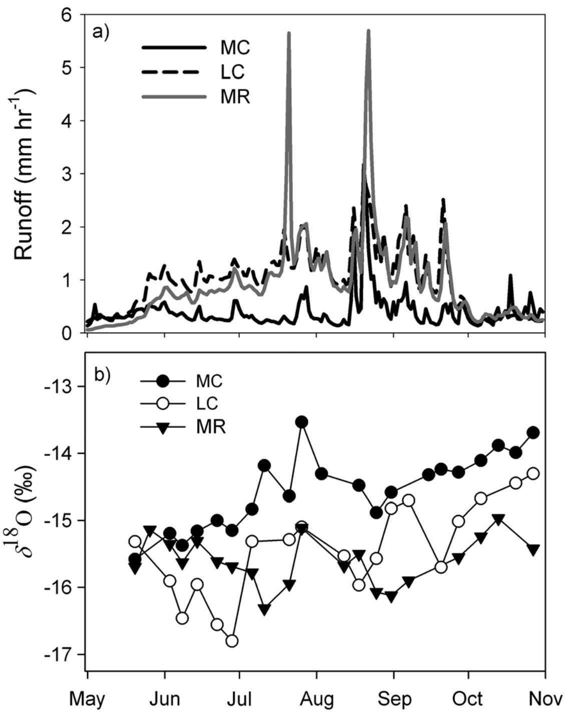

Figure 2. (a) Mean daily run-off (mm hr^{-1}) and (b) $\delta^{18}O$ values for the three USGS gauged watersheds during the 1 May through 31 October 2011 study period. MC is Montana Creek (2% watershed glaciation), LC is Lemon Creek (29% watershed glaciation) and MR is Mendenhall River (63% watershed glaciation)

Stream temperature

Mean stream temperature for the study period ranged from a low of 3.4 °C in the highly glacial Mendenhall River to a high of 14.7 °C in non-glacial Auke Creek, which has a large lake upstream of the sampling site (Figure 3a). Stream temperature decreased with increasing glacier coverage, reflecting the input of cold glacial meltwater to streamflow during the summer run-off period. Overall, stream temperature in non-glacial streams showed greater variability relative to glacial streams during the study period, with temperature varying most in the low gradient Auke Creek ($\sigma = 3.6$ °C) and least in the intermediate glaciated Lemon Creek ($\sigma = 0.6$ °C).

Increasing watershed glacier coverage decreased the correlative relationship between daily mean stream temperatures and air temperature (Figure 3b). Daily stream temperature for all nine sites was most similar in early May and late October when groundwater and rainfall were the main contributing sources of water to streamflow. Patterns in stream temperature diverged in late May when the three heavily glaciated watersheds exhibited maxima followed by an overall cooling during the summer glacier melt season. Maximum stream temperatures in the non/low glaciated watersheds were observed during July and August when the lowest temperatures were recorded in three heavily glaciated watersheds. Stream temperature also increased during the large frontal storm in mid-August for all watersheds except Auke Creek.

All streams showed a strong seasonal hysteresis (using 2-week moving averages) in the relationship between mean air temperature and mean water temperature (Figure 4). For instance, temperature in the forested and low glaciated watersheds increased with rising summer air temperatures but cooled as air temperature decreased during the late summer/early fall showing counterclockwise hysteresis (Figures 4a–e). The moderately glaciated Lemon Creek similarly showed a counterclockwise hysteresis, but stream temperature overall was rather insensitive to changes in air temperature (Figure 4f). In contrast, the three heavily glaciated watersheds showed a clockwise hysteresis across the study period (Figures 4g–i). Water temperature in the three heavily glaciated watersheds was warmest during May showing a strong positive relationship to increasing air temperature. However, water temperature showed a strong negative response to

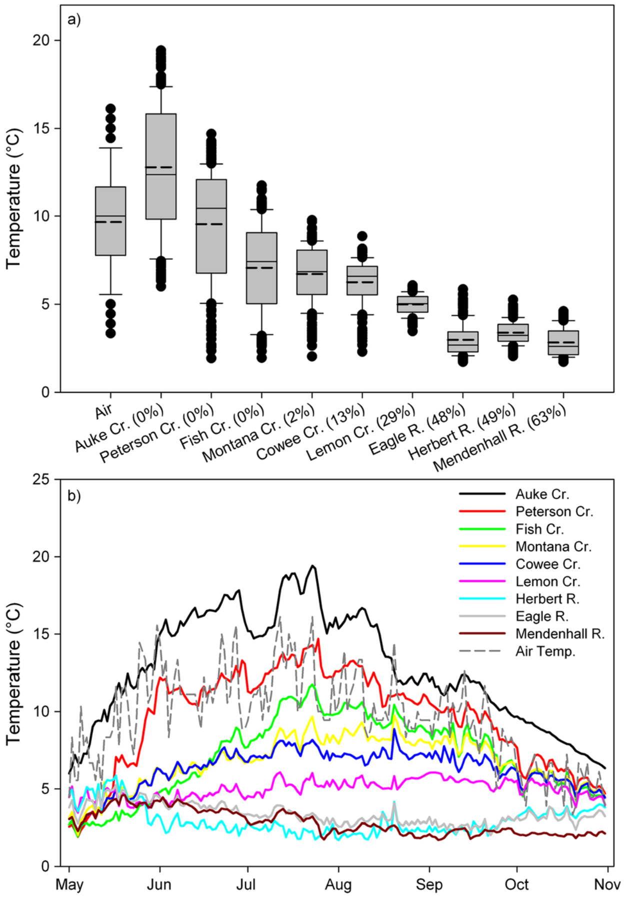

Figure 3. (a) Box plot with mean (dashed line), median (solid line), <10th and >90th percentile points (dots), and 25th and 75th percentiles (vertical bars) for air and stream temperature and (b) time series of mean daily air and water temperature for the nine study streams (% watershed glacier coverage) during the 1 May through 31 October 2011 study period

increasing air temperature in early summer (especially Herbert River) reflecting the cooling effect of glacial meltwater on stream temperature.

Air temperature and landscape control of seasonal stream temperature

Regressions of mean weekly water temperature against mean weekly air temperature were significant ($p \leq 0.01$) for all watersheds except Lemon Creek ($p = 0.58$) and Eagle River ($p = 0.39$) (Table II). However, the R^2 values were mostly low, between 0.01 and 0.41, with the exception of the two low gradient watersheds (Auke and Peterson Creeks, Table II). Analysis of the regression slopes of mean weekly air against mean weekly water temperature showed a substantial increase in the slope with declining watershed glacier coverage. For instance, regression slopes for the low gradient watersheds Peterson and Auke Creeks were more than 1.0, but slopes for the six glaciated watersheds were less than 0.4 and even negative (−0.18) in Herbert River (Table II).

Simple and MLR models identified watershed lake coverage (%) and mean watershed elevation (m) as the strongest landscape controls on mean monthly stream temperature, with the weakest (May) and strongest (July) models explaining 86% and 97% of the variance, respectively (Table III). Watershed glacier coverage (%) was also strongly related to monthly stream temperature ($R^2 = 0.51$–0.89, all $p < 0.03$) for all months except May ($R^2 = 0.14$, $p = 0.32$). However, mean watershed elevation was a slightly stronger predictor of monthly stream temperature compared with watershed glacial coverage.

Lake coverage had a slight warming affect in May through July equivalent to 0.9 to 1.5 °C for each 1% increase in watershed lake coverage. Mean watershed elevation alone was the strongest control of stream temperature from August through October. During the summer months of July and August, mean watershed elevation had a cooling effect equivalent to 1.6 to 1.8 °C for each 100 m rise in mean elevation, but only 0.6 to 1.2 °C per 100 m rise in elevation during the rainy season months of September and October. The combination of watershed lake coverage and mean watershed elevation explained the most variance in mean monthly stream temperature for the entire study period (MLR, $R^2_{adj} = 0.98$) as well as the MWAT ($R^2_{adj} = 0.98$) (Table III). Lake coverage and mean watershed elevation similarly explained the most variance in the regression slope of mean weekly air and mean weekly water temperature during the study period ($R^2_{adj} = 0.91$, $p < 0.01$, $y = 1.188 + 7.522[\text{lake}] - 0.001[\text{elevation}]$).

Thermal suitability for Pacific salmon

The MWAT ranged from 4.3 to 18.6 °C but was less than 9.0 °C in the six glacial streams (Table II). Peterson Creek was the only stream showing an MWAT (14.0 °C) within the optimal range for Pacific salmon (12.8–14.8 °C) (Sullivan *et al*., 2000). The MWAT value for the six glacial streams was 4.0 to 8.5 °C below the lower threshold for optimum salmon growth, and the MWAT for Auke Creek was 3.8 °C above the upper threshold. The date of the MWAT ranged from mid-May in the heavily glaciated watersheds of Eagle, Herbert and Mendenhall to the end of August in more moderately glacier-fed Lemon Creek. The MWAT for the three non-glacial streams occurred in mid-July coincident with the warmest weeks of the summer. There was also a strong linear correlation between the MWAT and glacial coverage for the six glacial streams ($R^2 = 0.96$, $p < 0.01$, $y = -0.075x + 8.77$), with MWAT increasing 0.8 °C for each 10% decrease in glacier coverage.

There were clear seasonal, inter-stream differences in thermal suitability for Pacific salmon. For instance, water temperature in Peterson Creek fell within the optimum range for salmon physiology (5–17 °C; Brett *et al*., 1969; Brett, 1971) for nearly 85% of the study period (Figure 5). Auke Creek had water temperature above the upper threshold for approximately 11% of the study period, but overall fell within the optimum range for 87% of the study period. In contrast, water temperature fell below the lower threshold for most of the study period in the glacial-fed Herbert (95% of study period) and Eagle Rivers (99% of study period) and the entire period in Mendenhall River. Overall, stream thermal suitability for Pacific salmon decreased with increasing glacial coverage in this region.

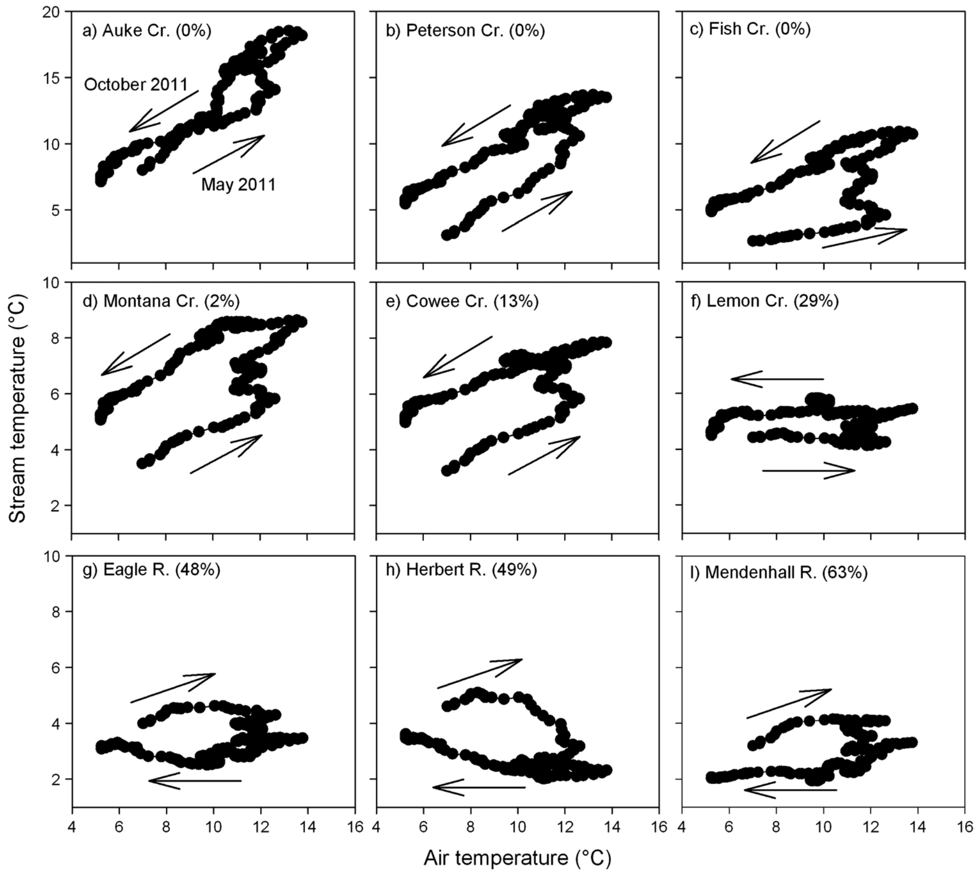

Figure 4. Scatter plots of mean air temperature (2-week moving average) and mean water temperature (2-week moving average) for the nine study streams (% watershed glacier coverage) during the 1 May through 31 October 2011 study period. Figures (a–f) showed a counterclockwise hysteresis, and the three heavily glaciated watersheds of Figures (g–i) showed clockwise hysteresis during the study period. Please note the difference in scale for stream temperature

DISCUSSION

The seasonal patterns in run-off and δ^{18}O across streams are consistent with an increase in the proportion of streamflow derived from δ^{18}O-depleted snow and ice melt in the higher elevation watersheds during the summer months (Rietti-Shati *et al*., 2000; Mark and McKenzie, 2007). The increase in glacial meltwater had a strong moderating effect on stream temperature (Hood and Berner, 2009; Blaen *et al*., 2012), especially during the months of July through September when the three heavily glaciated watersheds (Eagle, Herbert and Mendenhall Rivers) were at their coolest. This contrasts with low gradient, forested watersheds (e.g. Peterson and Auke Creeks), which were warmest during the mid-summer months when streamflow was generally low, and air temperatures were at a maximum. Large frontal storms in this region also affected stream temperature, as exemplified by a storm-induced temperature increase to a 6-month maximum in Cowee and Montana Creeks during a large storm in mid-August. Overall, these findings suggest that although stream temperature can be highly variable due to

Table II. Summary statistics for linear regression models of mean weekly stream temperature and mean weekly air temperature and the MWAT for the 1 May through 31 October 2011 study period

Site (%glacier cover)	R^2	Slope	SE	p value	MWAT, °C	MWAT Date
Auke Creek (0%)	0.83	1.282	1.49	<0.01	18.6	18–24 July
Peterson Creek (0%)	0.69	1.044	1.76	<0.01	14.0	19–25 July
Fish Creek (0%)	0.30	0.558	2.19	<0.01	11.1	19–25 July
Montana Creek (2%)	0.33	0.367	1.32	<0.01	8.8	3–9 Aug
Cowee Creek (13%)	0.41	0.326	1.00	<0.01	8.0	11–17 July
Lemon Creek (29%)	0.01	0.023	0.51	0.58	6.0	30 Aug–5 Sep
Eagle River (48%)	0.03	0.044	0.62	0.39	4.8	14–20 May
Herbert River (49%)	0.27	−0.180	0.76	0.01	5.4	13–19 May
Mendenhall River (63%)	0.23	0.151	0.70	0.01	4.3	15–21 May

SE, residual standard errors; MWAT, maximum weekly average temperature.

Table III. Summary statistics for the best MLR model (all $p < 0.001$) and linear regression with % glacier coverage only used to predict mean monthly stream temperature and MWAT for the nine study streams during the 1 May through 31 October 2011 study period

	Best linear regression model	R^2_{adj}	SE	Linear regression with %glacier	R^2_{adj}	SE
May	3.75 + 90.53(%lake)	0.84	0.83	5.64–3.13(%glacier)	0.02	2.07
June	12.84 + 95.54(%lake) – 0.01(elevation)	0.95	1.00	9.77–12.54(%glacier)	0.44*	3.27
July	16.69 + 60.78(%lake) – 0.02(elevation)	0.96	0.93	11.41–16.69(%glacier)	0.69*	2.75
August	16.98 – 0.02(elevation)	0.96	0.91	10.61–15.53(%glacier)	0.82*	1.82
September	13.69 – 0.01(elevation)	0.94	0.79	8.96–12.20(%glacier)	0.87*	1.16
October	8.76 – 0.01(elevation)	0.84	0.71	6.29–6.28(%glacier)	0.77*	0.86
Study period mean	11.52 + 46.45(%lake) – 0.01(elevation)	0.97	0.53	8.43–10.48(%glacier)	0.66*	1.84
MWAT	17.10 + 75.87(%lake) – 0.01(elevation)	0.98	0.71	12.46–15.31(%glacier)	0.59*	3.07

MLR, multiple linear regression; MWAT, maximum weekly average temperature. Residual standard errors (SE) are provided for each regression model. '%lake' corresponds to the extent of watershed lake coverage and 'elevation' corresponds to mean watershed elevation.
*Indicates significant at $p < 0.05$ for regression models with %glacier coverage.

the interaction of dynamic water source contributions and hydroclimatological conditions (Brown *et al.*, 2006; Blaen *et al.*, 2012), temperature follows generally consistent seasonal patterns based largely on landscape factors such as watershed elevation and lake area.

The results of our regression analyses showing that mean watershed elevation (mainly due to the strong relationship with glacier coverage, $R^2 = 0.88$, $p < 0.001$) and lake area were tightly linked with stream temperature are consistent with studies in Southcentral Alaska (Kyle and Brabets, 2001; Mauger, 2011) as well as other regions (Scott *et al.*, 2002; Moore, 2006; Hrachowitz *et al.*, 2010). Although glacier coverage is clearly a key control on stream temperature during the glacial run-off season, regression models showed that mean watershed elevation is a slightly stronger predictor of temperature. This is likely because watershed elevation reflects the input of seasonal snowpack in addition to glacier meltwater to streamflow, and to a lesser extent, air temperature differences related to elevation.

Lakes had a warming effect in late spring and summer (May through August) for all streams as a result of a sensitivity to atmospheric heating during the day. Similar heating of water downstream of exposed lentic environments has also been found in watersheds with large lakes, swamps and reservoirs (Webb and Walling, 1997; Mellina *et al.*, 2002; Moore, 2006) and in proglacial lakes between the lake inlet and outlet (Uehlinger *et al.*, 2003; Richards *et al.*, 2012). On the other hand, proglacial lakes in the Eagle and especially Mendenhall River watersheds had a cooling effect on stream temperature in August through October. For instance, temperature in Mendenhall River reached its summer minimum of 1.7 °C in late July but generally stayed below 2.5 °C for the remainder of the study period. However, temperature in Herbert River, which is a heavily glaciated watershed but does not contain a proglacial lake, reached its summer minimum of 1.7 °C in early August but gradually increased thereafter to nearly 4.0 °C by the end of October. This contrasting pattern is due to the accumulation of glacial meltwater in Mendenhall Lake during the summer glacial run-off season that slowly drains and cools stream temperature during the late summer and early fall (Richards *et al.*, 2012).

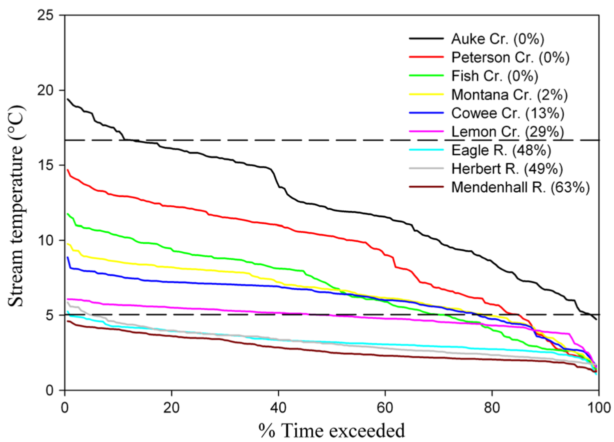

Figure 5. Stream temperature duration curves for the nine study streams (% watershed glacier coverage) during the 1 May through 31 October 2011 study period. The two horizontal dashed lines are the upper (17 °C) and lower (5 °C) water temperature thresholds for sockeye salmon physiology with a general physiological optimum of 15 °C (Brett *et al.*, 1969; Brett, 1971)

Glaciers had a cooling effect on monthly mean stream temperature during the summer (July through September) equivalent to a decrease of 1.1 °C for each 10% increase in glacier coverage. This decrease is similar to that reported for glaciated watersheds in British Columbia, Canada (1.2 °C per 10% increase in glacier coverage) (Moore, 2006). However, glaciers minimally influence temperature during late spring (May) and fall (0.4 °C decrease per 10% increase in glacier coverage) when meltwater discharge is relatively low.

Stream temperature in the intermediately glaciated Lemon Creek (29% glacier coverage) ranged from 3.5 to 6.1 °C during the study period and was the least variable of all streams. This suggests that at moderate glacier coverage, inputs of meltwater prevent stream temperature from rising with summer air temperature but are not sufficiently large to decrease stream temperature during the summer. In this context, the proportion of glacier coverage in Lemon Creek may represent an inflection point for stream thermal behaviour such that watersheds in northern Southeast Alaska with high glacial coverage (>30%) show seasonal cooling with rising summer air temperature, whereas seasonal warming will be observed in watersheds with less extensive glaciation (<30%). Overall, these results suggest that the continued loss of glacier ice in this region will have a steady and predictable impact on the temperature regime of coastal streams.

Previous studies have shown additional variables including discharge (Webb *et al*., 2003), catchment area (Hrachowitz *et al*., 2010) and riparian forest shading (Mellina *et al*., 2002) influence stream temperature. Although we found that simple regression models strongly predicted stream temperature, this is not to say that additional variables, such as watershed area, do not influence temperature in our study watersheds. For instance, our multiple regression models only included data from nine streams over a 6-month study period and therefore a larger sample size may be necessary to statistically identify other variables influencing stream temperature. Additional variables may be especially important in predicting stream temperature during May and October when our models were not as robust. Additionally, we found strong multicollinearity between some of our predictor variables, such as % glacier, mean watershed elevation and catchment area. Although we found watershed area as a good predictor of stream temperature (data not shown), watershed area was often excluded from multiple regression analysis because watershed elevation alone was such a strong predictor of stream temperature.

Air temperature control of stream temperature

Air temperature is often strongly related to stream thermal variability in forested watersheds (Mohseni *et al*., 1998; Webb *et al*., 2003), which results in its usage as a substitute for net heat exchange in regression models to evaluate the water temperature response to changes in land use (Kelleher *et al*., 2012) or climate warming (Webb, 1996; Hrachowitz *et al*., 2010). Our finding that mean weekly air temperature was only mildly related to stream temperature across the study period in all but the two low gradient watersheds (Auke and Peterson Creeks) suggest that air temperature alone may not be useful for predicting stream temperature in the relatively small and steeply sloping coastal watersheds common to this region. Short water residence times in the relatively small watersheds together with the cool and cloudy maritime climate in the region likely restrict the accumulation of heat via air–water exchange throughout the watershed network. Large variation in the seasonal winter snowpack together with differences in the timing and duration of the spring snowmelt will also make predicting the air–water relationship difficult over seasonal time scales. Another factor considered was the effect of a seasonal hysteresis between air and water temperature, especially in the forested and low glaciated watersheds. This was likely caused by the influx of snowmelt water in the spring (May), which results in stream temperature being colder during this period than at a similar air temperature during the autumn (October). Thus, snow and glacier ice can be considered key non-climatic local factors (Arismendi *et al*., 2012) that control stream temperature in this region. Overall, our findings and others (Morrill *et al*., 2005; Isaak et al., 2010) indicate that watershed landcover may be more influential than atmospheric temperature for predicting stream temperatures in the region, particularly in higher elevation watersheds.

Regression slopes of mean weekly water temperature against mean weekly air temperature for the three non-glacial, forested watersheds, which ranged from 0.56 to 1.28, were similar to values reported for other forested watershed in other regions (Crisp and Howson, 1982; Morrill *et al*., 2005; Kelleher *et al*., 2012). Both Auke and Peterson Creeks had a slope of >1.0 indicating a high sensitivity to increasing air temperature. Long water residence time in abundant wetlands together with the presence of large lakes in both watersheds allow for the atmospheric heating of water during long summer days, a process that may make these systems especially vulnerable to future climate warming. On the other hand, the six glacial watersheds showed low thermal sensitivity (all slopes <0.45) because increasing summer air temperature results in increased glacier run-off, which helps cool streams and offset atmospheric heating of streamwater. Similarly, low regression slopes have been found in streams with high groundwater inputs (O'Driscoll and DeWalle, 2006) or at higher elevations (>1000 m) (Morrill *et al*., 2005).

The fact that there was a strong relationship between regression slopes of mean water temperature against landcover parameters suggests that GIS-based landcover models may be useful for characterising the sensitivity of topographically diverse watersheds in this region to rising air temperatures. In particular, watersheds without monitoring instrumentation can be easily identified as thermally sensitive (or insensitive) to rising air temperatures based on the presence of easily identifiable landcover types such as wetlands, glacier ice and lakes. Because this study focused primarily on links between glacier coverage and stream temperature, it will also be crucial to study a more geographically diverse range of watersheds to improve our understanding of the relationship between stream temperature and landcover in forested and low gradient watersheds within this region. Overall, landcover-based modelling efforts will be crucial for predicting how climate change may influence aquatic habitat for salmon (Battin *et al*., 2007; Schindler *et al*., 2008) in the more than 5000 salmon streams in Southeast Alaska.

Implications for Pacific salmon

Stream temperature is a key control on salmonid physiology. Laboratory studies show that most fish, including salmon and trout, have specific temperature requirements for metabolic processes (Brett *et al*., 1969; Elliott and Hurley, 2001). Temperatures that exceed tolerance ranges have been shown to adversely affect brown trout populations (Hari *et al*., 2006), and in our study region, cause earlier migration of pink salmon fry (Taylor, 2008). Although the direct effects of stream temperature on Pacific salmon physiology are difficult to assess, partly due to the diverse freshwater habitats these fish utilise as well as their ability to tolerate fluctuating temperature (Thomas *et al.*, 1986), we found little evidence of adverse warm temperatures for salmon over the range of stream temperatures observed in this study.

Stream temperature in lower elevation, forested watersheds fell largely within the optimum temperature range for salmon physiology, whereas temperatures in heavily glaciated watersheds were predominantly below the optimal thermal range for salmon during summer. Previous research on salmon streams in Cook Inlet in Southcentral Alaska found pervasive evidence of adverse warm temperatures for salmon in low gradient, non-glacial streams (Mauger, 2011). Low gradient streams were under-represented in our study, but our findings from Peterson and Auke Creeks indicate that future increases in air temperature may adversely affect salmon populations in lower elevation watersheds (Taylor, 2008). This will be especially true as seasonal snowpacks increase in elevation and decrease in volume with climate warming (Neal *et al.*, 2010). Overall, our findings suggest that ongoing high rates of glacier volume loss in coastal watersheds that ring the Gulf of Alaska (Larsen *et al.*, 2007; Berthier *et al.*, 2010) will continue to provide thermal constraints to salmon growth in glacier-dominated streams.

Stream temperature has become a pressing environmental issue in many regions of the world, such as the Pacific Northwest of the USA, because warmer temperatures can negatively affect cold-water fish (Rieman *et al.*, 2007; Isaak *et al.*, 2010). In the range of glacier watersheds we studied, we found that MWAT values were well below the lower threshold for optimum salmon growth. Currently glaciers cover approximately 75 000 km^2 within the Coast Mountains along the Gulf of Alaska. Thus, our finding that MWAT values increased by only 0.8 °C for each 10% decrease in watershed glacier coverage suggests that (1) extensive deglaciation will have to occur before most moderate to large mainland watersheds in this region will be at risk of having stream temperatures that negatively affect Pacific salmon, and (2) future reductions in glacier meltwater input may actually enhance salmon survival and growth in some glacier-dominated streams because of greater food availability (Milner and Petts, 1994) and improved thermal suitability for salmon physiology.

CONCLUSIONS

Run-off from glaciers exerts a strong control on stream temperature suggesting that future climate warming and associated glacier volume loss will affect downstream aquatic ecosystems through changes in meltwater discharge and water temperature. We found that although temperatures in glacial streams were consistently low and insensitive to air temperature during summer months, streams in low gradient forested watersheds, especially those with large lakes and wetlands, may be sensitive to future increases in atmospheric temperature. In this context, watershed landcover is an especially useful parameter needed for predicting stream temperature responses to future increases in air temperature.

Identifying temperature-sensitive streams along the Gulf of Alaska is likely to become an increasingly important component of salmon habitat management in light of rising air temperatures. Favourable ocean conditions that allow for high salmon production over multi-decades (Mantua *et al.*, 1997) may mask the changes in the suitability of freshwater habitat that may become evident only once productivity in the ocean decreases (Schindler *et al.*, 2008). Moreover, salmon have varying ability to adapt to changes in regional climate (Hare *et al.*, 1999). Developing quantitative models that allow for projections of stream temperature and hydrologic conditions are clearly necessary for understanding how freshwater habitats that support salmon in this region will be affected by continued climate warming.

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