Stream Temperature Models and Applications in the Anchor, Kenai and Deshka River Watersheds

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1 INTRODUCTION

Stream temperature influences the growth, abundance, distribution, timing of life history events, and survival of Pacific salmon (Richter and Kolmes 2005). In the Lower 48, water temperatures are warming in response to climate change and cumulative stressors from population growth, resource extraction (e.g. logging, mining, and oil and gas), and expanded infrastructure (Isaak et al. 2011). Over the past 60 years, Alaska has warmed at more than twice the rate of the lower 48 states (Chapin III et al. 2014). Warm water temperatures can impact cold-water fish survival and increase the spread of diseases and non-native species (Zuray et al. 2012, Comte et al. 2013). Some streams in Alaska remain cool all summer, while others reach daily maxima that routinely exceed thresholds regarded as deleterious for salmon spawning, egg incubation, and fry emergence (13°C); and for rearing juveniles (18°C, U.S. Environmental Protection Agency 2003). During warm summers, some streams even reach temperatures that may be harmful to migrating salmon adults (>20°C). As climate continues to change, linking baseline monitoring with predictive models to map thermal habitats will provide a means for better understanding species distributions, thermal optimums, non-native invasions, and informing management of critical habitats (Wenger et al. 2011, Isaak et al. 2017a, 2017b).

There remains considerable uncertainty about how future climate change will influence stream thermal regimes in southcentral Alaska. The reasons for this uncertainty are a lack of understanding regarding the influence of hydrology (derived from rainfall, snowfall and glacier melt), geomorphology, and landcover controls on stream temperature. These knowledge gaps are a barrier to understanding how salmon populations may be impacted by climate change and underscore the need for decision support tools which can be used for regional and watershed scale assessments.

Recent advances in stream temperature monitoring within the state of Alaska now allow for the development of thermal stream networks which are frequently used for conservation and management in the contiguous US. This project links stream temperature monitoring efforts previously funded by the Mat-Su Basin Salmon Habitat and Kenai Peninsula Fish Habitat partnerships with the USGS National Hydrography Dataset (NHD) and State of Alaska's Anadromous Waters Catalog (AWC) to develop stream temperature models in the Anchor, Kenai, and Deshka River watersheds. Existing climate, hydrologic, and land-cover spatial datasets were used to predict daily stream temperatures. We modeled daily stream temperatures rather than weekly or monthly temperatures because daily temperatures can be used to calculate temperature metrics useful for describing stream thermal regimes (Steel et al. 2017, Shaftel et al. 2020), such as cumulative degree days, number of days above critical thresholds, and seasonal variability. Additionally, extrapolating daily temperatures in space and time to fish monitoring sites without temperature data will better reflect conditions at the time of sampling for modeling of detections or abundances (Hocking et al. 2018). Thermal maps can be used to (1) inform thermal regimes for species and life stages; (2) identify habitats at risk of invasive species; and (3) identify potential thermal refugia habitats under future climate conditions. Model predictions, maps and applied summaries provide useful tools that can be used by resource managers and decision-makers.

The objectives for this project include:

1. Build statistical models to predict daily stream temperatures from June 1 to September 15 over historical period 1980- 2019.
2. Predict future changes in stream temperature based on estimated increases in air temperature.
3. Calculate metrics useful for describing stream thermal regimes for historic period and future climate scenarios.
4. Summarize thermal regimes for Chinook Salmon and Coho Salmon life-history specific habitats.

We developed stream temperature models for the Deshka River, Kenai River, Anchor River, and Stariski Creek watersheds. All stream temperature, spatial, and climate data for the Anchor River and Stariski Creek watersheds were combined to create one geographic domain for the stream temperature model.

2 METHODS

2.1 STUDY AREAS

The project includes three study areas comprised of four rivers, all of which drain to Cook Inlet (Figure 1C). The Deshka River is a clearwater tributary that drains lowland wetland and forest habitats before entering the glacial Susitna River, the dominant freshwater input to northern Cook Inlet. The Anchor River and Stariski Creek are two adjacent clearwater systems that drain the Caribou Hills and discharge to Lower Cook Inlet near Anchor Point. Because these are adjacent systems of relatively small size, the Anchor River and Stariski Creek were combined into one stream temperature model (henceforth referred to as Anchor-Stariski). The Kenai River is a large glacial river that originates in the Kenai Mountains and empties to Lower Cook Inlet at the town of Kenai. These three systems were selected for stream temperature modeling due to the availability of stream temperature data from many sites (> 20) in addition to their important salmon fisheries (Table 1).

Northern pike are native to freshwaters north and west of the Alaska Range and were introduced to Southcentral Alaska in the 1950s and have since spread across the Susitna Basin (Sepulveda et al. 2013). Pike prefer habitats that are vegetated and slow-moving, where they preferentially target juvenile salmonids as prey (Sepulveda et al. 2013). Pike expansion in Alexander Creek in the 1990s coincided with a 15-year decline in the Chinook Salmon population, which was listed as a stock of concern in 2011 (Rutz et al. 2020). Pike are also found in many parts of the Deshka River watershed and could be a contributing factor in recent declines of Chinook Salmon. Pike were previously documented in the Soldotna Creek system, a tributary to the Lower Kenai River, but have since been eradicated. Pike have not been documented in the Anchor River or Stariski Creek.

2.1.1 Deshka

The Deshka River drains 1,700 km^2 before it enters the glacial Susitna River from the west at Susitna River mile 40. Forests and wetlands are dominant land cover types (54% and 40% of the watershed area, respectively, U.S. Geological Survey 2015) and elevation ranges from 20 meters at the outlet to 400 meters in the headwaters. Stream reaches are generally low gradient (over 70% are 1% gradient or less).

The Deshka watershed supports the largest run of Chinook Salmon in the Susitna River basin. Adult Chinook Salmon migrate into the Deshka River beginning in May and peak in mid-June and spawning initiates in July. The average Chinook escapement to the Deshka River from 2008 to 2017 was 16,466 fish (based on weir counts), and sport fish harvests over the same period have ranged from 723 to 2,899 fish (Oslund et al. 2020). Poor returns beginning in 2006 have led to fisheries restrictions and reduced harvest and escapement in the Deshka River. Coho Salmon escapement from 2013 to 2017 averaged 19,741 fish (Oslund et al. 2020). Coho Salmon migration into the Susitna River begins in mid-July and spawning occurs between mid-September and mid-October.

2.1.2 Anchor-Stariski

The Anchor River and Stariski Creek are two adjacent clearwater systems that drain a combined area of 722 km^2 to Lower Cook Inlet near Anchor Point, north of Homer. Mixed forests are found in 40% of the watershed and wetlands cover an additional 15% (U.S. Geological Survey 2015). The median slope of all stream reaches is 3% and 75% of reaches have slopes less than 6%. The maximum elevation across both watersheds is 621 m.

The Anchor River has a popular Chinook Salmon sport fishery but has suffered poor returns in recent years. Average escapement from 2016-2018 was 5,368 fish with a sport harvest of just over 700 fish (Oslund et al. 2020). Stariski Creek is closed to sport fishing for Chinook Salmon because of its small run size. Run timing for Chinook is from late May through early July. Coho Salmon are targeted by sport fishers in both the Anchor River and Stariski Creek roadside fisheries. Run timing extends from mid-July to mid-September and peaks in August.

2.1.3 Kenai

The Kenai River is a large glacial river that drains 5,500 km^2 and enters Lower Cook Inlet at the town of Kenai. The maximum elevation of 1974 m is in the Trail Creek headwaters in the Kenai Mountains. The median reach slope is 5% and 75% of reaches have slopes less than 20%. The Kenai receives meltwater from glaciers connected to the Harding Icefield, such as the Snow and Skilak glaciers. Total glacier cover is 12% across the watershed, while forests and wetlands are other important landcover types (35% and 8%, respectively U.S. Geological Survey 2015)).

There are two distinct runs of Chinook Salmon to the Kenai river. The first run peaks from mid-May to mid-June, whereas the late run extends from July to early August. Early run Chinook spawn in tributaries, the most important being the Killey and Funny Rivers, whereas the late run Chinook spawn in the mainstem Kenai River. The average Chinook run sizes over the past two decades were 12,759 and 55,017 for the early and late runs, respectively (1986-2015, Begich et al. 2017). For both runs, returns decreased beginning in 2009, with ~ 3,300 to 7,900 for the early run and ~ 20,000 to 36,000 for the late run (Begich et al. 2017). Coho Salmon migrate into the Kenai River in late July through mid-September. They are targeted by sport fishers and the average total run size from 1996-2015 was 45,766 (Begich et al. 2017).

Table 1. Documented habitats by species and life stage in the Deshka, Anchor-Stariski, and Kenai watersheds. Habitats for anadromous Chinook and Coho Salmon are from the ADF&G Anadromous Waters Catalog. Habitats for northern pike are from the ADF&G pike spatial dataset.

Life Stage	**Species**	**Stream Length (km)**
Deshka watershed		
Spawning	Chinook Salmon	320
	Coho Salmon	245
Rearing	Chinook Salmon	612
	Coho Salmon	681
Total[1]	Chinook Salmon	645
	Coho Salmon	808
	Northern pike	283
Anchor-Stariski watershed		
Spawning	Chinook Salmon	162
	Coho Salmon	163
Rearing	Chinook Salmon	89
	Coho Salmon	188
Total[1]	Chinook Salmon	182
	Coho Salmon	347
Kenai watershed		
Spawning	Chinook Salmon	270
	Coho Salmon	361
Rearing	Chinook Salmon	138
	Coho Salmon	257
Total[1]	Chinook Salmon	381
	Coho Salmon	604

[1] Total habitat is *not* the sum of spawning and rearing habitats as these may overlap in the stream network.

2.2 STREAM TEMPERATURE DATA

2.2.1 Deshka

The U.S. Fish and Wildlife Service (USFWS) and Cook Inletkeeper provided most stream temperature monitoring data for the Deshka watershed. Data collection began in 2017 and is currently ongoing. Data were received from Cook Inletkeeper for 2017 – 2019 for 61 sites arranged in tributary clusters (one logger in the tributary and two loggers in the mainstem reach upstream and downstream of the tributary confluence) along Kroto Creek, Moose Creek, and the Deshka River (Figure 1A). In addition, USFWS provided data for 29 road-accessible sites from early June to late August of 2019. All data underwent quality assurance measures and were reviewed for air temperature anomalies and burials by Cook Inletkeeper or USFWS. A separate dataset from a previous Partnership-funded project included nine sites with one to seven years of data collected between 1999 and 2015 (Shaftel et al. 2020).

We excluded eight sites with overlapping time series in the same catchment to avoid pseudo-replication. We further removed a groundwater-dominated site (mean daily temperatures never exceeded 10°C in 2019) because we lacked spatially explicit covariates representing groundwater inputs. The final Deshka dataset included 90 sites with one to seven years of data representing 219 site-years total. In the final dataset, 24 sites had data from 2019 only and 59 sites had three or more years of data.

2.2.2 Anchor-Stariski

Stream temperature data for the Anchor River and Stariski Creek watersheds were initially identified through the Alaska Online Aquatic Temperature Site (AKOATS) and datasets were received from Cook Inletkeeper, Alaska Pacific University, and the Kachemak Bay National Estuarine Research Reserve. All data underwent a quality assurance review where air temperatures and burials were removed. We used a custom function written in R to flag days with temperatures > 25 °C or < -1°C, hourly changes > 3°C and daily changes > 3°C. Stream temperature time series and flags were visually checked prior to removing suspect data.

We received data for 43 sites but removed seven sites with overlapping time series in the same catchment. The final dataset included 36 sites with one to 17 years of data representing 73 site-years of data from across the Anchor-Stariski watersheds. Most sites had 1-2 years of data, four sites had 3-4 years of data, and one site maintained by Cook Inletkeeper below the confluence of the north and south forks of the Anchor River had 17 years of data (Figure 2B).

2.2.3 Kenai

Stream temperature data for 28 sites in the Kenai watershed was initially identified through the Alaska Online Aquatic Temperature Site (AKOATS) and datasets were received from Cook Inletkeeper, Kenai Watershed Forum, and Ben Meyers, a University of Alaska Fairbanks graduate student. Data collected by USGS were imported directly into R using the dataRetrieval library (DeCicco et al. 2018). All data were reviewed for air temperatures and burials through visual inspection. Six of the sites were located directly downstream of lakes. Three sites were removed because they had overlapping time series in the same catchment.

The final Kenai dataset included 25 sites with one to 21 years of data representing 108 site-years total (Figure 2A). Fifteen of the sites had 1-2 years of data, eight sites had three to eight years of data, and the USGS sites on Cooper Creek and the Kenai River below Kenai Lake had 21 and 16 years of data, respectively.

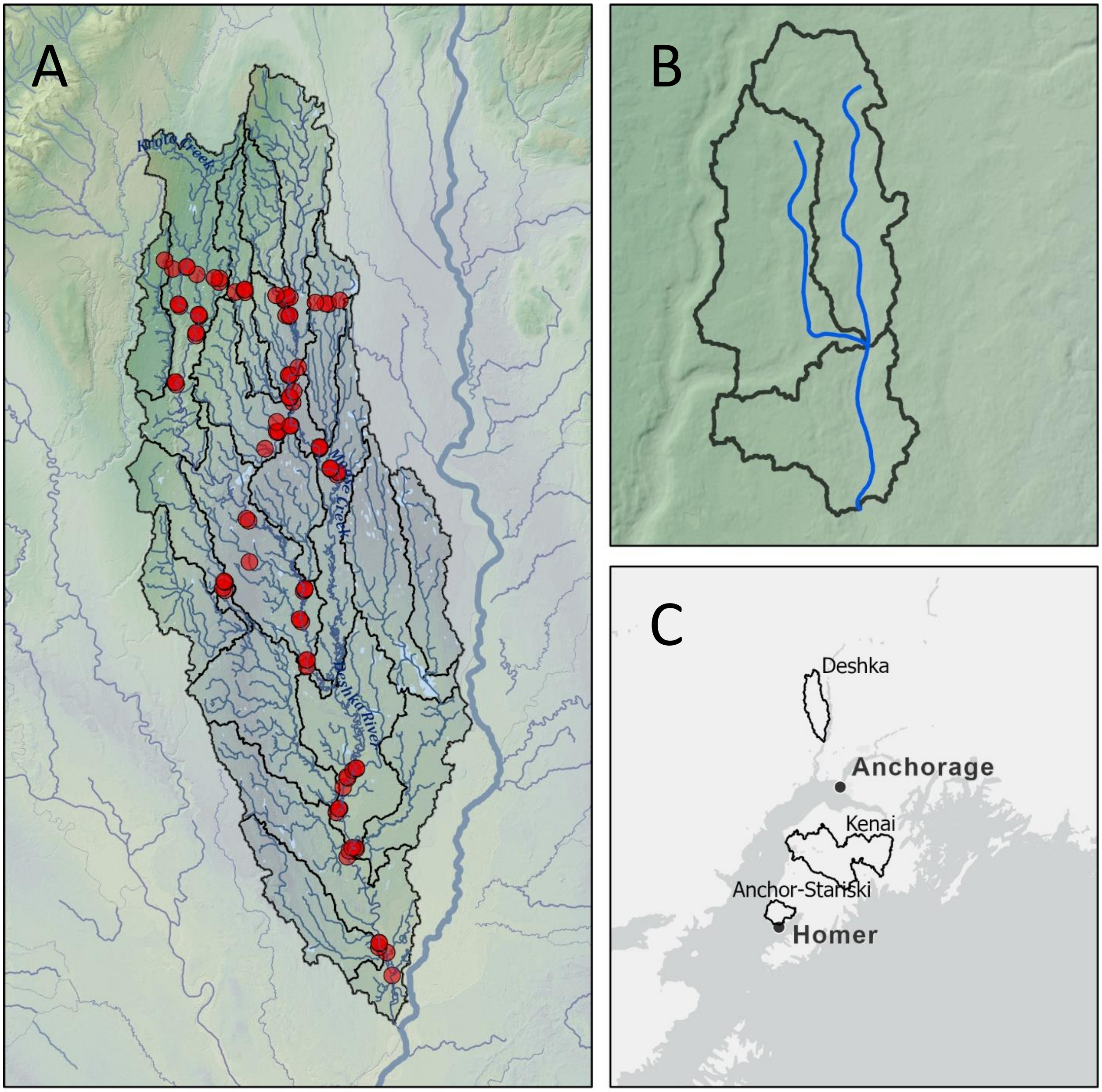


Figure 1. Stream temperature monitoring locations in the Deshka River watershed used in the stream temperature model (n = 90) with fifteen sub-watersheds outlined in black (A). Example of stream reach-catchment relationship where the catchment represents the land surface area draining to each confluence-to-confluence stream reach (B). Location of the Deshka, Kenai, and Anchor-Stariski watersheds in Southcentral Alaska (C).

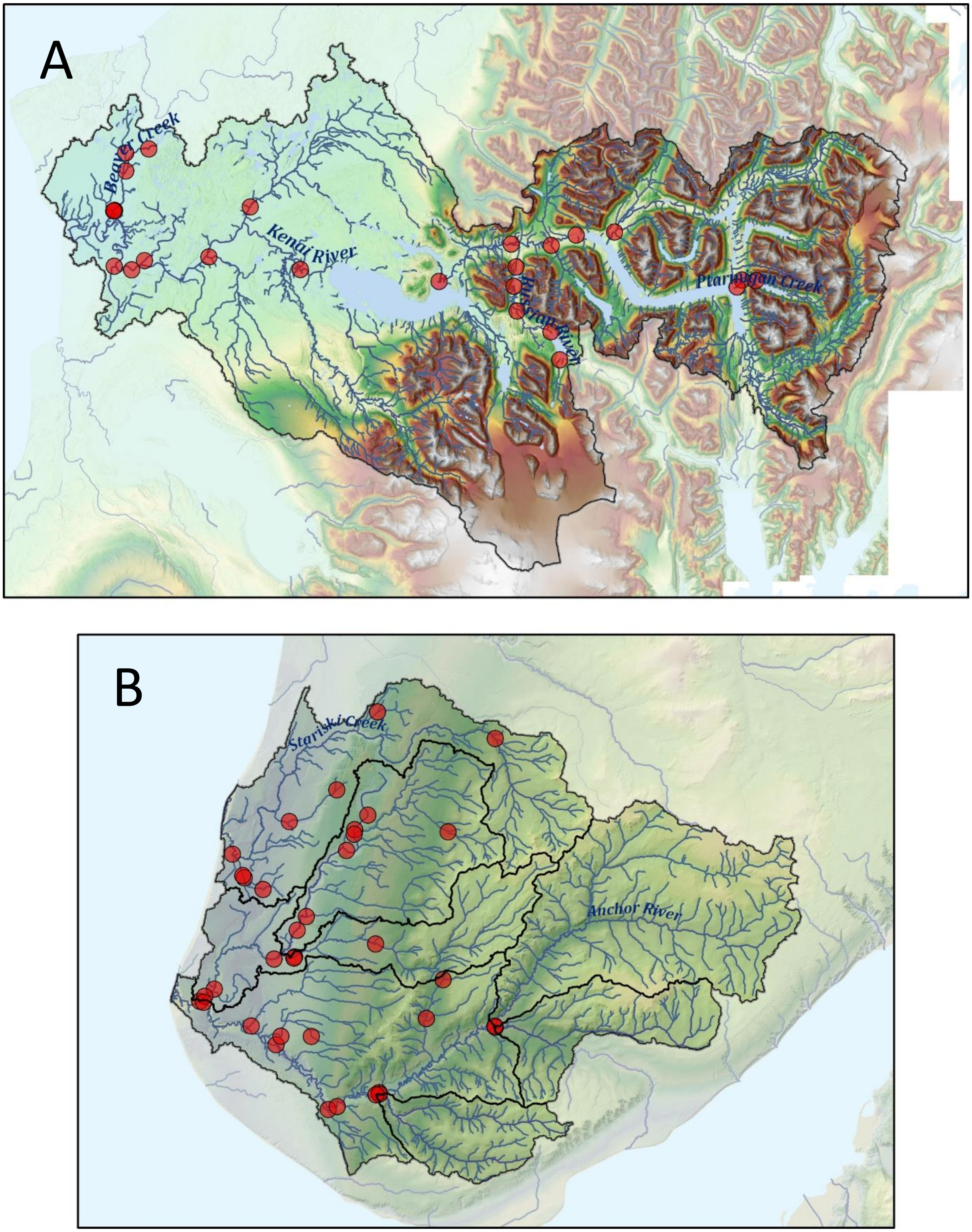


Figure 2. Stream temperature monitoring locations in the Kenai River watershed used in the stream temperature model (A, n = 25). Stream temperature monitoring locations in the Anchor-Stariski watershed used in the stream temperature model (n = 36) with seven sub-watersheds outlined in black (B).

2.3 PREDICTOR VARIABLES

We generated predictor variables for stream temperature models at both the catchment and contributing area scales using the NHD-Plus hydrography network for the Deshka River and elevation derived stream networks for the Anchor-Stariski and Kenai watersheds (Table 2). A catchment is defined as the land area draining to each confluence-to-confluence stream reach (Figure 1B), whereas the contributing area is defined as the entire upstream area draining to the downstream end of a catchment. For each catchment, we calculated reach slope, mean elevation, and the percent cover of wetlands and forests within a 30-meter buffer surrounding the stream reach to describe hydrologic contribution and shading effects on temperatures. For the contributing area draining to a given catchment, we calculated the area and mean elevation. For the Kenai River only, we included a term for sites located directly below a lake outlet and calculated the percent cover of glaciers in the watershed draining to each catchment.

All climate covariates were summarized by averaging over the catchment (Table 2). We used DAYMET gridded estimates of air temperature, precipitation, and snow-water-equivalent (SWE) to describe climatic effects on daily stream temperatures. Mean daily air temperatures were averaged over a 3-day moving window (two days prior and day of stream temperature), daily precipitation values were summed over a 5-day period (four days prior and day of stream temperature), and SWE values were extracted for April 1st of each year as an estimate of the previous winter's snowpack (Pederson et al. 2011). We included a quadratic term for air temperature to allow for a non-linear relationship between air and stream temperatures when stream temperatures are close to 0°C and 20°C (Mohseni 1998, McNyset et al. 2015). An additional quadratic term for day of year was added to capture the dome-shaped pattern of stream temperatures over the summer season. A season interaction term was added to allow for different relationships between air and stream temperatures in the spring when stream temperatures are rising, versus the fall, when stream temperatures are falling (i.e. hysteresis, Mohseni 1998). For each watershed, we calculated the most frequent date of maximum temperatures across all site-years: spring included all dates prior to the date of maximum summer temperatures, and fall included all dates thereafter. We tested for an interaction between SWE and wetlands because we expected that wetland hydrology would be closely linked to the previous winter's snowpack.

Table 2. Spatial and climate predictor variables used to model stream temperatures. Hypotheses linking each variable to stream temperatures are provided along with definitions (units) and data sources.

Variable	Definition	Hypothesis	Data source
reach_slope	Reach slope (%)	Steeper streams have higher velocities and lower exposure to heat sources per unit volume of water. Steep streams are usually located higher in the stream network where groundwater contributions are larger.	DEM
catchment_elev_mn	Mean elevation of catchment (m)	Stream reaches at higher elevations have higher relative contributions of cool groundwater.	DEM
cont_area	Upstream contributing area (km^2)	Larger streams have more thermal mass making them less sensitive to warming in summer months.	Synthetic stream network
ca_elev_mn	Mean elevation of upstream contributing area (m)	Stream reaches draining higher elevations have higher contributions of cold water from groundwater inputs or steep shaded streams.	DEM
wetland	Wetland cover in 100-meter buffer surrounding stream reach (%)	Wetlands store groundwater that warms along near surface flow paths and may increase stream temperatures. Emergent herbaceous and woody wetland classes from the NLCD were combined to create a single wetlands class for analysis.	NLCD
forest	Forest cover in 100-meter buffer surrounding stream reach (%)	Trees provide shade limiting stream warming in summer. Deciduous, mixed, and evergreen forest classes from the NLCD were combined to create a single forest class for analysis.	NLCD
glacier	Glacier cover in upstream contributing area (%)	Glacier meltwater increase with air temperatures and cool stream temperatures. This predictor was used for the Kenai sites only.	GLIMS
lake	Stream reach directly downstream of a lake outlet (1/0)	Lakes release warm surface waters to downstream outlets. This predictor was used for the Kenai sites only.	NHD
tair3 and $tair3^2$	Mean daily air temperature for previous three days averaged across the RCA (°C)	Air temperatures are a proxy for solar radiation heating streams. Adding a quadratic term allows for a non-linear relationship with stream temperatures at and above 20°C.	DAYMET

Table 2 continued.

Covariate	Definition	Hypothesis	Data source
day and day^2	Day of year	Day of year and its quadratic term captures the dome-shaped pattern in stream temperature over the June-September season.	NA
prcp5	Total precipitation over previous five days averaged across the catchment (mm)	Rain cools streams by increasing discharge and thermal capacity, which buffers streams from warming.	DAYMET
sweA1	Snow-water equivalent (SWE) on April 1st averaged across the catchment (mm)	Spring snowpack contributes cool meltwater and groundwater to streams.	DAYMET
sweA1 * wetland	SWE by wetland interaction	High snowpack years raise water tables, increasing exposure of wetland hydrology to solar radiation and increasing contributions of warm surface water to streams.	NLCD and DAYMET
season	Spring and fall	Spring represents the rising limb of stream temperatures and fall represents the descending limb of stream temperatures. The timing of maximum temperatures was calculated separately for each watershed.	NA
tair3 and $tair3^2$ * season	Air temperature by season interaction	The slope and shape of the relationship between air temperature and stream temperature varies by season due to hysteresis.	DAYMET

2.4 STREAM TEMPERATURE MODELS

For each watershed, we calculated mean daily stream temperatures for all dates with ≥90% of measurements and developed models to address two primary objectives: 1) identify important climatic and spatial drivers of stream temperatures (*descriptive model)*, and 2) select an optimal model for predicting stream temperatures across catchments and years (*predictive model*). Predictions for the Anchor-Stariski included all years from 1980 to 2018, whereas the Deshka model included predictions from 1980 to 2019.

Prior to modeling, we filtered the stream temperature data to include the open water period during which air and stream temperatures are synchronized using an index defined as

$$(DST_{ij} - tair3_{ij}) \,/\, (DST_{ij}), DST_{ij} > 0$$

where DST was mean daily stream temperature and tair3 was the three-day mean of lagged daily air temperatures (Letcher et al. 2016).

We used a linear mixed effects model to evaluate climatic and spatial drivers of daily stream temperatures and included a random intercept to account for spatial autocorrelation of stream temperatures within sub-watersheds (12-digit hydrologic units) of each watershed (n = 15 for Deshka, n = 7 for Anchor-Stariski, Jones et al. 2013). We centered all predictor variables (subtracted the mean) prior to modeling to address multicollinearity for interaction and quadratic terms. We further checked for multicollinearity using pairwise correlation coefficients (r) and variance inflation factors (VIF) and dropped variables with r greater than 0.7 or VIF greater than ten (Zuur et al. 2010).

To identify the best *descriptive model*, we considered a set of all possible models (1920 total), while retaining air temperature in all models. We used Akaike's Information Criterion (AIC), which balances model complexity with model fit, to identify the top model(s) and important variables driving daily stream temperature variability. Models were fit using maximum likelihood prior to calculating AIC. We defined our confidence set as all models with cumulative sum of Akaike weights (w_i) less than 0.95 and removed models with uninformative parameters, where the addition of a single parameter was within 0 – 2 ΔAIC units of another model in the confidence set (Arnold 2010). For the Kenai watershed, we developed *descriptive model* only due to limited data and poor model performance (see Section 3.1.3).

To select the most parsimonious *predictive model* across the stream network and years, we used cross-validation. For each cross-validation, we excluded a subset of validation sites (~10%) that were grouped in either space or time, trained the model on the remaining data, and predicted using the withheld validation subset. For the Deshka watershed, nine cross-validation subsets included sites close to one another and the tenth cross-validation subset included nine historic sites (see Section 3.1) to evaluate prediction performance for years not included in the training dataset (n = 9 to 13 sites in each subset). For the Anchor-Stariski watersheds, we created nine cross-validation subsets that grouped sites based on their proximity along the stream network (n = 4 sites in each subset). Predictions were made at the population level (i.e. without using the random intercept for sub-watershed) because the validation subsets included sub-watersheds not in the training data. We calculated the root-mean squared error (RMSE) and the mean absolute error (MAE), which is less sensitive to outliers, for each cross-validation subset and averaged them for each model.

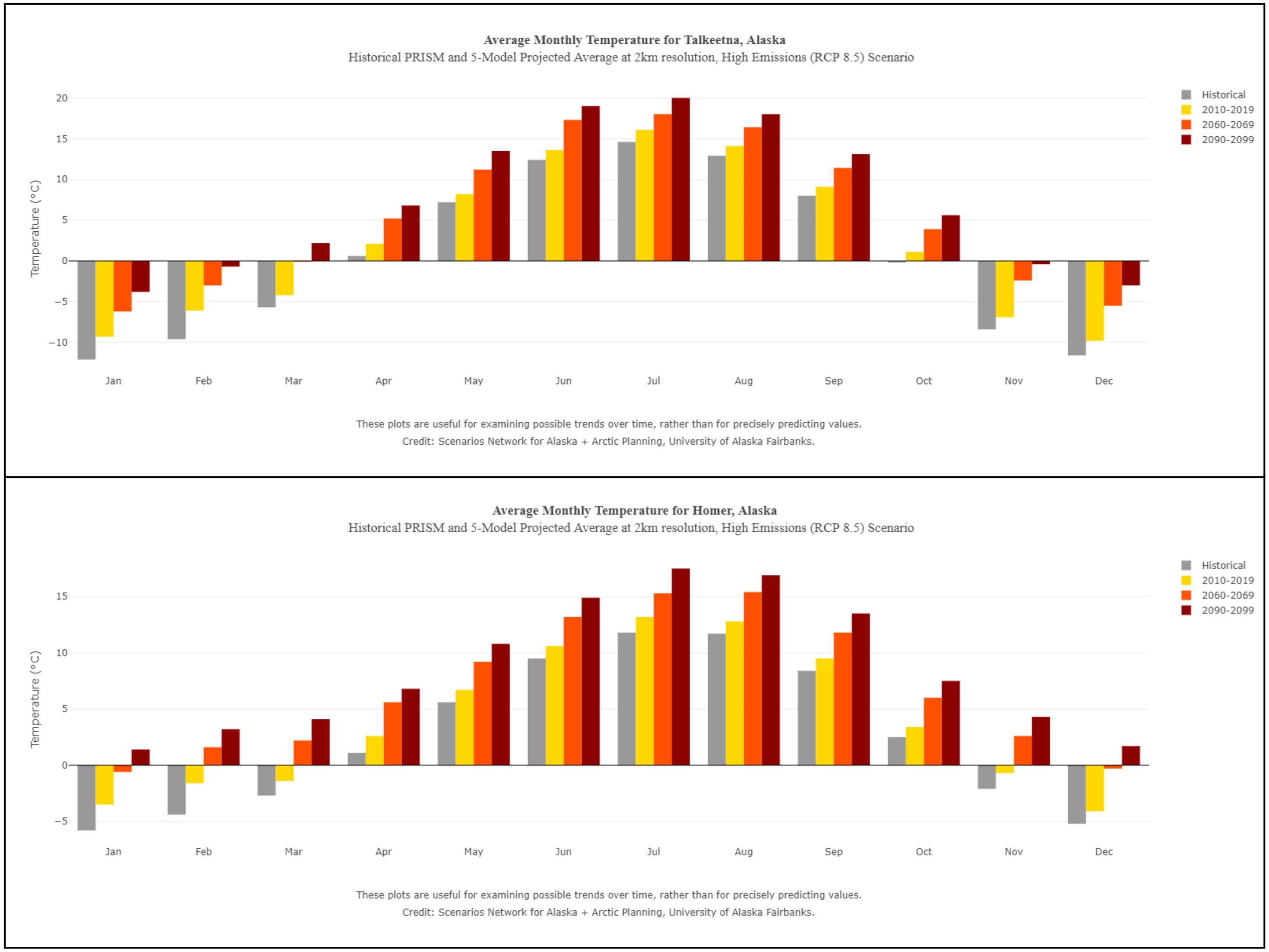
The final set of fixed effects for the *predictive model* was selected based on minimizing cross-validation error and model complexity. All data were used in the final model and predictions across the stream network and years were made at the innermost level of grouping, using the random intercept for sub-watersheds. Predictions for stream reaches in the four Deshka sub-watersheds without stream temperature monitoring data were made at the population level. We filtered all predictions to September 15 as predicted mean daily stream temperatures in both watersheds were negative in the latter half of September.

2.5 FUTURE SCENARIOS

Simulating future stream temperatures based on climatic changes relies on predictive models that predict baseline conditions from which future changes can be assessed (Elliott and Elliott 2010). For the *baseline period*, mean daily air temperatures were averaged for each catchment and julian day over the most recent 20 years (2000 – 2019). To assess future air temperature warming effects on stream temperatures , forecasted air temperature changes were added to the average daily air temperatures for the baseline period and used to predict future stream temperatures for two scenarios: + 2°C and 4°C air temperature changes (Isaak et al. 2017a).

Air temperature change scenarios were consistent with SNAP air temperature changes in the Cook Inlet basin for the Relative Concentration Pathway 8.5 (RCP 8.5) emissions scenario and decades 2060-2069 and 2090-2099, respectively (Figure 3). RCP 8.5 is a high emissions scenario that assumes limited climate change policy or legislation and results in increasing emissions through the 21st century. Global carbon emissions over the last three decades have been tracking the RCP 8.5 scenario (Peters et al. 2013).

In the Anchor-Stariski watershed, snowpack was an important predictor of mean daily stream temperature (see Section 3.1.2), however future changes in snowpack are uncertain and hard to quantify. We developed two scenarios of spring snowpack conditions (i.e., low and high snowpack years) that we combined with the air temperature scenarios described above for a total of four future scenarios for the Anchor-Stariski watershed. We calculated the average April 1st SWE values across all catchments and years and selected 2015 and 2008 for our low and high snowpack scenarios, respectively, because they approximated the 10th percentile and 90th percentiles across the historic period (1980-2018).


Average Monthly Temperature for Talkeetna, Alaska
Historical PRISM and 5-Model Projected Average at 2km resolution, High Emissions (RCP 8.5) Scenario

These plots are useful for examining possible trends over time, rather than for precisely predicting values.
Credit: Scenarios Network for Alaska + Arctic Planning, University of Alaska Fairbanks.

Average Monthly Temperature for Homer, Alaska
Historical PRISM and 5-Model Projected Average at 2km resolution, High Emissions (RCP 8.5) Scenario

These plots are useful for examining possible trends over time, rather than for precisely predicting values.
Credit: Scenarios Network for Alaska + Arctic Planning, University of Alaska Fairbanks.

Figure 3. Monthly air temperature changes for Talkeetna, AK (top) and Homer, AK (bottom) under the RCP 8.5 emission scenario. Figures are from the Scenarios Network for Alaska and Arctic Planning. Talkeetna and Homer are the closest weather stations to the Deshka and Anchor-Stariski watersheds, respectively.

2.6 STREAM TEMPERATURE METRICS

We calculated a suite of stream temperature metrics for each stream reach and year to describe magnitude, variability, duration, and timing of stream thermal regimes (Arismendi et al. 2013) across each watershed using historic predictions (Table 3). We selected non-redundant metrics (i.e. not highly correlated within a category) that are useful for describing thermal regime diversity in Alaskan systems (Shaftel et al. 2020).

For the two future scenarios (+2°C and +4°C), we calculated mean monthly metrics only. Because air temperature-change scenarios are static within a year (e.g. from May to September), timing and variability metrics remain unchanged from the baseline period. It is also important to note that the mean monthly metrics for the baseline and future scenarios should not be compared to the same metrics from the historic predictions because they are calculated over different temporal domains (baseline and future scenarios are 20-year averages whereas historic predictions are by year).

We used a subset of the stream temperature metrics to explore specific questions related to salmon and pike habitat use and changes in thermal habitats over time (see Section 2.7). All metrics are provided as a project product (See Appendix A).

Table 3. Stream temperature metrics used for describing thermal regimes for both historic and future predictions.

Category	Abbreviation	Description
Magnitude	June_mn, July_mn, Aug_mn, Sep_mn (°C)	Mean monthly temperatures
Magnitude	Mx_DAT (°C)	Maximum mean daily temperature
Magnitude	Ma7d_DAT (°C)	Maximum of the 7-day moving average of mean daily temperatures
Timing	Mx_DAT_jd (°C)	Julian date of Mx_DAT
Timing	Ma7d_DAT_jd (°C)	Julian date of MA7d_DAT
Variability	Var (°C^2)	Variance of mean daily temperatures from June - September
Variability	Range (°C)	Range of mean daily temperatures (max – min) from June - September
Duration	CDD (°C)	Sum of mean daily temperatures (cumulative degree days) from June - September
Duration	Sum_13_JAS (count)	Number of days above 13°C from July through September (salmon spawning window)
Duration	Sum_18_JJAS (count)	Number of days above 13°C from June through September (salmon rearing window)

2.7 SALMON AND PIKE THERMAL REGIMES

We used the ADF&G Anadromous Waters Catalog (AWC) to identify catchments documented as spawning or rearing habitats for Chinook and Coho Salmon. We selected these two species because they spend 1-2 years rearing in freshwater streams prior to outmigration to the ocean and therefore have the potential to be impacted by stream temperature during multiple life stages. The AWC data do not include the timing of species observations (date or year), which limits our ability to understand how species or life stages may select habitats based on seasonal or inter-annual variability in stream temperatures. We joined the habitat assignments for each catchment to our historical and future stream temperature predictions and metrics. ADF&G also monitors the spread of invasive northern pike across Southcentral Alaska and provides the data on their northern pike webpage, which we used to identify catchments in the Deshka watershed where northern pike have been documented. We used the stream temperature model predictions linked to fish distributions to answer five questions related to species interactions and positive and negative impacts of temperature on salmon growth and temperature stress.

1. *What are the thermal regimes for salmon species and life stages?*

To identify thermal regimes for species and life stages, we described the median and middle 90% of mean monthly temperatures (5th and 95th percentiles) calculated for each year and catchment over the historical period (1980-2019). To illustrate shifts in thermal regimes through time, we filtered on stream reaches by species and life stage and plotted the mean monthly metrics for each decade of our analysis (1980-1989, 1990-1999, 2000-2010, and 2011-2019, Jones et al. 2013). For the spawning life stage, we focused on describing thermal regimes for Chinook Salmon only since they initiate spawning in July, when temperatures reach their maxima and could be stressful to spawning adults and incubating embryos. For the rearing life stage, we described thermal regimes for both Chinook and Coho Salmon. Thermal regimes descriptions are tied directly to habitats defined in the AWC.

2. *What are the thermal regimes of current invasive northern pike distributions in the Deshka watershed and are salmon habitats at risk of invasion?*

Thermal regimes for invasive northern pike in the Deshka watershed were summarized using methodology described above. Thermal regimes for northern pike habitats (as defined by ADF&G's spatial data) were then used to identify stream reaches where pike are not currently documented but may be at risk of invasion. We identified at-risk stream reaches across the entire Deshka watershed based on stream temperatures within the middle 90% of mean June temperatures over the historical period for documented pike habitats. Previous research indicated that pike predation on salmon in the Deshka watershed peaked during the month of June (Sepulveda et al. 2013). Overlapping juvenile rearing habitats were also highlighted in this analysis.

3. *How do juvenile growth opportunities differ across the range of historically observed thermal regimes?*

Many salmon streams in the Cook Inlet basin are cooled by glacial meltwater, groundwater, and cold mountain tributaries. In these systems, there may be increased growth opportunities for juvenile salmon with warming stream temperatures (Jones et al. 2020). We plotted time series of mean daily temperatures across all catchments in representative warm and cold years to explore differences in growth opportunities across each watershed. We selected cold and warm years that approximated the 10th and 90th percentiles of mean July stream temperatures over the historic predictions (1980-2019). We also quantified the percent of reach-days within the optimal temperature range (12°C to 17°C, Richter and Kolmes 2005) for each watershed in a warm and cold year.

4. *Do historic stream thermal regimes indicate conditions that are stressful to salmon species or life stages?*

We evaluated stressful thermal conditions for two salmon life stages during representative warm and cold years (see above) over our historic predictions using two duration metrics. For thermal stress to salmon spawning, we focused on Chinook Salmon because spawning initiates in July. We filtered on stream reaches documented as Chinook spawning habitat, summed the days in July, August, and September with temperatures >13°C, and mapped this temperature metric across each watershed under representative years from our historic predictions (cold and warm years). To evaluate habitats with potentially stressful conditions for juvenile rearing, we summed the number of days greater than 18°C during the entire summer period (June through September) for Chinook and Coho Salmon rearing habitats.

5. *How have historic thermal regimes for salmon habitats changed and how might they change in the future? Where are cold-water refugia that may be important for sustaining salmon in the future?*

We examined changes in thermal regimes for combined Chinook and Coho Salmon habitats (both spawning and rearing) over the historical period by averaging each temperature metric across the salmon habitats for each year and plotting changes over time. We used linear regression to evaluate trends over the 40-year baseline and described rates of change per decade for metrics with significant changes. For the future scenarios, we plotted the distributions of mean monthly temperatures for Chinook and Coho Salmon habitats and described changes in the median values for each watershed and scenario.

We defined thermal refugia as those habitats that are below the 95th percentile of mean July temperatures for Chinook Salmon spawning habitats over the historical period, which we summarized above. We focused on Chinook Salmon spawning because spawning adults and embryos have the lowest upper temperature criteria (Richter and Kolmes 2005) and are also the most vulnerable life stages due to narrower temperature tolerance ranges (Dahlke et al. 2020). We mapped mean July temperatures under our future scenarios across both watersheds and outlined catchments that remained below this upper limit and could serve as thermal refugia in the future.

3 RESULTS

3.1 STREAM TEMPERATURE MODELS

3.1.1 Deshka

Temperature index values indicated a poor relationship between air and stream temperatures during the month of May, most likely due to snowmelt (Appendix B Figure 1), so we removed data prior to June 1. Maximum mean daily stream temperatures in the Deshka watershed occurred most frequently on or near July 7 (42% on July 7 and 71% between July 5 and July 9). We used July 7 as the cutoff for defining the rising and falling limbs of stream temperatures over the spring and fall seasons, respectively.

We dropped two variables that had strong collinearity with other variables: forest was negatively correlated to wetland (r = -0.83) and mean elevations of the watershed and catchment were correlated (r = 0.81). We kept wetland cover in the model because wetlands are an important land cover in the Deshka watershed and took caution interpreting associations with this covariate (i.e., a positive correlation with stream temperature could be due to wetlands contributing warm water to streams or low shading in the riparian area increasing direct solar radiation). We retained mean catchment elevation in the model because we expected that elevation would be most important at that spatial scale. Final VIF for the spatial predictor variables were all below two. Examination of the global model residuals indicated normality and no patterns between the predicted values and residuals (e.g. homogeneity).

We used a linear mixed effects model of daily mean stream temperatures in the Deshka watershed with a random intercept for sub-watersheds, which captured spatial autocorrelation not explained in the fixed effects (Eqn. 1).

$$\begin{aligned} DST_{ijk} = \; & tair3_{ij} + tair3_{ij}^{2} + jd_i + jd_i^{2} + prcp5_{ij} + sweA1_{ij} + reach\_slope_j \\ & + catchment\_elev\_mn_j + cont\_area_j + wetland_j + season + sweA1_{ij} * wetland_j \\ & + season * \left(tair3_{ij} + tair3_{ij}^{2}\right) + subwatershed_k \end{aligned}$$

$$subwatershed_k \sim (N, \sigma^2)$$

(Eqn. 1)

Predictor variable names match the descriptions in Table 2 and subscript *i* indicates date, *j* indicates catchment, and *k* indicates sub-watershed. Addition of the random intercept for sub-watershed decreased model AIC (ΔAIC = 3,427) and improved model RMSE (global model RMSE without random effect = 1.26, global model RMSE with random effect = 1.17).

We selected the top model in the confidence set as our *descriptive model* because it had the lowest AIC and a high model weight ($w_i < 1$, ΔAIC of next best model = 89). This model included all fixed effects in our original global model (Eqn. 1). Stream temperatures increased linearly in the spring and decreased non-linearly in the fall indicating a lagged response to cooling air temperatures (Appendix B Table 1 and Figure 2A). Higher elevation streams and higher gradient stream reaches had cooler temperatures, whereas stream temperatures warmed as contributing area increased (Appendix B Table 1). Precipitation also had a moderate warming effect on stream temperatures (Appendix B Table 1). The interaction between SWE and wetlands indicated that wetlands stored snowmelt from the previous winter, which cooled summertime stream temperatures (Appendix B Figure 3A). Day of year explained additional variation in summer stream temperatures not captured by climatic or spatial variables (Appendix B Table 1).

We selected a *predictive model* with similar cross validation error as the global model, but with a reduced number of fixed effects. Cross-validation results indicated that simpler models with fewer fixed effects had similar cross-validation error as the more complex global model (Appendix B Figure 4). Mean RMSE for the global model (across all 10 subsets) was 1.37 and mean MAE was 1.09. Cross-validation RMSE was minimized for a model with 10 parameters (mean RMSE = 1.30, mean MAE = 1.02). We selected a final *predictive model* with Mean RMSE of 1.34 and mean MAE of

1.06, which included coefficients for air temperature, julian date and its squared term, and watershed contributing area (Table 4). Stream temperatures increased by 0.8°C for each 1°C change in air temperature and by 0.1°C for each additional 100 km^2 of contributing area (Table 4). Julian date explained additional seasonal variation in rising and falling temperatures over the summer season.

Cross-validation RMSE for the *predictive model* ranged from 1.12 to 1.66 across all ten subsets and the subset comprised of historic data had RMSE of 1.32. The subsets with RMSE > 1.50 were in the headwaters of the Deshka watershed and included many sites with data from 2019 only, which was an extremely warm and dry summer. Sites with data from 2019 only had higher RMSE on average than other sites in the model (1.7°C versus 1.2°C), which included data from multiple years increasing their ability to describe inter-annual variation.

Table 4. Parameter estimates and 95% confidence intervals for the Deshka and Anchor-Stariski predictive models.

Predictors	Estimates	CI	*p-value*	Model RMSE	Cross-Validation RMSE
Deshka watershed					
(Intercept)	14.5073	14.1960 – 14.8187	**<0.001**	1.17	1.34
tair3	0.7692	0.7618 – 0.7765	**<0.001**		
jd	-0.0186	-0.0192 – -0.0181	**<0.001**		
jd^2	-0.0005	-0.0005 – -0.0005	**<0.001**		
cont_area	0.0013	0.0013 – 0.0014	**<0.001**		
Anchor-Stariski watershed					
(Intercept)	10.4556	10.0436 – 10.8676	**<0.001**	1.31	1.64
tair3	0.7942	0.7783 – 0.8100	**<0.001**		
jd	-0.0064	-0.0076 – -0.0052	**<0.001**		
sweA1	-0.0043	-0.0050 – -0.0036	**<0.001**		
catchment_elev_mn	-0.0114	-0.0120 – -0.0109	**<0.001**		

3.1.2 Anchor-Stariski

Temperature index values indicated a poor relationship between air and stream temperatures during the month of May (Appendix B Figure 1), so we removed data prior to June 1. The timing of maximum mean daily stream temperatures in the Anchor-Stariski watershed was highly variable with the middle 70% of maximums occurring between June 23 and July 27 but occurring most frequently on July 10 (27%). We used July 10 as the cutoff for defining the rising and falling limbs of stream temperatures over the spring and fall seasons, respectively.

The spatial predictor variables in the Anchor-Stariski watershed had similar multicollinearity patterns as the Deshka. Forest and wetland cover in the riparian buffer were strongly negatively correlated (r = -0.77) so we removed forest. The variance inflation factors were high when both mean elevation covariates and contributing area were included in the same model, so we removed mean elevation for the contributing area at which point VIF for the remaining spatial predictor variables were below three. Examination of the global model residuals indicated normality and no patterns between the predicted values and residuals (e.g. homogeneity).

We used a linear mixed effects model of daily mean stream temperatures in the Anchor-Stariski watershed with a random intercept for sub-watersheds, which captured spatial autocorrelation not explained by the fixed effects (Eqn. 1). In the Anchor-Stariski watershed, inclusion of the random intercept for sub-watershed decreased model AIC (ΔAIC = 449) and improved model RMSE (global model RMSE without random effect = 1.35, global model RMSE with random effect = 1.30). The model confidence set included 13 models that varied in their inclusion of precipitation, reach slope, season, and the season by air temperature interaction. The simplest model in the confidence set excluded these predictor variables and was within four AIC units of all other models. More complex models in the model set that added a parameter to the simplest model were still within two AIC units of the simplest model (i.e. additional parameters were uninformative). Our final *descriptive model* included air temperature and its squared term, julian day and its squared term, SWE, mean catchment elevation, contributing area, riparian wetland cover, and the SWE by wetland interaction (Appendix B Table 2).

Stream temperatures warmed more slowly than air temperatures in the Anchor-Stariski watershed during the coldest temperatures (Appendix B Table 2 and Figure 2B). Higher elevation streams had cooler temperatures, whereas stream temperatures warmed as contributing area increased (Appendix B Table 2). The interaction between SWE and wetlands indicated that, in high snow years, stream reaches with low wetland cover had colder temperatures (Appendix B Figure 3B). Day of year explained additional variation in summer stream temperatures not captured by climatic or spatial variables (Appendix B Table 2).

We selected a *predictive model* for the Anchor-Stariski with cross validation error close to the global minimum, but with a reduced number of fixed effects. Cross-validation results indicated that simpler models with fewer predictor variables had lower cross-validation error as more complex models (Appendix B Figure 4). Mean RMSE for the *descriptive model* (across all nine subsets) was 1.85 and mean MAE was 1.53. Cross-validation RMSE was minimized for a model with seven parameters (mean RMSE = 1.63, mean MAE = 1.29) and we selected a final *predictive model* with similar error (mean RMSE = 1.64 and mean MAE = 1.30), but only five parameters. Cross-validation RMSE for the *predictive model* ranged from 0.96 to 2.54 across all nine subsets. The subsets with the highest RMSE (> 2), were located on tributaries of the South Anchor River and headwaters of Stariski Creek.

The final *predictive model* included coefficients for air temperature, SWE, julian day, and mean catchment elevation (Table 4). Stream temperatures increased by 0.8°C for each 1°C change in air temperature and decreased by 0.1°C for each additional 10 m increase in mean catchment elevation (Table 4). An increase in the April 1st snowpack of 100 mm cooled stream temperatures by 0.4°C

(Table 4). Julian day explained additional variation in falling temperatures over the summer season not captured by air temperatures (Table 4).

3.1.3 Kenai

Stream temperature data for the Kenai were filtered to exclude values in May due to poor relationships between air and stream temperatures (Appendix B Figure 1). Maximum mean daily stream temperatures in the Kenai watershed were highly variable and the middle 70% occurred between July 7th and August 8th. The timing of maximum summer temperatures occurred most frequently on July 23 (8 site-years or 9% of total), which we used to split the spring and fall terms.

In the Kenai dataset, several of the spatial covariates were strongly correlated. Catchment and contributing area mean elevations were correlated (r = 0.78) so we removed elevation for the contributing area from the model. Reach slope and forest were correlated (r = 0.7) and we retained reach slope because we expected a stronger effect size on stream temperature based on previous research (Jones et al. 2013). Glacier cover and contributing area were positively correlated (r = 0.75) because the three mainstem sites on the Kenai River were the only monitoring locations with more than 10% glacier cover. We retained contributing area for the model because many sites had no glacier cover so that variable was less informative. Five sites in the Kenai watershed were located directly downstream of lakes and exploration of the air-stream temperature relationships across sites indicated colder maximum temperatures and warmer fall temperatures at lake outlets. To capture this effect, we included a binary lake effect variable (1/0) and a lake by air temperature interaction in the Kenai model.

The variance inflation factors for all spatial and climate predictor variables (without interaction terms) were below four. We did not add a random intercept for sub-watershed to the Kenai model because there were too few sites within the sub-watersheds (11 sub-watersheds had only one site). Examination of the global model residuals indicated normality. A plot of residuals versus predicted values indicated higher residual variation at higher predicted values. To address this problem, we use a generalized least squares model (e.g. weighted linear regression), which allowed for modeling unequal variances in the residuals (Eqn. 2, Zuur et al. 2009).

$$\begin{aligned} DST_{ij} = {} & tair3_{ij} + tair3_{ij}^{2} + jd_{i} + jd_{i}^{2} + prcp5_{ij} + sweA1_{ij} + reach\_slope_{j} \\ & + catchment\_elev\_mn_{j} + cont\_area_{j} + wetland_{j} + season + lake + sweA1_{ij} \\ & * wetland_{j} + season * \left(tair3_{ij} + tair3_{ij}^{2}\right) + lake * \left(tair3_{ij} + tair3_{ij}^{2}\right) \end{aligned}$$

$$\varepsilon_{ij} \sim \left(N, \sigma^{2} \times e^{2\delta \times tair3_{ij}}\right)$$

(Eqn. 2)

The model confidence set included five models that varied in their inclusion of the squared term for air temperature, both as a main effect and in interactions with season and lake-influenced sites. We selected a final *descriptive model* that contained all fixed effects except for non-linear patterns in air temperature because more complex models that added these terms were within 4 AIC units of the most parsimonious model (Appendix B Table 3).

The air-stream temperature relationship in the Kenai watershed varied by season and lake effect. Spring stream temperatures warmed more slowly for each unit increase in air temperature than fall stream temperatures (Appendix B Figure 2C). Likewise, stream temperatures in reaches immediately downstream of lakes also warmed more slowly than stream reaches not affected by lakes (Appendix B Figure 2D). Higher elevation stream reaches, steeper stream reaches, and stream reaches draining more contributing area all had colder stream temperatures, whereas precipitation had a warming effect on stream temperatures (Appendix B Table 3). The interaction between spring snowpack and riparian wetlands indicated that years with high snowpack supported colder stream temperatures in reaches with less wetland cover (Appendix B Table 3). The day of year explained additional variation in stream temperatures over the summer season not captured by other variables (Appendix B Table 3).

Due to limited temperature data available for the Kenai River watershed, we did not proceed with a predictive model. In order to interpolate predictions across catchments, the model requires empirical monitoring sites located across the range of geomorphic, hydrologic, and topographic characteristics. Streams in the Kenai watershed also have inputs from lakes and glaciers, which confound the response of stream temperatures to air temperatures (Fellman et al. 2014, Lisi and Schindler 2015). The limited data and complex interactions between lakes, glaciers, and stream temperatures led to a higher model RMSE for the final Kenai descriptive model as compared to the other watersheds (1.69 for Kenai, 1.31 for Anchor-Stariski, and 1.17 for Deshka).

3.2 SALMON AND PIKE THERMAL REGIMES

1. *What are the thermal regimes for salmon species and life stages?*

Documented spawning habitats in the AWC for Chinook and Coho Salmon in the Deshka watershed primarily overlap with a few exceptions (Table 1, Appendix C Figure 1). Coho Salmon spawn in the lowest reaches of the mainstem Deshka below the confluence of Trapper Creek and in an upper reach of Trapper Creek where adult Chinook have not been observed. Chinook Salmon spawn in the upper reaches of Chijuk and Kroto Creeks above the upper limits of documented Coho Salmon spawning habitat (Appendix C Figure 1). The total amount of spawning habitats for Coho and Chinook Salmon in the Anchor-Stariski watersheds are equal and mostly overlap (Table 1, Appendix C Figure 2).

The average July temperatures for the historical period (1980-2019) indicate that the middle 90% of Chinook Salmon spawning habitats in the Deshka watershed are >13.9°C and <17.6°C with a median value of 15.8°C (Figure 4). In August, the same Chinook spawning habitats cool significantly to become >11.7°C and <15.4°C with a median value of 13.6°C (Figure 4). Mean monthly temperatures for Chinook Salmon spawning habitats in the Anchor-Stariski watersheds are significantly colder. The middle 90% of Chinook spawning habitats over the historical period (1980-2018) are between 8.1°C and 12.9°C in July and decrease in August to >7.5°C and <12.3°C (Figure 4).

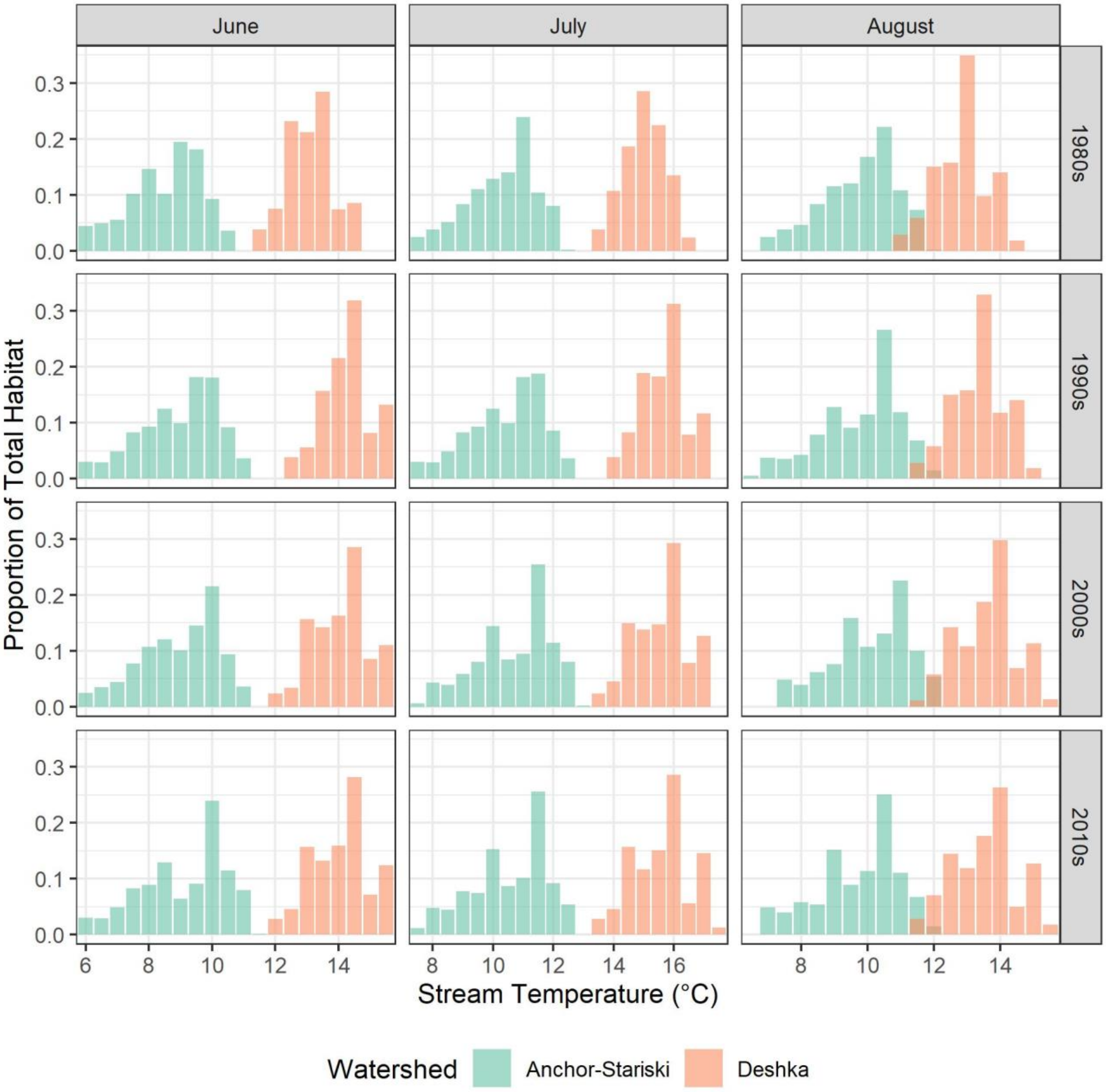


Figure 4. Distributions of mean monthly temperatures by decade for Chinook Salmon spawning habitats in the Anchor-Stariski and Deshka watersheds. The y-axis represents the proportion of total spawning habitat (based on stream length in km) in each one half-degree temperature bin.

There are over 600 km of documented rearing habitats in the AWC for Chinook and Coho Salmon across the Deshka watershed (Table 1). Mean monthly temperatures across the historical period indicate that these habitats have similar thermal regimes over the summer season (within 0.1°C, Figure 5 and Appendix C Figure 3). Mean July temperatures for the middle 90% of Chinook and Coho Salmon rearing habitats range from 13.9°C to 17.7°C with a median value of 15.7°C (Figure 5 and Appendix C Figure 3). In June, rearing habitats for both species are 12.1°C to 16.2°C with a median value of 14.1°C, while August thermal regimes in rearing habitats are 11.7°C to 15.5°C with a median value of 13.6°C (Figure 5 and Appendix C Figure 3).

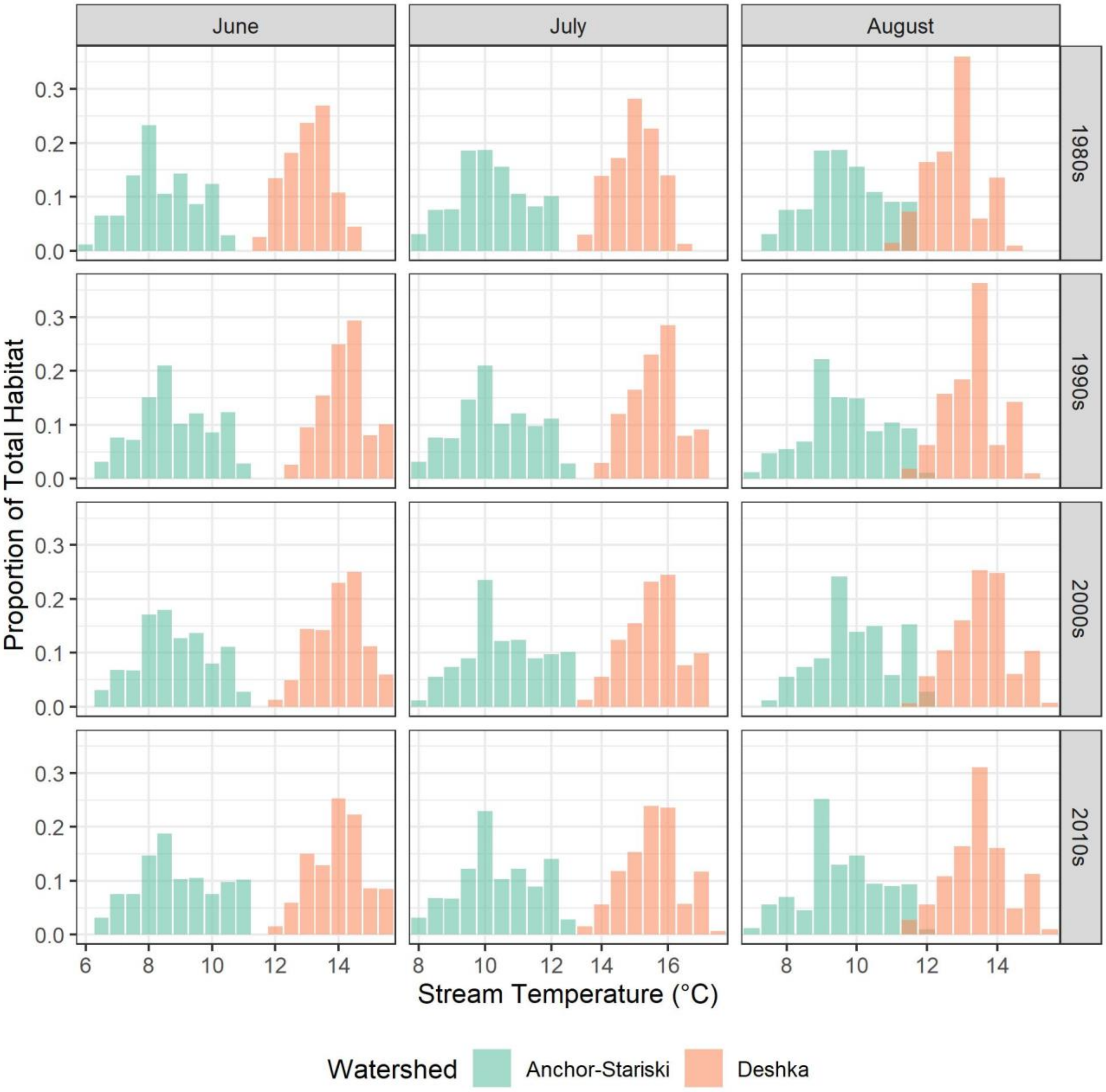


Figure 5. Distributions of mean monthly temperatures by decade for Chinook Salmon rearing habitats in the Anchor-Stariski and Deshka watersheds. The y-axis represents the proportion of total rearing habitat (based on stream length in km) in each one half-degree temperature bin.

In the Anchor-Stariski watershed, there are over 160 km of documented rearing habitats in the AWC for Coho Salmon and approximately 90 km of rearing habitats for Chinook Salmon (Table 1). Summer thermal regimes for the two species have similar upper limits (with 0.3°C), but lower limits (5th percentiles) are much colder for Coho Salmon (Figure 5 and Appendix C Figure 3). Mean July temperatures over the historical period for the middle 90% of rearing habitats are 8.4°C to 12.9°C for Chinook Salmon with a median value of 10.5°C (Figure 5). Coho Salmon thermal regimes for July range from 6.5°C to 12.7°C with a median value of 10.1°C (Appendix C Figure 3). In June, Chinook Salmon rearing habitats are 6.8°C to 11.3°C with a median value of 8.9°C (Figure 5), whereas Coho Salmon rearing habitats are 4.8°C to 11.1°C with a median value of 8.5°C (Appendix C Figure 3). Mean August temperatures for Chinook Salmon rearing habitats range from 7.8°C to 12.3°C with a median value of 9.9°C (Figure 5) and Coho Salmon rearing habitats range from 5.8°C to 12.0°C with a median value of 9.5°C (Appendix C Figure 3).

2. *What are the thermal regimes of current invasive northern pike distributions in the Deshka watershed and are salmon habitats at risk of invasion?*

According to ADF&G documented pike distributions, northern pike have invaded 283 km of stream habitat in the Deshka watershed (Table 1), which overlaps with rearing habitats for both Chinook and Coho Salmon (Appendix C Figure 1). Based on ADF&G data of invaded habitats, summer thermal regimes for northern pike are like those experienced by Chinook and Coho Salmon in the Deshka watershed (Appendix C Figure 4). The middle 90% of mean June temperatures for northern pike habitats over the historical period range from 12.4°C to 16.4°C with a median value of 14.3°C (Appendix C Figure 4). All catchments in the Deshka watershed are within this range for at least one year during the historical period, although northern pike are currently documented in only 15% of habitats. There are approximately 675 km of rearing habitats documented in the AWC for Chinook and Coho Salmon that are currently not invaded by northern pike, but have suitable thermal regimes based on mean June temperatures.

3. *How do juvenile growth opportunities differ across the range of historically observed thermal regimes?*

Time series of mean daily temperatures in all stream reaches in the Deshka watershed indicated that optimal temperatures for juvenile salmon growth extend from mid-June to the end of August in a cold year (1982, Figure 6A) and from the beginning of June (if not earlier) until early September in a warm year (2016, Figure 6B). In the warm year, there were nine days when median mean daily stream temperatures were greater than 17°C in mid-July (Figure 6B). The 90th percentile of mean daily stream temperatures was greater than 17°C for 22 days in a warm year. In the Deshka watershed, 67% of reach-days had optimal temperatures for growth in a cold year and 75% of reach-days were optimal in a warm year (Figure 6A and Figure 6B).

In a warm year for the Anchor-Stariski watershed (2004), 17% of reach-days had optimal temperatures for juvenile salmon growth in a period extending from mid-June until the end of August (Figure 6C). In a cold year (2011), less than 1% of reach-days reached optimal temperatures for growth during a short period in July (Figure 6D).

4. *Do historic stream thermal regimes indicate conditions that are stressful to salmon species or life stages?*

Mapping of days >13°C across documented Chinook Salmon spawning habitats in the Deshka watershed indicated a broader range of conditions in a cold year versus a warm year. In a cold year, Chinook Salmon spawning habitats experienced 14 to 60 days >13°C, whereas in a warm year, spawning habitats had from 38 to 69 days >13°C (Figure 7). Maximum mean daily temperatures in these same habitats and years ranged from 15.5°C to 18.2°C in a cold year and from 17.1°C to 20.7°C in a warm year.

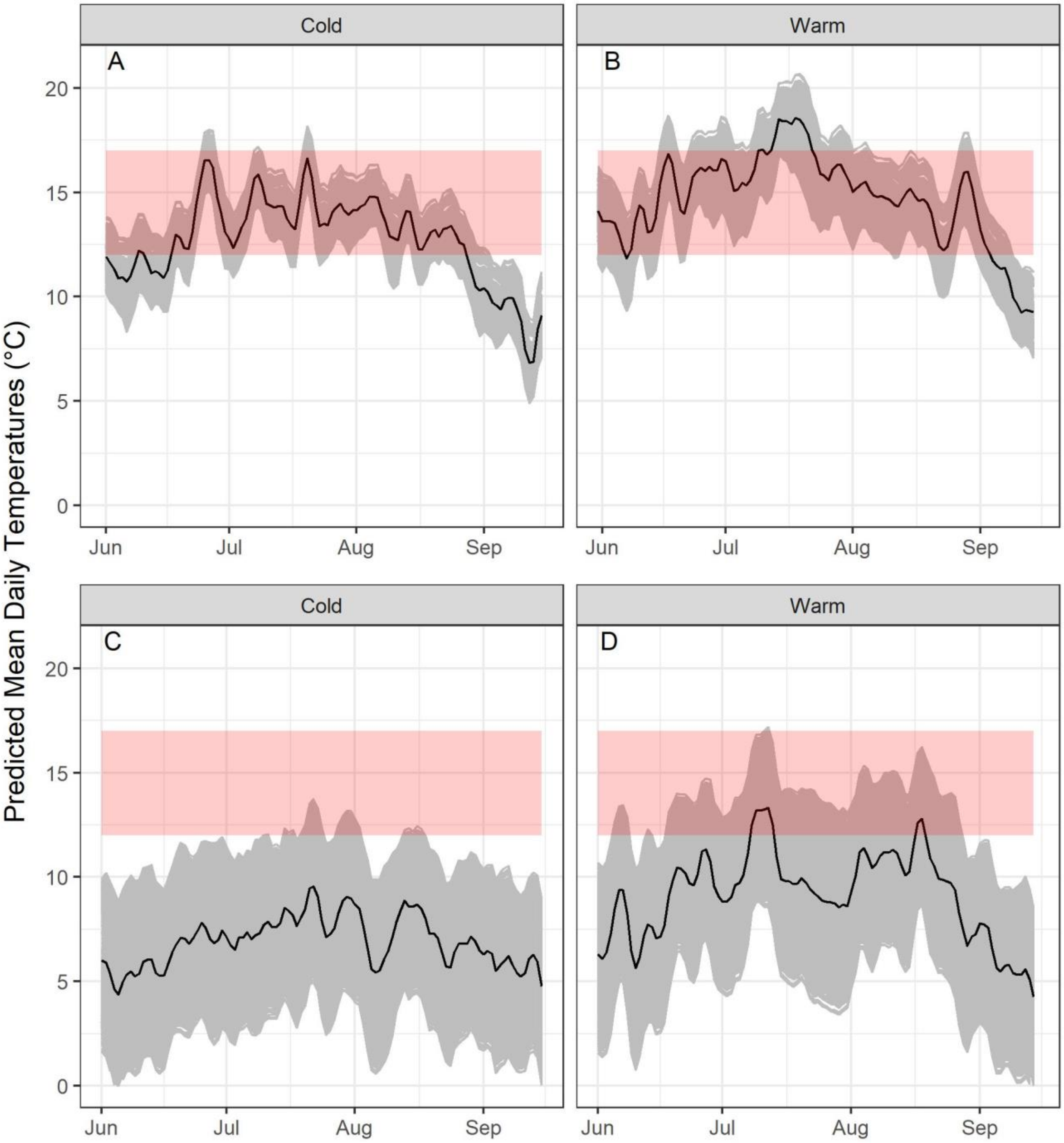


Figure 6. Mean daily temperatures in representative cold and warm years in the Deshka (A and B) and Anchor-Stariski watersheds (C and D). Gray lines are mean daily temperatures for each catchment and black lines are median daily temperatures across the watershed. The red ribbon indicates optimal temperatures for juvenile rearing (12°C - 17°C).

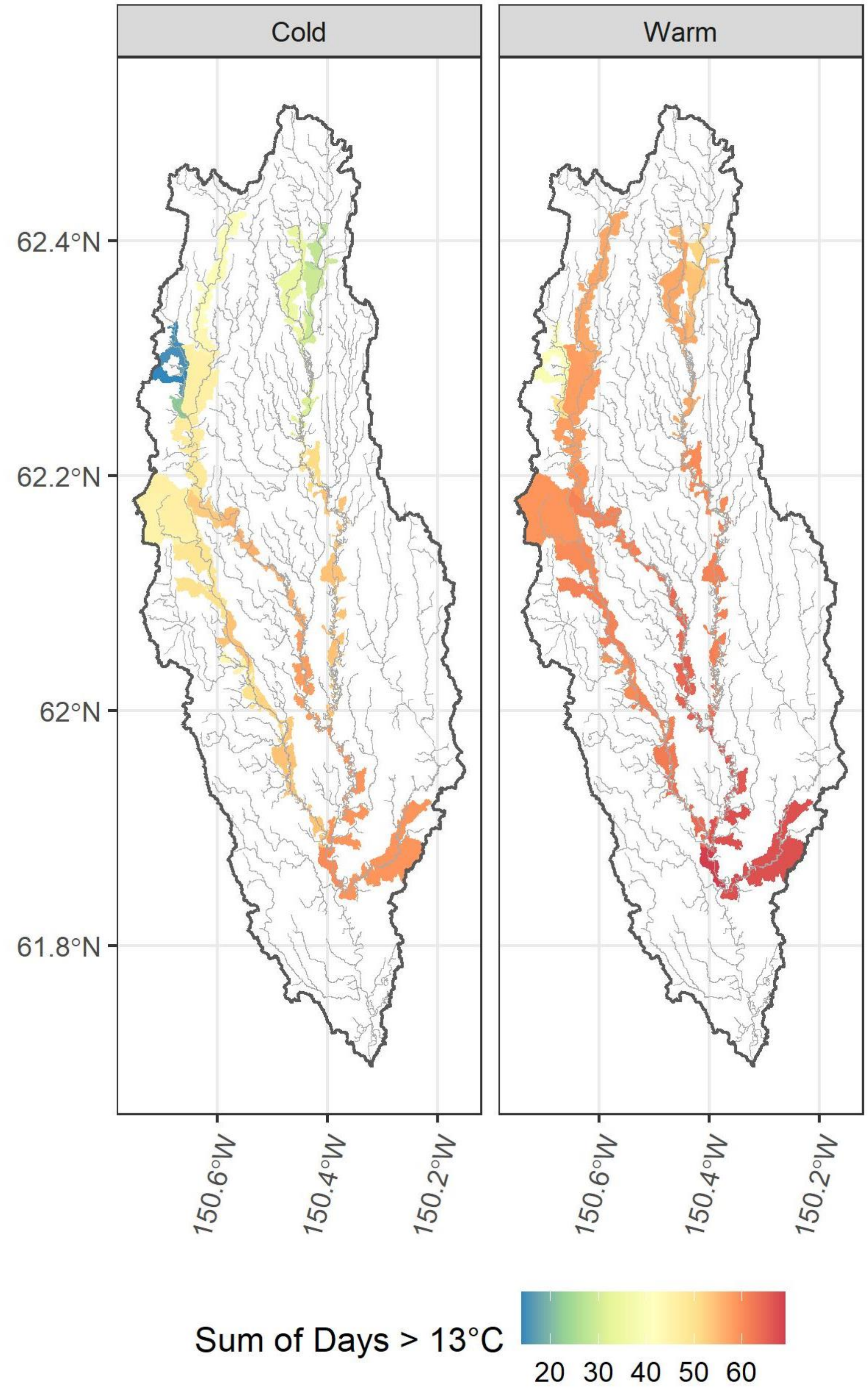


Figure 7. Chinook salmon spawning catchments in the Deshka watershed and number of days with daily stream temperatures greater than 13°C in July, August, and September in a representative cold (1982) and warm year (2016).

In the Anchor-Stariski watersheds, there were Chinook Salmon spawning habitats whose mean daily temperatures never exceeded 13°C in a warm or a cold year (Appendix C Figure 5). The maximum number of days >13°C was five in a cold year and 55 in a warm year across all Chinook spawning habitats (Appendix C Figure 5). Maximum mean daily temperatures ranged from 8.7°C to 13.7°C in a cold year and from 12.4°C to 17.2°C in a warm year across these same catchments.

Rearing habitats for Chinook and Coho Salmon in a cold year in the Deshka watershed rarely exceeded 18°C (Appendix C Figure 6). In a warm year, the number of days >18°C ranged from 0 to 24 with the warmest habitats found in the lower mainstem Deshka River and in Trapper Creek below Trapper Lake (Appendix C Figure 6). In a cold year, both Chinook and Coho Salmon rearing habitats had maximum mean daily temperatures that ranged from 15.2°C to 18.2°C. In a warm year, Chinook Salmon rearing habitats ranged from 17.1°C to 20.7°C, whereas Coho Salmon rearing habitats ranged from 16.7°C to 20.7°C.

In the Anchor-Stariski watersheds, predicted mean daily temperatures did not exceed 18°C in cold or warm years. In the empirical data used for the stream temperature model, only 7 out of ~6400 measurements were >18°C. The maximum mean daily temperatures ranged from 9.0°C to 13.6 for Chinook Salmon and 6.4°C to 13.6°C for Coho Salmon in a cold year across their respective rearing habitats. In a warm year, maximum temperatures ranged from 12.8°C to 17.0°C for Chinook Salmon and 10.1°C to 17.0°C for Coho Salmon.

5. *How have historic thermal regimes for salmon habitats changed and how might they change in the future? Where are cold-water refugia that may be important for sustaining salmon in the future?*

Salmon thermal regimes in the Deshka and Anchor-Stariski watersheds changed differently over the last 40 years (Figure 8, Appendix C Figure 7). In the Deshka watershed, there were significant increases in maximum temperatures and their durations, but no changes in the timing of maximum temperatures or in seasonal temperature variability (Appendix C Figure 7). Significant changes in temperature metrics for the Deshka watershed included increases in June and August temperatures by 0.2°C per decade, maximum daily temperatures by 0.4°C per decade, the 7-day rolling average of maximum daily temperatures by 0.3°C, cumulative degree days by 28°C per decade, and the number of days greater than 18°C by 1.7 days per decade. In the Anchor-Stariski watershed, the timing of maximum temperatures advanced by approximately four days per decade, but there were no significant changes in other aspects of stream thermal regimes (Figure 8, Appendix C Figure 7).

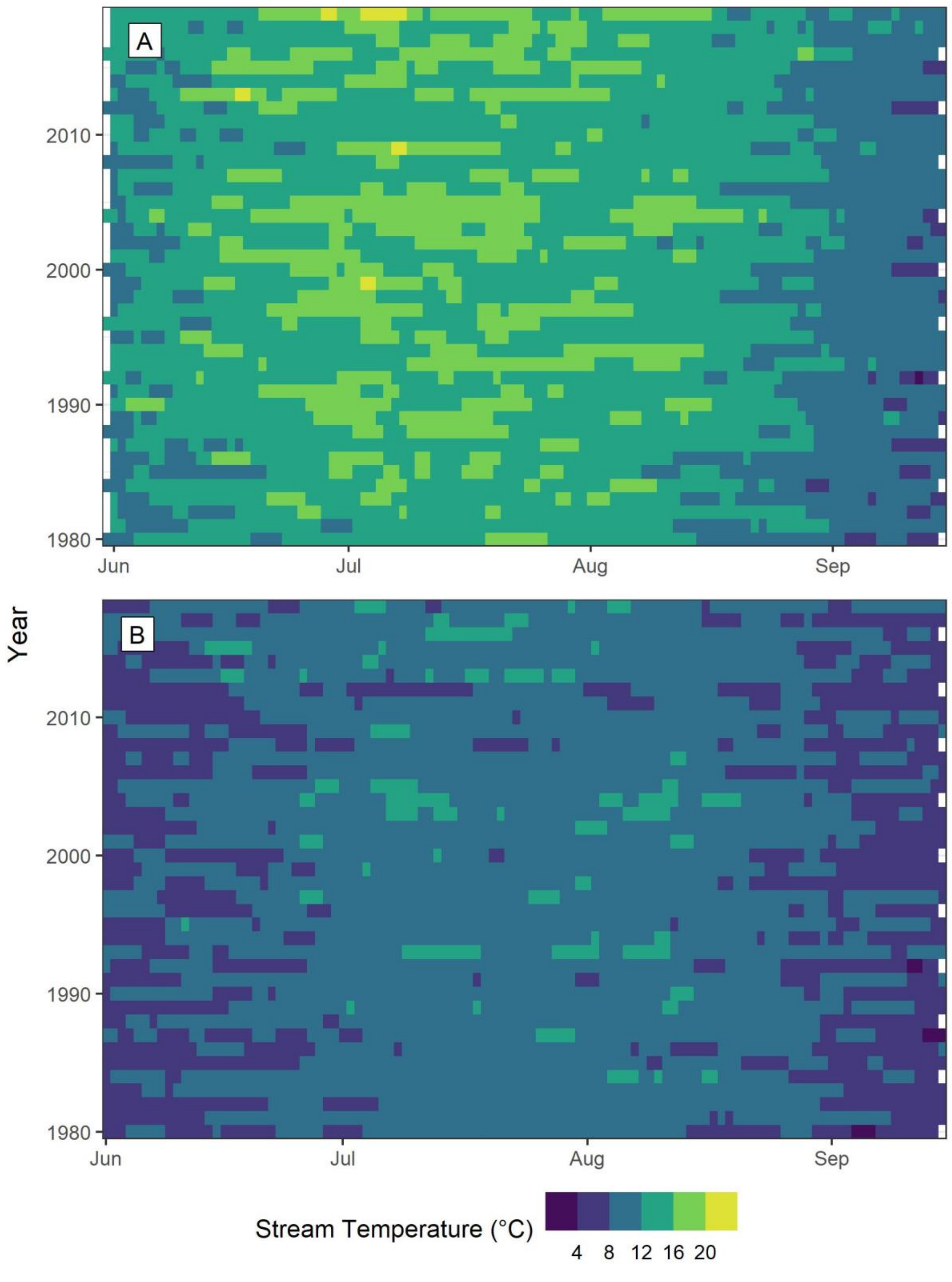


Figure 8. Seasonal and inter-annual variation in stream temperatures in the Deshka (A) and Anchor-Stariski (B) watersheds. Temperatures are averages of predicted mean daily stream temperatures across all Chinook and Coho Salmon catchments in each watershed.

Changes in salmon thermal regimes under future scenarios were similar across watersheds. In the Deshka, mean monthly stream temperatures increased by 1.5°C and 3.1°C for air temperature warming scenarios of +2°C and +4°C, respectively (Appendix C Figure 8). Increases in the Anchor-Stariski watershed were only slightly higher; 1.6°C and 3.2°C for the +2°C and +4°C warming scenarios, respectively (Appendix C Figure 8). Mean monthly temperatures in the Anchor-Stariski watershed in years with a low spring snowpack (April 1st SWE) were approximately 0.4°C warmer across all months (Appendix C Figure 8).

Chinook Salmon spawning habitats are below 17.6°C in the Deshka watershed for the historic period (95th percentile of mean July temperatures from 1980-2019). Under future warming scenarios of +2°C and +4°C air temperature increases, the amount of suitable spawning habitat decreases by 17% and 89%, respectively. For future warming of +2°C, important thermal refugia will include the upper reaches of Chijuk Creek, Kroto Creek, Moose Creek, and their tributaries as lower mainstem spawning habitats and Trapper Creek may become too warm (Appendix C Figure 9). For the highest warming scenario, remaining thermal refugia are in the uppermost headwaters of Kroto Creek and Moose Creek, and in a small tributary that enters the mainstem Deshka below Chijuk Creek (Appendix C Figure 9).

In the Anchor-Stariski watershed, Chinook Salmon spawning habitats are below 12.9°C for the historic period (95th percentile of mean July temperatures from 1980-2018). When snowpack is high, future air temperature increases of +2°C and +4°C result in 12% and 36% reductions in suitable spawning habitats, respectively. When snowpack is low, these reductions in suitable spawning habitat increase to 18% and 43%. Under warming of +2°C, thermal refugia in the Anchor-Stariski watershed are found in the upper reaches of Stariski Creek, and the North and South Forks of the Anchor River (Appendix C Figure 10). These refugia contract significantly under warming of +4°C and important cold-water habitats are found in small headwater streams throughout the three drainages as mainstem and lower elevation spawning reaches become unsuitable (Appendix C Figure 10).

4 CONCLUSIONS

We developed thermal maps that captured summer and early fall variation in daily stream temperatures over a four-decade period for two important salmon-producing watersheds in Cook Inlet. We used the model predictions to evaluate Chinook and Coho Salmon thermal regimes, describe growth potential for juvenile salmon, evaluate thermal stress for species and life stages, and identify thermal refugia. In the Deshka watershed, Chinook and Coho Salmon spawning and rearing habitats are several degrees warmer than those found in the Anchor-Stariski watershed. The warmer temperatures in the Deshka provide valuable growth opportunities for juvenile salmon that are more limited across the Anchor-Stariski watershed, where optimal temperatures for juvenile growth were reached only in the warmest years and over a shorter duration of the summer period as compared to the Deshka watershed. Estimated thermal regimes for invasive northern pike indicate that the entire Deshka watershed provides thermally suitable habitat and other habitat characteristics are likely limiting their distribution across the watershed (Sepulveda et al. 2013).

Analysis of temperatures above thresholds established to protect salmon life stages indicate the potential for temperature stress to spawning adults and incubating embryos in both watersheds, whereas temperature stress for juvenile salmon only occurred in the Deshka watershed. Hindcast temperatures indicate increasing maximum stream temperatures in the Deshka, which may already be impacting Chinook Salmon (Jones et al. 2020). In the Anchor-Stariski watershed, the timing of maximum temperatures is advancing, likely due to earlier onset of spring snowmelt caused by decreased winter snowpack and increased average air temperatures during winter and spring (Stewart et al. 2005). Snowfall predictions for the late 21st century indicate a change from snow-dominated to transitional hydrology (not snow-dominated) for much of southern Alaska (Littell et al. 2018). By 2090, average air temperatures for all months on the lower Kenai Peninsula are expected to be above freezing leading to potential snow-free conditions during winter (see Figure 3). Spring snowpack had a cooling effect on daily stream temperatures in the Anchor-Stariski watershed and decreased snowpack will lead to warmer stream temperatures and decreased thermal diversity (Cline et al. 2020).

Under future climate scenarios, suitable spawning habitats will contract in the Deshka watershed and thermal refugia will be restricted to tributary and headwater streams. Impacts to spawning habitats are less severe in the Anchor-Stariski watershed and important thermal refugia will also be found in tributary streams at higher elevations. Access to these critical habitats may be limited if temperature blockages exist in mainstem habitats. This has been observed historically in the Deshka system and highlights the importance of habitat connectivity to conservation and management.

Hydrologic data in Alaska are sparse and extremely limited. Additional data, such as stream discharge and locations of groundwater contributions, could improve our ability to understand climate impacts to Pacific Salmon. For example, thermal infrared imagery (TIR) obtained by Cook Inletkeeper for the Deshka watershed indicate that cold-water inflows to the mainstem resulted in an upstream to downstream cooling pattern in July 2020. These inputs are critical for maintaining suitable conditions for Chinook Salmon migration and connectivity to cold-water refugia in tributaries and headwater streams. Cold-water inflows identified by TIR could be used to develop topographic or landcover predictor variables for these features, which could then be used to improve geostatistical temperature models. In 2019, low water levels and unusually warm weather likely interacted to contribute to adult salmon mortality across Alaska (von Biela et al. In prep.). Understanding the effects of discharge on stream temperature, dissolved oxygen, and fish passage will be important in the future as extremes like 2019 may become more common.

Landcover change, both natural and human-driven, may also have consequences for stream temperatures and Pacific Salmon. Wetlands are an important contributor of baseflow to streams and wetland conversion (filling of wetlands for development) and drying (Klein et al. 2005) may impact summer stream flows and temperatures. We found contrasting influences of wetlands across our watersheds. In the Deshka, high snow and high wetland cover interacted to cool stream temperatures. In the Anchor-Stariski and Kenai watersheds, high snowpack decreased stream temperatures, but in reaches with low riparian wetland cover. Wetlands provide important hydrologic functions that warrant further investigation in Alaska watersheds as they are at risk due to human alteration and climate change.

Only in the past decade has stream temperature data become more widely available, enabling projects to investigate stream thermal regimes and evaluate relationships with Pacific Salmon (Mauger et al. 2017, Jones et al. 2020, Shaftel et al. 2020). Planning and leadership from Cook Inletkeeper and funding from the fish habitat partnerships have resulted in increased understanding of temperature effects on salmon in Southcentral Alaska. We found that limited temperature data for the Kenai River watershed precluded our ability to develop thermal maps and highlights a need for expanded temperature monitoring in this valuable resource area. Long-term monitoring locations in the Kenai watershed could be selected by identifying streams that represent different elevations, topography (e.g. lowland versus mountain), and glacier and lake influences; in addition to placing sites near to discharge or salmon escapement monitoring.

Thermal stream networks are valuable management tools that can be used to understand the biological and ecological consequences of spatial and temporal variability in stream temperatures (Steel et al. 2017). In this report, we used historic and future temperature predictions for the Deshka and Anchor-Stariski watersheds to examine several questions related to Pacific Salmon thermal regimes and climate change. We relied on static habitat designations from the AWC and opportunity exists to improve on this work by incorporating contemporaneous fish species occurrence information to define thermal niches (Al-Chokhachy et al. 2013, Isaak et al. 2017b). Additionally, our stream temperature scenarios could be enhanced by incorporating predictions for changing hydrologic regimes, which will improve our understanding of climate change impacts to Pacific Salmon. All model predictions and outputs have been made publicly available with the expectation that they will benefit resource managers and researchers interested in exploring stream thermal regimes experienced by freshwater taxa in these important watersheds.

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6 APPENDICES

Appendix A. Description of stream temperature modeling products

As part of this project, several data products have been generated that are publicly available for use on the ACCS Data Catalog: Stream Temperature Models. These products are described in the table below and reference report sections where additional information has been provided. Products for each watershed are aggregated into a single zip file for easy download.

Products	Format	Description	Temporal resolution[1]	Spatial resolution
Flowlines	Shapefile	Vector dataset of stream reaches	NA	Stream reach
Catchments	Shapefile	Polygon dataset of land area draining to each stream reach	NA	Catchment
Sites	csv	Sites with empirical stream temperature data (see Section 2.2)	NA	Point
Temperature data	csv	Empirical temperature data associated with sites (see Section 2.2)	Sub-daily, years vary	Point
Spatial variables	csv	Spatial predictor variables linked to stream reaches and stream catchments (see Table 2 for variables and definitions)	NA	Catchment
Climate variables	csv	3-day moving average of air temperature, 5-day moving sum of precipitation, and April 1st SWE for each year (see Table 2 for variables and definitions)	1980-2019	Catchment
Predictions	csv	Predicted mean daily stream temperature by catchment and year	1980-2019	Catchment
Future predictions	csv	Predicted mean daily stream temperature by catchment and scenario	Baseline and +2°C and +4°C scenarios	Catchment
Historic temperature metrics	csv	Annual temperature metrics that describe magnitude, variability, frequency, and timing of stream temperatures (see Table 3 for abbreviations and descriptions)	1980-2019	Catchment

Products	Format	Description	Temporal resolution[1]	Spatial resolution
Future temperature metrics	csv	Monthly means of stream temperatures	Baseline and +2°C and +4°C scenarios	Catchment

[1] Historic climate predictor variables, predictions, and historic temperature metrics extend to 2019 for the Deshka watershed and to 2018 for the Anchor-Stariski watershed.