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Title:
Summer temperature regimes in southcentral Alaska streams: watershed drivers of variation and potential implications for Pacific salmon

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Abstract

Climate is changing fastest in high latitude regions, focusing our research on understanding rates and drivers of changing temperature regimes in southcentral Alaska streams and implications for salmon populations. We collected continuous water and air temperature data during open-water periods from 2008 to 2012 in 48 non-glacial salmon streams across the Cook Inlet basin spanning a range of watershed characteristics. The most important predictors of maximum temperatures, expressed as mean July temperature, maximum weekly average temperature, and maximum weekly maximum temperature (MWMT), were mean elevation and wetland cover, while thermal sensitivity (slope of the stream-air temperature relationship) was best explained by mean elevation and area. Although maximum stream temperatures varied widely (8.4 to 23.7 °C) between years and across sites, MWMT at most sites exceeded established criterion for spawning and incubation (13 °C), above which chronic and sub-lethal effects become likely, every year of the study, which suggests salmon are already experiencing thermal stress. Projections of MWMT over the next ~50 years suggest these criteria will be exceeded at more sites and by increasing margins.

Keywords: stream temperature, climate change, Pacific salmon, Cook Inlet, Alaska

Introduction

Climate is changing fastest in high latitude regions like Alaska, where average annual air temperature has increased nearly 2 °C over the past 50 years and is projected to rise by an additional ~2–4 °C in coming decades (Karl et al. 2009). This warming is associated with ongoing, interrelated changes in the hydrologic and temperature regimes of Alaska’s fresh waters (Prowse et al. 2006), such as earlier ice breakup (Schindler et al. 2005, U.S. EPA 2015), earlier depletion of snowmelt-derived streamflow (Stewart et al. 2005), and increasing water temperature (Taylor 2008).

The effects of water temperature on Pacific salmon (*Oncorhynchus* spp.) are pervasive. The abundance and taxonomic composition of prey and the seasonal timing of its availability are closely linked with temperature regimes (Caissie 2006; Burgmer et al. 2007). Physiological growth potential increases to an optimum temperature and declines as temperature increases (Brett et al. 1969). Timing of life history events, like spawning, emergence and the onset of exogenous feeding, and smolting, are adapted to prevailing environmental conditions and are largely driven by temperature (Brannon 1987, Quinn 2005). High temperatures can block migration corridors (Quinn et al. 1997, Salinger and Anderson 2006), increase disease virulence (Fryer and Pilcher 1974, Kocan et al. 2009), and cause stress or outright death (Richter and Kolmes 2006). As such, warming temperature has the potential to alter the suitability of waterbodies for salmon populations.

Anticipating the magnitude and scope of ecological changes to freshwater habitats is essential for the management of Alaska’s salmon populations, which contribute substantially to global wild salmon production (Ruggerone et al. 2010) and are exceedingly important to Alaska’s ecology, economy, and societal well-being. Despite the rapidly warming climate, and recent studies projecting decreases in

suitable habitat for Pacific salmonids elsewhere (Morrison et al. 2002, Isaak et al. 2011, Ruesch et al. 2012, Jones et al. 2013), researchers are just beginning to understand rates and drivers of changing temperature regimes in Alaska streams and the implications for salmon (e.g., see Kyle and Brabets 2001, Davis and Davis 2008, Lisi et al. 2013, Fellman et al. 2014, Leppi et al. 2014, Wobus et al. 2015).

Regional analyses conducted outside of Alaska have relied on the compilation and synthesis of extensive data collected by multiple agencies and organizations over the last few decades (e.g. Isaak et al. 2010, Mantua et al. 2010). Long-term stream temperature datasets and regional monitoring networks in Alaska are limited, likely due to the minimal need for restoration planning in Alaska's relatively intact watersheds and relatively cool climate toward the northern end of Pacific salmon distribution. However, interest in developing stream and lake monitoring networks across Alaska is growing because a coordinated monitoring approach can generate regional-scale data useful for prioritizing sensitive areas for conservation and targeting other management strategies that can increase resiliency in aquatic ecosystems to a changing climate (Reynolds et al. 2013).

Summer stream temperature regimes, and the sensitivity of streams to climatic warming, are influenced by climate, landscape features, and characteristics of the stream and its channel (Mayer 2012). For the non-glacial salmon streams examined in this study, we expected the warmest and most thermally sensitive streams to drain low-elevation landscapes with features that enhance opportunities for absorption of solar radiation and equilibration to air temperature, such as low valley slope, large watershed area, and relatively high cover of wetlands, standing water, and non-forested areas (Caissie 2006, Lisi et al. 2013). We anticipated that lakes would have a warming, rather than moderating, effect on summer stream temperatures (Jones 2010, Lisi et al. 2013), particularly because lakes drained by our study streams tend to be shallow and dark-bottomed. However, we expected that higher streamflow,

through the thermal mass it affords (Caissie 2006, Kelleher et al. 2012), and permeable landscapes conducive to the recharge and discharge of groundwater (O’Driscoll and DeWalle 2006, Chang and Psaris 2013, Johnson et al. 2013) would act to moderate water temperature and thermal sensitivity.

Our research focused on answering the following questions related to summer temperature regimes, specifically thermal maxima and thermal sensitivity, in salmon streams of the Cook Inlet region, southcentral Alaska:

- 1) How do temperature regimes vary among streams and years?
- 2) How are temperature regimes related to site and watershed characteristics and site-specific air temperature?
- 3) What are the potential implications of these temperature regimes for different salmon species and life stages now and in the future?

Methods

Study area and temperature monitoring

This work focused on non-glacial salmon streams in southcentral Alaska’s Cook Inlet basin (Fig. 1). Cook Inlet opens southward to the Gulf of Alaska and its basin (121,700 km²) consists of coastal and valley lowlands surrounded by rugged mountains, including some of North America’s highest peaks. The climate ranges from continental to maritime, with mean annual temperatures between -6 and 6 °C (Brabets 1999). Precipitation, much of which falls as snow during winter months, ranges annually from 50 cm across the continental zone to 180 cm across the maritime zone, with the greatest amounts falling in mountainous areas (Brabets 1999). The basin’s major river systems drain alpine glaciers and therefore have high sediment loads and turbidity (Lloyd et al. 1987), although many of the tributary

streams and smaller watersheds have little or no glacial influence and are clear. Cook Inlet basin has 12,000 km of documented salmon streams and supports substantial wild runs of all five North American Pacific salmon plus other anadromous and resident fishes (Johnson and Coleman 2014). The basin's salmon populations are harvested in commercial, personal use, subsistence, and sport fisheries. Most of the basin is free from anthropogenic watershed disturbances, although urban and suburban development occurs around Anchorage (Alaska's largest city) and several smaller communities which, collectively, are home to more than two thirds of Alaska's human population.

We monitored water temperature in 48 non-glacial salmon streams across the basin (Fig. 1) spanning a range of watershed characteristics (Table 1), and in most cases, could be accessed by the region's sparse road network. We focused on non-glacial streams because they tend to be warmer during summer than those that receive glacial meltwater (Kyle and Brabets 2001, Fellman et al. 2014) and thus likely more susceptible to thermal change over the next 50 years. Water temperature in the larger glacial systems of the region may be buffered in the short-term as monthly streamflows are projected to increase through the mid-21st century (Debjani et al. 2015). We established one temperature monitoring site in the lowest accessible reach of each stream's watershed; 22 of the streams flow directly to the ocean (all sites on these streams are within 5 km of Cook Inlet), 23 streams flow into glacial river systems, and three streams flow into another non-glacial system. With only one site per watershed, we did not expect to capture the spatial heterogeneity of water temperature and cold-water refugia within each watershed; instead, our sampling approach allowed us to identify characteristics that influence cumulative stream temperature patterns and describe temperature heterogeneity at a regional scale.

All 48 streams are listed in the Alaska Department of Fish and Game's Anadromous Waters Catalog (Johnson and Coleman 2014), with Coho salmon (*Oncorhynchus kisutch*) being the most widespread

(documented in 47 streams) followed by Pink salmon (*Oncorhynchus gorbuscha*, 36 streams), Chinook salmon (*Oncorhynchus tshawytscha*, 34 streams), Sockeye salmon (*Oncorhynchus nerka*, 31 streams) and Chum salmon (*Oncorhynchus keta*, 23 streams). In 44 streams the temperature monitoring site was located in documented spawning habitat for one or more salmon species, while all but one had documented spawning habitat upstream of the monitoring station (Johnson and Coleman 2014). Locations (latitude/longitude) and stream names for all sites are provided in Table S1.

From 2008 to 2012, we deployed paired water and air temperature loggers programmed to record at 15- or 30-minute intervals starting mid-May to mid-June, as conditions allowed, and collected them after October 1 (see Mauger 2008 for more details). For water temperature, we secured HOBO Pro v2 and StowAway TidbiT data loggers (Onset Computer Corporation, Bourne, Massachusetts) in well-mixed locations within the water column of the mainstem channel to minimize the influence of direct groundwater connection or other reach-scale dynamics. For air temperature, we placed a data logger within a solar shield and secured it 8-30 meters away from the stream and at least 1.8 meters off the ground. Our five years of open-water sampling captured a period comparable to or slightly colder than the most recent 35 years in the Cook Inlet region (NOAA 2015). The regional summertime temperature anomaly (June–August mean temperature difference from 1980-2014 baseline) ranged from -1.1 °C to +0.3 °C, with 2009 being the warmest year of the study period.

We checked data loggers against a NIST (National Institute of Standards and Technology) thermometer before and after each deployment in 0 and 20 °C water baths to ensure we met our 0.25 °C accuracy goal. We reviewed downloaded logger data and deleted erroneous measurements following Mauger et al. (2015). We attempted to collect five years of stream and air temperature data at 48 sites, thus potentially generating 240 “site-years” of data; however, data for 24 site-years were not collected due

to loggers being lost during high flow events or other deployment failures. In addition, we removed site-years due to missing or problematic local air temperature data and nine site-years due to deployment periods that likely missed the thermal maxima. The final dataset included 48 sites with 1-5 years of data totaling 190 site-years of stream and air temperature data. Deployment dates spanned at least June 16 – August 31 for 168 sites-years, with 22 sites-years having shorter deployment periods which we evaluated to have captured the thermal maxima.

Stream temperature metrics

We aggregated the quality-controlled stream and air temperature time series for all days with at least 90% of daily measurements into daily means and maximums, which we then used to calculate temperature metrics. We selected three metrics to describe aspects of the summer temperature regimes in the 48 streams: mean July temperature, maximum weekly average temperature (MWAT), and maximum weekly maximum temperature (MWMT). We chose mean July stream temperature because this is typically the hottest month in southcentral Alaska. We calculated mean July temperature only for site-years when at least 90% of the days were captured (>27 days). We used MWAT and MWMT because they represent an intermediate time period over which transient high temperatures may affect fitness in aquatic organisms. We calculated MWAT by selecting the maximum from a weekly (7-day rolling) average of mean daily stream temperatures and calculated MWMT by selecting the maximum from a weekly (7-day rolling) average of maximum daily stream temperatures across the entire deployment period. All three of these temperature metrics have been useful for describing relative differences in thermal maxima between streams and potential impacts to salmonids (Wehrly et al. 2009, Isaak et al. 2010, Ruesch et al. 2012, Moore et al. 2013).

As a fourth response variable, we calculated thermal sensitivity for all sites with at least 3 years of stream and air temperature data ($n=45$), which we expressed as the slope of the stream-air temperature relationship (Kelleher et al. 2012, Mayer 2012, Chang and Psaris 2013, Luce et al. 2014) based on weekly average temperatures during July. Although others have shown the stream-air relationship to flatten out at high air temperatures ($>20^{\circ}\text{C}$) due to the effect of evaporative cooling (Mohseni et al. 1998, Mayer 2012), southcentral Alaska's air temperatures in July rarely exceed 20°C . Because streams in colder climates do not show a significant change of slope at these moderate air temperatures (Mohseni and Stefan 1999), we chose to use a linear relationship. We selected weekly measurements over daily because the relationship between stream and air temperatures becomes stronger as the time scale increases (Erickson and Stefan 2000). We used a linear mixed effects model with a random intercept for year to account for the temporal correlation between weekly values within a year. We used Akaike's Information Criterion to compare results from a mixed effects model to one without a random intercept; the mixed effects model resulted in better model fit at 29 of the 48 sites. The slopes from the mixed effects model were generally lower than the slopes from the fixed effects model (37 of 48 sites), which we hypothesized was due to the variable influence of snowmelt on stream temperatures during July in some streams.

In addition to the temperature metrics described above, we calculated overall maximum temperature; weekly and monthly average, maximum, and minimum temperature; daily minimum temperature; and maximum daily fluctuation for each site-year (Table S2).

Independent predictors of water temperature: site, watershed, and air temperature

We generated a suite of 12 site or watershed characteristics that we hypothesized directly or indirectly affect stream temperatures. Land-cover statistics (percent wetlands, forested, and open water) were

derived for each watershed from 30-meter resolution LANDSAT imagery (1999, 2003). Maximum watershed elevation, mean watershed elevation, logger site elevation, mean watershed slope, and watershed area, were derived from the U.S. Geological Survey (USGS) National Elevation Dataset 2-arc-second (about 60-meter grid spacing) Digital Elevation Model (DEM). The 60-meter DEM was chosen because it had seamless coverage of the project area. Stream gradient was derived from the USGS National Hydrography Dataset (NHD). Lake influence was calculated for 23 watersheds with lakes larger than 0.5 km² connected to the stream network. The area for each lake (n=51) was divided by its distance to the monitoring site to generate an inverse-distance weighted lake effect and summed across each watershed since some sites had more than one lake in their watershed. As a proxy for aquifer permeability and groundwater contribution to streams, we calculated the percent unconsolidated fluvial surficial geology (Wilson et al. 2012). Mean annual discharge was calculated using a regression equation developed for southcentral Alaska based on watershed area and mean annual precipitation (Verdin 2004); mean annual precipitation inputs to the equation were based on an average for the years 1980-2009 (SNAP 2014). Watersheds for each site were delineated by manually editing the watershed boundary dataset (6th level Hydrologic Unit Codes) and all watershed attributes were developed using ArcGIS 10.1.

In addition to site and watershed predictors, we used site-specific air temperatures to help explain variation in mean July water temperature, MWAT, and MWMT. For mean July water temperature, we used corresponding mean July air temperature; for MWAT and MWMT we used the concurrent 7-day moving average air temperature.

Data Analysis

We used mixed effects models to approximate the relationships between temperature metrics (mean July temperature, MWAT, and MWMT) and the suite of predictors, with a random intercept for site because each site was sampled repeatedly over five years. We selected our analysis methods so that we would be able to make site-specific predictions under a changing climate and also because they enabled us to understand the relative importance of different predictors and their effect sizes. We used multiple linear regressions to model the thermal sensitivity because there was only one response for each stream. Given our relatively small sample size, we reduced the original list of 12 site and watershed characteristics by examining pairwise plots and variance inflation factors and sequentially removing highly correlated predictors ($r > 0.7$), while keeping predictors that we hypothesized would have the most direct effect on stream temperatures. The final set of predictors consisted of five watershed attributes: mean watershed elevation, wetland cover, watershed area, permeable geology cover, and lake influence, each with a variance inflation factor less than three.

We built a set of all possible models using the five watershed attributes, resulting in 32 models, and compared them using Akaike's Information Criterion (AIC). We used this approach for two reasons. First, we expected our five watershed attributes to have additive effects on stream temperatures, so constructing a smaller set of a priori models would not have been meaningful. Second, one of our primary goals was to identify the most important watershed attributes for our stream temperature responses and a balanced model set allows for relative variable importance to be calculated and compared (Burnham and Anderson 2002). In addition to watershed attributes, the appropriate air temperature predictor was included in all models for mean July temperature, MWAT, and MWMT.

We defined our confidence set as all models with $\Delta AIC < 4$ while removing any models with uninformative parameters (adding an additional parameter to a better model, Arnold 2010). Parameter

estimates were averaged over all models in the confidence set by substituting zero when a parameter was missing from a model (Anderson 2008, Grueber et al. 2011). Confidence intervals were estimated for each parameter using unconditional standard errors based on the final model set. Variable importance was calculated as the sum of the Akaike weights ($\sum w_i$) over all the models in which a parameter occurred. Model assumptions were evaluated using a global model with all five predictors and included normality of the residuals, normality of the random effects, homogeneity of variances (normalized residuals plotted against fitted values and each predictor), and a check for outliers using Cook's distance.

We used several measures to quantify model performance for each of the stream temperature responses. We report marginal and conditional R^2 for the responses modeled using mixed effect models, which are equivalent to the variance explained by the fixed effects and the variance explained by the fixed and random effects, respectively (Nakagawa and Schielzeth 2013). We used adjusted R^2 for each model in the confidence set for the thermal sensitivity response. Finally, we evaluated the accuracy of predictions by calculating the root mean-squared error (RMSE) in addition to the observed versus predicted coefficient of determination (r^2 , Piñeiro et al. 2008).

Stream temperature regimes under climate change scenarios

We predicted future MWMT by using air temperature projections for 2030-2039 and 2060-2069 from two emissions scenarios based on an average of the five best-performing global climate models for Alaska (Walsh et al. 2008). The Scenarios Network for Alaska and Arctic Planning (SNAP) provided average decadal July air temperature predictions for every decade in the 2000s for the A1B scenario (mid-range CO₂ emissions scenario) and A2 scenario (rapid increase in CO₂ emissions scenario) for each of our study sites. The 2000-2009 air temperatures were subtracted from the predictions for the two

time periods and two emissions scenarios to calculate the predicted air temperature changes. The air temperature changes were then multiplied by each stream's July sensitivity to calculate the predicted stream temperature changes. The stream temperature changes were added to the maximum daily stream temperatures measured for each stream in 2009 because it was the year with the smallest deviation from the 35-year baseline. Future MWMTs for each climate scenario were calculated from the maximum daily stream temperatures.

Results

Mean July stream temperatures across all sites and years ranged from 6.5 to 18.9 °C, with three sites having values above 18 °C in 2009. Of the 15 warmest mean July temperatures, 11 occurred in 2009 and the remaining four occurred in 2011. Averaged across all years, the highest mean July temperature was 17.3 °C at Jim Creek, which drains a low-elevation wetland and lake complex. Inter-annual variability in mean July temperatures ranged from 1.2 to 5.1 °C for 44 sites with three or more years of data. The highest maximum daily stream temperatures across all years varied broadly among sites, ranging from 11.9 to 24.5 °C, and predominantly occurred in July 2009 (e.g., Fig. 2). Maximum daily ranges across sites varied from 3.5 °C to 11.6 °C.

Maximum weekly average temperature (MWAT) ranged from 7.5 to 21.9 °C across all sites and years. MWAT exceeded 18 °C at 11 sites in 2009 and for two of these sites MWAT averaged over all years exceeded 18 °C. There were 17 sites where MWAT averaged across all years was below 13 °C. Inter-annual variability in MWAT across sites with three or more years of data ranged from 1.1 to 6.4 °C.

Maximum weekly maximum temperature (MWMT) ranged from 8.4 to 23.7 °C across all sites and years (Fig. 3). We recorded 18 MWMT measurements over 20 °C at 13 different sites. When averaged across all years, 13 sites (27%) had mean MWMT above 18 °C. On the cool end of the spectrum, 10 sites had mean MWMT below 13 °C. Of the sites with three or more years of data, inter-annual variation in MWMT ranged from 2.1 to 7.3 °C. MWMT typically occurred in late June and July and less frequently in August (Fig. 4). In 2010, two streams in southern Cook Inlet had MWMT measurements that occurred in September.

Thermal sensitivity ranged from 0.32 to 1.51. Fifteen sites had sensitivities greater than 1.0. (Fig. 5), demonstrating that July water temperature at these sites increased faster than air temperature and underscoring the fact that although air temperature is highly correlated with water temperature, absorption of solar radiation is the primary driver (Johnson 2003).

For mean July temperature, MWAT, and MWMT, average watershed elevation was the most important predictor ($\Sigma w_i \geq 0.95$) and negatively correlated (-); percent wetland cover (+) was of secondary importance ($\Sigma w_i = 0.71\text{--}0.90$); and geology, watershed area, and lakes were less important ($\Sigma w_i \leq 0.53$) (Table 2). Average watershed elevation (-) was also the most important predictor for sensitivity ($\Sigma w_i > 0.95$), while watershed area (+) was secondary ($\Sigma w_i > 0.74$), and wetlands, geology, and lakes were of diminishing importance ($\Sigma w_i \leq 0.31$).

The final confidence set for each response included two or three models (Table 3). The marginal R^2 was similar across the models in the confidence sets for mean July temperature and MWAT, ranging from 0.56 to 0.62. The marginal R^2 was slightly lower for MWMT and ranged from 0.48 to 0.53. The amount of variation explained for sensitivity was much lower than the other responses; the top model had an R^2

of 0.25. The r^2 for the observed versus predicted values closely matched the results for the marginal and adjusted R^2 with the best predictions for mean July temperature and MWAT, followed by MWMT, and relatively poor predictions for thermal sensitivity. The slopes of the observed-versus-predicted lines for mean July temperature, MWAT, and MWMT were all slightly less than one (0.89 to 0.97), indicating a tendency to under predict these responses in the warmest streams.

All of the predictors except for lake influence were informative for one or more stream temperature responses (Table 4). To demonstrate effect sizes for each predictor, we calculated the change in each that would elicit a 0.1 °C change in modeled mean July temperature, MWAT, or MWMT, or a 0.1 change in thermal sensitivity. Mean watershed elevation was negatively correlated with all responses, and a change of roughly 20 m was associated with a 0.1 °C change in mean July temperature, MWAT, and MWMT and a 0.1 change in thermal sensitivity. A small increase in wetland cover ($\leq 2\%$) was associated with a 0.1 °C increase in mean July temperature, MWAT, and MWMT, while thermal sensitivity was essentially unresponsive to wetland cover. All temperature responses increased with watershed area, but increasing estimates of these responses by 0.1 units required a relatively large increase in area (i.e., 229 – 848 km²). Percent permeable geology was associated with decreasing mean July temperature and MWAT, although these effect sizes were also modest. The effect of air temperature predictors was approximately 1:1 on mean July temperature and MWAT, but MWMT was slightly less sensitive to changes in air temperature. It should be noted that the effects of some of the lesser important predictors are inconclusive as their confidence intervals overlapped zero.

Predicted MWMT for 2030-2039 ranged from 13.1 to 23.7 °C under the A1B emissions scenario and from 13.8 to 26.0 °C under the A2 emissions scenario (Fig. 6). Twenty-nine sites (69%) had MWMT greater than 18 °C under the A2 emissions scenario for 2030-2039. MWMT predictions for 2060-2069

ranged from 13.8 to 25.8 °C under the A1B emissions scenario and were similar to the 2030-2039 predictions under the A2 emissions scenario. The predictions for 2060-2069 under the A2 emissions scenario ranged from 14.4 to 27.6 °C and 26 sites (62%) had MWMT greater than 20 °C. It is important to note that at the higher air temperatures predicted in future decades, stream temperature may not increase with air temperature at the same rate as in the past, and a leveling off of stream temperatures, not seen during the study period, is likely (Mohseni and Stefan 1999). If this is the case then we would expect our predicted MWMT to be biased high for 13 sites (30%).

Discussion

Regional variation

The salmon streams we monitored varied widely in summertime thermal maxima with a range of 10.1 to 21.0 °C in MWMT across sites. Although the availability of temperature data for other streams in Alaska is limited, the temperatures we document here are higher than any presently reported data. A previous study of 32 glacial and non-glacial streams in Cook Inlet reported maximum weekly stream temperatures that ranged from 6.9 °C to 20.6 °C (Kyle and Brabets 2001). MWAT for nine streams in southeast Alaska in 2011 ranged from 4.3 to 18.6 °C, although only three of the sites were on non-glacial rivers (Fellman et al. 2014). A study of 33 streams in the Wood River watershed of western Alaska reported a maximum summertime average temperature of 12.6 °C (Lisi et al. 2013), but these systems were much smaller than those included in our study, and did not include monthly or weekly values. Our maximum recorded temperatures, from the northern end of Pacific salmon distribution, are approximately 4 °C less than thermal maxima observed in salmon streams across the Pacific Northwest (e.g., MWMT in Luce et al. 2014), >1000 km to the south.

The upper range of thermal sensitivity we report for non-glacial streams in Cook Inlet (1.51) is greater than those reported in other studies: thermal sensitivities calculated using year-round daily data for streams in the Columbia River basin ranged from 0.10 to 0.81 (Chang and Psaris 2013), sensitivities based on year-round daily data for streams in Pennsylvania ranged from 0.02 to 0.93 (Kelleher et al. 2012), and thermal sensitivities calculated from August weekly data ranged from 0.50 to 1.26 for streams in the Pacific Northwest (Mayer 2012). Our thermal sensitivities calculated from July weekly data may be higher because the slope of the stream-air temperature regression increases as the time step increases from daily to weekly (Erickson and Stefan 2000). Also, the change in stream temperatures decreases at higher air temperatures due to evaporative cooling (Mohseni et al. 1998), so slopes based on linear regressions from study areas with higher ($> 20^{\circ}\text{C}$) air temperatures may be biased low (Mohseni and Stefan 1999). Since southcentral Alaska's air temperatures in July are rarely above 20°C , this would not have affected our results.

Inter-annual variability in thermal maxima was high; MWATs varied by more than 3°C during the study period for 33 sites (ranges in MWAT were 1.1 to 6.4 over all sites). Streams in British Columbia with six or more years of data had similar or higher variability in MWAT; two sites had standard deviations greater than 3°C (Moore et al. 2013). The maximum standard deviation for MWAT in our dataset was 2.8°C . We expect that inter-annual variability at our sites could be higher than our dataset captured, given that the warmest year in our study period (2009) was only the 12th warmest summer over the 35-year baseline period (1980 to 2014).

Watershed drivers of variation in stream thermal regimes

Watershed elevation and wetland cover were the most important predictors of summer temperature regimes across our sites. We suspect that high elevation watersheds tended to be colder because these

sites had snowpacks that persisted into early June (<http://www.wcc.nrcs.usda.gov/snow/>) extending the inputs of cold meltwater (Caissie 2006, Luce et al. 2014, Lisi et al. 2015). Wetlands, by contrast, lead to warmer stream temperatures because of surface or near-surface flow paths and flat topographies that produce longer residence times and receive more direct radiation than groundwater flow paths (King et al. 2012, Callahan et al. 2014). Watershed elevation and, to a lesser extent, wetland cover were correlated with other predictors representing a gradient of characteristics associated with elevation. Mean watershed elevation was positively correlated with mean watershed slope and negatively correlated to percent forest cover, which decreases with elevation in this high-latitude region. Steeper watersheds receive less incoming solar radiation than horizontal surfaces (depending on aspect, Buffo et al. 1972), and also have shorter water residence times and increased water velocities, all of which lead to colder stream temperatures (Jones et al. 2013, Lisi et al. 2013).

The most important predictors of stream thermal sensitivity were mean watershed elevation and watershed area. The same mechanisms that lead to cold temperatures in high elevation watersheds likely also moderate those temperatures to warming. Snowmelt contributions at higher elevations buffer stream temperatures to thermal loading during the early part of the summer (Lisi et al. 2015). High elevation watersheds in our study area were also steeper so they receive less direct solar radiation throughout the summer and flowpaths have shorter water residence times during which they may equilibrate with air temperatures (Mayer 2012). Larger watersheds had higher thermal sensitivities. We attribute this positive effect to decreased shading in larger and wider streams, and longer water residence times allowing surface and near surface flowpaths to equilibrate to surrounding air temperatures.

Our calculations of thermal sensitivity using local air temperatures at coastal sites may be biased high. Of the 15 sites with thermal sensitivity greater than 1.0, 11 were within 6 km of the coast and eight were within 2 km. Air temperatures recorded at these sites are moderated by Cook Inlet and are likely lower than the air temperatures experienced higher in the watershed where much of the warming occurs. Mayer (2012) also observed abnormally high summer sensitivities at coastal sites in Washington.

Other studies have found groundwater inputs to be the predominant driver of thermal sensitivity in streams (Kelleher et al. 2012, Mayer 2012). Groundwater contribution is commonly expressed as a baseflow index derived from continuous streamflow data. We calculated baseflow index for 16 of our streams with historic or current streamflow data using the Web based Hydrograph Analysis Tool (WHAT, Lim et al. 2005) and the daily baseflow index as calculated by Mayer (2012). Neither index correlated with the residuals of the sensitivity model, indicating that the baseflow indices could not explain variance in the thermal sensitivities of these 16 sites. The years of streamflow data for most sites did not overlap with each other or with our temperature monitoring efforts. However, both of the baseflow indices we calculated correlated with watershed coverage of permeable geology ($r = 0.69$ for WHAT and $r = 0.58$ for daily baseflow index), which supports our original hypothesis that this watershed characteristic reflects groundwater inputs despite the fact that it was not an important predictor in the sensitivity model.

Snowmelt may be another important predictor controlling differences in stream sensitivity. Lisi et al. (2015) found that snowmelt-dominated streams in Bristol Bay were less sensitive than streams in rain-dominated low elevation watersheds. They also observed statistically different sensitivities for streams before and after July 15: high elevation streams were less sensitive in the early part of the summer due to snowmelt, whereas low elevation streams were less sensitive later in the summer due to shorter day

length and, possibly, increasing rainfall. The magnitude of the previous winter's snowpack and timing of snowmelt likely affects stream sensitivities between years as well as over the summer season. Future investigations into controls on stream thermal sensitivity in Alaska may need to consider more complex models that account for differences in sensitivity as the summer progresses and between summers in addition to differences among sites. Our stream sensitivity response included temporal variability both within and between years that made it difficult to model relative differences between watersheds.

Our research does not explore the variability of stream temperatures likely present within some watersheds, but our results indicate that larger, low elevation watersheds will be most impacted by increases in air temperature. These findings are further supported by research in other regions that identified the influence of elevation and slope angle on thermal properties of streams and indicate that steep, high elevation tributaries are likely to provide future refugia for cold water species (Isaak et al. 2010, Isaak and Rieman 2013, Isaak et al. 2015). We think that our monitoring locations integrated the general stream temperature regimes for each watershed, but a variety of factors (e.g. localized groundwater inputs, snowmelt-fed tributaries, and variable shading from riparian vegetation) undoubtedly created thermal mosaics at smaller spatial scales that were undetectable by our current study design. Future research intensively exploring temperature regimes and thermal sensitivity throughout watersheds will provide useful information for understanding patterns and drivers of variability.

Our summary of predictors controlling variation in stream temperature responses highlights the importance of developing better topographic and hydrologic data for Alaska. Improved digital elevation models and a networked hydrography dataset are likely needed to develop stream temperature models for Alaska with similar performance as models developed in the Pacific Northwest. Including hydrologic

predictors (e.g. discharge or baseflow index) in stream temperature models may be especially important in Alaska due to expected changes in the amount, timing, and form of precipitation (McAfee et al. 2014), in addition to interactions between stream hydrology and thawing permafrost (Walvoord and Striegl 2007, Jones and Rinehart 2010). Finally, as we continue to bring together existing temperature data and build new monitoring networks, stream network spatial statistical models are important tools that several studies have used to reduce spatial autocorrelation related to network topology, flow, and longitudinal connectivity (e.g., Isaak et al. 2010).

Potential implications of temperature regimes for salmon

We found that numerous non-glacial watersheds in the Cook Inlet region currently have stream temperatures that exceed threshold MWMT ranges identified by the U.S. Environmental Protection Agency (U.S. EPA) for the protection of salmon life stages. These criteria, above which chronic and sub-lethal effects become likely, are 13 °C for spawning and egg incubation, 16–18 °C for juvenile rearing, and 18–20 °C for adult migration (U.S. EPA 2003). Surprisingly, even in our relatively cool sampling period, MWMT at most sites exceeded the established criterion for spawning and incubation during every year of the study, which suggests salmon are already experiencing thermal stress in the Cook Inlet region.

While impacts can be expected for populations that are consistently exposed to elevated stream temperatures, a variety of complex physical factors could mediate the effects on salmon population in the Cook Inlet region. Spawning sites are likely to be distributed across a diversity of stream reaches and habitat types that have different stream temperature regimes and, in some cases, may be driven by the presence of groundwater upwelling (Curry and Noakes 1995, Geist et al. 2012). Our temperature measurements from the lower section of each watershed won't be representative of every spawning

location, especially in larger watersheds. In the absence of buffering effects (e.g. stream channel shade, groundwater inputs) stream temperature tends to increase in a downstream direction due to atmospheric warming that occurs along a stream's flow path (Sullivan et al. 1990). Further, a stream's physical structure exerts internal control over water temperature by influencing stream channel resistance to warming or cooling (Poole and Berman 2001) and creates a mosaic of stream temperature patterns within a watershed. While we would expect individuals that use high elevation tributaries for spawning to be generally buffered from impacts, our research suggests that salmon who use main channel habitat to spawn are likely to be negatively impacted by elevated water temperatures.

Timing of spawning also varies widely among species, populations, and years (Quinn 2005) and each salmon species has a slightly different optimal temperature for growth and survival (Murray and McPhail 1988, Beacham and Murray 1990). Data that would allow us to relate the timing of MWMT to spawning in individual streams do not exist. However, available information from around Cook Inlet suggests that most Pink, Chum, and Chinook salmon populations and many Sockeye salmon populations spawn during July and August (ERT 1984; Burger et al. 1985; Hollowell et al. 2015), during which time high temperatures may result in reduced gamete viability (U.S. EPA 2003). It is also possible that accelerated embryonic development associated with increased incubation temperatures could lead to fry emergence prior to the seasonal onset of optimal rearing conditions (Taylor 2008) and that resulting selective pressure may lead to later spawning (Crozier et al. 2008). Previous research from the Cook Inlet region suggests that fry survival for Coho salmon, which spawn during September and October, may be enhanced under warming scenarios, barring substantial modifications to the flow regime (Leppi et al. 2014).

Elevated summer stream temperature could have negative or positive impacts on the region's salmon populations, and the direction of the response will likely be determined by a suite of factors. Exceedances of thermal criteria for juvenile rearing (16–18 °C) occurred in most streams during the warmest summer of the study (2009) and in several streams during cooler years. These exceedances would most directly impact juvenile Chinook and Coho salmon, which rear in streams throughout the study area for one or two years (respectively), and may result in reduced growth and increased vulnerability to disease, predation, and competition (see U.S. EPA 2003). For example, predation by invasive northern pike, introduced to the Cook Inlet basin in the 1950s, appears to have contributed to a salmon population collapse in at least one low-gradient watershed and salmonid susceptibility to pike predation is expected to increase as waters warm (Sepulveda et al. 2015). However, impacts on juvenile rearing could be mitigated to some extent by the availability of thermal refugia (Torgersen et al. 1999) or by shifting habitat use to higher elevations (Keleher and Rahel 1996, Isaak and Rieman 2013). Additionally, the impacts of warming waters may not be entirely negative. In colder streams, Coho salmon have been shown to exploit spatial thermal heterogeneity by migrating to warmer areas after feeding, which increased their metabolic and growth rates (Armstrong and Schindler 2013, Armstrong et al. 2013). Further, temperatures in many of our study streams were continually below the optimum for salmon growth; warming in these streams may enhance growth in coming decades, given adequate food resources (Beer and Anderson 2011).

Projections for the next ~50 years suggest that, if climate scenarios hold and our thermal sensitivity estimates are robust to extrapolation, MWMT in an increasing number of streams will exceed spawning, rearing, and migration temperature criteria by increasing margins. However, our projections also suggest that more than 30% of our study streams will be insensitive to thermal change and continue to provide critical cold-water habitat for salmon populations into the future. We expect temperature-

related impacts to be greatest at low-elevation sites because these had the warmest summer temperature regimes and are also warming the fastest (i.e., they showed the highest thermal sensitivity). MWMT in excess of 20 °C during one or more years at 13 sites may have affected upstream migrations of adult salmon, five species of which move up the region's streams during summer. These impacts may include delayed migration (Quinn et al. 1997, Salinger and Anderson 2006), increased vulnerability to disease (Fryer and Pilcher 1974; Kocan et al. 2004, 2009), and reduced swimming performance (Brett 1995, Lee et al. 2003). In extreme cases, warming conditions coupled with low water may lead to mass salmon die-offs, as have been observed in Cook Inlet and elsewhere in Alaska (Murphy 1985, Woolsey 2013, Viechnicki 2013, Georgette 2014, Doogan 2015). Many of the region's largest salmon runs migrate up glacier-fed rivers to reach upstream spawning areas. Since glacial meltwater cools rivers considerably (Kyle and Brabets 2001, Fellman et al. 2014), these runs will avoid exposure to warm temperatures along some or all of their riverine migratory route, but the accelerating loss of glacial mass may reduce or eliminate this effect (Milner et al. 2009).

While we can reasonably suggest the above impacts associated with ongoing summer warming, a complex set of additional factors will help shape the responses of the region's salmon populations to increasing greenhouse gas emissions in coming decades. For example, increasing winter streamflow may lead to scouring of spawning redds and mortality of incubating embryos (Leppi et al. 2014) while at the same time increasing the availability of wintering habitat. Advancing spring freshets (Stewart et al. 2005) may lead to increased predation during low flows if smolts do not adjust migration timing or mismatches with optimal ocean rearing conditions if they do. Ocean acidification may disrupt the food webs that support salmon at sea (Fabry et al. 2009). The overall effects of these phenomena, combined with increasing temperatures, are complex and uncertain. And although the Cook Inlet basin currently lacks the widespread human disturbance associated with salmon declines in the Pacific Northwest, high

potential exists for future urban impacts especially in lowland, coastal areas where most Alaskans live and where streams have the highest summer temperatures and sensitivity to climate warming. However, targeted management strategies can increase resilience in aquatic ecosystems to a changing climate, such as improving riparian vegetation to shade streams, restoring fish passage to provide access to thermal refugia, and identifying sensitive areas for conservation (Rieman and Isaak 2010, Isaak et al. 2010). These strategies, in addition to maintaining habitat connectivity and complexity, along with salmon’s inherent life history diversity and evolutionary potential will help the long-term viability of the region’s salmon populations (Hilborn et al. 2003, Crozier et al. 2008, Schindler et al. 2010, Reed et al. 2011).

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Table 1. Watershed characteristics across the range of 48 sites in the Cook Inlet basin.

Predictor	Mean	SD	Minimum	Maximum	Hypothesized Effect	References
Mean watershed elevation (m)	352	254	42	1158	Higher elevations contribute more snowmelt and have colder air temperatures (-)	Isaak et al. 2010, Lisi et al. 2013, Fellman et al. 2014
Watershed area (km ²)	272	297	10	1623	Larger watersheds have more discharge and higher thermal capacity (-), but also have longer water residence times (+)	Imholt et al. 2013, Hill et al. 2013, Lisi et al. 2013, Chang and Psaris 2013
Wetland cover (%)	12	11	0	40	Wetlands increase surface water residence times (+)	Callahan et al. 2014
Lake influence (km)	0.2	0.4	0.0	2.7	Lakes increase water residence times (+)	Garrett 2010, Jones et al. 2013, Lisi et al. 2013
Permeable geology cover (%)	72	29	8	100	Unconsolidated sediments retain groundwater (-)	Kelleher et al. 2012, Mayer 2012, Hill et al. 2013

Table 2. Relative variable importance ($\Sigma w_i \leq$) by response variable for each predictor.

Temperature response variable	Predictors				
	Mean Watershed Elevation	Wetland Cover	Watershed Area	Permeable Geology Cover	Lake Influence
mean July temperature	0.99	0.90	0.36	0.45	0.33
MWAT	1.00	0.90	0.37	0.53	0.38
MWMT	0.96	0.71	0.40	0.33	0.32
sensitivity	0.95	0.31	0.74	0.28	0.28

Table 3. Confidence set for each stream temperature response along with model performance measures.

Response	Fixed Effects	Model type	ΔAIC	Weight	R^2 marginal	R^2 conditional	r^2 Observed v. Fitted	RMSE
Mean July Temperature	Air + geo + elev + wetland	mixed effects	0	0.47	0.60	0.95	0.58	1.71
Mean July Temperature	Air + elev + wetland	mixed effects	0.08	0.45	0.59	0.95		
Mean July Temperature	Air + elev + area	mixed effects	3.69	0.07	0.56	0.95		
MWAT	Air + geo + elev + wetland	mixed effects	0	0.58	0.62	0.93	0.61	1.83
MWAT	Air + elev + wetland	mixed effects	1.01	0.35	0.61	0.93		
MWAT	Air + elev + area	mixed effects	3.95	0.08	0.58	0.93		
MWMT	Air + elev + wetland	mixed effects	0	0.56	0.53	0.91	0.47	2.34
MWMT	Air + elev + area	mixed effects	1.63	0.25	0.51	0.91		
MWMT	Air + elev	mixed effects	2.08	0.20	0.48	0.90		
Sensitivity	Elev + area	multiple regression	0	0.77	*0.25	NA	0.28	0.25
Sensitivity	Elev	multiple regression	2.44	0.23	*0.19	NA		

*Adjusted R-squared

Note: Models are ordered for each response based on Akaike’s Information Criterion (AIC) values. The r^2 for observed versus fitted values are based on model averaged parameter estimates. RMSE is root mean square prediction error.

Table 4. Parameter estimates (with 85% confidence intervals [CI]) and estimates of effect size.

Response	Predictor	Parameter estimate	Lower 85% CI	Upper 85% CI	Change in predictor to elicit a 0.1 °C increase in mean July temperature, MWAT, or MWMT or a 0.1 increase in thermal sensitivity
Mean July temperature	elevation (m)	-0.0044	-0.0062	-0.0026	-23 m
	wetland (%)	0.0742	0.0324	0.1159	1%
	area (km ²)	0.0001	-0.0011	0.0014	848 km ²
	geology (%)	-0.0070	-0.0218	0.0078	-14%
	July ave air (°C)	1.0589	0.9915	1.1263	0.09 °C
MWAT	elevation (m)	-0.0053	-0.0072	-0.0033	-19 m
	wetland (%)	0.0804	0.0347	0.1260	1%
	area (km ²)	0.0001	-0.0012	0.0015	727 km ²
	geology (%)	-0.0110	-0.0269	0.0048	-9%
	MWAT air (°C)	0.8938	0.8321	0.9556	0.11 °C
MWMT	elevation (m)	-0.0052	-0.0076	-0.0028	-19 m
	wetland (%)	0.0401	-0.0107	0.0910	2%
	area (km ²)	0.0004	-0.0012	0.0021	229 km ²
	MWMT air (°C)	0.6098	0.5588	0.6609	0.16 °C
July sensitivity	elevation (m)	-0.0005	-0.0007	-0.0003	-197 m
	wetland (%)	0.0004	-0.0061	0.0069	239%
	area (km ²)	0.0002	0.0000	0.0004	525 km ²

Fig. 1. Cook Inlet stream temperature monitoring network data logger locations.

279x361mm (300 x 300 DPI)

Fig. 2. Daily average stream temperatures from 2008 to 2012 at four sites during the open-water season. These sites represent much of the variation in thermal regimes and are examples of small streams with extensive permeable geology (Wasilla Creek); lowland coastal streams (Anchor River); high elevation, lake systems (Byers Creek); and large, wetland dominated streams (Deshka River).

114x114mm (300 x 300 DPI)

Fig. 3. Range of maximum weekly maximum temperature (MWMT) for 48 sites over five years. The vertical dashed lines represent U.S. EPA's (2003) recommended maximum temperatures for (1) salmon and trout spawning and egg incubation at 13 °C, (2) migration plus non-core juvenile rearing at 18 °C, and (3) adult migration at 20 °C. Site locations (latitude/longitude) and complete stream names can be found in Table S1.

165x165mm (300 x 300 DPI)

Fig. 4. Daily occurrence of maximum weekly maximum temperature (MWMT) across all sites and years.

127x127mm (300 x 300 DPI)

Fig. 5. Thermal sensitivity for sites with at least 3 years of stream and air temperature data (n=45), calculated as the slope of the stream-air temperature relationship based on weekly average July temperatures.

279x361mm (300 x 300 DPI)

Fig. 6. Maximum weekly maximum temperature (MWMT) predictions for 42 streams in Cook Inlet. Two climate scenarios (A1B and A2) are plotted for each time period, which provide a range of possible outcomes depending on future emissions. Observed 2009 MWMT is also plotted for reference. The vertical dashed lines represent U.S. EPA's (2003) recommended maximum temperatures for (1) salmon and trout spawning, egg incubation, and fry emergence at 13 °C, (2) migration plus non-core juvenile rearing at 18 °C, and (3) adult migration at 20 °C.

165x165mm (300 x 300 DPI)

Stream name	Abbreviated site name used in figures	Latitude (WGS84)	Longitude (WGS84)
Alexander Creek	Alexander	61.440	-150.596
Anchor River	Anchor	59.773	-151.834
Beaver Creek	Beaver	60.561	-151.123
Bishop Creek	Bishop	60.768	-151.103
Byers Creek	Byers	62.712	-150.204
Cache Creek	Cache	62.389	-151.081
Chenik Creek	Chenik	59.209	-154.190
Chester Creek	Chester	61.205	-149.896
Chijuk Creek	Chijuk	62.080	-150.583
Chuitna River	Chuitna	61.101	-151.190
Cottonwood Creek	Cottonwood	61.525	-149.527
Crooked Creek	Crooked	60.316	-151.284
Deception Creek	Deception	61.762	-150.034
Deep Creek	Deep	60.033	-151.671
Chulitna River	Chulitna	63.145	-149.421
English Bay River	English Bay	59.343	-151.912
Fish Creek	Fish	61.438	-149.781
Fox Creek	Fox	59.799	-151.056
Funny River	Funny	60.490	-150.860
Hidden Creek	Hidden	60.439	-150.208
Jim River	Jim	61.529	-148.933
Deshka River	Deshka	61.740	-150.320
Little Willow Creek	Little Willow	61.810	-150.099
McNeil River	McNeil	59.117	-154.279
Meadow Creek	Meadow	61.563	-149.824
Montana Creek	Montana	62.128	-150.019
Moose Creek (tributary to Matanuska River)	Moose2	61.682	-149.043
Moose Creek (tributary to Deshka River)	Moose1	62.229	-150.441
Moose River (tributary to Kenai River)	Moose3	60.557	-150.735
Campbell Creek	Campbell	61.140	-149.923
Nikolai Creek	Nikolai	60.195	-151.009
Ninilchik River	Ninilchik	60.049	-151.656
Quartz Creek	Quartz	60.493	-149.700
Rabbit Creek	Rabbit	61.085	-149.823
Resurrection Creek	Resurrection	60.918	-149.643
Seldovia River	Seldovia	59.389	-151.680
Shantatalik Creek	Shantatalik	60.291	-150.985
Ship Creek	Ship	61.227	-149.831
Silver Salmon Creek	Silver Salmon	59.982	-152.679
Slikok Creek	Slikok	60.483	-151.131
Soldotna Creek	Soldotna	60.489	-151.044
Stariski Creek	Stariski	59.851	-151.787
Swanson River	Swanson	60.792	-151.012
Theodore River	Theodore	61.266	-150.884

Trapper Creek	Trapper	62.266	-150.184
Troublesome Creek	Troublesome	62.627	-150.227
Wasilla Creek	Wasilla	61.553	-149.314
Willow Creek	Willow	61.780	-150.161

¹ Thermal sensitivity was not calculated for sites with less than three years of data (Chester, McNeil, and Mea

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Mean watershed elevation (m)	Watershed area (km ²)	Wetland cover (%)	Lake influence	Permeable geology cover (%)
209	848	24	0.06	45
298	579	11	0.00	72
44	145	33	0.16	96
42	94	12	0.30	92
554	124	3	0.25	44
685	179	2	0.00	53
221	10	0	2.67	25
200	77	4	0.00	89
230	46	26	0.00	91
326	366	7	0.00	25
133	89	3	0.20	98
209	147	20	0.00	97
343	155	11	0.00	99
409	558	8	0.00	98
1,158	400	2	0.00	25
239	55	0	0.88	19
77	308	23	0.63	92
401	87	18	0.18	88
299	360	11	0.11	99
177	66	4	1.57	55
493	124	19	0.75	50
148	1,623	40	0.11	94
538	401	12	0.00	81
440	283	0	0.12	8
94	170	17	0.07	95
630	403	7	0.00	44
932	132	0	0.00	34
227	221	31	0.70	100
112	635	27	0.00	94
541	174	2	0.00	74
351	152	3	0.00	99
204	350	22	0.00	100
782	265	1	0.52	21
627	38	0	0.00	75
787	415	0	0.00	37
345	69	0	0.06	16
146	76	5	0.00	100
719	315	2	0.00	61
346	27	3	0.57	18
70	66	28	0.03	100
76	120	15	0.00	93
214	128	26	0.00	95
66	646	17	0.09	95
333	307	14	0.00	79

180	68	28	0.02	100
581	100	2	0.00	24
259	117	3	0.00	81
655	663	6	0.11	67

idow Creeks).

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Thermal sensitivity ¹	Overall maximum daily maximum temperature (°C)
1.32	22.6
1.13	20.0
0.67	17.9
1.22	22.2
0.50	22.8
0.57	20.7
NA	14.4
0.60	16.4
0.83	24.3
1.36	22.0
0.89	22.0
1.11	18.5
0.73	18.8
1.19	20.6
0.32	15.5
0.69	19.6
1.03	22.7
1.02	22.0
0.90	16.1
0.92	22.8
1.51	23.9
0.98	24.5
0.69	19.5
NA	15.5
NA	20.2
0.46	18.8
0.51	14.8
0.66	20.5
1.01	19.5
0.89	17.6
1.03	18.2
1.04	20.2
0.39	14.4
0.62	13.1
0.67	13.9
0.93	14.1
0.54	14.8
0.70	15.1
0.48	11.9
0.63	17.9
0.75	19.2
1.02	19.5
1.31	21.7
1.41	20.7

0.72	22.2
0.61	19.9
0.60	15.0
0.67	18.8

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Stream name	Abbreviated site name used in figures	Year	MWAT (°C)	MWMT (°C)
Alexander Creek	Alexander	2008	15.9	18.2
Anchor River	Anchor	2008	12.6	15.0
Beaver Creek	Beaver	2008	13.1	14.0
Bishop Creek	Bishop	2008	15.9	17.6
Byers Creek	Byers	2008	14.2	17.3
Cache Creek	Cache	2008	10.3	12.7
Campbell Creek	Campbell	2008	10.7	12.3
Chijuk Creek	Chijuk	2008	15.7	18.0
Chulitna River	Chulitna	2008	8.0	11.0
Cottonwood Creek	Cottonwood	2008	15.7	17.8
Deception Creek	Deception	2008	12.1	14.0
Deep Creek	Deep	2008	12.5	14.4
Deshka River	Deshka	2008	16.5	18.3
English Bay River	English Bay	2008	14.3	14.9
Fish Creek	Fish	2008	16.0	17.9
Funny River	Funny	2008	10.5	11.7
Hidden Creek	Hidden	2008	14.5	15.9
Little Willow Creek	Little Willow	2008	11.5	13.4
Meadow Creek	Meadow	2008	15.2	18.0
Montana Creek	Montana	2008	11.9	14.1
Moose Creek (tributary to Deshka River)	Moose1	2008	14.6	16.9
Moose Creek (tributary to Matanuska River)	Moose2	2008	8.4	10.7
Moose River (tributary to Kenai River)	Moose3	2008	14.2	15.2
Nikolai Creek	Nikolai	2008	10.9	12.7
Ninilchik River	Ninilchik	2008	12.6	14.7
Quartz Creek	Quartz	2008	8.2	9.5
Rabbit Creek	Rabbit	2008	7.5	8.4
Resurrection Creek	Resurrection	2008	7.5	8.8
Seldovia River	Seldovia	2008	9.5	10.4
Shantatalik Creek	Shantatalik	2008	10.9	11.8
Ship Creek	Ship	2008	9.2	10.5
Silver Salmon Creek	Silver Salmon	2008	8.1	9.4
Slikok Creek	Slikok	2008	12.0	13.0
Soldotna Creek	Soldotna	2008	14.2	15.3
Stariski Creek	Stariski	2008	12.2	14.5
Swanson River	Swanson	2008	15.9	16.9
Trapper Creek	Trapper	2008	15.5	17.2
Troublesome Creek	Troublesome	2008	12.0	14.3
Wasilla Creek	Wasilla	2008	10.4	11.7
Willow Creek	Willow	2008	11.1	12.9
Alexander Creek	Alexander	2009	20.8	21.9
Anchor River	Anchor	2009	15.9	18.9
Beaver Creek	Beaver	2009	14.6	16.1

Bishop Creek	Bishop	2009	19.5	21.4
Byers Creek	Byers	2009	19.1	22.2
Cache Creek	Cache	2009	16.3	19.9
Campbell Creek	Campbell	2009	15.3	17.2
Chester Creek	Chester	2009	13.9	15.8
Chijuk Creek	Chijuk	2009	19.9	23.7
Chulitna River	Chulitna	2009	11.8	14.7
Cottonwood Creek	Cottonwood	2009	19.1	21.0
Crooked Creek	Crooked	2009	14.8	17.3
Deception Creek	Deception	2009	16.4	18.6
Deep Creek	Deep	2009	16.5	19.4
Deshka River	Deshka	2009	21.9	23.4
English Bay River	English Bay	2009	17.6	18.8
Fish Creek	Fish	2009	19.9	21.8
Fox Creek	Fox	2009	16.7	21.3
Funny River	Funny	2009	13.5	15.3
Hidden Creek	Hidden	2009	19.1	22.0
Jim River	Jim	2009	21.8	23.4
Little Willow Creek	Little Willow	2009	17.2	19.1
Montana Creek	Montana	2009	15.9	18.6
Moose Creek (tributary to Matanuska River)	Moose2	2009	11.6	14.1
Moose River (tributary to Kenai River)	Moose3	2009	17.8	18.8
Nikolai Creek	Nikolai	2009	14.1	17.2
Ninilchik River	Ninilchik	2009	16.1	18.9
Quartz Creek	Quartz	2009	11.8	14.1
Rabbit Creek	Rabbit	2009	11.3	13.0
Resurrection Creek	Resurrection	2009	11.4	13.5
Seldovia River	Seldovia	2009	11.9	13.4
Shantatalik Creek	Shantatalik	2009	11.6	12.9
Ship Creek	Ship	2009	12.6	14.5
Slikok Creek	Slikok	2009	11.8	14.1
Soldotna Creek	Soldotna	2009	15.4	18.3
Stariski Creek	Stariski	2009	15.9	18.4
Swanson River	Swanson	2009	19.0	20.8
Theodore River	Theodore	2009	17.8	20.2
Trapper Creek	Trapper	2009	19.6	21.8
Troublesome Creek	Troublesome	2009	16.6	19.6
Wasilla Creek	Wasilla	2009	13.0	14.2
Willow Creek	Willow	2009	16.5	18.3
Alexander Creek	Alexander	2010	16.4	18.1
Anchor River	Anchor	2010	12.8	15.5
Beaver Creek	Beaver	2010	13.3	14.8
Bishop Creek	Bishop	2010	16.6	18.3
Byers Creek	Byers	2010	15.2	18.2
Campbell Creek	Campbell	2010	12.1	14.0
Chester Creek	Chester	2010	13.1	14.3
Chijuk Creek	Chijuk	2010	15.7	17.8

Chuitna River	Chuitna	2010	14.4	16.5
Chulitna River	Chulitna	2010	9.7	12.2
Cottonwood Creek	Cottonwood	2010	15.9	17.9
Crooked Creek	Crooked	2010	12.7	15.0
Deception Creek	Deception	2010	13.0	14.9
Deshka River	Deshka	2010	15.5	17.3
English Bay River	English Bay	2010	13.7	14.3
Fox Creek	Fox	2010	14.3	17.7
Funny River	Funny	2010	12.0	14.2
Hidden Creek	Hidden	2010	14.2	16.6
Jim River	Jim	2010	17.0	18.8
Little Willow Creek	Little Willow	2010	13.3	15.2
Moose Creek (tributary to Deshka River)	Moose1	2010	14.9	17.1
Moose Creek (tributary to Matanuska River)	Moose2	2010	9.4	11.4
Moose River (tributary to Kenai River)	Moose3	2010	15.0	15.8
Nikolai Creek	Nikolai	2010	11.7	14.5
Ninilchik River	Ninilchik	2010	13.5	16.4
Quartz Creek	Quartz	2010	9.1	10.8
Rabbit Creek	Rabbit	2010	9.4	10.1
Resurrection Creek	Resurrection	2010	8.8	10.0
Seldovia River	Seldovia	2010	9.6	10.3
Shantatalik Creek	Shantatalik	2010	11.0	12.6
Ship Creek	Ship	2010	10.4	11.9
Silver Salmon Creek	Silver Salmon	2010	9.1	9.8
Slikok Creek	Slikok	2010	12.4	14.5
Stariski Creek	Stariski	2010	12.9	15.1
Swanson River	Swanson	2010	16.3	18.0
Theodore River	Theodore	2010	14.3	16.2
Troublesome Creek	Troublesome	2010	13.1	15.5
Wasilla Creek	Wasilla	2010	10.9	12.1
Alexander Creek	Alexander	2011	16.3	17.6
Anchor River	Anchor	2011	14.2	17.3
Beaver Creek	Beaver	2011	13.5	15.2
Bishop Creek	Bishop	2011	16.8	18.9
Byers Creek	Byers	2011	16.0	18.5
Cache Creek	Cache	2011	11.8	14.7
Campbell Creek	Campbell	2011	13.2	15.3
Chenik Creek	Chenik	2011	12.4	13.5
Chester Creek	Chester	2011	13.8	15.4
Chijuk Creek	Chijuk	2011	16.7	18.8
Chuitna River	Chuitna	2011	16.2	19.4
Crooked Creek	Crooked	2011	13.7	16.5
Deception Creek	Deception	2011	12.6	14.5
Deep Creek	Deep	2011	14.3	17.6
Deshka River	Deshka	2011	17.9	20.0
English Bay River	English Bay	2011	15.1	15.9
Fish Creek	Fish	2011	16.8	18.7

Fox Creek	Fox	2011	14.4	18.4
Funny River	Funny	2011	12.4	14.6
Hidden Creek	Hidden	2011	16.9	19.6
Jim River	Jim	2011	19.2	20.8
Little Willow Creek	Little Willow	2011	12.6	14.3
McNeil River	McNeil	2011	12.0	13.9
Meadow Creek	Meadow	2011	15.6	18.2
Montana Creek	Montana	2011	12.7	14.8
Moose Creek (tributary to Matanuska River)	Moose2	2011	9.5	11.4
Moose River (tributary to Kenai River)	Moose3	2011	14.9	16.1
Nikolai Creek	Nikolai	2011	12.2	15.7
Ninilchik River	Ninilchik	2011	14.5	17.6
Resurrection Creek	Resurrection	2011	9.5	11.1
Seldovia River	Seldovia	2011	10.9	11.8
Shantatalik Creek	Shantatalik	2011	11.2	12.8
Ship Creek	Ship	2011	10.9	12.8
Silver Salmon Creek	Silver Salmon	2011	9.5	11.2
Slikok Creek	Slikok	2011	12.3	15.5
Soldotna Creek	Soldotna	2011	13.5	16.2
Stariski Creek	Stariski	2011	14.1	16.6
Swanson River	Swanson	2011	16.5	18.7
Theodore River	Theodore	2011	13.6	15.4
Troublesome Creek	Troublesome	2011	13.7	16.5
Wasilla Creek	Wasilla	2011	10.8	11.7
Willow Creek	Willow	2011	12.5	14.0
Anchor River	Anchor	2012	13.5	16.2
Beaver Creek	Beaver	2012	15.1	16.8
Byers Creek	Byers	2012	15.2	17.9
Cache Creek	Cache	2012	11.0	13.8
Campbell Creek	Campbell	2012	11.6	12.7
Chijuk Creek	Chijuk	2012	17.2	20.3
Chulitna River	Chulitna	2012	9.9	12.2
Cottonwood Creek	Cottonwood	2012	17.1	19.5
Crooked Creek	Crooked	2012	14.4	17.2
Deshka River	Deshka	2012	19.0	20.9
English Bay River	English Bay	2012	13.9	14.4
Fish Creek	Fish	2012	18.6	20.8
Fox Creek	Fox	2012	14.4	18.3
Funny River	Funny	2012	11.4	13.1
Hidden Creek	Hidden	2012	14.9	17.0
Little Willow Creek	Little Willow	2012	13.3	14.8
Moose Creek (tributary to Deshka River)	Moose1	2012	16.4	18.9
Moose River (tributary to Kenai River)	Moose3	2012	16.2	18.1
Nikolai Creek	Nikolai	2012	12.2	15.6
Resurrection Creek	Resurrection	2012	8.8	10.2
Seldovia River	Seldovia	2012	9.6	11.3
Shantatalik Creek	Shantatalik	2012	12.0	13.8

Slikok Creek	Slikok	2012	13.6	16.8
Soldotna Creek	Soldotna	2012	14.9	17.7
Stariski Creek	Stariski	2012	14.2	16.6
Trapper Creek	Trapper	2012	17.4	19.3
Troublesome Creek	Troublesome	2012	12.9	15.1
Wasilla Creek	Wasilla	2012	11.2	12.3

¹ Monthly values were only calculated when 90% of the days in the month were captured.

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Mean June temperature ¹ (°C)	Mean July temperature ¹ (°C)	Mean August temperature ¹ (°C)	Maximum weekly temperature (°C)	Maximum daily range (°C)
NA	14.3	NA	15.2	7.5
NA	11.5	11.5	12.3	6.9
10.8	12.1	11.6	12.8	4.0
13.6	14.6	14.2	15.4	6.2
10.6	13.6	13.1	14.0	7.0
NA	8.8	9.7	10.2	7.4
8.3	9.9	10.3	10.5	5.8
NA	13.8	13.3	15.2	6.3
5.9	7.3	7.2	8.0	6.7
NA	14.6	14.1	15.5	5.1
9.4	10.7	10.6	11.8	5.7
NA	10.9	11.0	12.3	6.7
NA	NA	14.5	16.5	9.1
NA	12.3	14.1	14.1	1.7
14.1	14.8	14.5	15.8	5.6
NA	8.7	9.2	10.3	4.9
11.0	13.3	13.7	14.3	6.8
8.8	10.4	10.5	11.3	5.0
NA	13.6	13.0	15.1	6.9
8.9	10.9	10.7	11.6	5.6
12.4	13.1	12.3	14.2	6.2
6.8	7.8	7.9	8.3	5.6
NA	12.4	12.6	13.6	5.8
7.7	9.5	9.5	10.8	7.3
NA	11.3	11.1	12.4	7.0
NA	7.2	8.1	8.2	5.5
5.1	6.5	7.3	7.4	4.6
NA	NA	7.3	7.4	4.3
NA	7.2	9.0	9.3	4.2
8.0	9.2	9.6	10.5	4.9
6.8	8.3	8.8	9.1	5.2
NA	NA	7.7	7.9	3.2
9.0	10.3	10.0	11.8	6.4
10.3	11.9	11.7	13.8	7.8
NA	11.3	11.2	12.2	6.1
NA	14.1	14.1	15.2	5.8
13.4	14.2	13.4	15.1	5.1
8.5	11.0	10.7	11.5	5.5
9.3	9.9	9.4	10.3	3.0
NA	10.2	10.5	11.1	4.8
NA	18.1	14.6	20.8	10.2
10.5	13.4	11.7	15.9	8.1
11.4	13.2	11.5	14.6	4.3

15.0	17.2	14.7	19.5	6.1
11.9	17.1	13.9	18.9	7.8
8.3	13.9	10.4	15.8	9.0
10.2	13.4	11.5	15.2	4.9
11.2	13.1	11.7	13.9	5.0
14.0	17.8	13.1	19.9	8.1
6.8	10.5	8.1	11.3	7.1
14.6	16.6	14.1	19.0	6.6
10.4	12.5	10.5	14.8	6.5
11.0	14.1	11.4	16.3	5.2
10.6	13.9	11.9	16.5	7.8
15.6	18.7	13.7	21.9	5.3
NA	15.6	13.5	17.2	3.0
15.3	17.5	14.3	19.9	5.8
11.8	14.8	12.5	16.7	11.6
9.6	11.7	9.9	13.5	5.0
12.4	16.5	14.4	19.0	6.8
16.0	18.9	16.1	21.8	4.7
10.7	14.6	11.7	17.1	4.7
10.2	14.2	11.8	15.7	5.9
NA	10.3	8.8	11.5	6.4
13.0	15.5	13.2	17.8	5.0
NA	11.7	9.6	14.1	8.5
10.5	13.4	11.4	16.1	7.1
7.4	10.4	9.4	11.3	5.8
6.9	10.3	9.1	11.2	5.2
7.2	10.3	9.4	11.2	5.5
7.5	10.4	9.6	11.7	4.6
NA	10.3	9.3	11.6	4.9
8.5	11.3	10.0	12.6	5.6
9.5	10.2	8.8	11.8	6.7
11.9	13.6	11.7	15.4	7.0
10.5	13.3	11.5	15.9	6.4
14.3	16.7	14.1	19.0	6.3
NA	15.5	12.9	17.8	5.5
13.8	17.3	13.7	19.5	5.0
10.1	14.8	11.4	16.4	6.4
9.7	11.4	9.6	12.9	3.3
NA	14.3	11.8	16.3	5.2
NA	14.8	13.9	16.4	6.4
NA	11.2	10.9	12.8	7.3
11.1	12.0	11.9	13.3	4.3
14.5	14.9	14.3	16.6	5.1
12.4	14.0	13.4	15.1	8.3
9.6	11.1	11.0	12.1	5.4
11.7	12.4	12.1	12.9	4.9
13.4	13.8	12.8	15.3	6.3

NA	12.6	11.8	14.4	5.9
7.3	8.5	8.5	9.6	6.9
14.2	15.0	14.5	15.7	5.5
10.5	11.1	10.7	12.7	6.2
NA	11.8	11.3	13.0	9.4
13.7	14.0	11.8	15.5	6.4
NA	12.4	13.5	13.7	4.1
11.8	12.8	12.8	14.0	8.6
8.7	10.2	9.9	12.0	5.3
11.5	13.0	13.8	14.1	6.4
15.3	15.2	15.6	16.7	6.4
10.6	11.9	11.0	13.3	5.7
12.5	13.3	12.5	14.5	6.3
7.3	8.4	8.6	9.1	5.9
12.2	13.2	12.6	15.0	3.8
NA	10.2	9.6	11.7	7.5
NA	11.7	11.2	13.5	7.8
6.8	8.0	8.9	9.1	4.8
6.2	8.2	8.6	9.0	4.6
6.1	7.6	8.4	8.6	5.0
NA	7.5	9.3	9.5	3.6
NA	10.0	10.0	11.0	4.6
7.7	9.4	9.8	10.1	5.2
NA	7.4	8.4	9.1	3.1
9.9	10.9	11.0	12.3	6.3
10.3	11.3	11.0	12.9	6.7
14.0	14.4	14.0	16.3	5.2
NA	12.5	11.4	14.3	5.5
10.6	11.7	10.9	12.9	6.7
9.8	10.3	10.1	10.6	3.5
NA	15.9	13.5	16.3	4.0
10.6	13.4	11.2	14.0	8.0
11.0	13.0	11.8	13.4	5.1
14.7	16.3	14.0	16.7	5.3
11.9	15.5	12.7	15.9	7.7
8.4	11.1	8.7	11.6	8.8
NA	12.6	10.2	13.0	5.1
NA	10.6	NA	12.3	4.2
11.5	13.3	12.0	13.6	4.6
14.4	15.6	12.4	16.3	7.6
10.0	15.1	12.2	16.0	7.2
11.0	12.9	10.8	13.4	6.2
10.4	12.2	9.6	12.6	6.0
10.4	13.2	11.4	14.0	7.9
15.5	17.2	NA	17.6	5.8
NA	14.0	14.1	14.8	3.0
15.1	16.3	13.9	16.8	5.1

11.5	13.7	12.0	14.1	10.3
9.2	11.4	9.6	12.1	5.6
11.9	15.7	14.1	16.5	7.3
NA	17.8	14.2	19.0	4.1
9.7	12.2	10.0	12.4	4.5
NA	9.9	NA	11.1	7.1
13.9	15.2	12.3	15.5	7.6
10.0	12.3	10.6	12.6	6.6
7.4	9.2	7.6	9.4	6.0
11.9	14.0	12.3	14.8	5.3
9.1	11.1	9.6	11.9	8.3
11.3	13.7	11.4	14.2	7.1
6.9	8.9	8.1	9.5	5.6
NA	9.3	10.0	10.4	3.8
9.2	10.8	9.6	11.0	4.6
8.2	10.4	9.1	10.7	5.0
7.2	8.6	8.4	9.4	3.9
10.0	11.6	10.2	12.0	7.5
11.1	12.9	11.8	13.3	6.2
10.7	13.3	11.1	13.9	6.4
14.0	15.9	13.6	16.4	5.7
NA	11.6	9.4	13.1	5.4
10.5	13.2	10.3	13.6	8.3
9.5	10.3	9.2	10.7	3.2
9.2	12.0	9.9	12.4	4.6
10.3	11.3	11.5	13.5	6.9
12.7	12.7	12.3	15.1	4.7
11.4	14.3	13.7	14.9	6.9
7.7	10.0	9.2	11.0	8.0
8.2	9.7	10.2	11.0	4.9
13.6	14.6	13.1	17.2	6.5
NA	8.2	7.9	9.2	6.3
14.1	14.6	14.1	17.1	5.8
11.5	11.2	11.0	14.4	6.7
15.1	16.0	NA	19.0	5.3
NA	12.0	13.2	13.8	1.9
15.0	15.7	14.8	18.6	5.0
NA	12.6	12.2	14.4	9.1
8.9	9.9	10.0	11.2	5.0
11.6	13.2	13.8	14.7	5.9
8.6	11.2	11.3	12.5	4.1
13.0	13.8	12.4	16.4	5.1
12.9	13.1	12.7	16.2	5.3
NA	9.8	10.0	12.2	7.7
5.6	6.8	7.9	8.5	5.0
4.8	7.2	8.8	9.5	5.5
NA	10.0	9.7	12.0	4.8

11.1	11.1	10.5	13.6	7.3
12.2	12.5	11.9	14.9	6.1
11.4	11.6	11.5	14.2	6.2
NA	14.8	13.6	17.4	4.2
9.6	11.9	11.0	12.8	5.6
9.2	9.7	9.5	11.2	3.0

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