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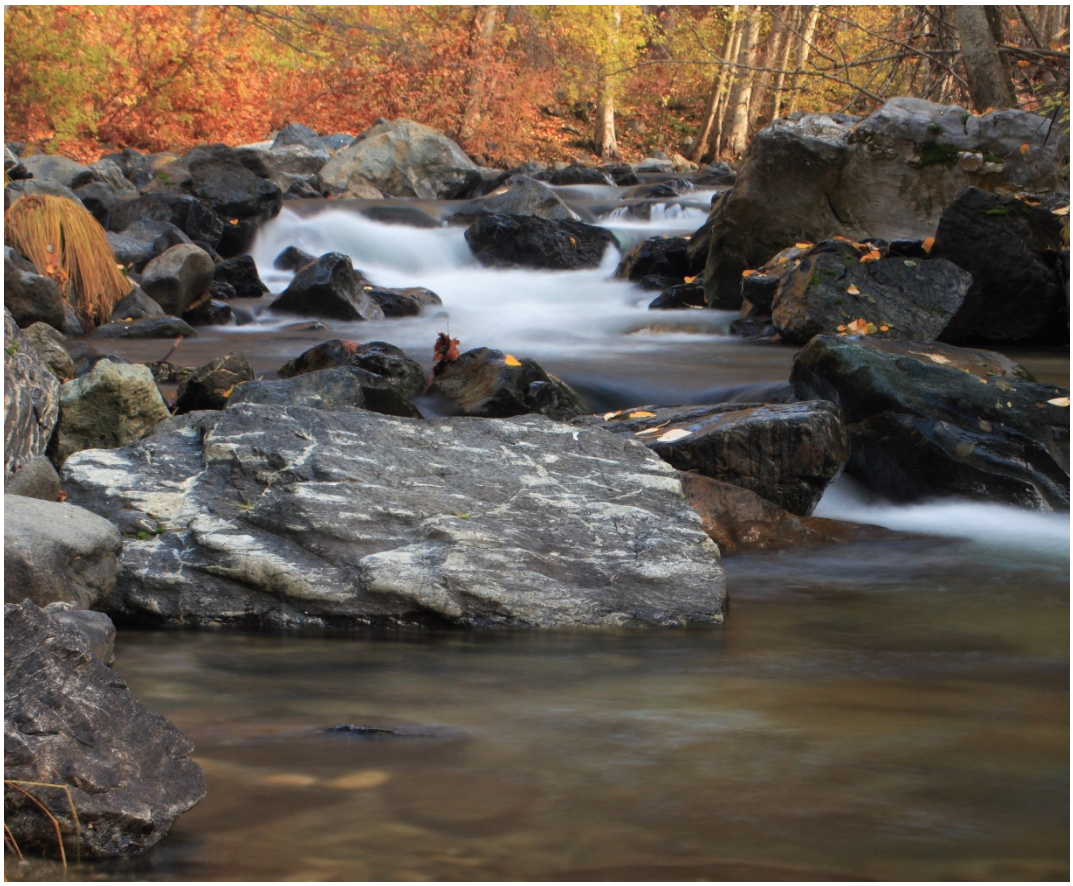
Estimation of Stream Conditions in Tributaries of the Klamath River, Northern California

Christopher V. Manhard, Nicholas A. Som, Edward C. Jones, Russell W. Perry



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Estimation Of Stream Conditions In Tributaries Of The Klamath River, Northern California

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Abstract.— Because of their critical ecological role, stream temperature and discharge are requisite inputs for models of salmonid population dynamics. Coho Salmon inhabiting the Klamath Basin spend much of their freshwater life cycle inhabiting tributaries, but environmental data are often absent or only seasonally available at these locations. To address this information gap, we constructed daily averaged water temperature models that used simulated meteorological data to estimate daily tributary temperatures, and we used flow differentials recorded on the mainstem Klamath River to estimate daily tributary discharge.

Observed temperature data were available for fourteen of the major salmon bearing tributaries, which enabled estimation of tributary-specific model parameters at those locations. Water temperature data from six mid-Klamath Basin tributaries were used to estimate a global set of parameters for predicting water temperatures in the remaining tributaries. The resulting parameter sets were used to simulate water temperatures for each of 75 tributaries from 1980-2015. Goodness-of-fit statistics computed from a cross-validation analysis demonstrated a high precision of the tributary-specific models in predicting temperature in unobserved years and of the global model in predicting temperatures in unobserved streams.

Klamath River discharge has been monitored by four gages that broadly intersperse the 292 kilometers from the Iron Gate Dam to the Klamath River mouth. These gages defined the upstream and downstream margins of three reaches. Daily

discharge of tributaries within a reach was estimated from 1980-2015 based on drainage-area proportionate allocations of the discharge differential between the upstream and downstream margin. Comparisons with measured discharge on Indian Creek, a moderate-sized tributary with naturally regulated flows, revealed that the estimates effectively approximated both the variability and magnitude of discharge.

Introduction

Stream conditions, temperature and discharge in particular, modulate a number of processes in the freshwater life cycle of salmonids, including growth rates, movement patterns, reproductive success, and disease susceptibility. The relationship between environmental variation and ecological processes is of importance to fisheries and water managers interested in predicting the effects of water management decisions on threatened Coho Salmon (*Oncorhynchus kisutch*) inhabiting reaches downstream of dams in the Klamath Basin, Northern California. Extensive monitoring of water temperature and discharge has been used in concert with water-temperature models to provide continuous environmental data throughout the mainstem Klamath River. However, the freshwater life cycle of Coho Salmon in this basin occurs primarily in the numerous tributaries of the Klamath River. Therefore, the construction of a freshwater life cycle model for the purpose of evaluating the effects of water management decisions in the mainstem also requires accounting for environmentally driven ecological processes occurring in tributaries. Efforts to monitor water temperature in tributaries have focused on sampling the larger tributaries and have been concentrated during the summer. Monitoring of discharge in tributaries has been largely limited to four major tributaries: the Trinity, Salmon, Scott, and Shasta Rivers. Hence, estimation procedures are needed to supply continuous tributary temperature and discharge data as inputs for life cycle models.

In this report, we present a series of water temperature models for Klamath River tributaries. Like the Trinity River temperature model developed by Jones et al. (2016), our models use publically available simulated meteorological data to estimate daily mean water temperatures. Estimation of model parameters requires observed daily water temperatures collected throughout the year, which were available at fourteen of the major Coho Salmon bearing tributaries. However, there are numerous small tributaries that may also play an important role in Coho Salmon ecology. To account for these locations, we estimated a set of global model parameters with data from six small tributaries. Collectively, these water temperature models will enable us to simulate continuous daily water temperatures at all Coho Salmon rearing tributaries in the Klamath Basin and, when linked with the previously developed Klamath River mainstem temperature model, will provide a comprehensive framework for water temperature in the Klamath Basin. Additionally, we detail a procedure for estimating tributary discharge, based on discharge data collected at gages on the mainstem Klamath River. Discharge within the mainstem has been continuously monitored at four broadly interspersed sites spanning the extent of anadromy, and mainstem discharge has been estimated at 17 additional sites via interpolation (R. Perry, USGS, personal communication). Together, these methods of estimating water temperature and discharge will provide basin-wide estimates of environmental data, which will serve as essential inputs to models of juvenile Coho Salmon production in the Klamath Basin.

Methods

Study site

The Klamath River originates in Southern Oregon and flows for approximately 423 kilometers, draining a basin area of nearly 41,440 square kilometers, before entering the Pacific Ocean in Northern California. The upper reaches of the Klamath River run through arid deserts which have been subjected to substantial agricultural development, whereas the lower reaches run through relatively undeveloped land that is dominated by temperate rainforests. Five hydropower dams, constructed in the upper reaches of the Klamath River during the first half of the 20th century, impact the hydrology of the mainstem, contributing to reduced summer discharge, elevated water temperature, and impaired water quality downstream of the dams (Stocking and Bartholomew 2007). The lowest of these dams, Iron Gate Dam, establishes the upper limit of anadromy in the Klamath Basin at river kilometer 292. The four major tributaries of the Klamath River are the Shasta (RKM 288), Scott (RKM 234), Salmon (RKM 107), and Trinity (RKM 69) Rivers.

Data sources

Stream temperatures ·

Mean daily water temperatures in Klamath River Basin tributaries were obtained from surveys conducted by the U.S. Forest Service and U.S. Fish and Wildlife Service over a broad expanse of the Klamath Basin (Figure 1). Among these data were time series for fourteen of the largest and most productive salmonid bearing tributaries in the Klamath River Basin (Table 1). Because of their putative importance to the population dynamics of Klamath River Coho Salmon, unique estimates of the temperature model parameters were made for each of these tributaries. These large tributaries had complete daily coverage of temperature (i.e. observations were collected on every calendar date) in many of the survey years (Figure 2). To capitalize on this feature, the dataset used to estimate each tributary-specific model was primarily limited to years with complete daily coverage. While these major tributaries are recognized as providing a substantial portion of Coho Salmon habitat, there are numerous other tributaries in the Klamath River Basin that are thought to provide rearing habitat for juvenile Coho Salmon. Because daily water temperature data were absent for many of these sites, a global model was estimated with year-round daily water temperature data from several small tributaries. The coverage of temperature data for small tributaries was seasonally heterogeneous, with sampling effort concentrated in the summer (Figure 3). To obtain broad representation of seasonal temperature patterns, six tributaries were selected to estimate the global model on the basis that they had been sampled on each calendar date at some point in their time series (Table 2). Parameters estimated by the global model were assumed to be reflective of the numerous small, thermal refuge streams that exist in the mid-Klamath River.

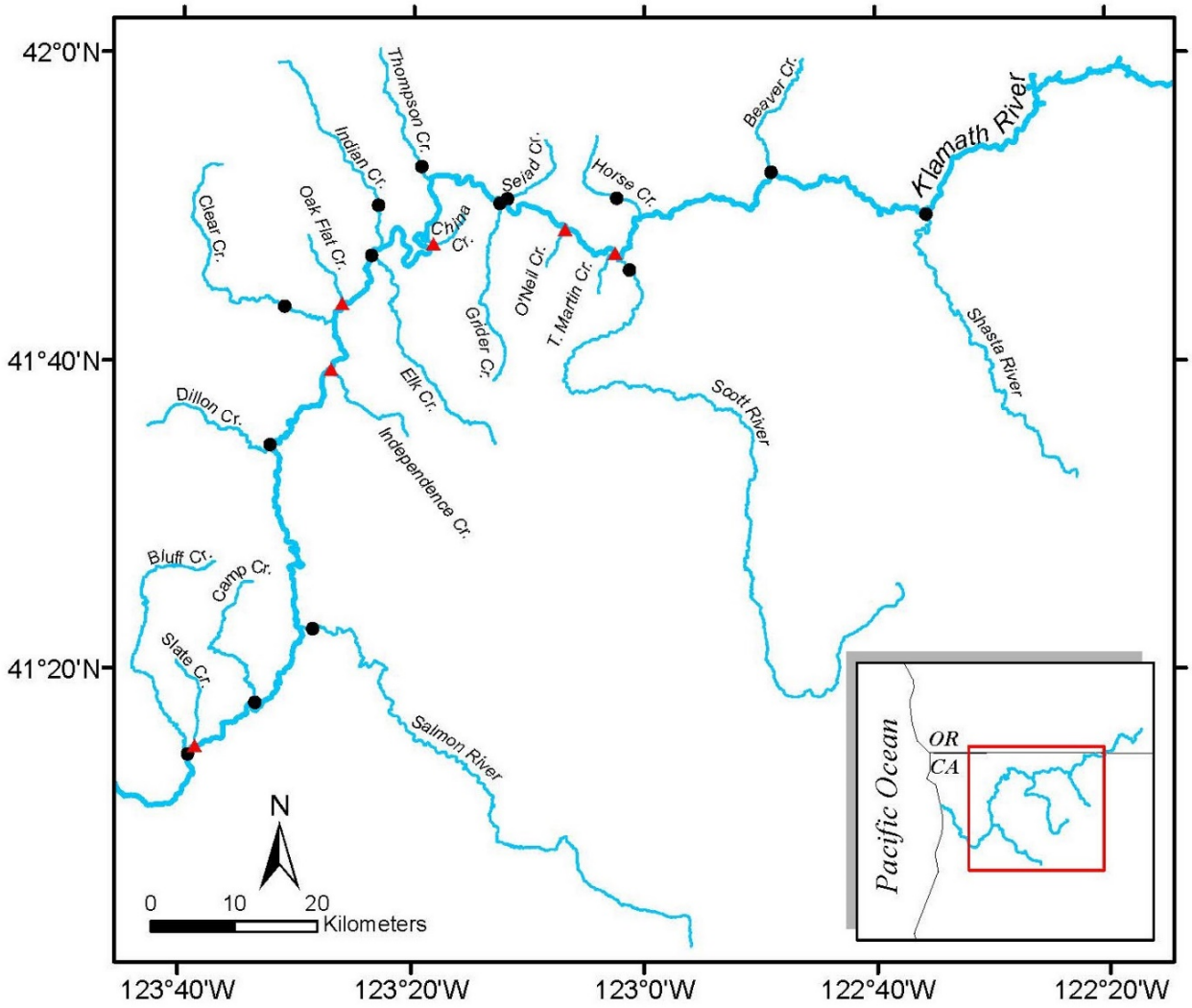

Figure 1. Locations of temperature monitoring gages on Klamath River tributaries. Sites used to fit individual temperature models are marked by solid black circles, and those used to fit the global temperature model are marked by solid red triangles.

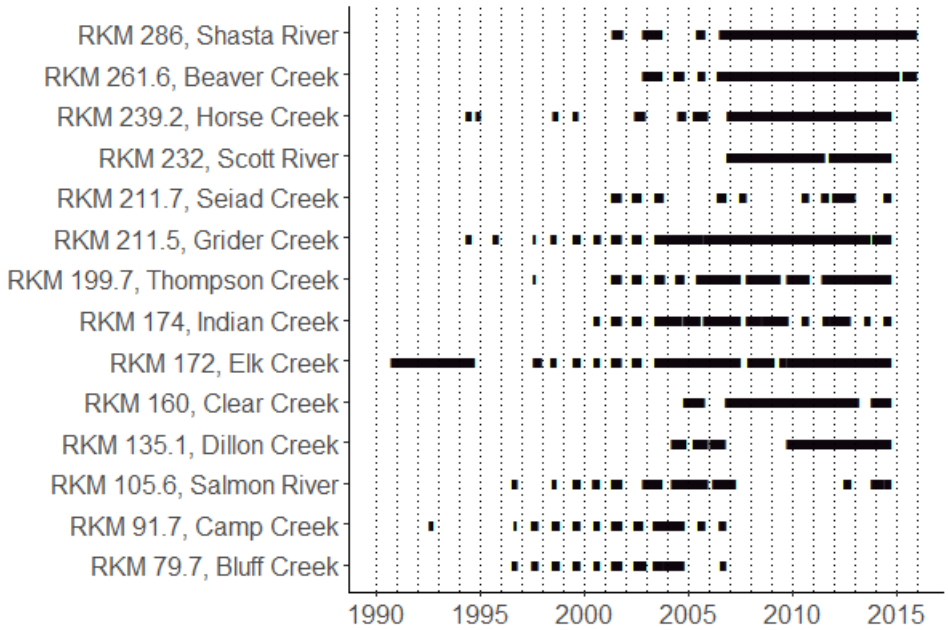

Figure 2. The extent of observed water temperature data for individually modeled tributaries, at specified river kilometers (RKMs), of the Klamath River. Horizontal bars depict the chronological range of available data.

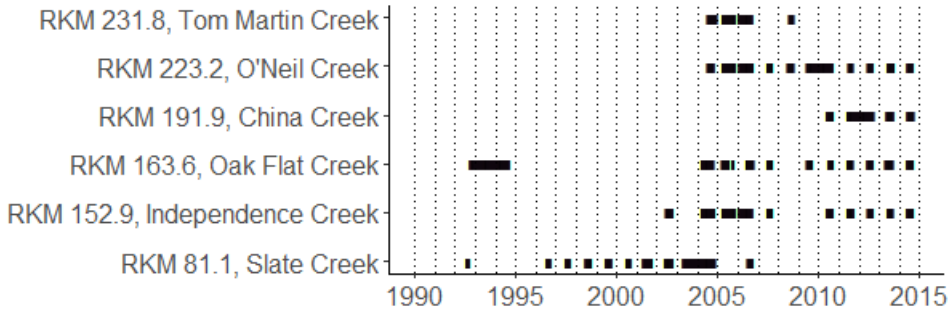

Figure 3. The extent of observed water temperature data for Klamath River tributaries used in fitting the global tributary model. Horizontal bars depict the chronological range of available data.

Table 1. Source of input datasets used to estimate tributary-specific models of water temperature.[Source: USFS, U.S. Forest Service; USFWS, U.S. Fish and Wildlife Service. Station ID: A field identifier used to distinguish source data]

Tributary	Data extent	Source	Station ID	Latitude	Longitude
Shasta River	2007-2014	USFWS	SHKR1	41.8250	-122.5925
Beaver Creek	2007-2014	USFS	H2O_Temp_LOCID245	41.8708	-122.8158
Horse Creek	2007-2013	USFS	H2O_Temp_LOCID125	41.8433	-123.0384
Scott River	2007-2013	USFS	SCKR1	41.7658	-123.0211
Seiad Creek	2001; 2003; 2006; 2011-2012	USFS	H2O_Temp_LOCID053	41.8425	-123.1974
Grider Creek	2004; 2007-2012	USFS	H2O_Temp_LOCID057	41.8375	-123.2080
Thompson Creek	2005-2014	USFS	H2O_Temp_LOCID055	41.8771	-123.3211
Indian Creek	2003-2012	USFS	H2O_Temp_LOCID056	41.8351	-123.3831
Elk Creek	1991-1993; 2004-2005; 2010-2013	USFS	H2O_Temp_LOCID014	41.7806	-123.3927
Clear Creek	2005-2014	USFS	H2O_Temp_LOCID283	41.7251	-123.5182
Dillon Creek	2009-2014	USFS	H2O_Temp_LOCID289	41.5756	-123.5383
Salmon River	2003-2006; 2012-2014	USFWS	SAKR1	41.3767	-123.4758
Camp Creek	2001-2006	USFS	H2O_Temp_LOCID007	41.2970	-123.5574
Bluff Creek	2000-2006	USFS	H2O_Temp_LOCID089	41.2406	-123.6532

Table 2. Source of input datasets used to estimate the global model of water temperature. [Source: USFS, U.S. Forest Service. Station ID: A field identifier used to distinguish source data]

Tributary	Data extent	Source	Station ID	Latitude	Longitude
Tom Martin Creek	2004-2006	USFS	H2O_Temp_LOCID203	41.7840	-123.0421
O'Neil Creek	2005-2006; 2009-2010	USFS	H2O_Temp_LOCID202	41.8102	-123.1148
China Creek	2010-2012	USFS	H2O_Temp_LOCID282	41.7944	-123.3041
Oak Flat Creek	1993-1994; 2004	USFS	H2O_Temp_LOCID037	41.7298	-123.4354
Independence Creek	2004-2006; 2014	USFS	H2O_Temp_LOCID154	41.6585	-123.4514
Slate Creek	2001-2004	USFS	H2O_Temp_LOCID045	41.2504	-123.6433

Meteorological data

Because time series of meteorological data were not available for most of the Klamath River tributaries, simulated data were used to construct model inputs. Time series of daily minimum and maximum air temperature (°C) were extracted from the 1 x 1 km spatial grid of Daymet (Thornton and Running 1999) at the mouth of each of the fourteen modeled tributaries and of each of the six global model tributaries (see table for geographic coordinates). Daily mean air temperature was estimated as the mean of the minimum and maximum daily air temperature.

Stream discharge

Daily average stream discharge measurements, collected by U.S. Geological Survey operated survey stations on the Klamath River and its tributaries, were downloaded from http://waterdata.usgs.gov/nwis/dv. Gage sites (Table 3) included four locations on the mainstem Klamath River, which ranged from near the mouth to the limit of anadromy (Iron Gate Dam), and its four largest tributaries (Figure 4). An additional gage site was located at Indian Creek.

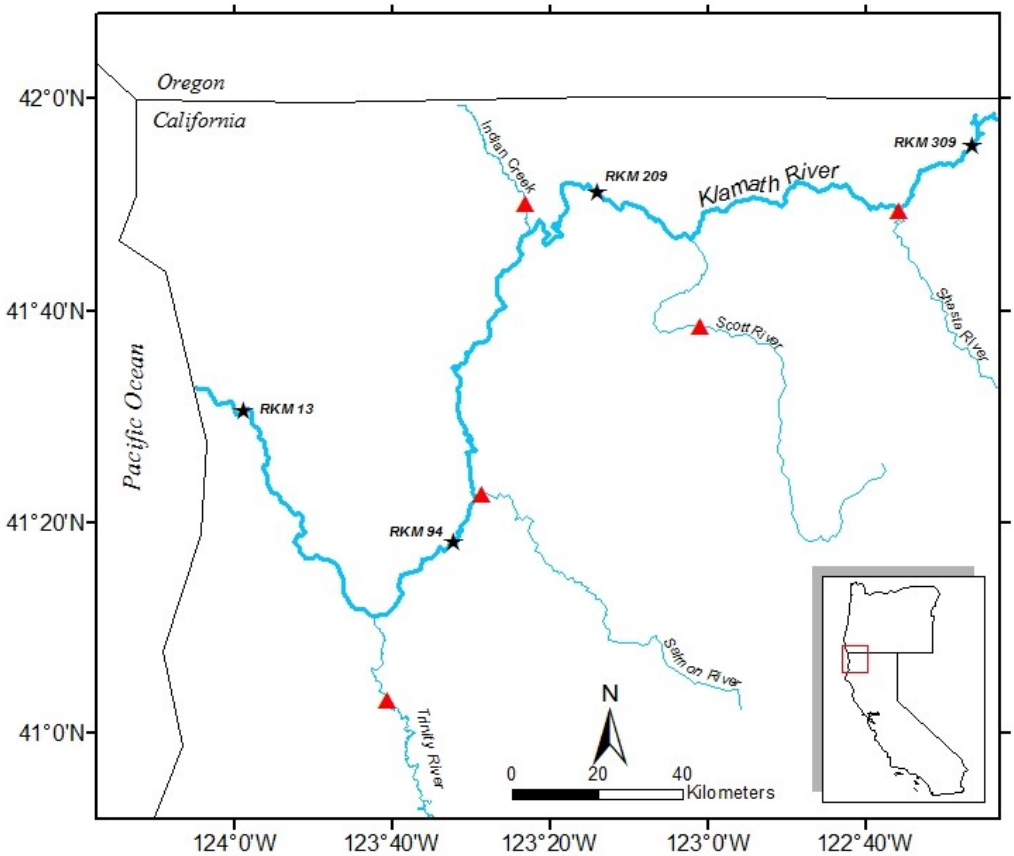

Figure 4. Locations of USGS gages on the mainstem Klamath River (black stars) and on Klamath River tributaries (red triangles).

Table 3. USGS gage sites on the Klamath River and its major tributaries. Equations used to estimate the aggregate discharge from non-gaged tributaries in each reach are listed. [USGS gages: Iron Gate Dam (IGD, 11516530); Shasta River (11517500); Scott River (11519500); Seiad Valley (11520500); Salmon River (11522500); Orleans (11523000); Trinity River (11530000); Klamath (11530500)]

Reach	Distance (km)	Major tributaries	Equation
IGD to Seiad	100	Shasta R., Scott R.	Seiad – IGD – (Shasta R. + Scott R.)
Seiad to Orleans	115	Salmon R.	Orleans – Seiad – Salmon R.
Orleans to Klamath	77	Trinity R.	Klamath – Orleans – Trinity R.

Tributary temperature model

Model structure

A nonlinear regression model was used to estimate weekly stream temperatures in Klamath River tributaries as a function of weekly air temperatures (Mohseni et al. 1998),

$$T_s = \mu + \frac{\alpha - \mu}{1 + e^{\gamma(\beta - T_a)}}, \qquad (1)$$

where T_s is the predicted stream temperature, Ta is the measured air temperature, μ is the minimum stream temperature, α is the maximum stream temperature, γ is the steepest slope, and β is the air temperature at the inflection point. To account for hysteresis, separate models were estimated with data from the rising and falling limbs of air temperature. The limbs were defined by the Julian weeks in which the minimum and maximum air temperatures typically occurred. For all streams, data from weeks 1 to 29 were classified as belonging to the rising limb, and data from weeks 30 to 52 were classified as belonging to the falling limb. Non-linear least squares regression was used to produce separate estimates of the parameters α, μ, γ, and β for each limb with an optimization routine in R (R Core Team 2016). Given estimates of parameters for the rising and falling limbs of each tributary, daily water temperature was estimated on each day from 1980 to 2015 with a seven-day moving average of air temperature.

Model validation

Graphical and statistical methods were used to evaluate the fit of each model. Plots of observed and model-predicted temperatures were constructed for four year subsets of data at each modeled tributary to determine whether there were systematic departures of the model. Statistical measures of goodness-of-fit, which were computed for each model, included the Nash-Sutcliffe statistic (NSS), root-mean-square error (RMSE), mean error (ME), and mean absolute error (MAE).

To evaluate capacity of the model to predict data outside of the range that was used to fit it, k-fold cross validation was used (Davidson and Hinkley 1997). This process entails (1) splitting the model input datasets into k=1,…,K subsets; (2) excluding the kth subset (the 'assessment set') and estimating the model parameters with the remaining data (the 'training set'); (3) predicting stream temperatures with the estimated parameters from the training set; and (4) computing goodness-of-fit statistics for the assessment set. This process is repeated for each of K subsets, and then an aggregate measure of fit is computed as the mean of each goodness-of-fit statistic over all subsets. To evaluate the ability of the tributary-specific models to predict daily stream temperatures in unobserved years, we performed the cross-validation procedure by splitting the dataset of each tributary into subsets by year. To evaluate the ability of the global model to predict daily stream temperatures in unobserved streams, we performed the cross-validation procedure by splitting the dataset into subsets by stream. To account for disparities in subset size, resulting from missing data, we used a weighted average of the goodness-of-fit-statistics where weights were equal to the fraction of observations in the kth year or stream.

Tributary discharge estimation

Daily discharge of Klamath River tributaries was estimated from flow measurements collected at gaged sites on the mainstem and its major tributaries. The Klamath River was divided into three reaches based on the locations of mainstem gages (Table 3), and the collective inflow from non-gaged tributaries in each reach, $\hat{Q}_R$, was estimated by,

$$\hat{Q}_R = Q_D - Q_U - Q_T \ , \tag{2}$$

where Q_D and Q_U are the daily discharge rates of the downstream and upstream gages of the reach, respectively, and Q_T is the collective daily discharge from gaged tributaries of the reach.

The collective inflow from non-gaged tributaries in each reach was allocated to individual tributaries based on watershed area (Tables 4-6). Watershed areas were extracted from NHDPlus (Moore and Dewald 2016) with ArcGIS (ESRI, 2015). The daily discharge of a non-gaged tributary, $\hat{Q}$, was estimated as,

$$\hat{Q} = \hat{Q}_R * P_A \tag{3}$$

where P_A is the proportion of watershed area attributed to a tributary relative to the total watershed area of all non-gaged tributaries in its reach.

Table 4. River kilometer (rkm), watershed area (km^2), and proportion of aggregate watershed area (P_A) for Klamath River tributaries within the Iron Gate Dam–Seiad Valley reach.

Stream	rkm	Area (km^2)	P_A
Bogus Creek	307.4	135.8	0.124
Humbug Creek	278.1	95.7	0.088
Lumgrey Creek	268.4	22.6	0.021
Empire Creek	268.4	23.5	0.021
Beaver Creek	261.6	270.4	0.247
Little Humbug Creek	255.9	25.1	0.023
Barkhouse Creek	254.9	26.4	0.024
Doggett Creek	250.1	31.3	0.029
McKinney Creek	249.9	29.5	0.027
Dona Creek	247.0	7.5	0.007
Kohl Creek	246.1	14.4	0.013
Horse Creek	239.2	157.7	0.144
Tom Martin Creek	231.8	6.8	0.006
Kuntz Creek	226.5	8.6	0.008
Negro Creek	225.0	8.6	0.008
O'Neil Creek	223.2	10.0	0.009
Walker Creek	216.8	31.1	0.028
Seiad Creek	211.7	76.0	0.070
Grider Creek	211.5	111.8	0.102

Table 5. River kilometer (rkm), watershed area (km^2), and proportion of aggregate watershed area (P_A) for Klamath River tributaries within the Seiad Valley–Orleans reach.

Stream	rkm	Area (km^2)	P_A
Portuguese Creek	207.6	22.7	0.013
Fort Goff Creek	206.0	33.5	0.019
Thompson Creek	199.7	94.1	0.054
China Creek	191.9	25.2	0.014
Cade Creek	178.1	11.7	0.007
Indian Creek	174.0	349.2	0.199
Little Grider Creek	172.4	21.5	0.012
Elk Creek	172.0	246.3	0.140
Wilson Creek	165.7	3.0	0.002
Oak Flat Creek	163.6	22.8	0.013
Clear Creek	160.0	288.7	0.164
Titus Creek	155.6	22.6	0.013
Independence Creek	152.9	46.6	0.027
Crawford Creek	150.3	5.2	0.003
King Creek	147.1	14.8	0.008
Ukonom Creek	146.1	84.7	0.048
Coon Creek	144.8	11.7	0.007
Swillup Creek	144.2	22.6	0.013
Thomas Creek	143.2	3.1	0.002
Elliot Creek	141.3	4.2	0.002
Aubrey Creek	140.2	4.3	0.002
Dillon Creek	135.1	189.5	0.108
Ti Creek	128.9	22.1	0.013
Rock Creek	127.1	86.2	0.049
Sandy Bar Creek	123.6	13.4	0.008
Stanshaw Creek	122.5	11.0	0.006
Irving Creek	120.7	22.1	0.013
Halverson Creek	118.0	6.5	0.004
Rogers Creek	116.0	17.3	0.010
Reynolds Creek	112.3	9.6	0.005
Teneyck Creek	109.9	4.3	0.002
Natuket Creek	109.58	4.9	0.003
Donahue Flat Creek	104.74	5.0	0.003
Ikes Creek	104.33	3.0	0.002
Roselano Creek	104.01	2.2	0.001
Whitemore Creek	100.44	3.0	0.002
Pearch Creek	95.76	16.6	0.009

Table 6. River kilometer (rkm), watershed area (km^2), and proportion of aggregate watershed area (P_A) for Klamath River tributaries within the Orleans–Klamath reach.

Stream	rkm	Area (km^2)	P_A
Cheenitch Creek	94.6	4.7	0.004
Camp Creek	91.7	109.0	0.088
Crawford Creek	91.3	6.8	0.006
Ullathorne Creek	90.6	6.3	0.005
Boise Creek	89.3	40.4	0.033
Red Cap Creek	84.7	157.9	0.128
Slate Creek	81.1	35.5	0.029
Bluff Creek	79.7	192.1	0.155
Aikens Creek	77.6	10.4	0.008
Hopkins Creek	73.9	23.4	0.019
Tully Creek	60.7	44.8	0.036
Miner's Creek	57.9	11.7	0.009
Coon Creek	56.6	1.9	0.002
Cappell Creek	52.1	21.9	0.018
Roach Creek	49.6	76.1	0.061
Pecwan Creek	39.4	71.4	0.058
Blue Creek	25.4	325.1	0.262
McGarvey Creek	8.9	23.3	0.019
Hunter Creek	1.4	76.0	0.061

Prediction evaluation ·

Data collected from a USGS operated flow gage on Indian Creek were used to evaluate the accuracy of discharge estimates. Indian Creek is a moderately sized tributary (watershed area = 349.2 km2) of the mid-Klamath River, which has naturally regulated flow regimes. Because of these attributes, Indian Creek was assumed to exhibit flow patterns similar to many of the tributaries of the Klamath River and, therefore, provide an assessment of predictive accuracy at non-gaged sites. Indian Creek was classified as a non-gaged stream, and discharge was estimated using the previously detailed procedure. Plots of observed and estimated discharge at Indian Creek were constructed from 1990-2013 to determine whether estimates accurately reflected the pattern and magnitude of observed flow regimes.

Results

Temperature model

The tributary-specific temperature models produced a broad range of parameter estimates among the fourteen tributaries (Table 7). Mean parameter estimates of the minimum water temperature (μ) ranged from -19.6 to 6.5. The standard errors of estimates of μ were generally large; of the 28 estimates of this parameter, 17 had confidence intervals that overlapped zero. Estimates of the maximum water temperature (α) ranged between 16.7 and 33.7, excluding the rising limb of Beaver Creek, which had a high standard error. The standard errors of estimates of α were smaller than those of μ, and only three had confidence intervals that overlapped zero. Estimates of the air temperature (β) and slope (γ) at the inflection point generally had small standard errors; only two estimates of β and four estimates of γ had confidence intervals that overlapped zero.

Model-predicted weekly water temperatures generally fit the observed relationship between weekly air and water temperature closely (Figures 5-8). At some tributaries (e.g. Seiad Creek, Beaver Creek), the relationship between air and water temperature was approximately linear, with little evidence of a minimum or maximum water temperature over the available range of data. Model-predicted daily water temperatures, estimated with seven-day running averages of daily air temperatures, closely paralleled observed daily water temperatures, capturing both seasonal and short-term changes in temperature at each of the individually- and globally-modeled tributaries (Figures 9-13). The Nash-Sutcliffe statistic exceeded 0.9 for twelve of the individually-modeled tributaries and four of the globally-modeled tributaries (Tables 8 and 9), indicating a generally close correspondence between model-predicted and observed temperatures. The root-mean square error (RMSE) ranged from 0.75 to 1.75 °C and the mean absolute error (MAE) ranged from 0.58 to 1.16 °C among tributaries. The mean error (ME) was close to zero for most of the individually-modeled tributaries, indicating low bias in the model predictions. The mean errors for the globally-modeled tributaries suggested that temperature estimates were moderately biased at some streams. In particular, there was evidence of positive bias at Tom Martin Creek and negative bias at Slate Creek.

Table 7. Mean parameter estimates and standard errors (parentheses) from non-linear regression models of water temperature in Klamath River tributaries. [Parameters are defined as follows: μ, minimum water temperature; α, maximum water temperature; β, air temperature at inflection point; γ, slope at inflection point]

Model	Limb	μ	α	β	γ
Shasta River	rising	-1.69 (1.56)	27.77 (1.01)	9.75 (0.55)	0.14 (0.02)
	falling	-1.01 (1.94)	34.74 (4.63)	16.52 (1.78)	0.11 (0.02)
Beaver Creek	rising	-8.03 (7.86)	63.96 (83.01)	37.22 (37.52)	0.05 (0.04)
	falling	-14.32 (9.63)	27.68 (5.52)	8.13 (3.49)	0.07 (0.03)
Horse Creek	rising	-0.29 (1.13)	19.66 (1.73)	15.11 (0.91)	0.13 (0.02)
	falling	-5.23 (3.81)	19.12 (1.67)	7.70 (2.08)	0.10 (0.02)
Scott River	rising	-2.28 (2.93)	33.89 (6.38)	17.51 (2.26)	0.11 (0.03)
	falling	-0.68 (1.49)	28.75 (2.21)	14.40 (0.79)	0.15 (0.02)
Seiad Creek	rising	-3.36 (15.42)	24.99 (14.57)	13.48 (4.03)	0.09 (0.11)
	falling	1.21 (9.60)	27.92 (17.74)	17.58 (8.37)	0.09 (0.09)
Grider Creek	rising	-1.39 (2.62)	34.66 (16.43)	23.20 (8.29)	0.09 (0.04)
	falling	-19.63 (26.83)	32.48 (15.97)	7.14 (8.96)	0.05 (0.04)
Thompson Creek	rising	3.25 (0.51)	17.03 (0.77)	14.99 (0.52)	0.19 (0.02)
	falling	0.10 (1.01)	16.74 (0.50)	9.71 (0.61)	0.16 (0.02)
Indian Creek	rising	3.33 (0.55)	21.98 (1.97)	16.44 (0.90)	0.22 (0.03)
	falling	-0.58 (1.75)	24.42 (2.03)	13.19 (0.70)	0.14 (0.03)
Elk Creek	rising	2.47 (0.62)	23.76 (1.78)	17.14 (0.77)	0.19 (0.02)
	falling	-2.61 (2.26)	26.52 (3.07)	14.55 (1.00)	0.13 (0.03)
Clear Creek	rising	4.10 (0.36)	21.58 (0.93)	15.93 (0.42)	0.27 (0.03)
	falling	2.44 (0.64)	21.40 (0.70)	13.19 (0.36)	0.24 (0.02)
Dillon Creek	rising	3.22 (0.81)	22.26 (1.27)	15.90 (0.55)	0.23 (0.03)
	falling	2.38 (0.89)	20.80 (0.70)	12.83 (0.44)	0.25 (0.03)
Salmon River	rising	5.11 (0.76)	24.40 (1.55)	16.48 (0.59)	0.27 (0.04)
	falling	2.40 (0.99)	23.02 (0.66)	12.48 (0.43)	0.27 (0.03)
Camp Creek	rising	6.49 (0.76)	17.60 (0.99)	15.21 (0.54)	0.35 (0.09)
	falling	6.41 (1.05)	19.46 (1.48)	15.45 (0.71)	0.27 (0.07)
Bluff Creek	rising	6.10 (0.67)	18.55 (0.95)	14.79 (0.42)	0.35 (0.07)
	falling	3.59 (2.12)	20.58 (1.27)	12.07 (0.93)	0.19 (0.04)
Global	rising	3.48 (0.64)	18.56 (0.79)	14.54 (0.42)	0.19 (0.02)
	falling	-4.67 (4.67)	20.75 (1.69)	8.19 (2.52)	0.11 (0.03)

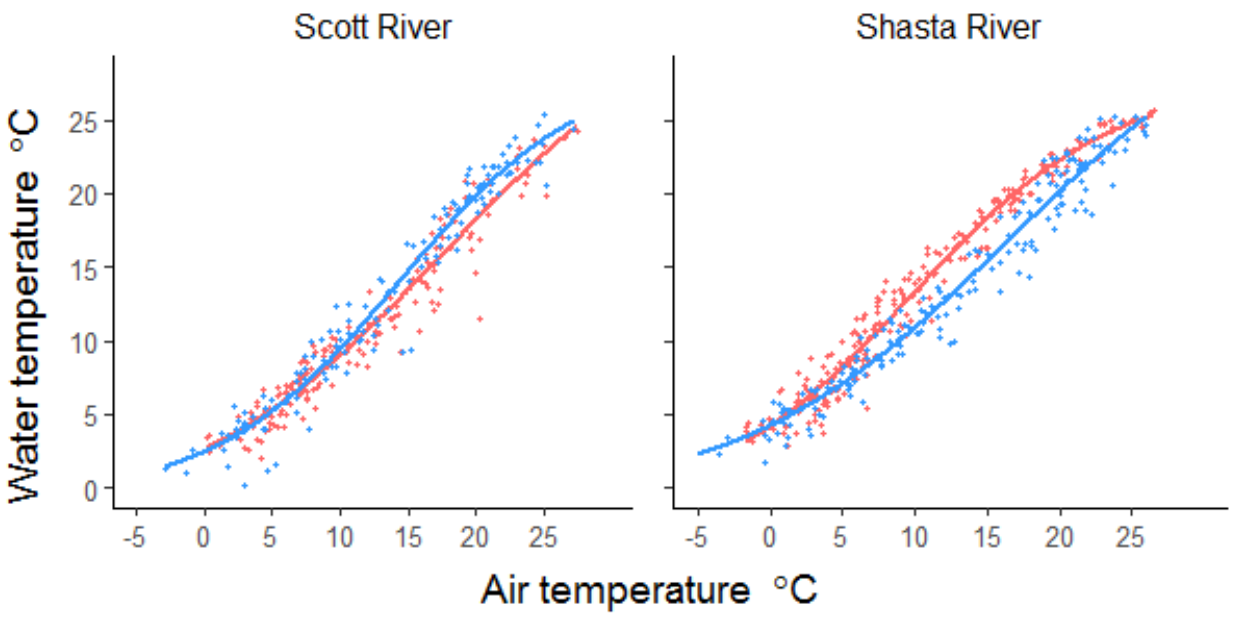

Figure 5. Scatter plots of observed weekly mean water temperature versus observed weekly mean air temperature for the Scott and Shasta Rivers. Predicted values from the non-linear regression model are indicated by separate lines corresponding to the rising (red line) and falling (blue line) limbs of air temperature.

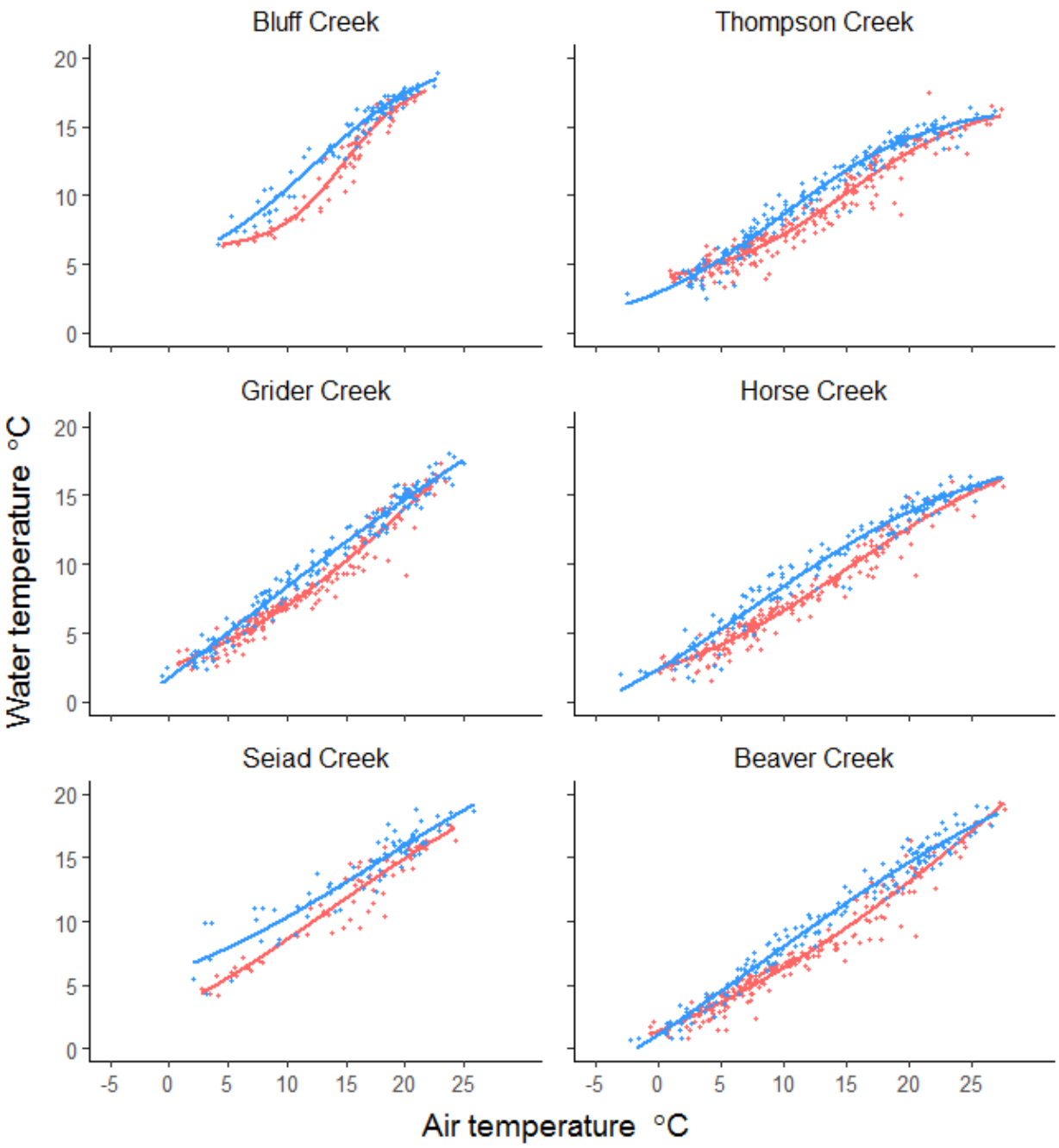

Figure 6. Scatter plots of observed weekly mean water temperature versus observed weekly mean air temperature for six of the individually modeled Klamath River tributaries. Predicted values from the non-linear regression model are indicated by separate lines corresponding to the rising (red line) and falling (blue line) limbs of air temperature.

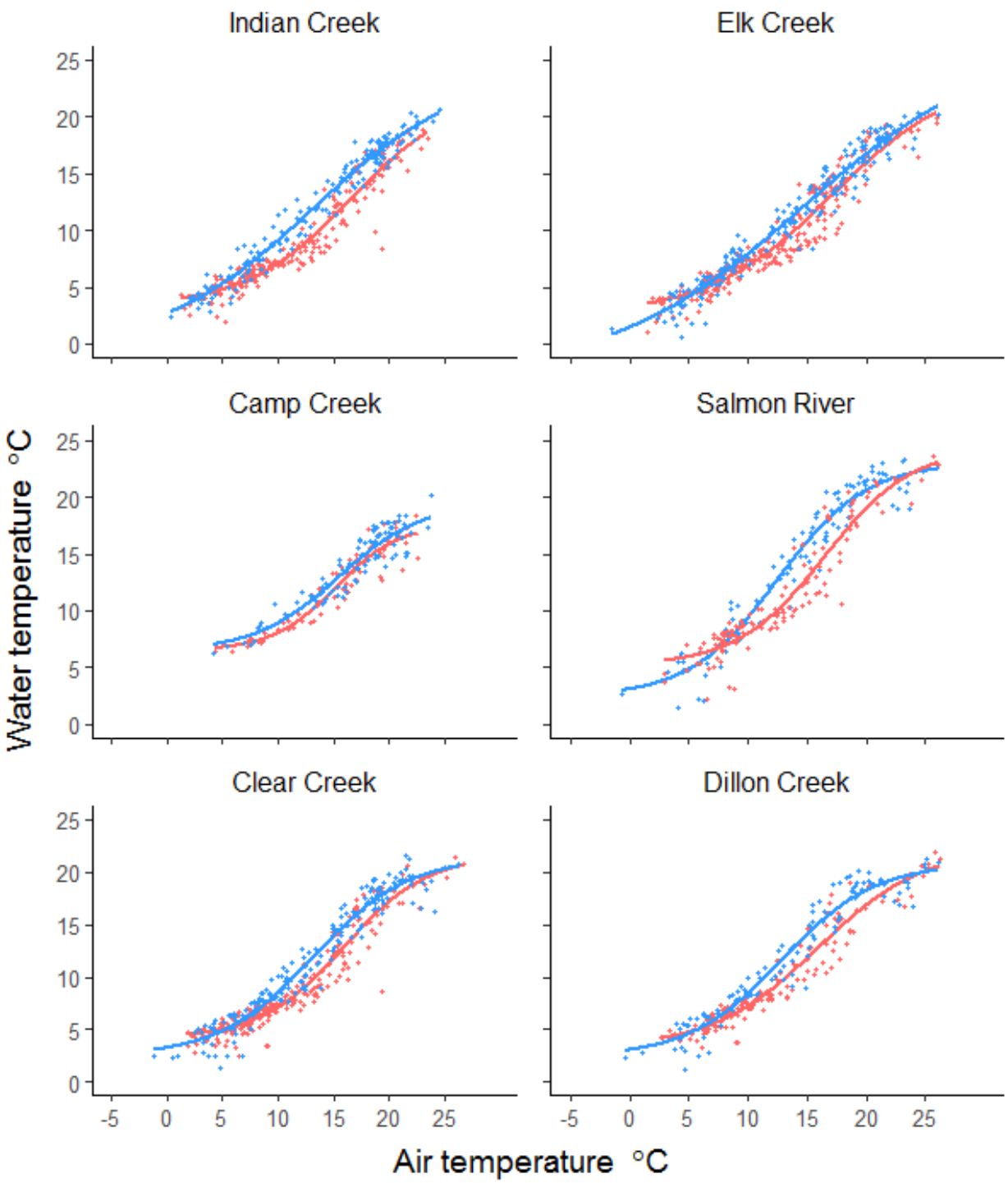

Figure 7. Scatter plots of observed weekly mean water temperature versus observed weekly mean air temperature for six of the individually modeled Klamath River tributaries. Predicted values from the non-linear regression model are indicated by separate lines corresponding to the rising (red line) and falling (blue line) limbs of air temperature.

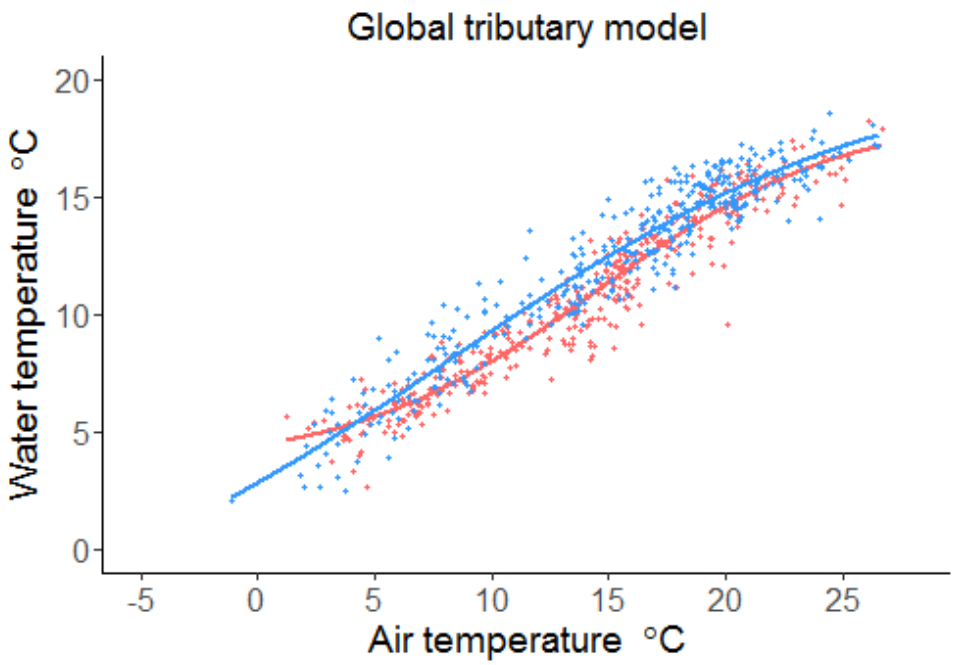

Figure 8. Scatter plot of observed weekly mean water temperature versus observed weekly mean air temperature for six tributaries included in the global model. Predicted values from the global, non-linear regression model are indicated by separate lines corresponding to the rising (red line) and falling (blue line) limbs of air temperature.

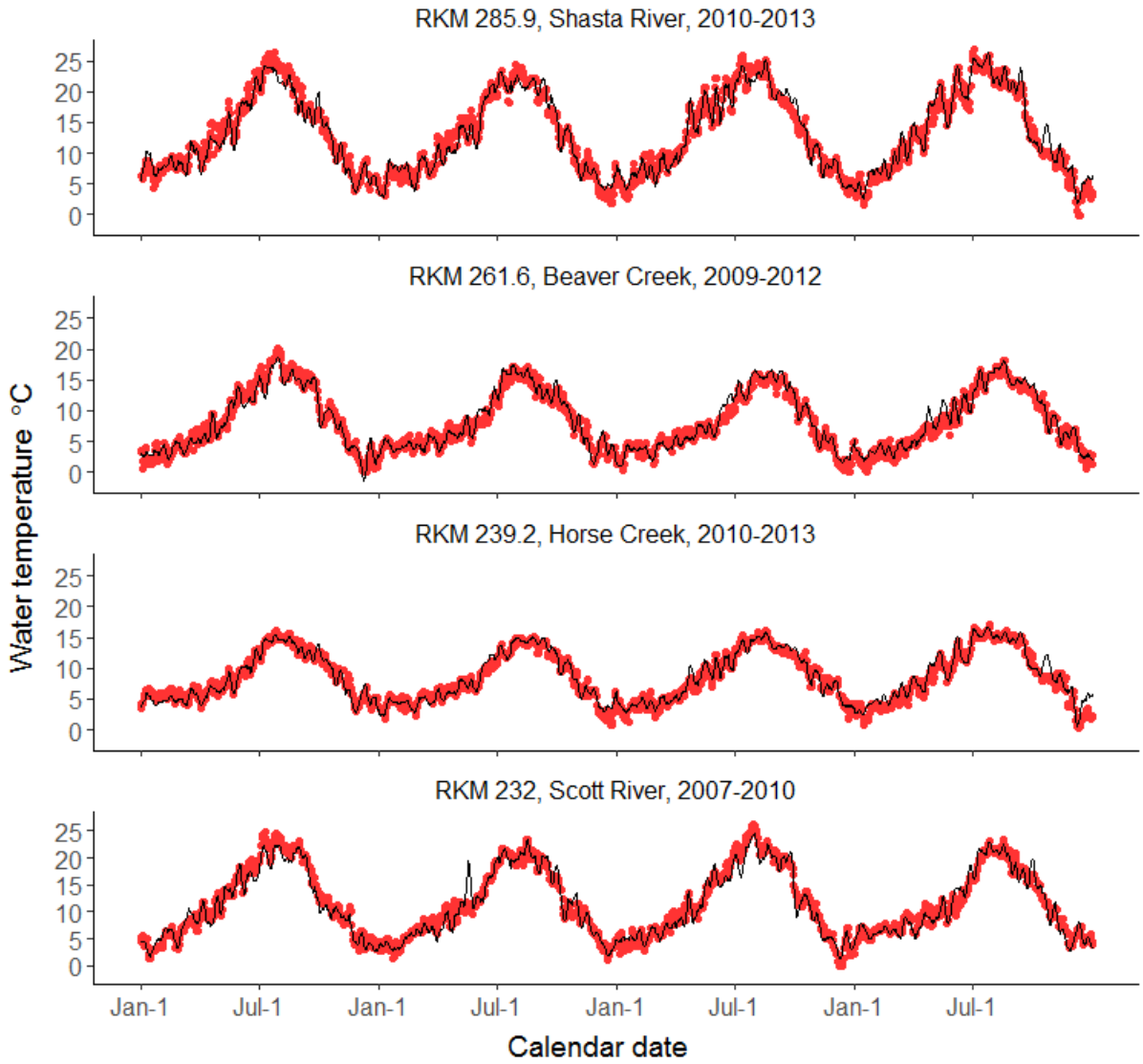

Figure 9. Predicted (solid lines) and observed (red points) daily water temperature during four year periods at four Klamath River tributaries. Daily water temperatures were predicted from seven-day running averages of air temperatures and with coefficients from tributary-specific models. The tributaries are arranged by descending river kilometer (RKM) from top to bottom.

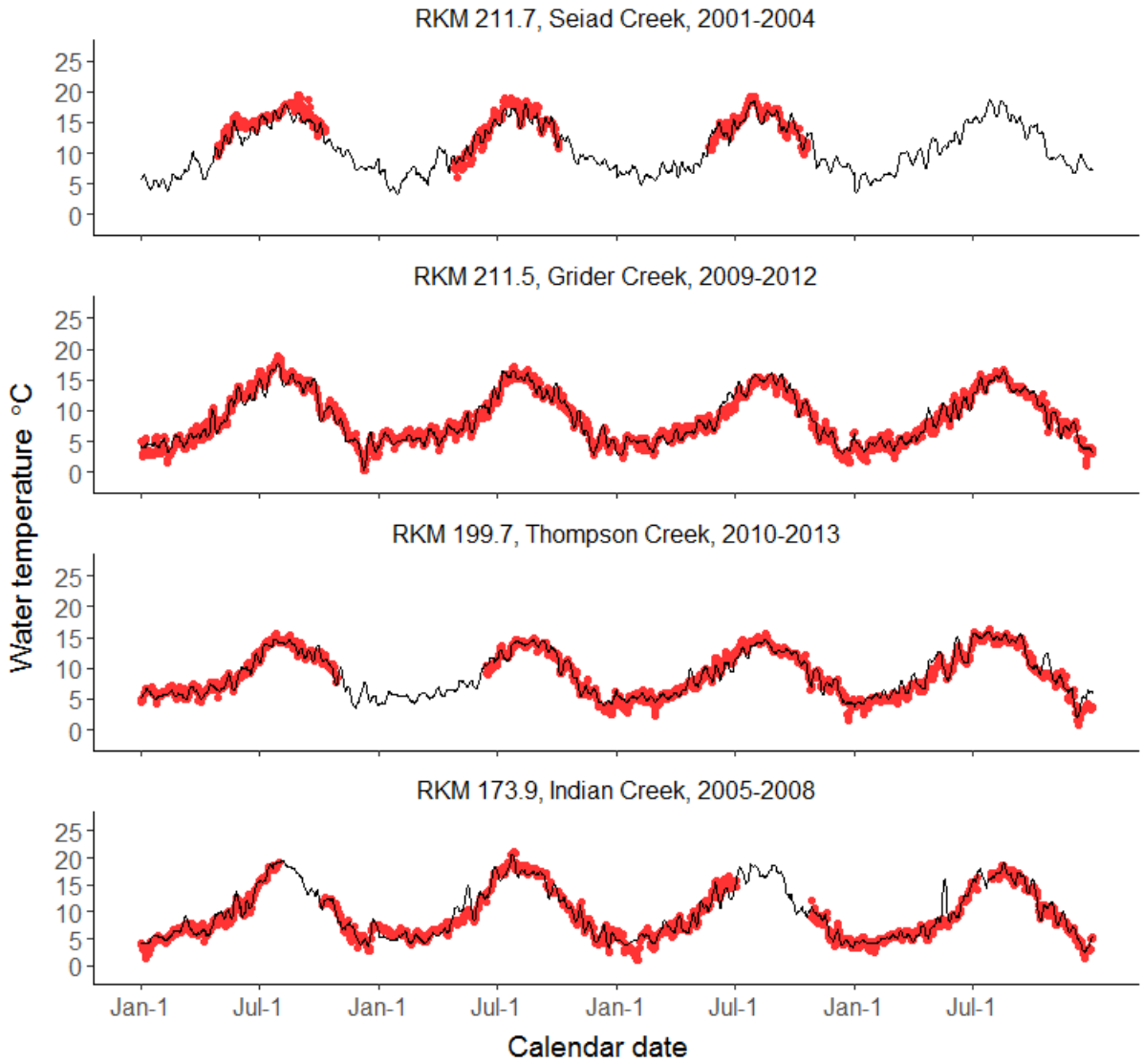

Figure 10. Predicted (solid lines) and observed (red points) daily water temperature during four year periods at four Klamath River tributaries. Daily water temperatures were predicted from seven-day running averages of air temperatures and with coefficients from tributary-specific models. The tributaries are arranged by descending river kilometer (RKM) from top to bottom.

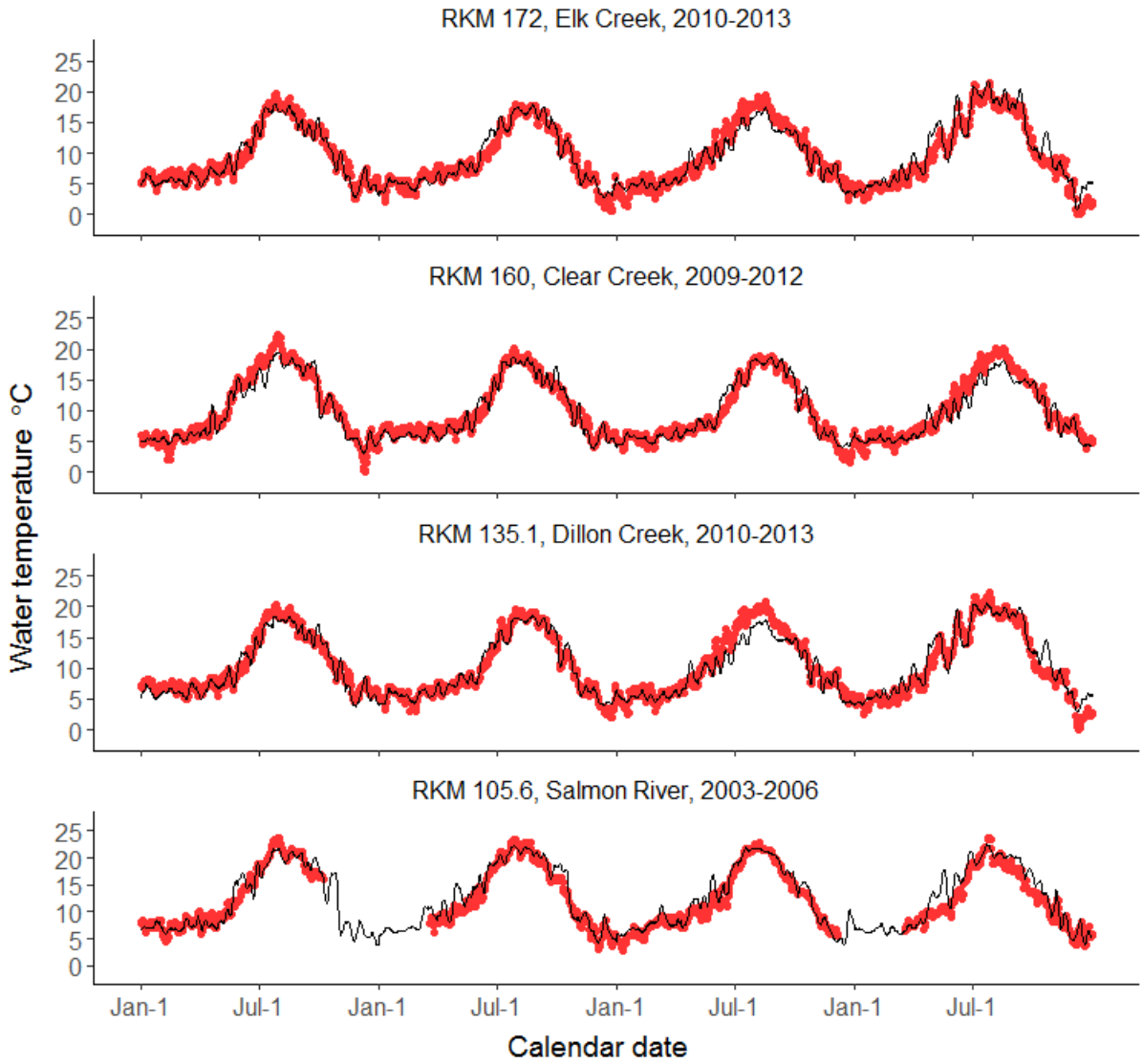

Figure 11. Predicted (solid lines) and observed (red points) daily water temperature during four year periods at four Klamath River tributaries. Daily water temperatures were predicted from seven-day running averages of air temperatures and with coefficients from tributary-specific models. The tributaries are arranged by descending river kilometer (RKM) from top to bottom.

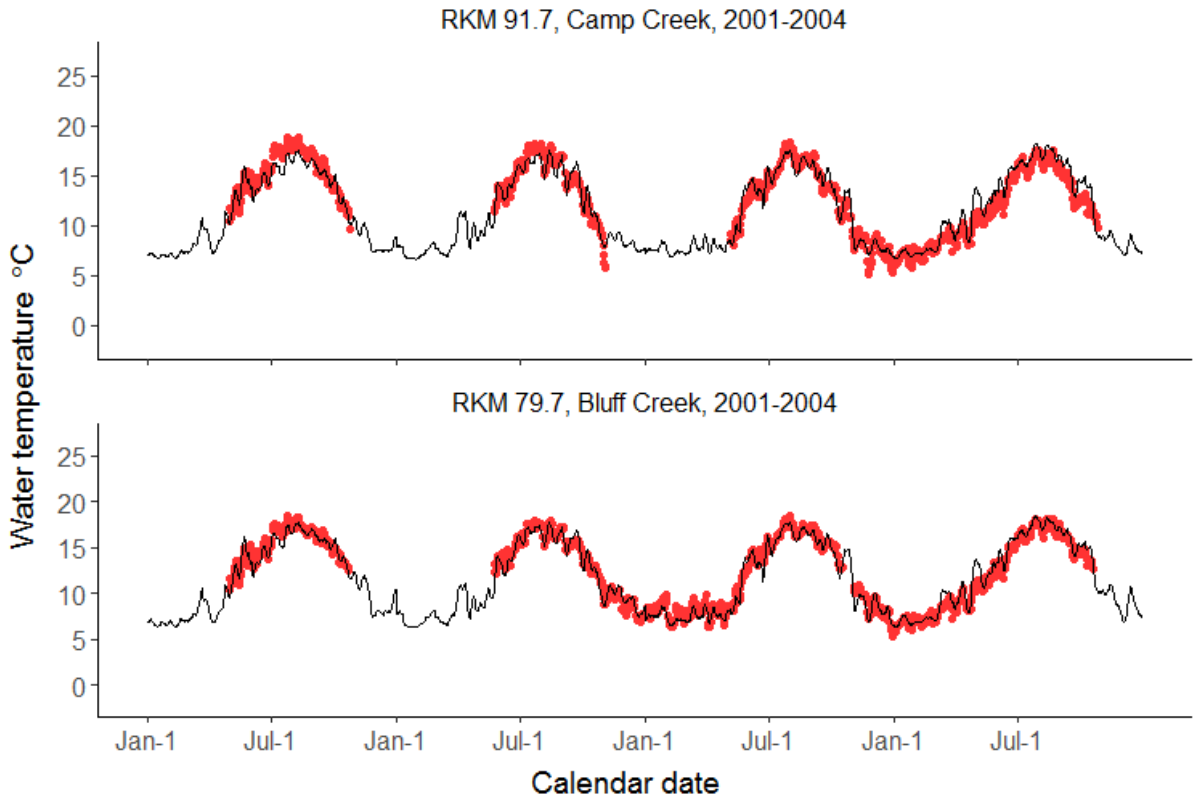

Figure 12. Predicted (solid lines) and observed (red points) daily water temperature during four year periods at two Klamath River tributaries. Daily water temperatures were predicted from seven-day running averages of air temperatures and with coefficients from tributary-specific models. The tributaries are arranged by descending river kilometer (RKM) from top to bottom.

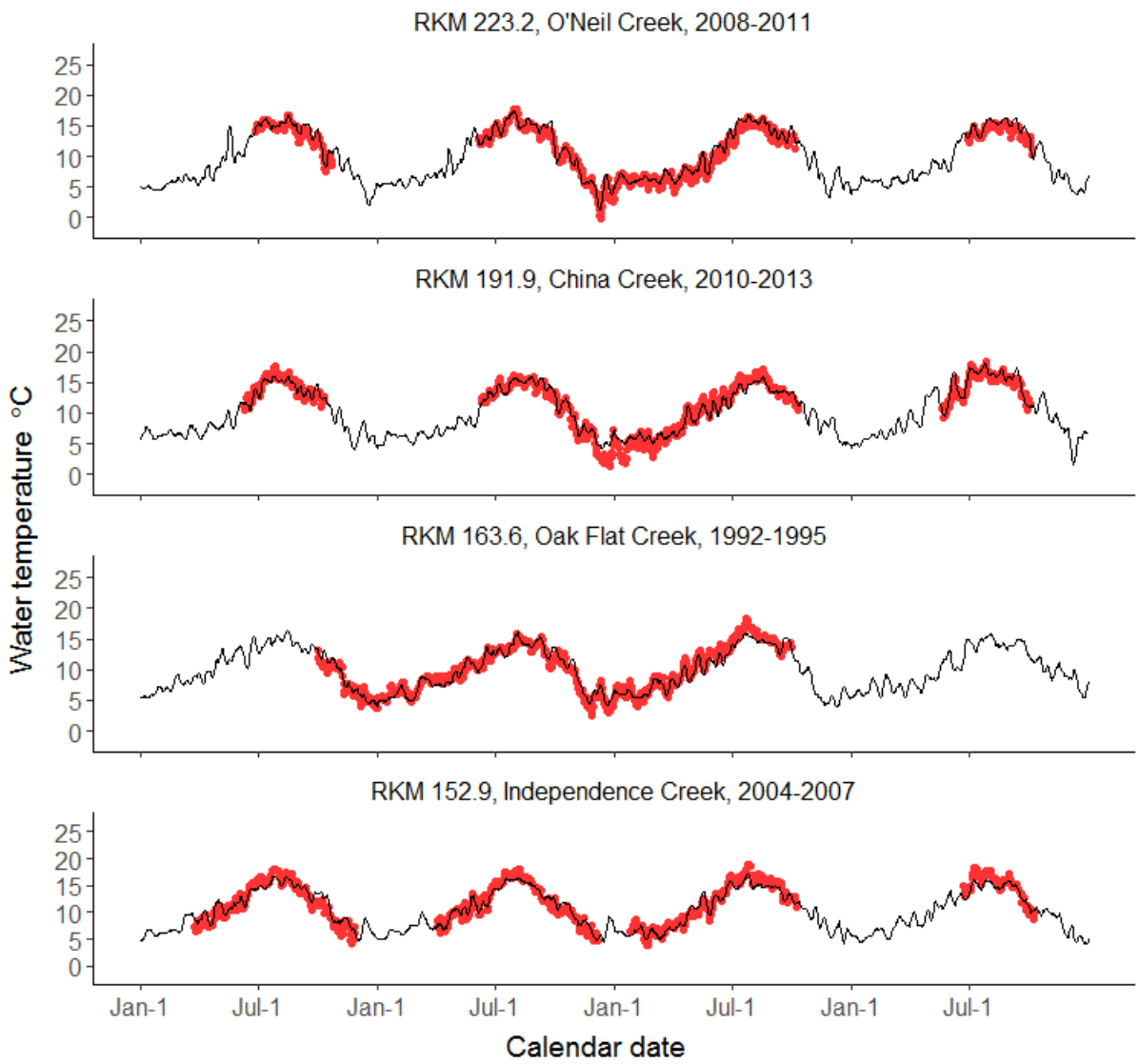

Figure 13. Predicted (solid lines) and observed (red points) daily water temperature during four year periods at four Klamath River tributaries. Daily water temperatures were predicted from seven-day running averages of air temperatures and with coefficients from the global model. The tributaries are arranged by descending river kilometer (RKM) from top to bottom.

We used a cross-validation analysis to evaluate the ability of each model to estimate temperatures outside of the range of data used to fit the model. For tributary-specific models, goodness-of-fit statistics computed from a dataset that included all years (Table 8) were generally close to those computed from the cross-validation analysis and aggregated across years (Table 10), indicating that the tributary-specific models predicted temperature in unobserved years with favorable precision. For the global model, goodness-of-fit statistics computed from the cross-validation analysis and aggregated across streams (Table 11) were favorable, indicating that the global model predicted temperatures in unobserved streams with reasonable precision.

Table 8. Goodness-of-fit statistics for observed and predicted water temperatures at fourteen individually modelled Klamath River tributaries. [Statistics are defined as follows: *n*, number of days of water temperature data; NSS, Nash-Sutcliffe statistic; RMSE, root-mean-square error; ME, mean error; MAE, mean absolute error]

Stream	RKM	*n*	NSS	RMSE	ME	MAE
Shasta River	285.9	2,919	0.955	1.399	0.000	1.099
Beaver Creek	261.5	2,555	0.955	1.059	0.009	0.823
Horse Creek	239.1	2,554	0.947	0.958	0.000	0.737
Scott River	232.1	2,189	0.945	1.526	0.000	1.158
Seiad Creek	211.6	706	0.736	1.174	-0.005	0.895
Grider Creek	211.4	2,554	0.956	0.896	-0.017	0.698
Thompson Creek	199.6	2,936	0.943	0.880	0.010	0.672
Indian Creek	173.9	2,672	0.947	1.146	-0.014	0.870
Elk Creek	172.0	3,284	0.934	1.283	-0.002	1.003
Clear Creek	160.0	2,951	0.937	1.301	-0.008	0.978
Dillon Creek	135.1	1,817	0.930	1.399	-0.002	1.078
Salmon River	105.6	1,648	0.912	1.746	0.744	1.338
Camp Creek	91.6	1,102	0.870	1.208	0.341	0.955
Bluff Creek	79.6	1,228	0.959	0.750	-0.032	0.576

Table 9. Goodness-of-fit statistics for observed and predicted water temperatures at the six tributaries that were used to fit the global model. [Statistics are defined as follows: *n*, number of days of water temperature data; NSS, Nash-Sutcliffe statistic; RMSE, root-mean-square error; ME, mean error; MAE, mean absolute error]

Stream	RKM	*n*	NSS	RMSE	ME	MAE
Tom Martin Creek	231.8	680	0.855	1.391	0.833	1.103
O'Neil Creek	223.2	994	0.951	0.875	0.443	0.684
China Creek	191.9	615	0.940	1.011	0.140	0.788
Oak Flat Creek	163.6	960	0.940	0.898	-0.092	0.729
Independence Creek	152.9	887	0.916	1.067	0.054	0.869
Slate Creek	81.1	914	0.777	1.318	-1.115	1.144

Table 10. Weighted average goodness-of-fit statistics from the cross-validation evaluation of observed and predicted water temperatures at fourteen Klamath River tributaries. [Statistics are defined as follows: *n*, number of days of water temperature data; NSS, Nash-Sutcliffe statistic; RMSE, root-mean-square error; ME, mean error; MAE, mean absolute error]

Stream	RKM	*n*	NSS	RMSE	ME	MAE
Shasta River	285.9	2,919	0.951	1.439	0.006	1.137
Beaver Creek	261.5	2,555	0.941	1.190	-0.080	0.924
Horse Creek	239.1	2,554	0.943	0.990	0.006	0.777
Scott River	232.1	2,189	0.938	1.599	0.024	1.250
Seiad Creek	211.6	706	0.717	1.257	-0.001	0.978
Grider Creek	211.4	2,554	0.952	0.923	-0.003	0.724
Thompson Creek	199.6	2,936	0.931	0.896	0.016	0.698
Indian Creek	173.9	2,672	0.927	1.184	-0.014	0.908
Elk Creek	172.0	3,284	0.923	1.357	0.025	1.079
Clear Creek	160.0	2,951	0.893	1.369	0.021	1.053
Dillon Creek	135.1	1,817	0.910	1.505	0.016	1.188
Salmon River	105.6	1,648	0.841	1.899	0.840	1.550
Camp Creek	91.6	1,102	0.828	1.198	0.181	0.978
Bluff Creek	79.6	1,228	0.893	1.008	0.072	0.781

Table 11. Goodness-of-fit statistics from the cross-validation evaluation of observed and predicted water temperatures at six tributaries that were used to fit the global model. The weighted average of each statistic is listed in bold in the final row. [Statistics are defined as follows: *n*, number of days of water temperature data; NSS, Nash-Sutcliffe statistic; RMSE, root-mean-square error; ME, mean error; MAE, mean absolute error]

Stream	RKM	*n*	NSS	RMSE	ME	MAE
Tom Martin Creek	231.83	680	0.828	1.518	0.941	1.229
O'Neil Creek	223.19	994	0.937	0.995	0.633	0.788
China Creek	191.91	615	0.932	1.075	0.159	0.830
Oak Flat Creek	163.61	960	0.934	0.937	-0.115	0.764
Independence Creek	152.90	887	0.908	1.119	0.041	0.919
Slate Creek	81.14	914	0.644	1.664	-1.488	1.497
			0.863	**1.207**	**-0.014**	**0.999**

Discharge estimation

Daily discharge rates were estimated from 1990-2015 at 75 Klamath River tributaries, and the predictive precision of estimates was evaluated with data from Indian Creek. Estimated daily water discharge closely paralleled observed daily discharge at Indian Creek (Figures 14 and 15). The estimates were consistently effective in capturing seasonal and short-term variability in discharge, as well as the magnitude of discharge, over a 24-year period.

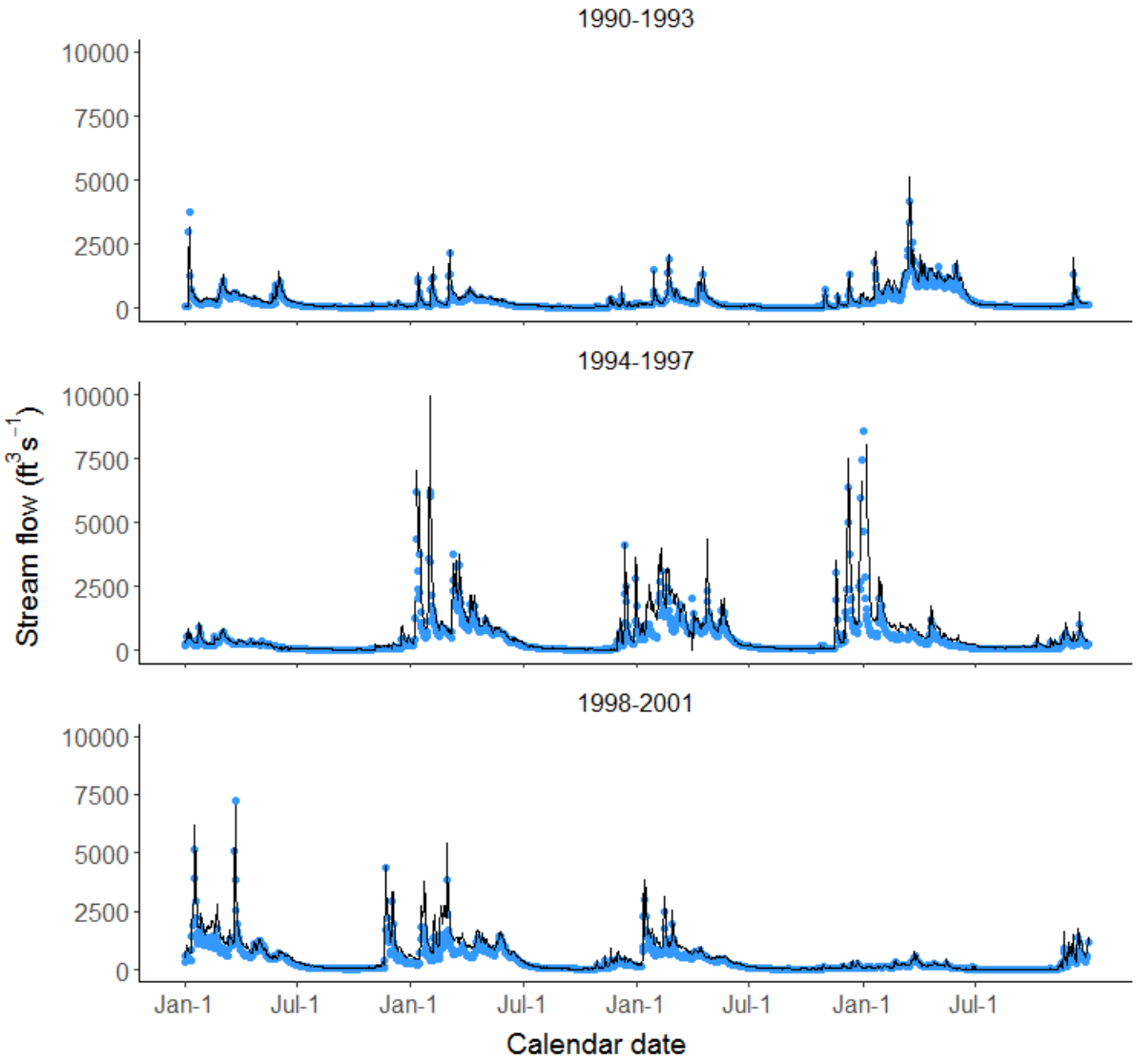

Figure 14. Estimated (solid lines) and observed (blue points) daily stream discharge at Indian Creek from 1990-2001.

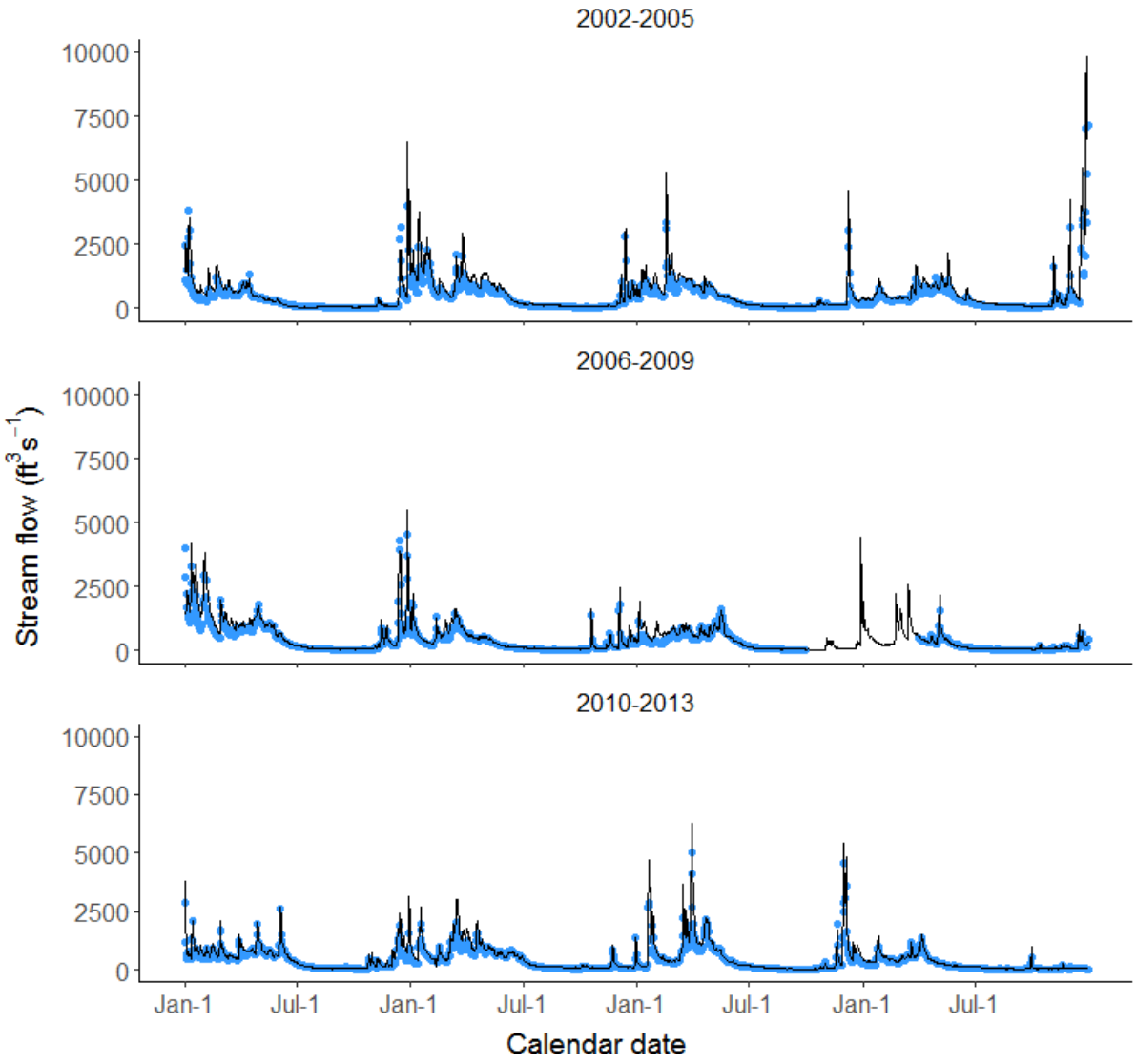

Figure 15. Estimated (solid lines) and observed (blue points) daily stream discharge at Indian Creek from 2002-2013.

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