Lower Tuolumne River Water Temperature Modeling Study

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Table of Contents

List of Tables

List of Figures

List of Appendices

1 BACKGROUND

The Federal Energy Regulatory Commission (FERC) issued a July 16, 2009 order (128 FERC ¶ 61,035) wherein Ordering paragraph (F) directed the Turlock Irrigation District (TID) and the Modesto Irrigation District (MID) (the Districts) to develop a water temperature model in conjunction with instream flow studies of the lower Tuolumne River. As described by the July 16, 2009 Order, the goal of the temperature modeling study is "to determine the downstream extent of thermally suitable habitat to protect summer juvenile *Oncorhynchus mykiss*, rearing under various flow conditions and to determine flows necessary to maintain water temperatures at or below 68 degrees Fahrenheit from La Grange Dam to Roberts Ferry Bridge." In response to the July 16, 2009 Order, the Districts proposed using a recently completed HEC-5Q water temperature model that was developed for the Tuolumne River and other tributaries of the San Joaquin River with CALFED funding (RMA 2008).

A Draft Lower Tuolumne River Water Temperature Modeling Study Plan was distributed for Agency review on September 3, 2009. The Districts submitted the Final Study Plan (Stillwater Sciences 2009a) to FERC on October 14, 2009 along with documentation of Agency consultation, copies of comments and recommendations on the Draft Study Plan, and descriptions of how the agencies' comments and recommendations are accommodated by the Final Study Plan. Along with examination of the flow vs. temperature relationship for the benefit of *O. mykiss*, the Final Study Plan included scenarios intended to determine flows necessary to maintain seasonal water temperature objectives for specific life stages of both *O. mykiss* and Chinook salmon (*O. tshawytscha*) at various locations in the lower Tuolumne River. Additionally, the water temperature model predictions developed in this study will be used in conjunction with instream flow incremental methodology (IFIM) estimates of weighted usable area (WUA) for the benefit of these species, as described in a separate study plan (Stillwater Sciences 2009b).

In its May 12, 2010 Order (131 FERC ¶ 62,110) on Modifying and Approving Instream Flow and Water Temperature Model Study Plans, FERC approved the October 2009 Final Study Plan and provided for the Districts to file, for FERC approval, a request for extension of time as may be required by the timing of the May 12, 2010 Order. The Districts sent proposed revised schedules to the fishery agencies on May 28, 2010 and following a 30-day comment and review period, submitted this extension request to FERC on June 30, 2010. The FERC approved the extension request on July 21, 2010 and the temperature model validation was completed in August 2010. Using the validated temperature model, initial scenario evaluation was conducted in August and September 2010. A progress report was filed with FERC on November 9, 2010, followed by a draft report for Districts review by mid-November, a revised draft submitted for Agency review on December 10, 2010. Following a comment period for Agency review from December 11, 2010 to January 10, 2011, this report represents the final report for submission to the FERC on March 12, 2011.

2 APPROACH AND STUDY QUESTIONS

The goal of the FERC-ordered water temperature modeling study is to test a series of flow scenarios to determine the flows needed to maintain specified water temperatures at particular river locations and seasonal windows relevant to life history requirements of California Central Valley steelhead and fall–run Chinook salmon. The Final Study Plan outlined an approach in which the existing HEC-5Q water temperature model would be validated by developing model predictions for flow and meteorological data corresponding to periods of measurement of *in situ* water temperature data not used in the initial model calibration.

To examine potential water temperature management scenarios for the benefit of lower Tuolumne River salmonids, two primary study questions were included in the July 16, 2009 Order:

1. What flows are required to maintain summer water temperatures (MWAT[1]) of 20ºC (68°F) or less from La Grange Dam downstream to Roberts Ferry Bridge at river mile (RM) 39.5?
2. What is the relationship between flow and water temperature at various time periods during the year in specified reaches of the lower Tuolumne River?

Although peak air and water temperatures are typically during July of most summers, Question 1 was assessed from June through September for the period of record. In addition to Study Question 1 above, four additional scenarios corresponding to Study Question 2 were recommended by the Agencies in their review of the Draft Study Plan for the protection of various life stages of *O. mykiss* and fall-run Chinook salmon.

3. What flows are required to maintain a summer MWAT of 18ºC (64.4ºF) downstream of La Grange Dam to Roberts Ferry Bridge (RM 39.5)?
4. What flows are required to maintain a MWAT of 18ºC (64.4ºF) downstream of La Grange Dam to the confluence with the San Joaquin River (RM 0) from October 15 to December 1?
5. What flows are required to maintain a MWAT of 13ºC (55.4ºF) downstream of La Grange Dam to Roberts Ferry Bridge (RM 39.5) from October 15, to February 15?
6. What flows are required to maintain a MWAT of 15ºC (59.0ºF) downstream of La Grange Dam to the confluence with the San Joaquin River (RM 0) from March 20 to May 15?

In all, five scenarios were evaluated using the validated temperature model and the period of record meteorology included with the model (1980–2008)(AD Consultants et al 2009) in an effort to determine flows required to maintain the target temperatures above under normal and extreme meteorology. Because simulations were run at similar flows in all years, the highest flow that met the target temperatures above was used to represent extreme meteorology (i.e., 26 of 27 years, or approximately 95% exceedance).

Additional alternative scenarios (i.e., temperature, location, timing, etc.) may be evaluated in the future, following the completion of this study, drawing upon findings from the literature or field observations, such as information provided to FERC by the Districts, the City and County of San Francisco (CCSF), and the fishery agencies. For example, IFIM estimates of WUA of suitable habitat meeting particular life-stage-specific criteria (i.e., depth, velocity, and substrate) will be developed in a separate IFIM Study (Stillwater Sciences 2009b), with these results superimposed upon areas meeting particular water temperature criteria to create an estimate of effective WUA, or EWUA.

[1] The maximum weekly average temperature, or MWAT, is calculated as the maximum 7-day running average of the daily mean temperatures for the period of record or a time period of concern (e.g., a salmonid life stage) (Brungs and Jones 1977).

3 STUDY AREA

As shown in Figure 1, the study area extends from La Grange Dam (RM 52.2) downstream to the San Joaquin River confluence (RM 0.0). The upper reach from La Grange to Roberts Ferry Bridge (RM 39.5) specified in the Study Question 1 of the July 16, 2009 Order represents the upstream to downstream extent of most summer *O. mykiss* observations in past snorkel surveys (TID/MID 2009). It also contains the Dominant Spawning Reach (down to RM 46.6) and the Dredger Tailing Reach (down to RM 40.3), which represents the majority of historical Chinook salmon spawning activity (McBain and Trush 2000). In order to examine water temperature objectives for upmigrating and outmigrating life stages of Chinook salmon (Scenarios 2 and 4, respectively), the study reach extends from La Grange Dam to the confluence of the San Joaquin River (RM 0.0).

4 METHODS

The units of measure used to report water temperature in the text follow the convention used by the Agencies in their study plan recommendations. For example, goodness of fit metrics and error statistics refer to degrees Celsius (°C). Results of water temperature model simulations are presented in °C, followed by conversions to degrees Fahrenheit (°F) in parentheses. Because the HEC-5Q model output provides water temperatures in °F, some analyses are presented in °F, only.

4.1 Validate Existing HEC-5Q Water Temperature Model

Documentation of the existing HEC-5Q water temperature model as provided in the AD Consultants et al. (2009) "Calibration Report", as well as model input files downloaded from the RMA (2008) website, were used to evaluate the model calibration and uncertainty in modeled water temperature predictions. The HEC-5Q model was then validated using water temperature data not used in the original model calibration, as recorded by District thermographs at various locations in the lower Tuolumne River during 1996–2009.

Water temperatures have been recorded continuously by the Districts under their real time monitoring (RTM) program at various locations in the lower Tuolumne River since 1986 (TID/MID 2005). In addition the California Department of Fish and Game (CDFG) has deployed thermographs in the lower Tuolumne River (called "HWMS") at nearby locations since 1999 (Table 4-1). The periods of record for HWMS data used in the HEC-5Q model calibration are shown in Figure 2 along with available RTM data between 1999–2008.

Table 4-1. Period of record summary for hourly water temperature data used to assess HEC-5Q model accuracy.

River mile	TID/MID location	HWMS location(1)	Hourly data period of record	
51.8	La Grange RTM site(2)		11/14/2001	Present
51.6		Riffle A1	7/27/2001	12/31/2007
50.7	Riffle A7		11/14/2001	Present
49.7		Riffle C1	3/1/2002	12/31/2007
49.1	Riffle 3B		12/10/1997	Present
47.5		Basso Bridge(2)	3/1/2002	12/31/2007
45.5	Riffle 13B		11/14/2001	Present
43.2		Riffle I2	12/19/2001	12/31/2007
43.3	Riffle 19		12/10/1997	5/27/2004
42.9	Riffle 21		5/27/2004	Present
42.6		Riffle K1(2)	3/1/2002	12/31/2007
39.5	Roberts Ferry Bridge		8/11/1998	Present
38.0		7-11 Gravel(2)	3/1/2002	12/31/2007
36.5	Ruddy (Santa Fe) Gravel	Santa Fe Gravel	12/10/1997	Present
35.0		Riffle Q3	5/31/2002	12/31/2007
31.0		Hickman Bridge(2)	7/15/2002	12/31/2007
26.0		Fox Grove	9/9/2005	12/31/2007
23.6	Hughson WWTP		12/10/1997	Present
19.0		Mitchell Road	8/12/2005	12/31/2007
15.9		Modesto(2)	8/12/2005	12/31/2007
12.0		Carpenter Road	8/12/2005	12/31/2007
3.5	Shiloh	Shiloh(2)(3)	12/11/1997	Present

[1] Data included in HEC-5Q "HWMS" file distribution by RMA (2008) and AD Consultants.
[2] Data used in initial HEC-5Q model calibration.
[3] CDFG HWMS and TID/MID RTM thermograph data at the Ruddy/Santa Fe Gravel plant location (RM 36.5) and at Shiloh Road (RM 3.5) are identical.

As recommended by the Agencies, model performance was assessed using the following temperature modeling goodness of fit metrics, adapted from Theurer et al. (1984), using both 6-hr averaged (minimum time-step of the HEC-5Q model) and daily averaged thermograph data:

- Maximize the correlation coefficient ($R^2 \leq 1.0$) between modeled and observed water temperatures at individual thermograph locations, as well as across all locations not used in the original calibration data set.
- Determine the fraction of observed temperatures deviating from modeled temperatures by more than 0.5°C (0.9°F), 1°C (1.8°F), and 1.5°C (2.7°F)
- Determine any trends in the residual errors (observed minus modeled) either spatially (across several locations) or temporally (at individual locations).

Goodness of fit metrics and other summary statistics and graphics used for model validation were generated using the "R" statistical software package (Bowman and Azzalini 1997). If the goodness of fit results indicated large errors between observed and predicted temperatures, updated model uncertainty estimates could be developed for particular locations or times of year.

4.2 Scenario Development and Model Simulations

The current FERC (1996) flow schedules and the actual flow releases during the 1996–2009 periods were simulated as part of the model validation exercise. The validated HEC-5Q model was then used to predict conditions relating directly to the initial scenario included in the July 16, 2009 FERC Order (see Section 2, Study Question 1), as well as to determine the general relationship between flow and temperature in the lower Tuolumne River (Study Question 2). The flow and temperature relationships for specific reaches and times of year were addressed by four additional scenarios corresponding to Study Questions 3–6 (see Section 2) were included as recommended by the Agencies for the protection of various life stages of California Central Valley steelhead and fall–run Chinook salmon. The HEC-5Q model was used to determine the downstream extent of suitable water temperatures for these key species and life stages under normal and extreme meteorology as provided in the Calibration Report for the years 1980–2008.

5 RESULTS

5.1 Validation of Initial HEC-5Q Model Calibration

The Calibration Report provided with the model distribution shows that the modeled temperatures are consistently close to the temperatures actually observed at the seven “calibration” locations for the period or record shown in Figure 2. This remains true for all 16 HWMS thermograph locations provided as background data in the model distribution (Figure 3). Detailed plots showing modeled and measured water temperatures for these locations are provided in Appendix A

The Calibration Report uses the r-squared (r^2) statistic for the linear regression of modeled versus observed values, and this statistic was also calculated for the HWMS thermograph locations, using mean daily water temperatures (Table 5-1). Table 5-1 shows the r^2 statistic is considerably lower for thermograph locations at up-stream sites Riffle A1 and Riffle C1 than for downstream locations. On closer examination, this is a consequence of the fact that the proximity to Don Pedro Dam means a much smaller range of temperatures are represented at upstream sites on an annual basis than for downstream locations. As can be seen in Figure 3, the modeled-observed pairs are clustered around the 1:1 (modeled:observed) diagonal to a broadly similar extent at all sites, meaning the magnitude of the error is similar at all locations. Ordinarily one would also report the “p-value” for the regression fit, but in all cases this was numerically indistinguishable from 0 by the algorithm used in the R software ($p<2.2e-16$).

Table 5-1. Comparison of modeled and observed daily mean water temperatures at the CDFG (HWMS) thermograph locations.

Site	Days	r²	Model-observed (°C)			Percent coverage [1]		
			mean	stdev	rms	±0.5°C	±1°C	±1.5°C
Riffle A1	1,553	0.67	0.14	0.49	0.52	64%	96%	100%
Riffle C1	1,486	0.87	-0.18	0.55	0.58	64%	90%	100%
Basso Bridge	1,532	0.95	-0.07	0.54	0.54	66%	91%	100%
Riffle I2	1,544	0.98	-0.21	0.56	0.59	59%	91%	99%
Riffle K1	1,787	0.98	-0.07	0.58	0.59	63%	92%	99%
7-11 Gravel	1,517	0.99	-0.17	0.55	0.57	64%	92%	98%
Santa Fe Gravel	1,458	0.98	-0.32	0.64	0.72	56%	84%	95%
Riffle Q3	935	0.99	-0.22	0.56	0.60	61%	91%	99%
Hickman Bridge	1,340	0.99	-0.36	0.56	0.67	54%	87%	98%
Fox Grove	700	0.98	-0.84	0.56	1.01	27%	68%	87%
Hughson WWTP	2,562	0.99	-0.67	0.64	0.93	35%	72%	90%
Mitchell Road	490	0.99	-0.69	0.41	0.80	36%	79%	97%
Modesto	1,861	0.98	0.03	1.12	1.12	36%	62%	82%
Carpenter Road	222	0.98	-0.08	0.89	0.89	44%	74%	91%
Grayson	183	0.97	0.01	0.83	0.82	49%	76%	91%
Shiloh	2,539	0.97	0.17	1.28	1.29	32%	58%	75%

[1] Coverage refers to the percentage of the modeled time period during which model predictions are within a particular temperature range above or below the observed temperature for that date and time.

Another model validation approach is to consider how the differences (modeled minus observed water temperature) are distributed. Table 5-1 shows the mean and standard deviation of this difference, as well as the root-mean-square (rms) error, and Figures 4 and 5 show various order statistics (i.e., deviations by quartiles). The largest errors shown in Table 5-1 are in the vicinity of the Hughson WWTP and Mitchell Road (0.67°C and 0.87°C, respectively), which were not shown at the Hickman Bridge and Modesto sites used in the Calibration Report. The last three columns of Table 5-1 show "Percent Coverage", defined as the fraction of time that the temperatures predicted by the model are within some deviation from the observed value. For example, the Percent Coverage at Riffle A1 is 96%, showing that the modeled daily mean temperature was within 1°C of the observed value for 96% of the time period simulated.

Table 5-2 shows similar results to those above, but the 6-hour interval data results in slightly larger (model minus observed) error statistics and lower model fit (r^2 and percent coverage) statistics. However, this should be expected based upon the shorter averaging period of the data.

Table 5-2. Comparison of modeled and observed instantaneous water temperatures (6-hour intervals) at the CDFG (HWMS) thermograph locations.

Site	Intervals	r^2	Model-observed (°C)			Percent coverage (1)		
			mean	stdev	rms	±0.5°C	±1°C	±1.5°C
Riffle A1	6,233	0.63	0.14	0.59	0.61	61%	91%	99%
Riffle C1	5,982	0.84	-0.20	0.66	0.69	56%	86%	97%
Basso Bridge	6,144	0.85	-0.08	1.02	1.03	53%	82%	90%
Riffle I2	6,182	0.95	-0.21	0.88	0.91	43%	77%	92%
Riffle K1	7,157	0.97	-0.08	0.80	0.81	49%	81%	94%
7-11 Gravel	6,077	0.97	-0.18	0.92	0.94	44%	78%	91%
Santa Fe Gravel	5,837	0.98	-0.32	0.74	0.81	51%	82%	93%
Riffle Q3	3,750	0.99	-0.23	0.64	0.68	56%	87%	97%
Hickman Bridge	5,367	0.99	-0.37	0.64	0.74	51%	82%	95%
Fox Grove	2,810	0.96	-0.85	0.72	1.11	32%	62%	84%
Hughson WWTP	10,262	0.98	-0.67	0.75	1.01	33%	66%	87%
Mitchell Road	1,968	0.98	-0.69	0.53	0.87	35%	73%	93%
Modesto	7,482	0.97	0.01	1.21	1.21	33%	59%	78%
Carpenter Road	899	0.97	-0.08	0.93	0.93	42%	71%	90%
Grayson	746	0.96	0.00	0.94	0.94	41%	72%	89%
Shiloh	10,178	0.96	0.16	1.35	1.36	30%	56%	73%

[1] Coverage refers to the percentage of the modeled time period during which model predictions are within a particular temperature range above or below the observed temperature for that date and time.

Although the overall model fit appears to match the Calibration Report, examination of the time series of observed HWMS thermograph data and temperatures predicted by the HEC-5Q model suggests the model tends to under-predict temperatures in the reach immediately downstream of La Grange Dam. The model also under-predicts temperatures between Fox Grove (RM 26) and Mitchell Road (RM 19) and over-predicts temperatures downstream of Modesto (RM 15.9). Figure 4 shows the median deviation of model-predicted temperatures from observed HWMS temperatures is generally within ±1°F on an annual basis but is most pronounced during June, when this discrepancy increases to ±2°F and above. As discussed below, extending the comparison to the TID/MID RTM thermograph period of record reveals that this apparent discrepancy is related to the water year types and meteorological conditions represented in the two datasets (Table 4-1).

5.2 Validation of HEC-5Q Model Against Data Not Used in the Initial Calibration

Table 4-1 shows there are a number of thermograph locations maintained by TID/MID under the Districts' RTM program covering portions of the 1999–2007 calibration period. These data provide an opportunity to evaluate model performance using data that have not contributed, even indirectly, to model calibration.

Thermographs associated with the RTM program are operated primarily in connection with river-wide monitoring for the benefit of Chinook salmon and *O. mykiss*, and consequently are concentrated in approximately the upper third of the lower Tuolumne River. The only stations occupied by the RTM program downstream of RM 25, at the Hughson Waste Water Treatment Plant (RM 23.6) and Shiloh Road (RM 3.5), are also included in the HWMS dataset. The RTM stations therefore provide less extensive geographical coverage in the lower portion of the river than do the HWMS stations. On the other hand, the RTM stations generally provide longer periods of record: in particular, the HWMS stations have no data for the upper half of the river before June 15, 2001 or between December 18, 2002 and July 21, 2004 (Figure 2).

Using available RTM data from 1999–2007 (Figure 2) the overall model fit shown in Table 5-3, as measured by r-squared, rms error, and the percent coverage statistics for mean daily temperature appears similar to the HWMS data summarized in Table 5-1. Generally, the model predicts observed water temperatures within 1–1.5°C, but under-predicts water temperatures for particular locations and times of year. Table 5-4 shows comparisons based on 6-hour interval data are similar to the corresponding comparisons between the daily and 6-hour data shown for the HWMS data in Tables 5-1 and 5-2.

Table 5-3. Comparison of modeled and daily mean water temperatures at the TID/MID (RTM) thermograph locations.

Site	Days	r^2	Model-observed (°C)			Percent coverage [(1)]		
			mean	stdev	rms	±0.5°C	±1°C	±1.5°C
La Grange RTM site	2,239	0.58	0.43	0.86	0.96	51%	77%	86%
Riffle A7	2,030	0.76	0.40	0.91	0.99	50%	73%	88%
Riffle 3B	2,497	0.95	0.54	0.58	0.79	43%	77%	96%
Riffle 13B	2,239	0.98	0.33	0.64	0.72	54%	84%	96%
Riffle 19	1,973	0.99	0.12	0.63	0.64	61%	88%	97%
Riffle 21	986	0.98	0.26	0.63	0.68	53%	88%	97%
Roberts Ferry Bridge	3,076	0.99	0.18	0.62	0.64	57%	89%	98%
Ruddy Gravel	3,287	0.99	0.22	0.68	0.72	56%	84%	95%
Fox Grove	179	0.98	-0.68	0.73	1.00	27%	76%	91%
Hughson WWTP	3,001	0.99	-0.59	0.68	0.91	40%	75%	91%
Shiloh Bridge	2,804	0.96	0.22	1.32	1.33	31%	55%	73%

[1] Coverage refers to the percentage of the modeled time period during which model predictions are within a particular temperature range above or below the observed temperature for that date and time.

Table 5-4. Comparison of modeled and observed instantaneous water temperatures (6-hour intervals) at the TID/MID (RTM) thermograph locations.

Site	Intervals	r^2	Model-observed (°C)			Percent coverage [(1)]		
			mean	stdev	rms	±0.5°C	±1°C	±1.5°C
La Grange RTM site	8,949	0.59	0.43	0.90	1.00	51%	75%	86%
Riffle A7	8,109	0.78	0.40	0.97	1.05	48%	74%	87%
Riffle 3B	9,973	0.94	0.54	0.74	0.91	46%	76%	90%
Riffle 13B	8,948	0.95	0.33	0.88	0.94	54%	78%	88%
Riffle 19	7,878	0.97	0.11	0.87	0.88	44%	76%	92%
Riffle 21	3,939	0.97	0.25	0.85	0.89	40%	73%	92%
Roberts Ferry Bridge	12,301	0.98	0.17	0.81	0.82	47%	79%	93%
Ruddy Gravel	13,129	0.98	0.23	0.79	0.82	50%	80%	92%
Fox Grove	717	0.82	-0.74	1.98	2.12	30%	57%	79%
Hughson WWTP	11,982	0.98	-0.59	0.82	1.01	37%	69%	88%
Shiloh Bridge	11,195	0.96	0.21	1.39	1.40	29%	53%	71%

[1] Coverage refers to the percentage of the modeled time period during which model predictions are within a particular temperature range above or below the observed temperature for that date and time.

Detailed plots showing modeled and measured water temperatures for the RTM locations (Appendix B) indicate that the model may systematically over-predict water temperature in the upper river in June by 1–2°F (Figure 5). However, this is the opposite of the results of the comparison using the HWMS data which suggest that the model may systematically under-predict water temperature in the upper river in June (Figure 4). As discussed further below, this apparent discrepancy is explained by differences in the period-of-record of the two data sets (Table 4-1).

Appendix C provides direct comparison of daily HWMS and RTM data for the seven locations where thermographs were located in close proximity, with the greatest separation at less than 0.7 miles. Overall agreement between the two sets of thermographs is considered to be very good, with deviations above and below the 1:1 (observed:expected) line, depending upon upstream or downstream location. From these comparisons, it is apparent that discrepancies between modeled and observed data may be attributed to differences in the period of record represented in the two datasets.

Closer inspection of the full time-series of modeled and predicted temperature (Appendix A and B) shows that the model tended to over-predict temperatures in the upper portions of the river in drier water year types (2002, 2003, and 2004), especially in the spring and summer, and to under-predict temperatures at these locations in wetter years (2005 and 2006).[2] The model also tends to under-predict temperatures in the middle portion of the river during both dry and wet water year types. As a means of examining the spatial and temporal extent of this error, a non-parametric technique called kernel smoothing was used within the "R" statistical software (Bowman and Azzalini 1997) to evaluate the temperature difference of observed and modeled temperatures by month for 1999–2007 across all HWMS and RTM thermograph locations (Appendix D). It is apparent that a number of flow-related artifacts appear in the calibrated model, likely due to the limited number of water-years covered by the HWMS calibration data. The HWMS thermographs in the upper river include complete data from only four water years (2002, 2005, 2006, and 2007), with only limited data for water year 2004 (Figure 2).

5.3 Discharge-Flow-Temperature Relationships

In direct response to the July 16, 2009 Order, the validated temperature model was used to examine the relationship between flow and water temperature at various time periods during the year in specified reaches of the lower Tuolumne River. It is apparent from the model validation results discussed above that the HEC-5Q model may systematically over- or under-predict water temperatures to some degree within portions of the lower Tuolumne River under various flow regimes and meteorological conditions. For this reason, it is important to gain a clearer understanding of the behavior of the model to better inform its use in evaluating the various temperature targets included in the Final Study Plan.

The kernel smoothing technique described above was used to evaluate the temperature difference of observed and modeled temperatures as a function of river mile and flow at Modesto flow (USGS 11290000) for 1999–2007 across all HWMS and RTM thermograph locations. Figure 6 illustrates the pattern of discrepancy between modeled and observed water temperature up to ±2°F. The results show that the calibrated model systematically over-predicts water temperatures in the upper reach (RM 35 – RM52) and lower reach (RM 4 – RM 15).by 1–2°F at typical summer flows, with errors in excess of 2°F at the lowest flows.

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[2] General water year classification used here are based on the San Joaquin Basin 60-20-20 Index and the CDWR San Joaquin Valley unimpaired runoff forecasts, as published in the various reports of CDWR Bulletin 120-3-[year], Water Conditions in California. http://cdec.water.ca.gov/cgi-progs/iodir/wsihist

5.4 Preliminary Evaluation of Flow Requirements to Meet Seasonal Water Temperature Targets

The primary approach used to address the second study question included in the July 16, 2009 Order was to simulate the variation of Don Pedro release flows over historical meteorological conditions in order to identify the expected flows necessary to meet various water temperature thresholds downstream. It should be recognized that antecedent meteorology and reservoir operations will greatly affect the available storage volume and temperature structure of the reservoir. For the purposes of this evaluation, we have used the simplifying assumption that the water volumes necessary to meet the water temperature objectives have no effect upon water storage levels. That is, for all scenarios, we assume that release temperatures from Don Pedro reservoir are known and water storage levels are relatively consistent from year-to-year. To accomplish this, historical Don Pedro Reservoir storage levels, inflows and outflows were set to large values within the HEC-5Q model and the reservoir artificially maintained at near full pool, thereby eliminating reservoir drawdown effects on release temperatures. Using this assumption for the historical record of air temperatures, Figure 7 shows that daily average water temperatures entering the lower Tuolumne River downstream of La Grange Dam would vary between 9.8ºC (49.7ºF) and 11.2ºC (52.2ºF) on an annual basis. This constant reservoir management assumption allowed the HEC-5Q model to be used strictly as a reach-based model for the purposes of this study, with a number of constant flow simulations carried out as described below.

To provide estimates of flows necessary to meet various temperature targets, all simulations used the same time series of Don Pedro Reservoir release temperatures at the upstream end of the modeled reach below La Grange Dam and then used the within-year meteorology to determine the downstream extent of various temperatures over a range of potential flows in the lower Tuolumne River. As such, the validated HEC-5Q model was used in an iterative process of running a series of constant flows over a range of historical meteorology and recording the predicted water temperatures at all modeled locations in the river. After amassing the results of a number of temporally- and spatially-constant flow scenarios, interpolation was used to describe a time series of flows necessary to meet a particular temperature target at a given location and time of year. This modeling approach should be considered an approximation of the required flow as it assumes there is an unlimited volume of cold water in the Don Pedro Reservoir that is available for release downstream.

As required under Ordering Paragraph (F) of the July 16, 2009 Order, Figures 8–12 present model simulation results to determine the downstream extent of several temperature based scenarios for the benefit of various life stages of Chinook salmon and *O. mykiss*. The initial scenario evaluated includes an estimate of flows necessary to meet water temperatures below 20ºC (68°F) from La Grange Dam to Roberts Ferry Bridge at RM 39.5. In addition, the USFWS and other fishery resource agencies identified additional scenarios that were included in the Final Study Plan. As described in the Final Study Plan, the water temperature standard chosen for this evaluation is the maximum value of the moving 7-day average temperature (i.e., the “maximum weekly average temperature” or “MWAT”).

5.4.1 Flows meeting a summer MWAT of 20ºC at Roberts Ferry Bridge

The initial evaluation scenario requested in the July 16, 2009 Order was to determine the flow required to maintain a summertime (analyzed for June 1st through September 30th) MWAT of 20ºC (68°F) or less downstream to Roberts Ferry Bridge (RM 39.5). As stated above, the validated HEC-5Q model was used to evaluate this initial scenario for a range of flows with water temperature predictions varying by year across the meteorological period of record. Results of this evaluation indicate that flows of 200–300 cfs would be required to regularly meet this condition (Figure 8). An incremental increase of approximately 25 cfs would be required to provide 1°F (0.6°C) of additional cooling at Roberts Ferry Bridge for this range of dates. Accounting for model uncertainty (95% exceedance of 1.66°F [0.92°C]), meeting an MWAT of 20ºC (68°F) would correspond to a reduced temperature target of 19.1°C (i.e., 20.0°C minus 0.9°C) and could require flows on the order of 230 cfs in any single year. Based upon this analysis, the summertime MWAT typically occurs in the second half of July in most years.

5.4.2 Flows meeting a summer MWAT of 18ºC at Roberts Ferry Bridge

In addition to the initial evaluation scenario included in the July 16, 2009 Order and described in Section 5.4.1 above, the first of four additional scenarios evaluated at the request of Agency reviewers of the Final Study Plan is to estimate flows required to maintain a summertime MWAT of 18ºC (64.4ºF) from La Grange Dam downstream to Roberts Ferry Bridge (RM 39.5). Results of this evaluation indicate that flows of 300–400 cfs will be required to regularly meet this condition (Figure 9). An incremental increase of approximately 40 cfs would be required to provide 1°F (0.6°C) of additional cooling at Roberts Ferry Bridge for this range of dates. Accounting for model uncertainty (95% exceedance of 1.66°F [0.92°C]), the average release flows needed to meet an MWAT 18ºC (64.4°F) would be on the order of 410 cfs in any single year. As with the 20ºC evaluation described above in Section 5.4.1, the summertime MWAT typically occurs in the second half of July in most years.

5.4.3 Flows meeting a fall MWAT of 18ºC at the San Joaquin River confluence from October 15 to December 1

The second additional scenario evaluated at the request of Agency reviewers of the Final Study Plan is to estimate flows required to maintain a fall MWAT of 18ºC (64.4ºF) from La Grange Dam downstream to the confluence with the San Joaquin River (RM 0) from October 15 to December 1. Results indicate that meeting this temperature target from La Grange Dam all the way to the San Joaquin River confluence cannot be achieved under any feasible flow release condition during the second half of October in eleven years modeled. For the years in which the temperature objective could be met, flows of approximately 400 cfs or less would be required to meet this condition during the second half of October, with only 100 cfs or less required by early November (Figure 10). Based upon this analysis, the fall MWAT typically occurs at the very beginning of this simulation period (October 15–22) in all years and it is apparent that this temperature objective is infeasible during the second half of October.

5.4.4 Flows meeting a fall/winter MWAT of 13ºC at Roberts Ferry Bridge from October 15 to February 15

The third additional scenario evaluated at the request of Agency reviewers of the Final Study Plan is to estimate flows required to maintain a fall/winter MWAT of 13ºC (55.4ºF) from La Grange Dam downstream to Roberts Ferry Bridge (RM 39.5) from October 15 to February 15. Results indicate that flows of 300–500 cfs would be required to meet this condition during mid-October, falling below 200 cfs by mid-November (Figure 11). An incremental increase of approximately 30 cfs would be required to provide 1°F (0.6°C) of additional cooling at Roberts Ferry Bridge for this range of dates. Accounting for model uncertainty (95% exceedance of 1.29°F [0.72°C]), the average release flows needed to meet an MWAT 13ºC (55.4ºF) would be on the order of 200 cfs in any single year. As stated above, the fall/winter MWAT typically occurs at the very beginning of this simulation period (October 15–22) in all years.

5.4.5 Flows meeting a spring MWAT of 15ºC at the San Joaquin River confluence from March 20 to May 15

The last scenario evaluated at the request of Agency reviewers of the Final Study Plan is to estimate flows required to maintain a spring MWAT of 15ºC (59ºF) from La Grange Dam downstream to the confluence with the San Joaquin River (RM 0) from March 20 to May 15. Results indicate that meeting this temperature target from La Grange Dam all the way to the San Joaquin River confluence cannot be achieved under any feasible flow release condition during late March in all but six years (1980, 1982, 1983, 1991, 1995, and 2006). Although flows of 700–1,000 cfs prior to April 1st would be required to meet this condition in these six years, this temperature objective cannot be met at any time after mid-April for the remaining period of interest (Figure 12). Based upon this analysis, the springtime MWAT typically occurs at the end of this simulation period (May 15) and it is apparent that this temperature objective is infeasible under any circumstances.

6 DISCUSSION

The existing HEC-5Q water temperature model developed for the Tuolumne River was evaluated and independently validated for use in predicting downstream water temperatures in relation to flows released at La Grange Dam. Overall, although the original model calibration appear to exceed the model uncertainty identified in the Final Study Plan (1–2°F [0.6–1°C]) less than 10% of the time, 20–25% error exceedances of this temperature range were found in comparison to thermographs not used in the model calibration. This difference was shown to be generally related to the different WY types contained in each data set and it is apparent that model biases appear under various combinations of flow and meteorology. Although we have used the existing HEC-5Q model calibration for the purposes of examining the overall feasibility of meeting various temperature target scenarios included in the Final Study Plan, we have included updated estimates of model uncertainty. Without recalibration of the model, we recommend that the identified model biases should be taken into consideration in setting any potential future flow requirements based upon water temperature.

In all, five scenarios were evaluated using the validated water temperature model. Results of the model simulations indicate that flow ranges of 200–300 cfs and 300–400 cfs would be required to regularly meet summertime water temperature targets (MWAT) of 20ºC (68°F) and 18ºC (64.4ºF) or less downstream to Roberts Ferry Bridge (RM 39.5). Although the model systematically over-predicts summertime water temperatures in this portion of the river at flows of this magnitude, including the identified model uncertainty would require flows on the order of 230 cfs and 410 cfs for these scenarios under extreme meteorology (95% exceedance).

The three additional scenarios simulated by the model predicted the flows necessary to meet water temperature targets only during certain portions of the year. Because the hottest portion of the fall (October 15 to December 1) and fall/winter (October 15 to February 15) simulation periods typically occurs at the beginning of the period (October 15–22), more flow is required to maintain the water temperature targets during mid-October than in subsequent weeks. In the hottest years, the model predicts that an 18ºC (64.4ºF) MWAT target cannot be maintained downstream to the confluence with the San Joaquin River (RM 0) during mid-October under any flow release conditions. Flows required for meeting fall and fall/winter temperature targets decline rapidly during late October and early November with the onset of cooler weather conditions. Model predictions indicate that from November 1–December 1, only 100 cfs or less is required to maintain an MWAT of 18ºC (64.4ºF) downstream to the confluence with the San

Joaquin River (RM 0), and only 200 cfs or less is required to maintain an MWAT of 13ºC (55.4ºF) downstream to Roberts Ferry Bridge from mid-November to February 15.

As would be expected, water temperatures during the spring simulation period (March 20 to May 15) are highest at the end of the simulation period. Flows required to maintain an MWAT of 15ºC (59.0ºF) downstream to the confluence with the San Joaquin River (RM 0) therefore increase over the course of the spring. After March 31, model predictions indicate that an MWAT of 15ºC (59.0ºF) cannot be maintained downstream to the confluence with the San Joaquin River under any flow release conditions.

The results of the model validation and simulations indicate that model predictions are appropriate for use in determining the feasibility of meeting various temperature targets included in the Final Study Plan. Further, the validated model is suitable for determination of effective weighted usable area (EWUA) as part of the Districts' instream flow (IFIM) study included in the July 16, 2009 Order with appropriate consideration of the model biases and uncertainties identified here. However, it should be stressed that the model results presented here are not suitable for establishing flow schedules on a long-term basis. Recognizing that water temperatures and reservoir operations may be specifically evaluated in the future to determine the feasibility of achieving various downstream temperature targets on a long-term basis, the results presented here may substantially over- or under-predict the release water temperatures encountered under real-world reservoir operations.

7 REFERENCES

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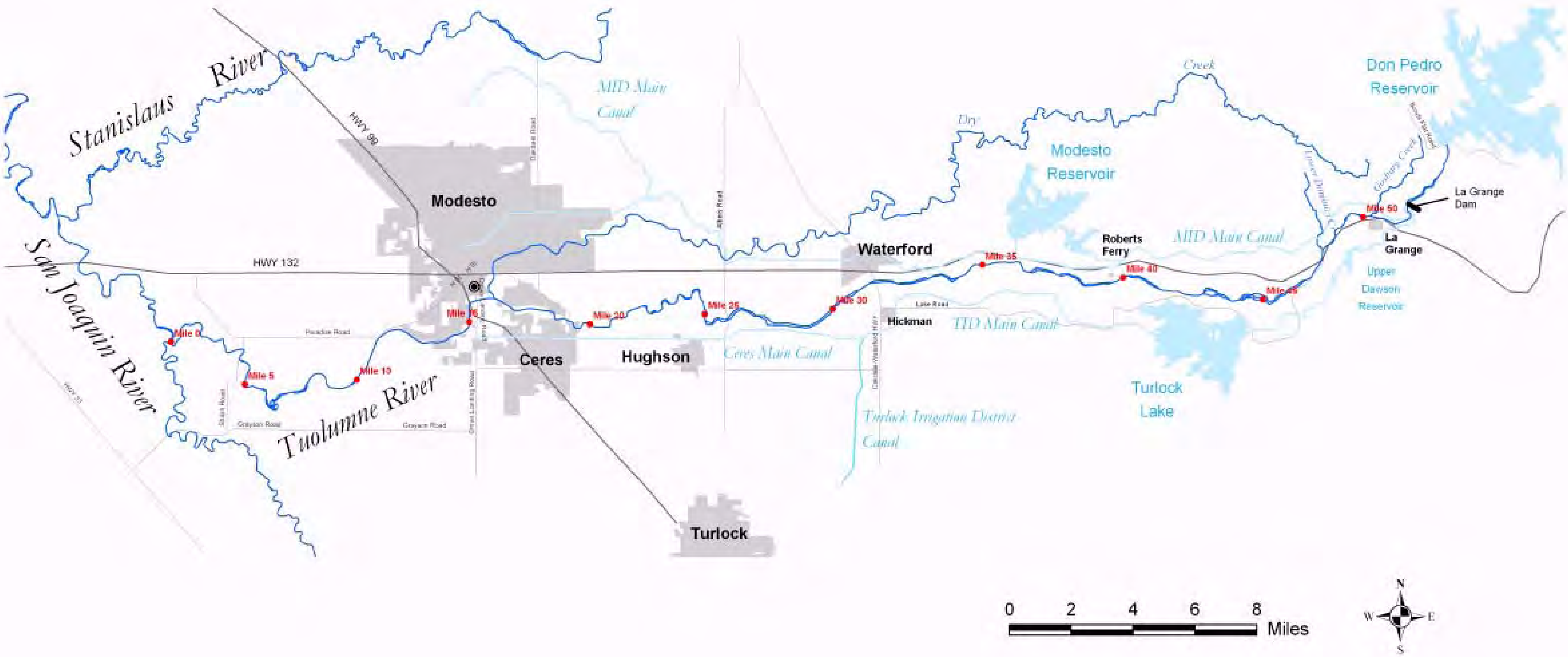

Figure 1. Vicinity map for the Tuolumne River water temperature modeling study.

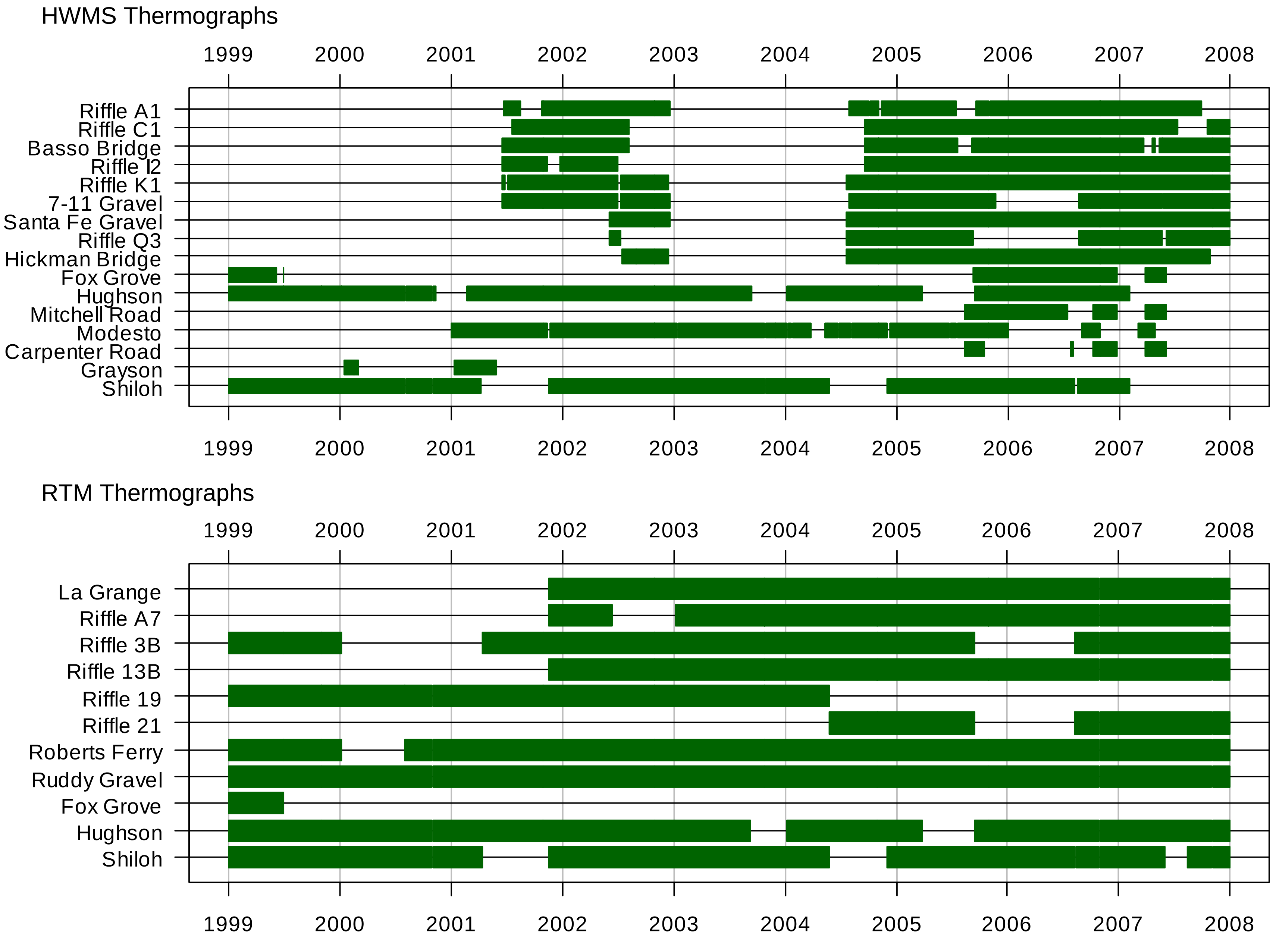

Figure 2. Dates represented by the CDFG ("HWMS") and TID-MID ("RTM") thermographs. Only days from 1/1/1999 through 12/31/2007, and for which 10 or more observations were recorded, are shown.

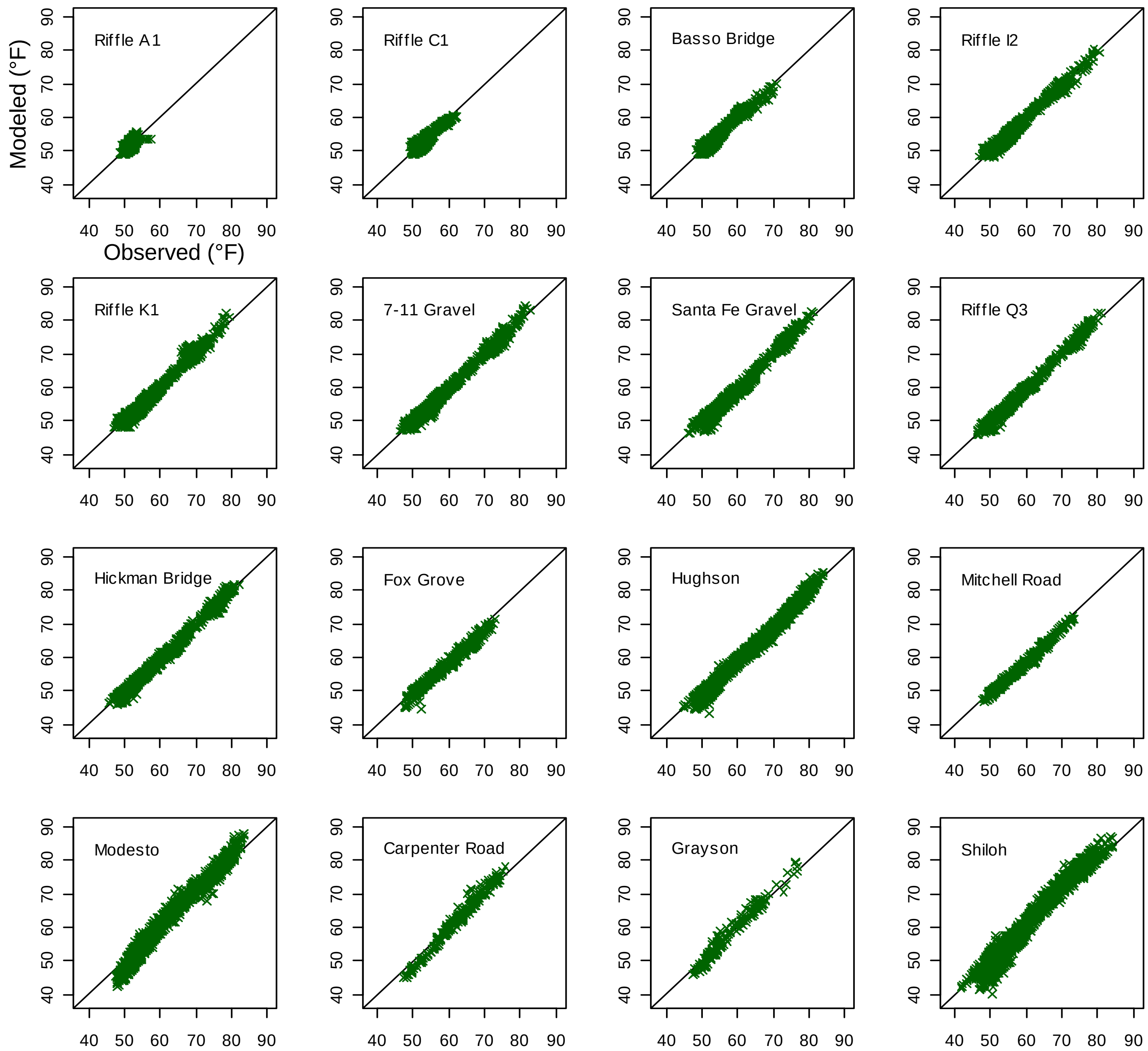

Figure 3. Modeled vs. observed mean daily water temperatures at various locations in the Tuolumne River below La grange dam. These are all the Tuolumne River comparisons directly accessible in the HWMS GUI. The historical values are mostly from CDFG thermographs.

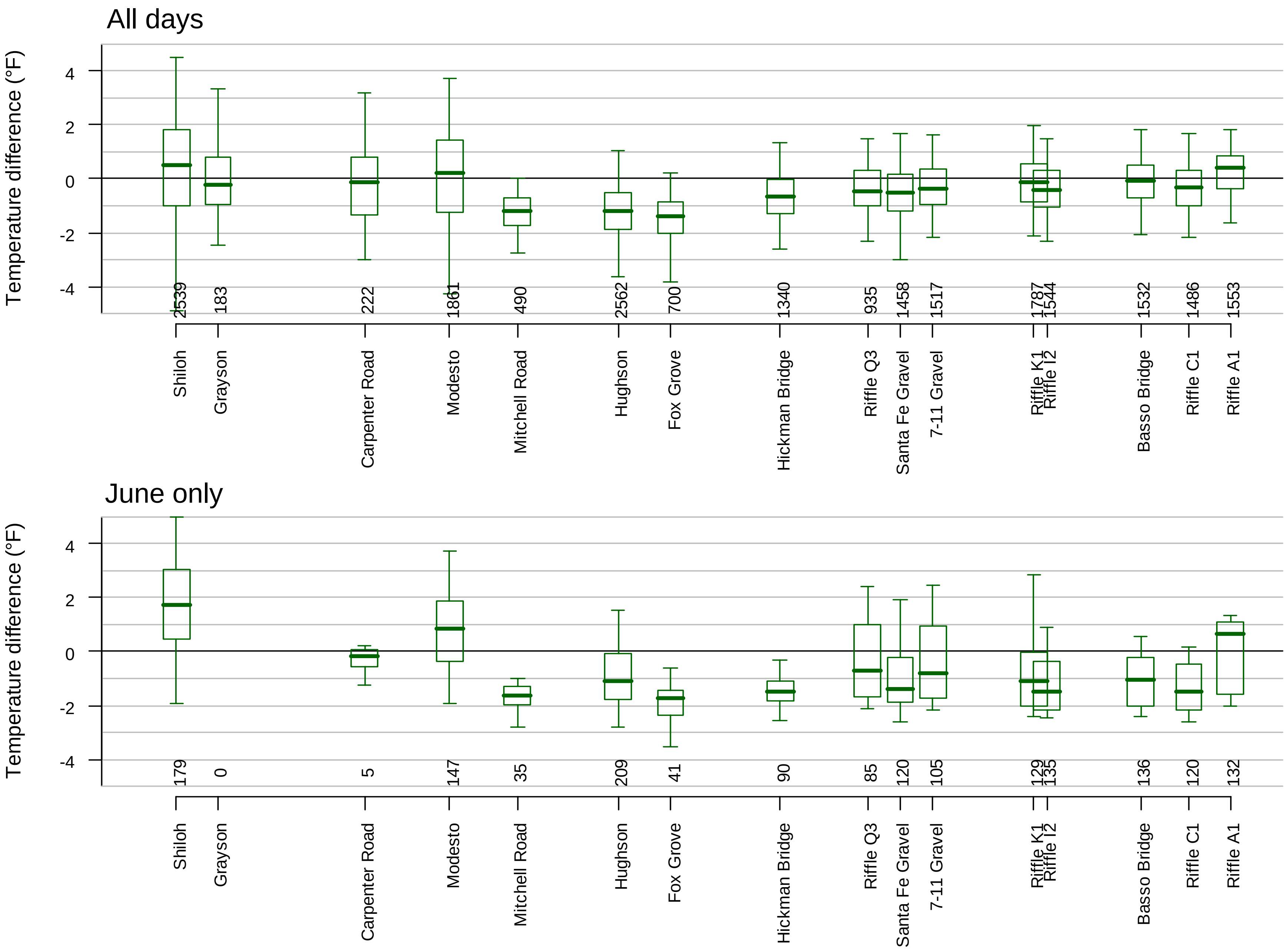

Figure 4. Difference (modeled - observed) between mean daily water temperatures at the CDFG ("HWMS") thermographs in the Tuolumne River below La Grange dam (1999-2007). Boxes show median, first, and third quartiles; whiskers show 2.5 and 97.5 percentiles.

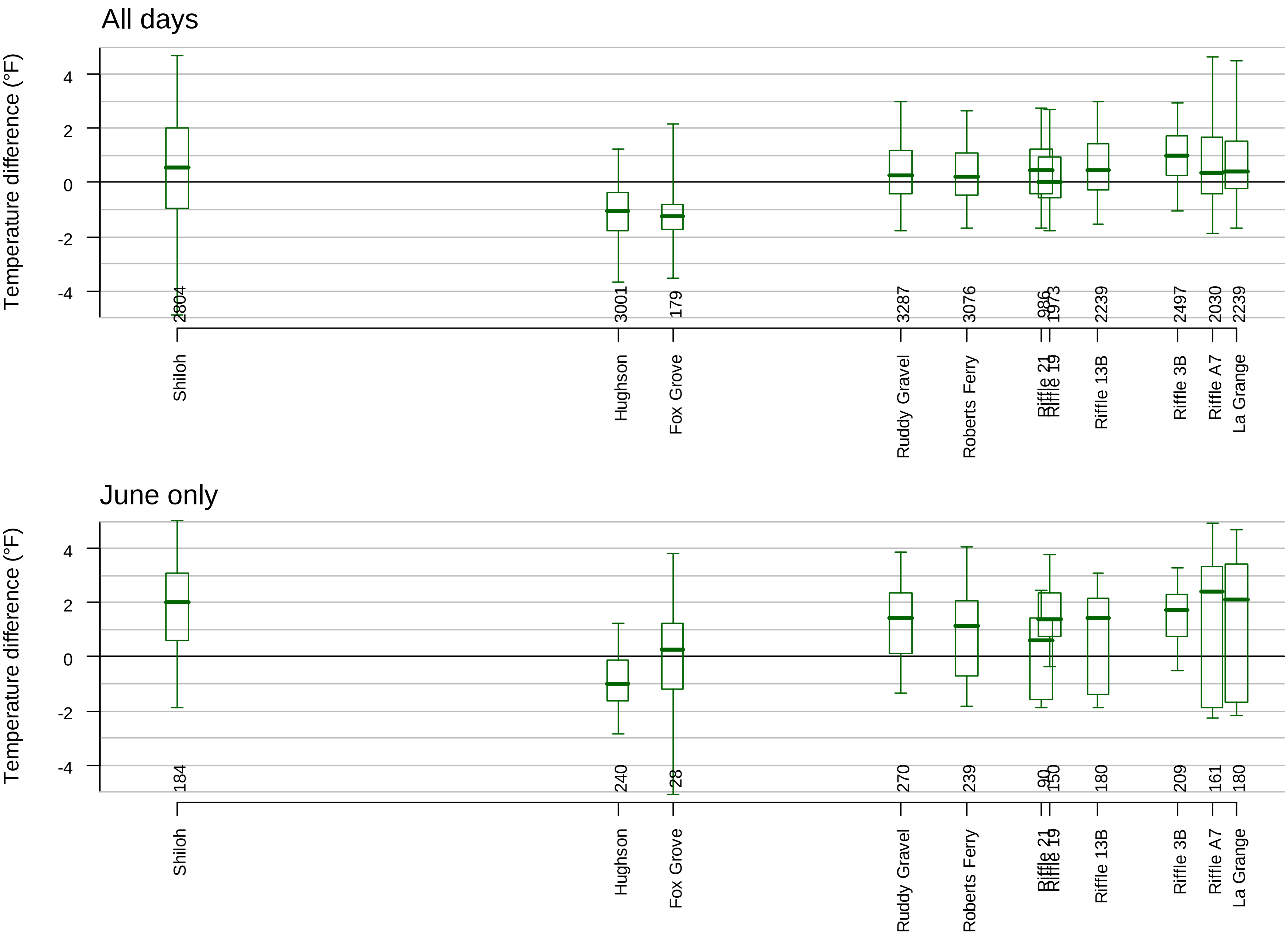

Figure 5. Difference (modeled - observed) between mean daily water temperatures at the TID-MID ("RTM") thermographs in the Tuolumne River below La Grange dam (1999-2007). Boxes show median, first, and third quartiles; whiskers show 2.5 and 97.5 percentiles.

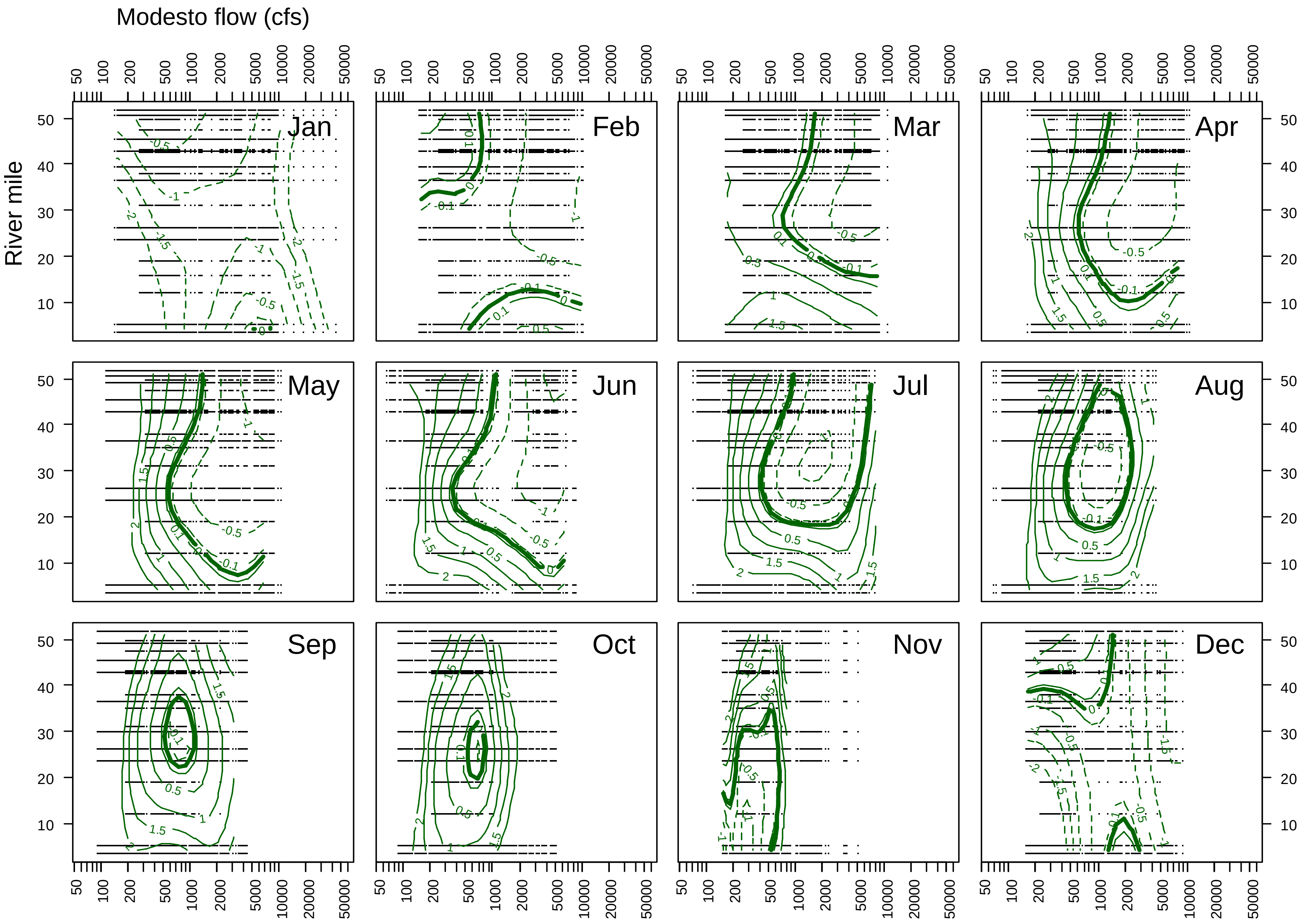

Figure 6. Modeled minus observed water temperatures (°F) for all HWMS and RTM thermographs (1999-2007), by location and observed flow range within each month. *Note each observed combination of flow, location, and temperature difference is marked. Error surface fitted by non-parametric regression with contours in excess of 2F not shown at the lowest flows during summer.*

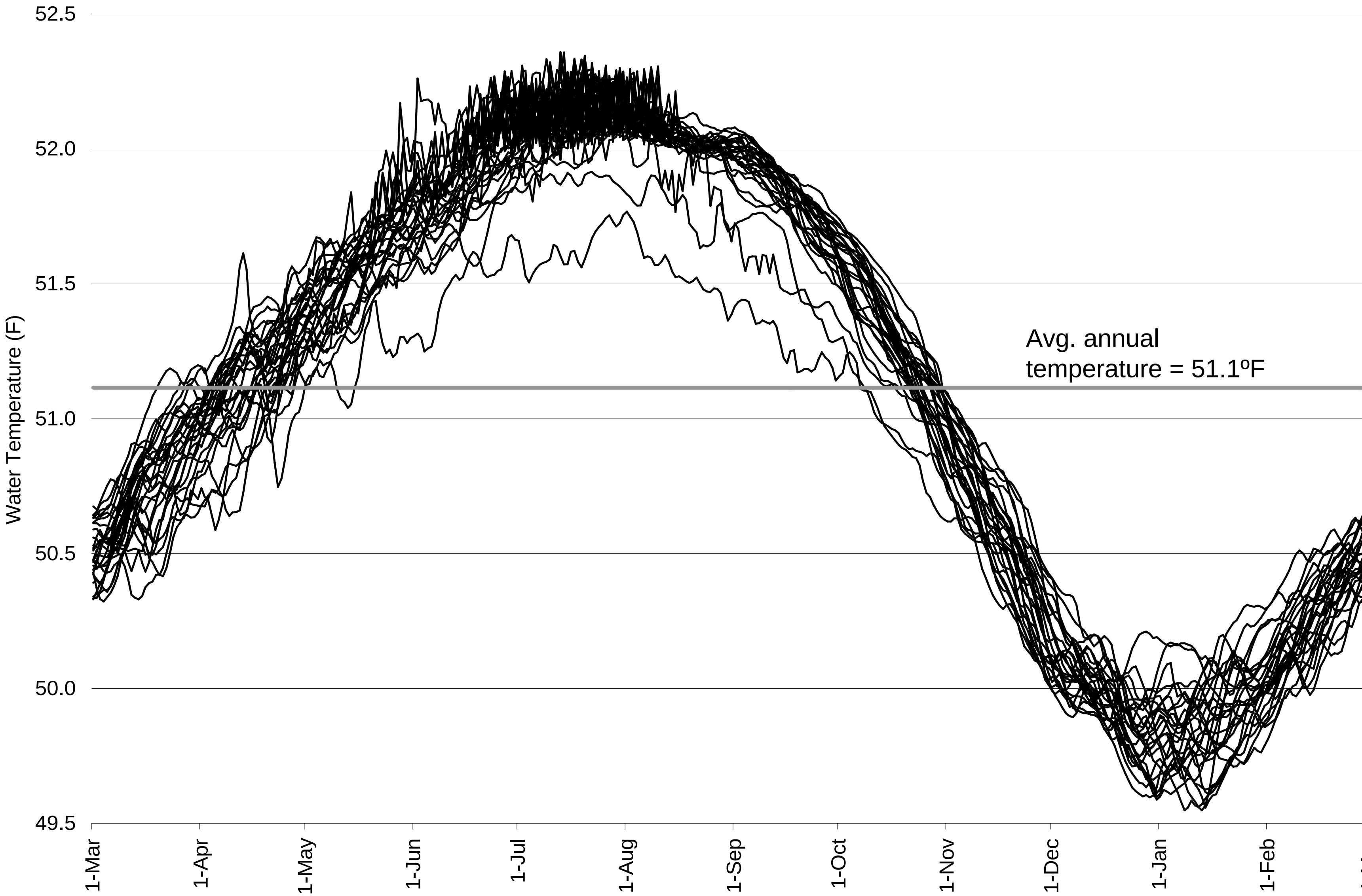

Figure 7. Estimated average daily water temperatures exiting La Grange Dam (RM 52) using period of record meteorology (March 1980 through December 2007).

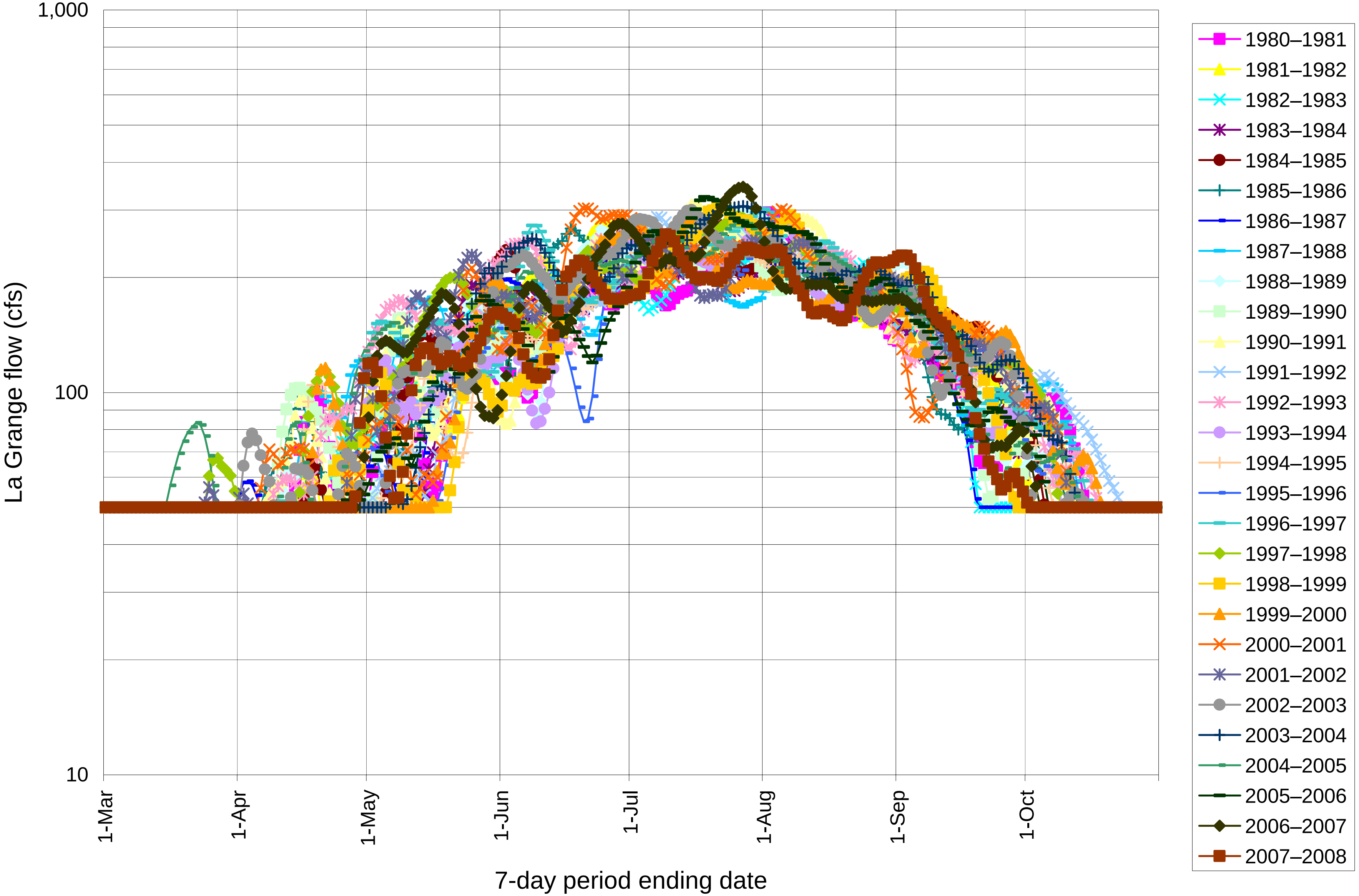

Figure 8. Simulation of flows required to maintain a summer MWAT of 20ºC (68ºF) downstream of La Grange Dam (RM 52) to Roberts Ferry Bridge (RM 39.5), for the period of record meteorology (1980-2007).

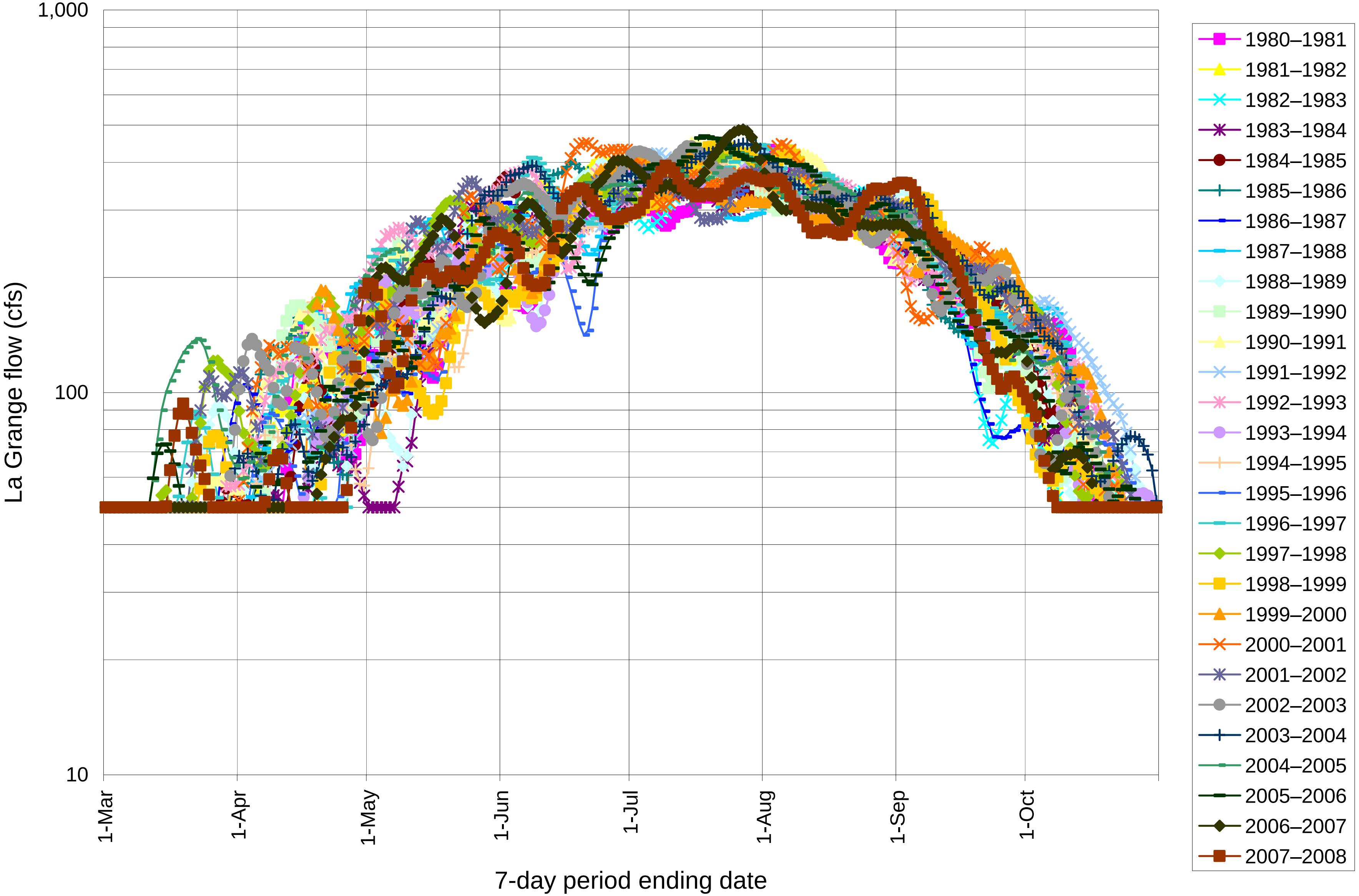

Figure 9. Simulation of flows required to maintain a summer MWAT of 18ºC (64.4ºF) downstream of La Grange Dam (RM 52) to Roberts Ferry Bridge (RM 39.5), for the period of record meteorology (1980-2007).

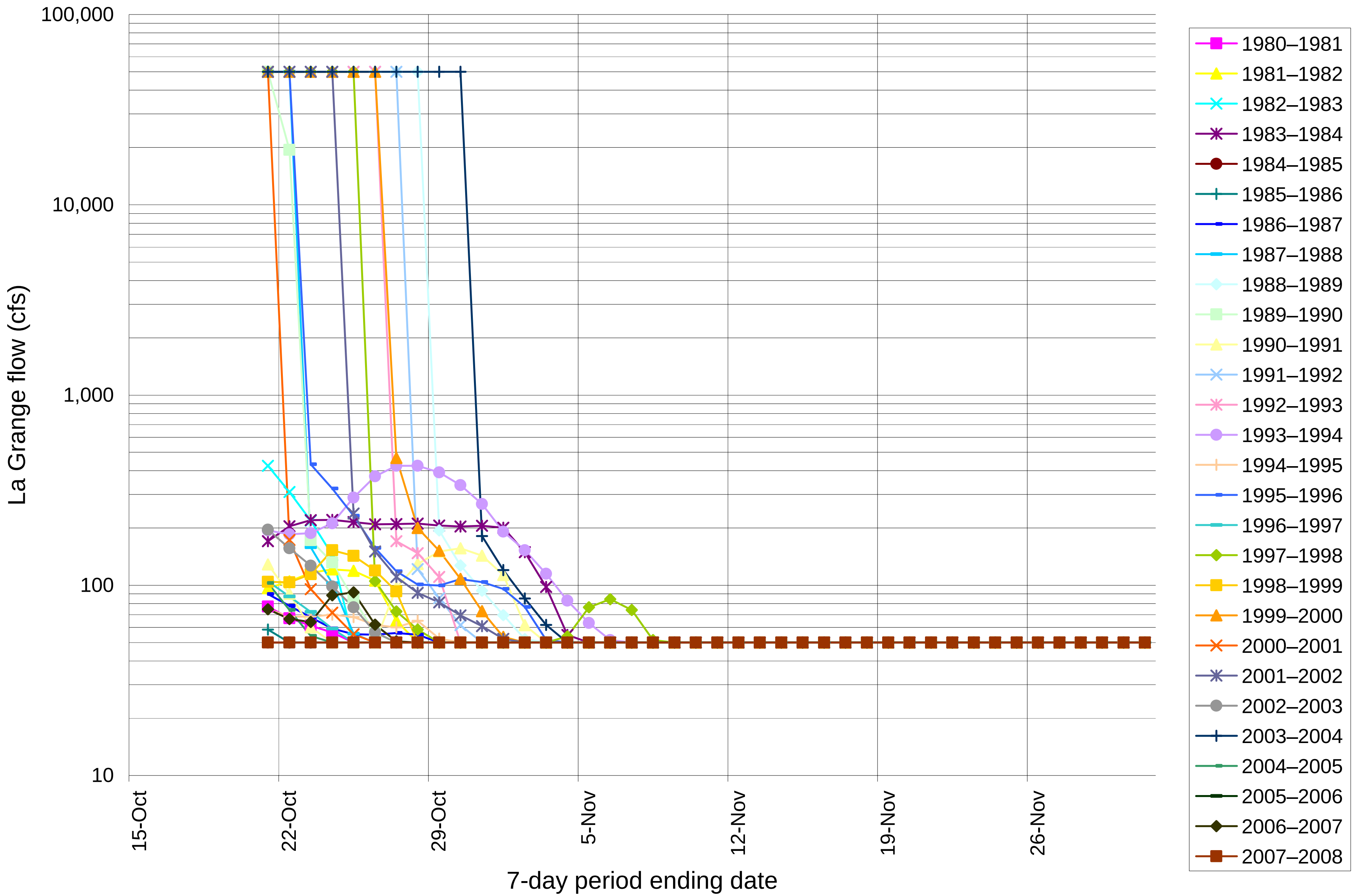

Figure 10. Simulation of flows required to maintain a fall MWAT of 18ºC (64.4ºF) downstream of La Grange Dam (RM 52) to the confluence with the San Joaquin River (RM 0) from October 15 to December 1, for the period of record meteorology (1980-2007). *Note: Simulation indicates that MWAT would not be met prior to November 1 in eleven years modeled.*

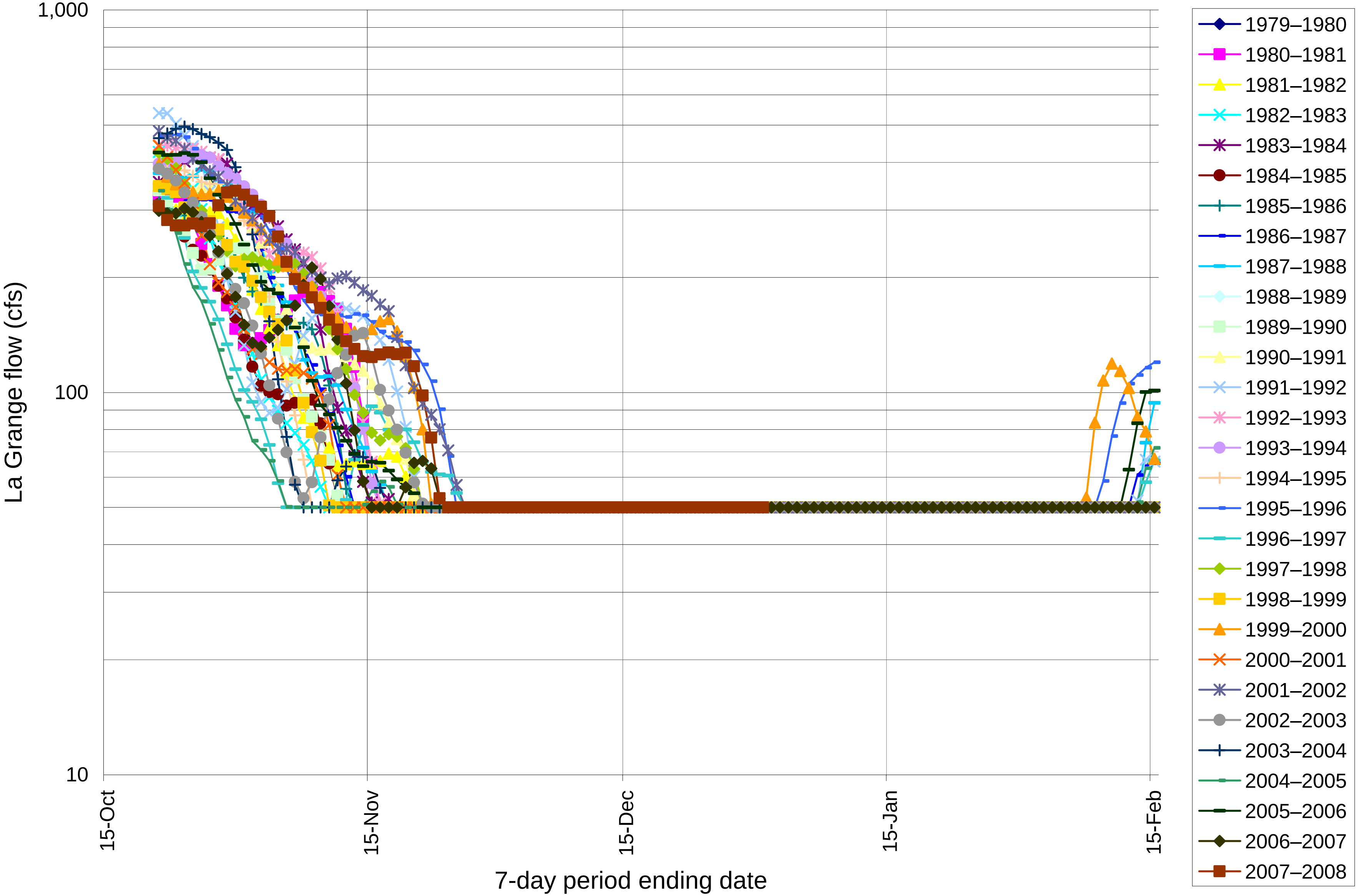

Figure 11. Simulation of flows required to maintain a fall/winter MWAT of 13ºC (55.4ºF) downstream of La Grange Dam (RM 52) to Roberts Ferry Bridge (RM 39.5) from October 15 to February 15, for the period of record meteorology (1980-2007).

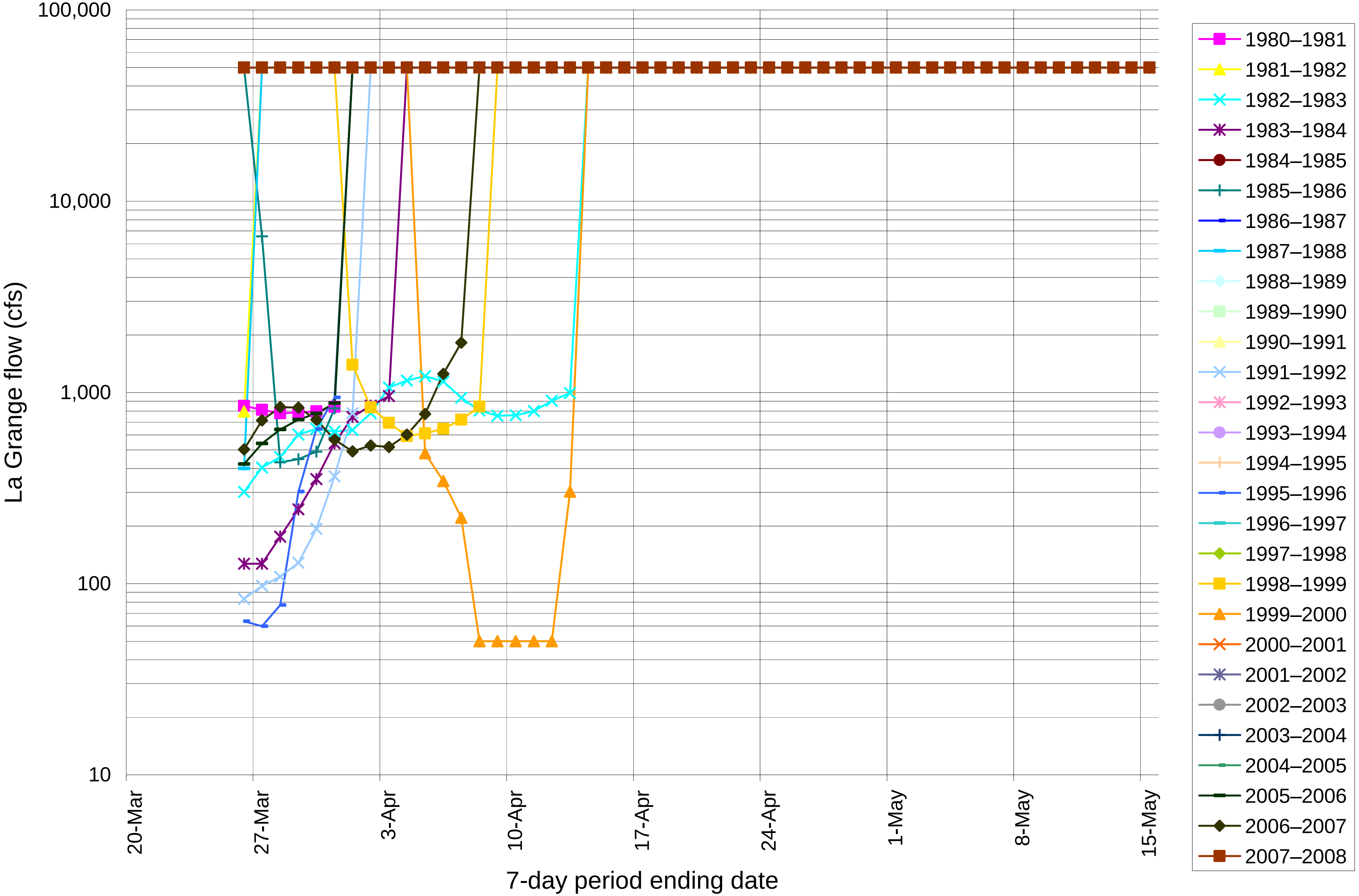

Figure 12. Simulation of flows required to maintain a spring MWAT of 15ºC (59ºF) downstream of La Grange Dam (RM 52) to the confluence with the San Joaquin River (RM 0) from March 20 to May 15, for the period of record meteorology (1980-2007). *Note: MWAT would not be met prior to April 1st in all but six years (1980, 1982, 1983, 1991, 1995, and 2006) and at no time after mid-April.*

Appendices

Appendix A

HEC-5Q Modeled water temperatures (1999-2007) vs. CDFG HWMS thermograph data

Riffle A1

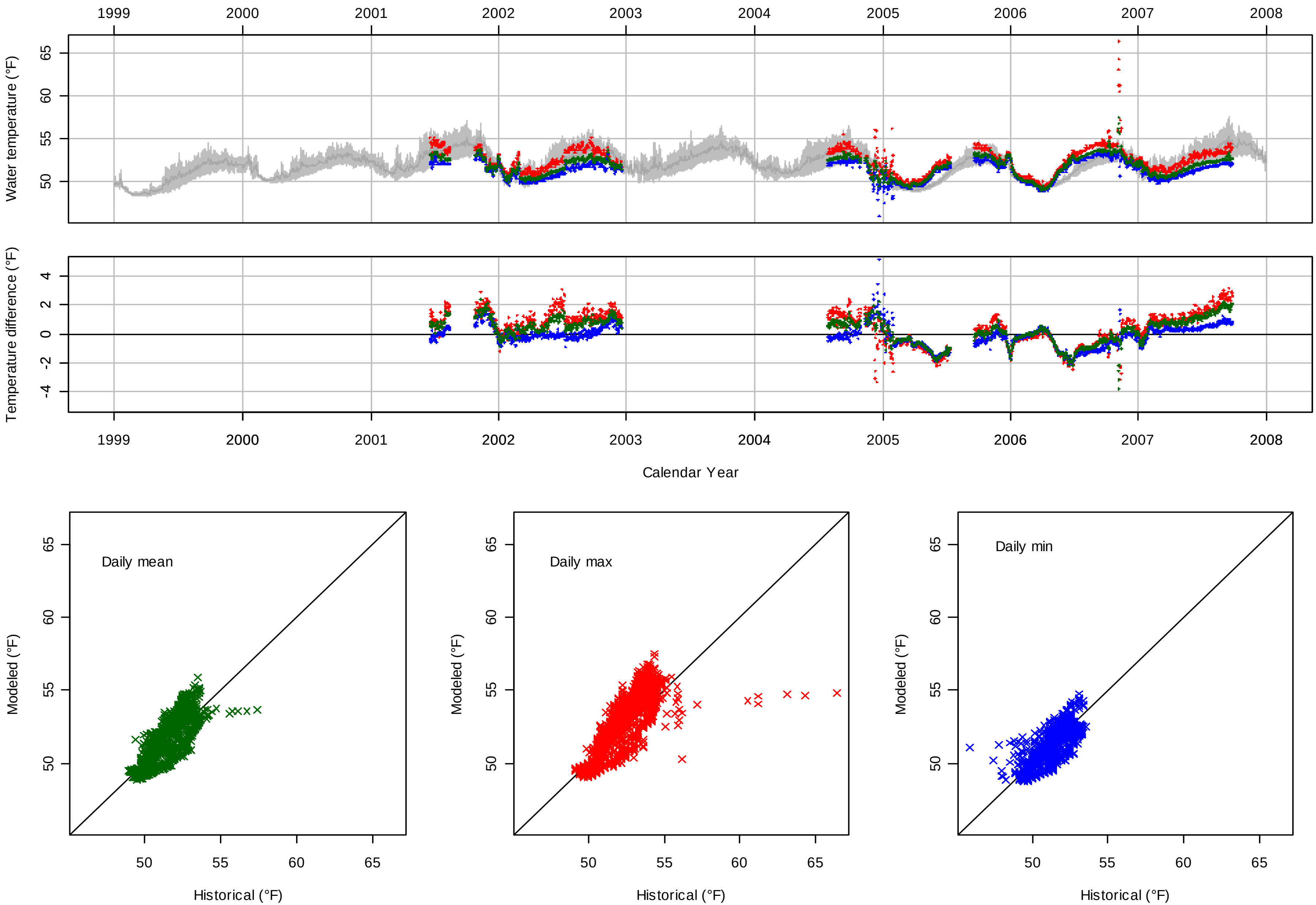

Figure A1. Model performance at Riffle A1. Model time-series "LaGrange Dam to Don Pedro control (U/S RM 53.5) Segment 1-T_cal," historical time-series "RIFFLE_A1_RM516_TRA1."

Riffle C1

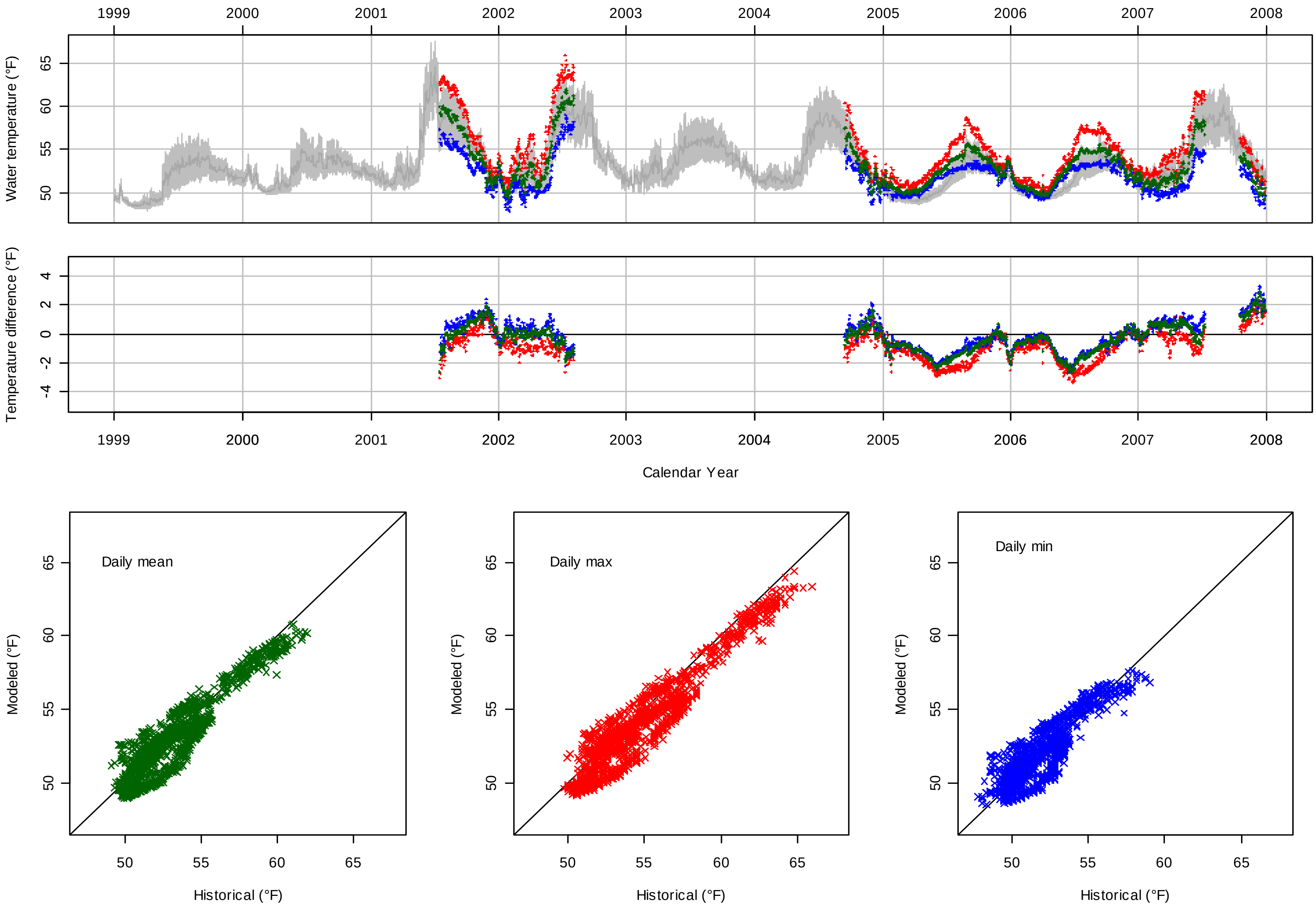

Figure A2. Model performance at Riffle C1. Model time-series “LaGrange Dam to Turlock State Park (D/S RM 42.9) Segment 2-T_cal,” historical time-series “RIFFLE_C1_RM497_TRC1.”

Basso Bridge

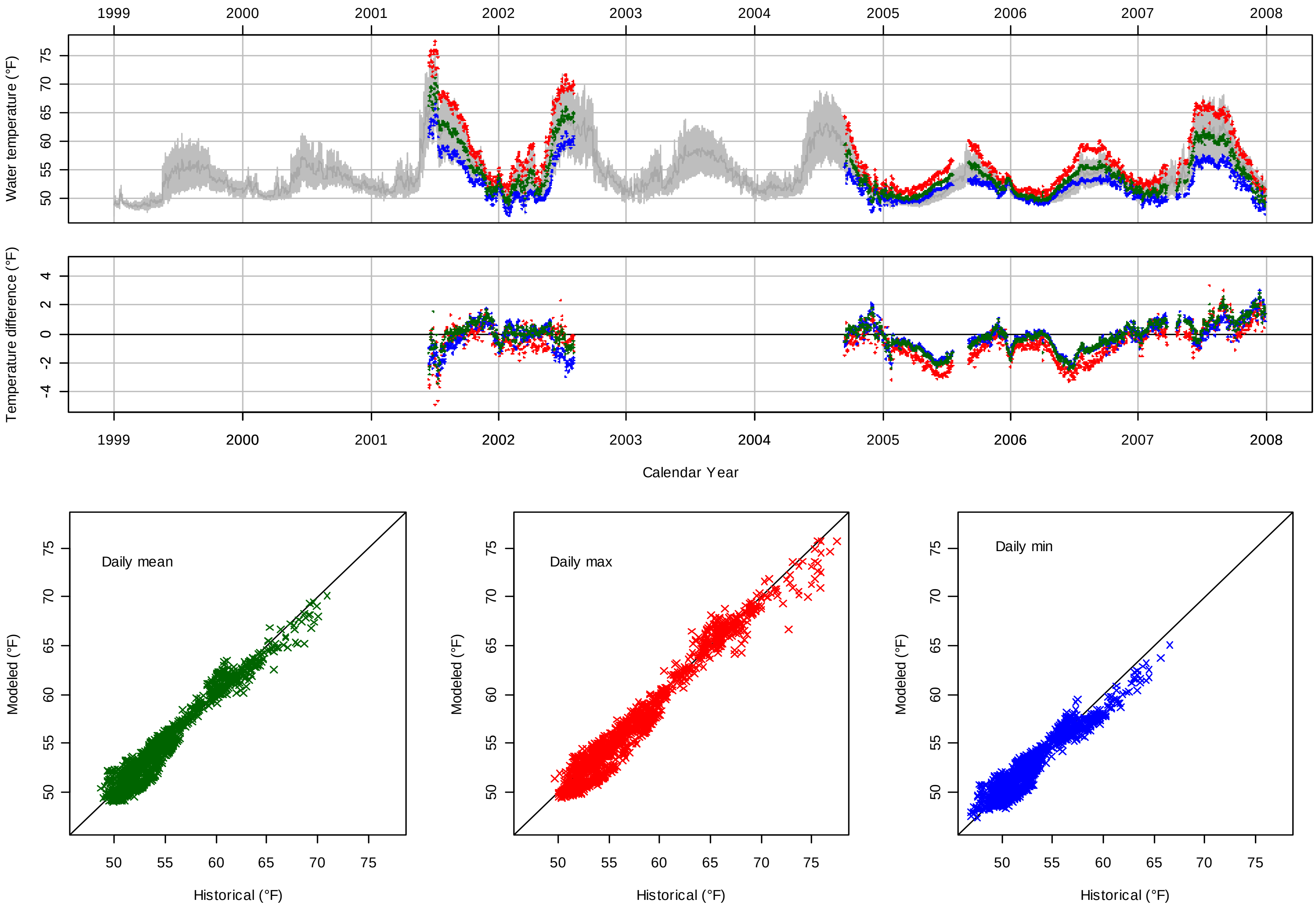

Figure A3. Model performance at Basso Bridge. Model time-series “LaGrange Dam to Turloch State Park (D/S RM 42.9) Segment 5-T_cal,” historical time-series “BASSO_BRIDGE_RM475_TBAS.”

Riffle I2

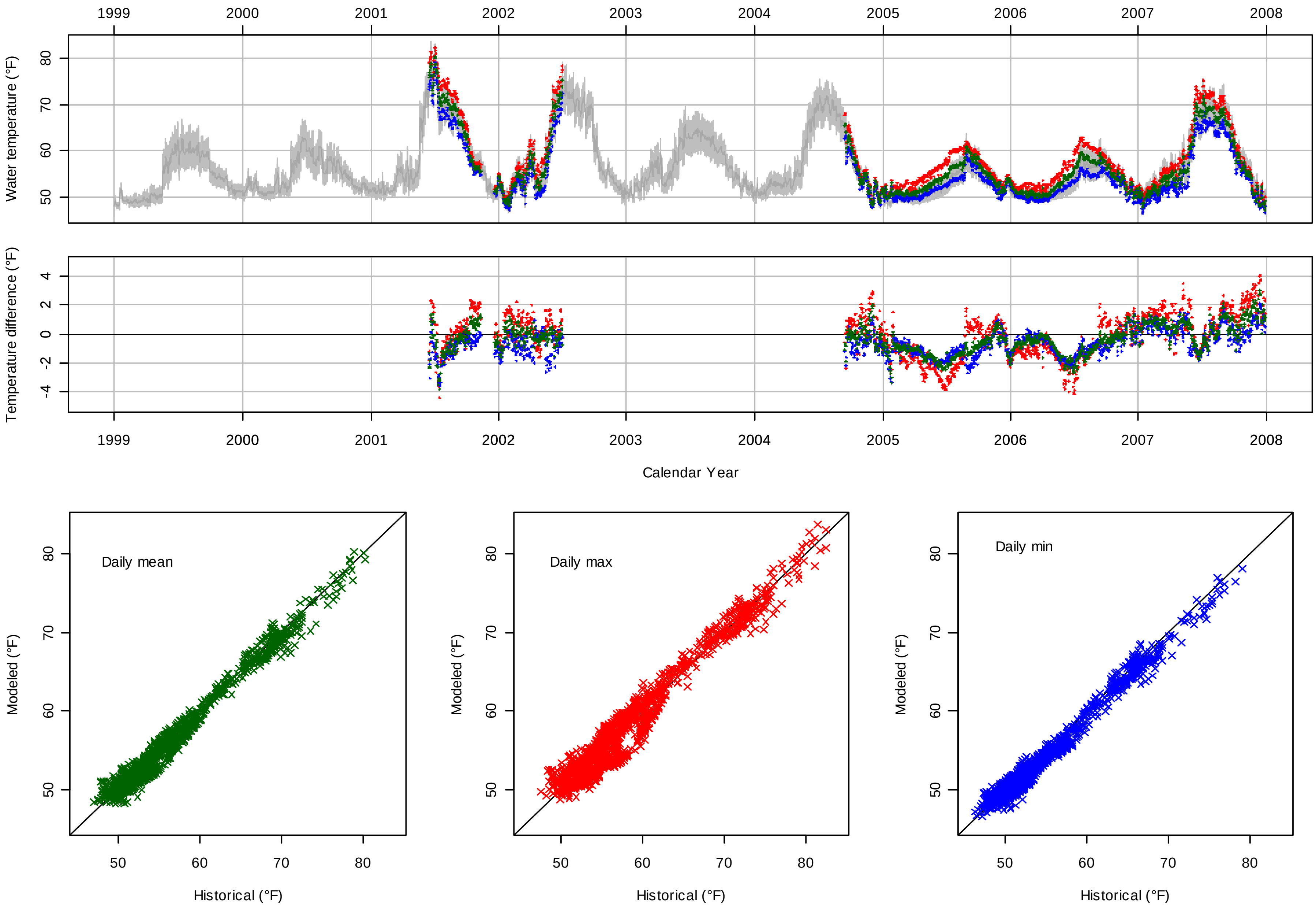

Figure A4. Model performance at Riffle I2. Model time-series “LaGrange Dam to Turloch State Park (D/S RM 42.9) Segment 12-T_cal,” historical time-series “RIFFLE_I2_RM432_TRI2.”

Riffle K1

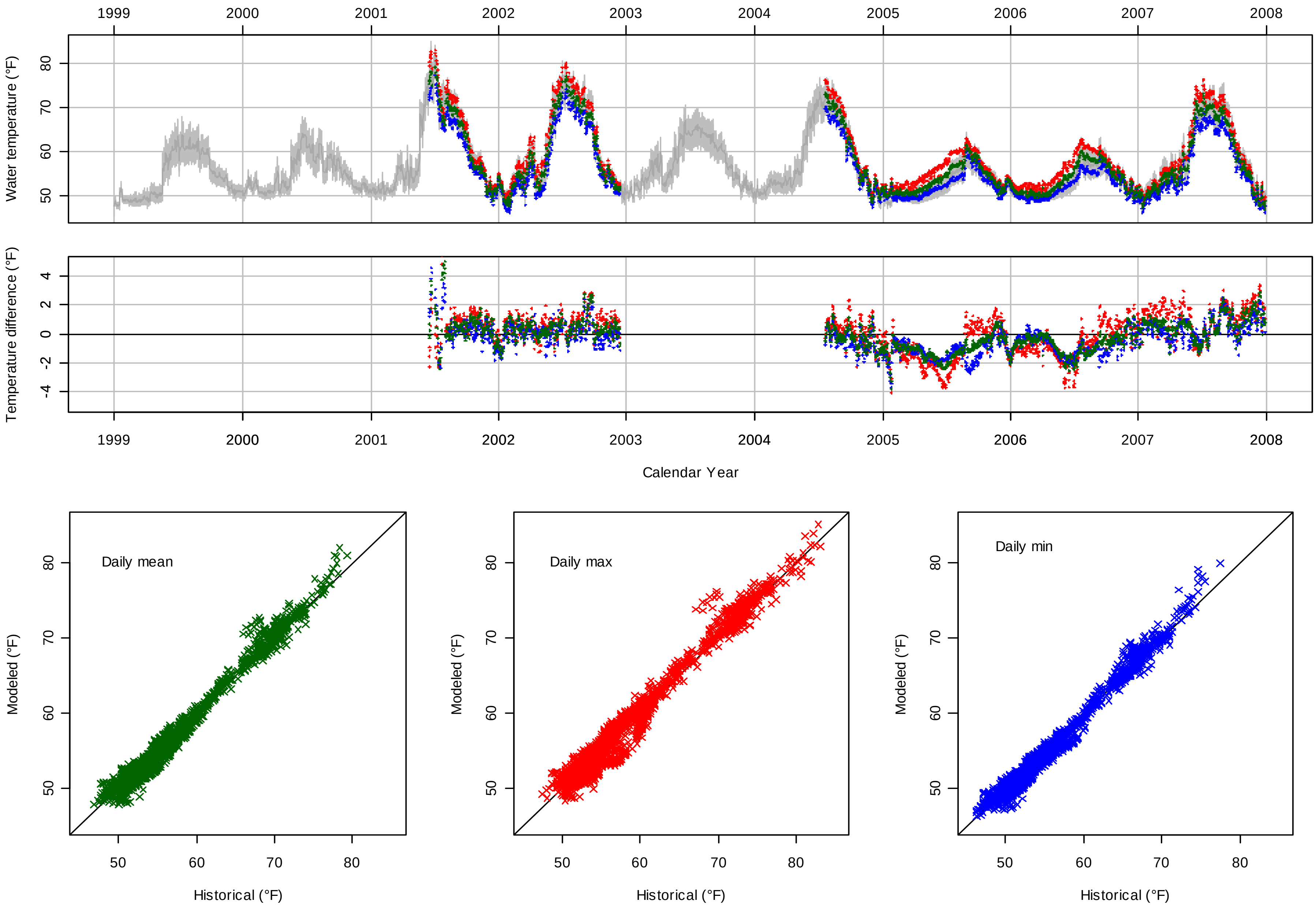

Figure A5. Model performance at Riffle K1. Model time-series “LaGrange Dam to Turloch State Park (D/S RM 42.9) Segment 14-T_cal,” historical time-series “RIFFLE_K1_RM426_TRK1.”

7-11 Gravel Company

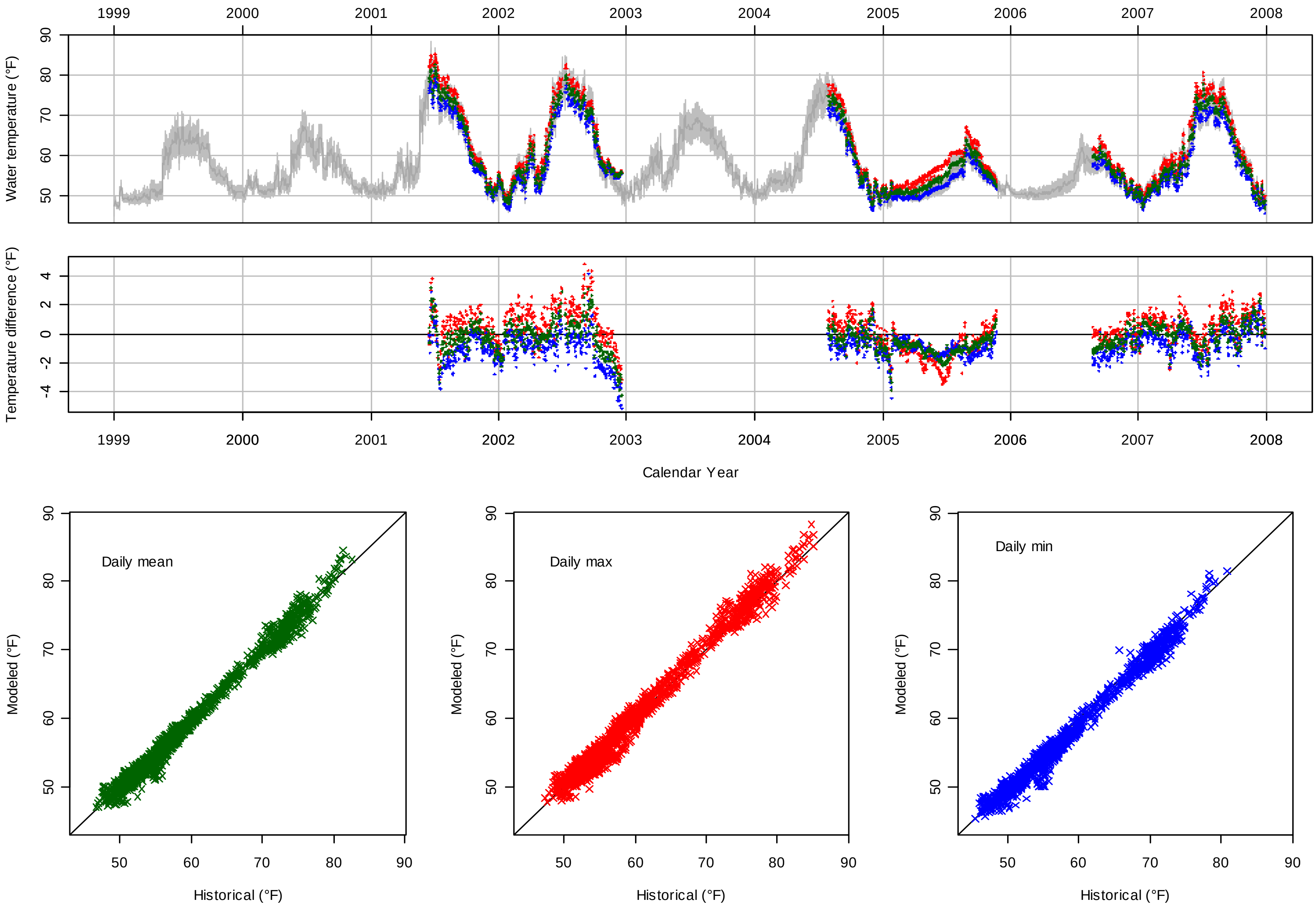

Figure A6. Model performance at 7-11 Gravel Company. Model time-series “Turloch State Park to J9 Bridge @ Waterford (D/S RM 33.1) Segment 3-T_cal,” historical time-series “7-11_GRAVEL_CO_RM38_T7-11.”

Santa Fe Gravel Company

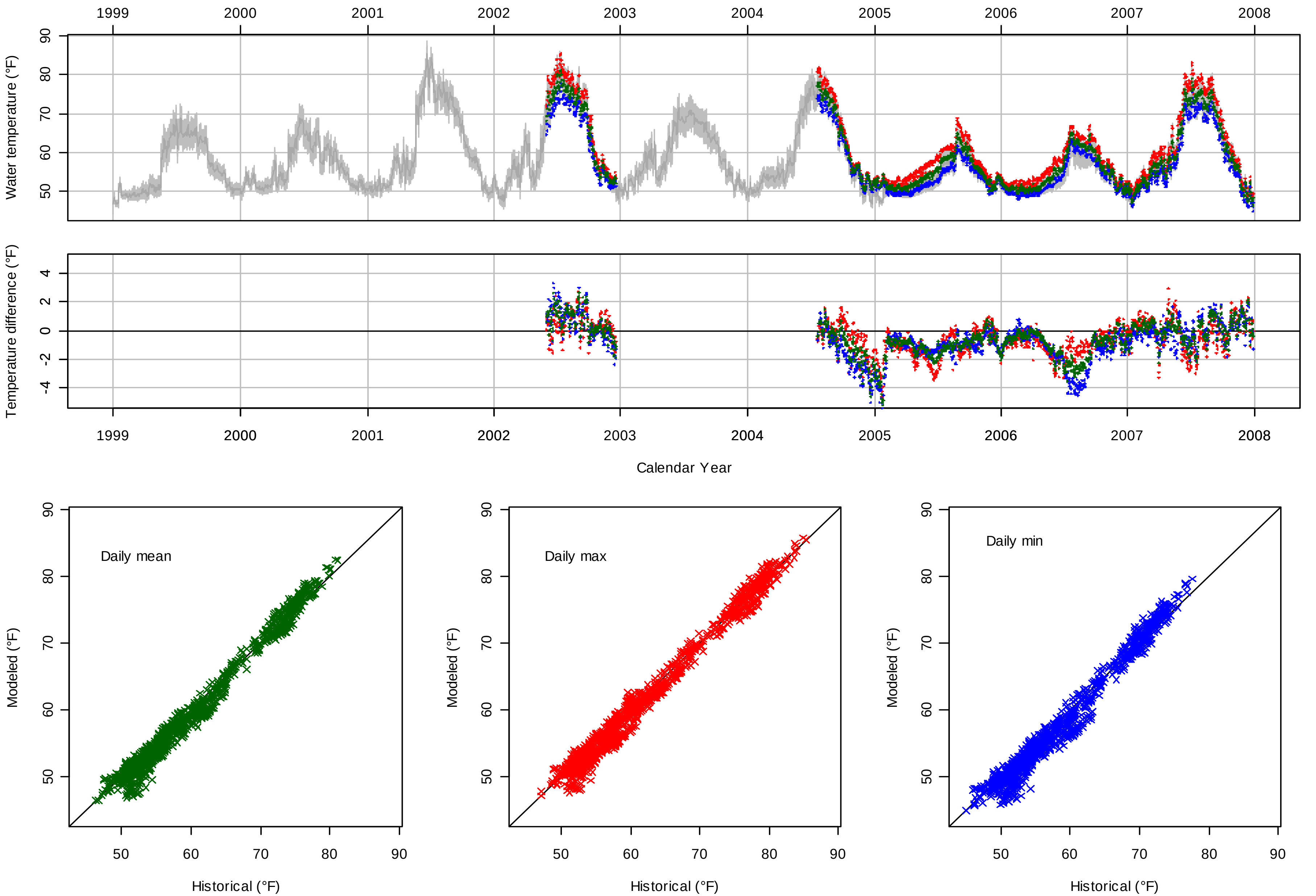

Figure A7. Model performance at Santa Fe Gravel Company. Model time-series "Turloch State Park to J9 Bridge @ Waterford (D/S RM 33.1) Segment 6-T_cal," historical time-series "SANTEFE_GRAVEL_RM365_TSF."

Riffle Q3

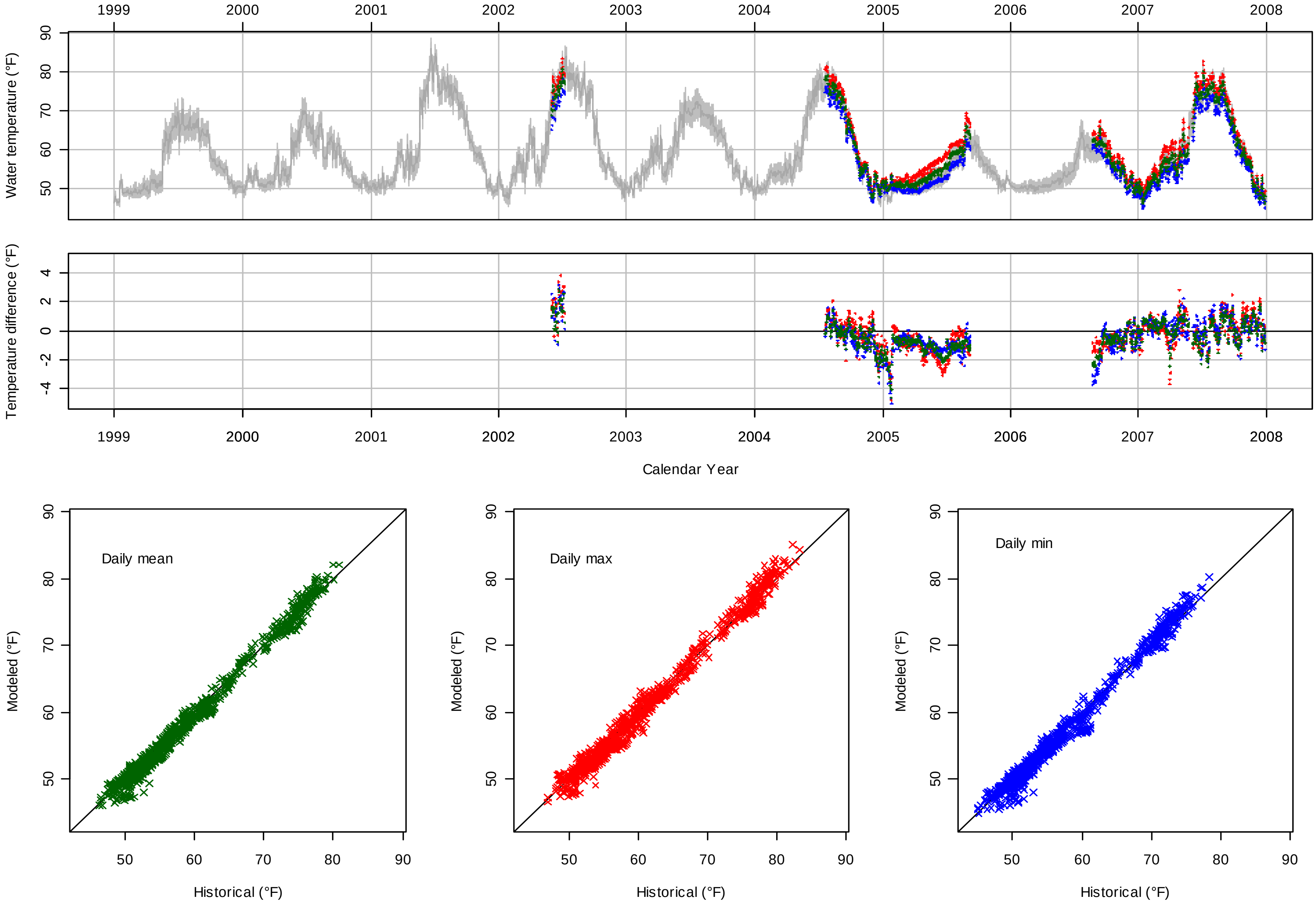

Figure A8. Model performance at Riffle Q3. Model time-series “Turloch State Park to J9 Bridge @ Waterford (D/S RM 33.1) Segment 8-T_cal,” historical time-series “RIFFLE_Q3_RM35_TRQ3.”

Hickman Bridge

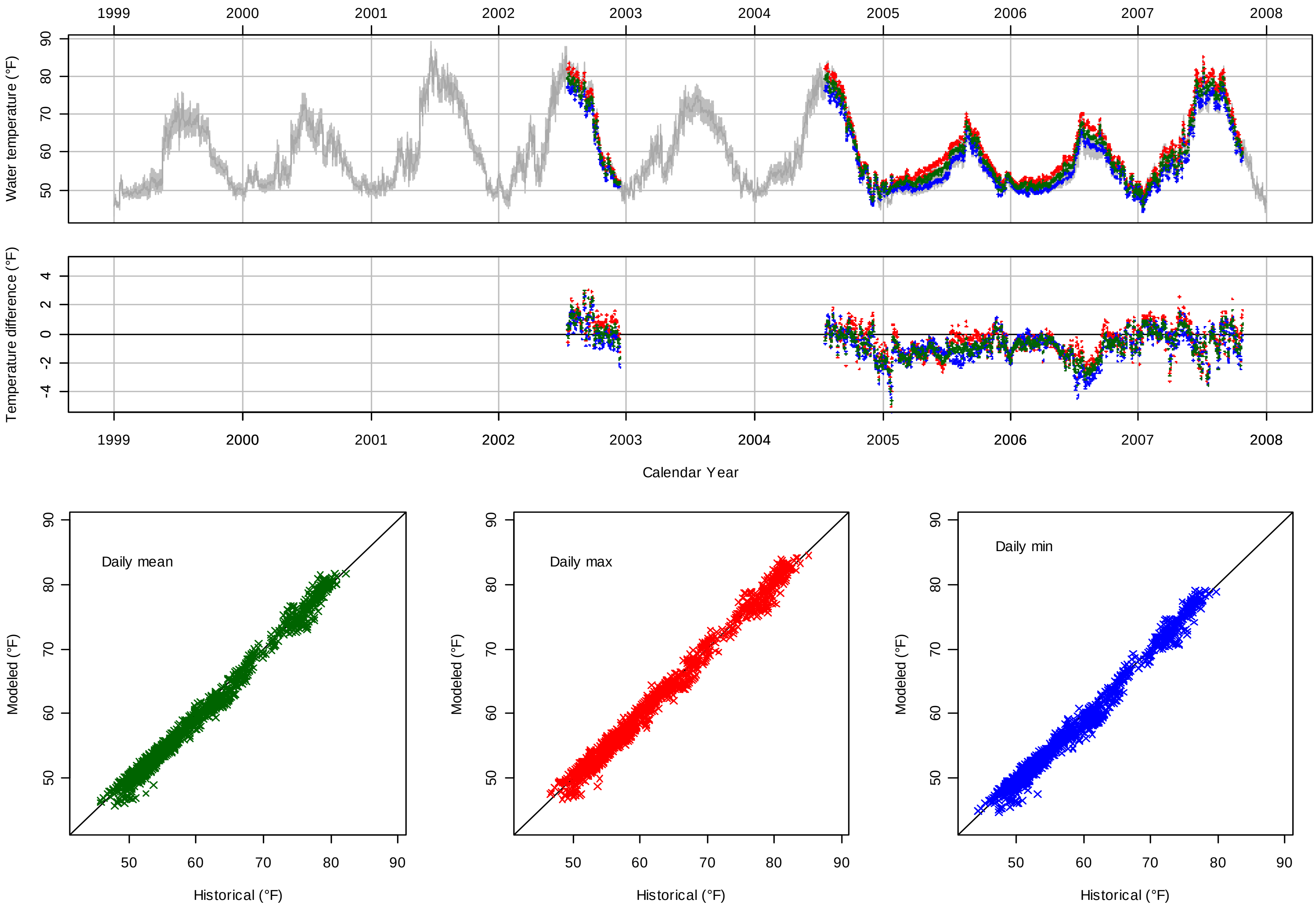

Figure A9. Model performance at Hickman Bridge. Model time-series “Turloch State Park to J9 Bridge @ Waterford (D/S RM 33.1) Segment 13-T_cal,” historical time-series “HICKMAN_BRIDGE_THB.”

Fox Grove

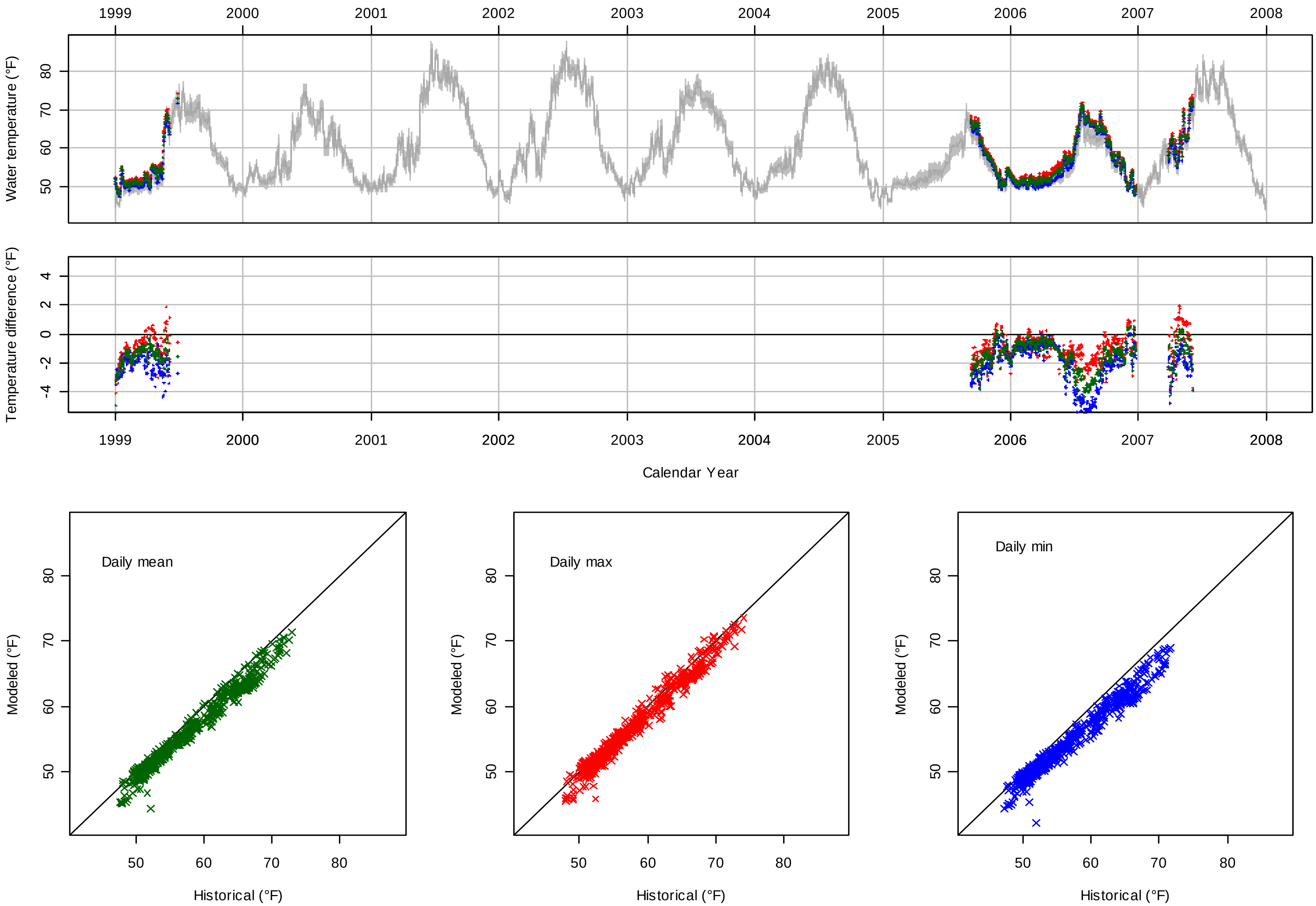

Figure A10. Model performance at Fox Grove. Model time-series “J9 Bridge @ Waterford to Santa Fe Ave Br (D/S RM 22.5) Segment 6-T_cal,” historical time-series “FOX_GROVE_BR_TRFGB.”

Hughson WWTP

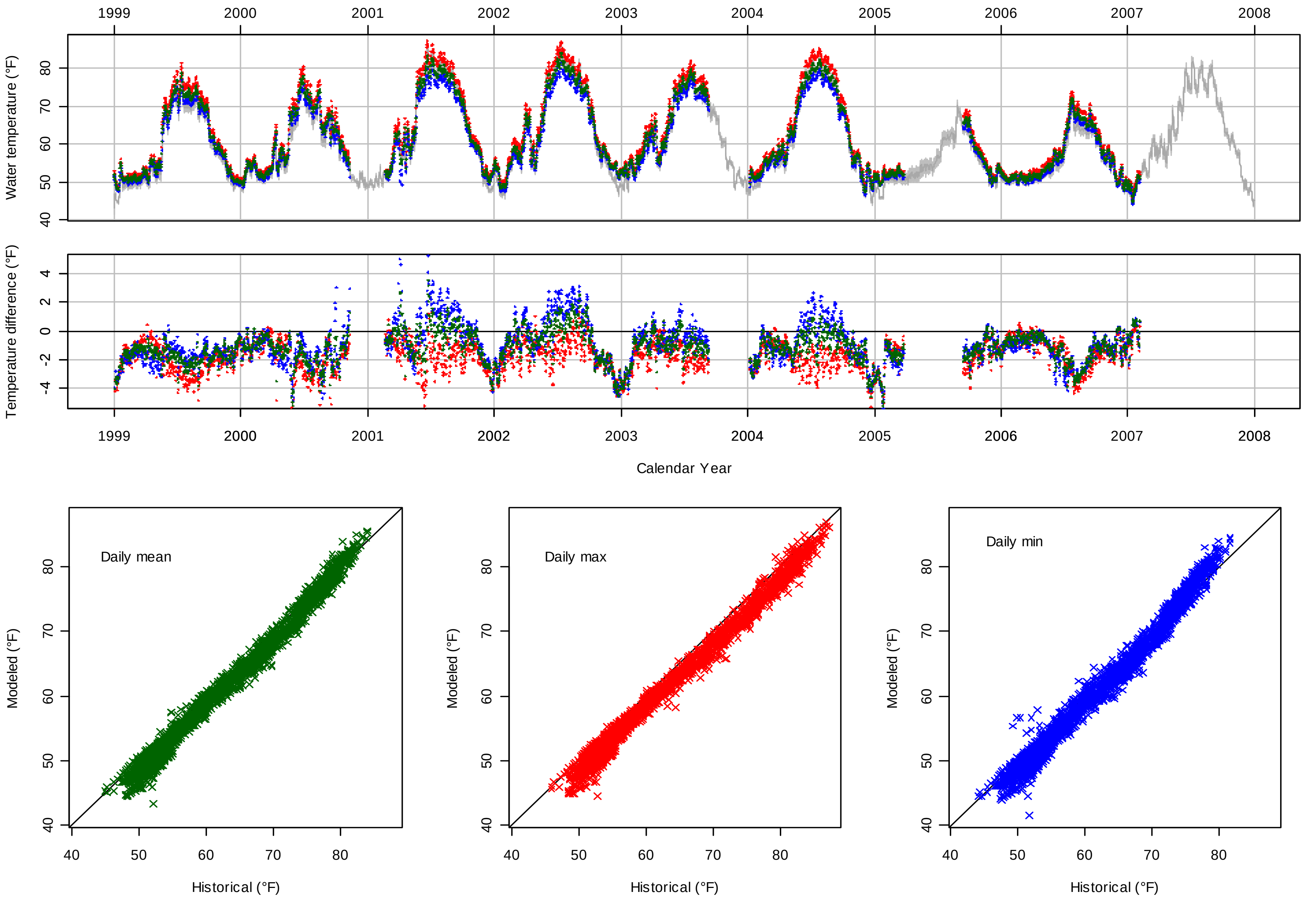

Figure A11. Model performance at Hughson WWTP. Model time-series “J9 Bridge @ Waterford to Santa Fe Ave Br (D/S RM 22.5) Segment 11-T_cal,” historical time-series “HUGHSON_S_RM236_TRHUSN.”

Mitchell Road

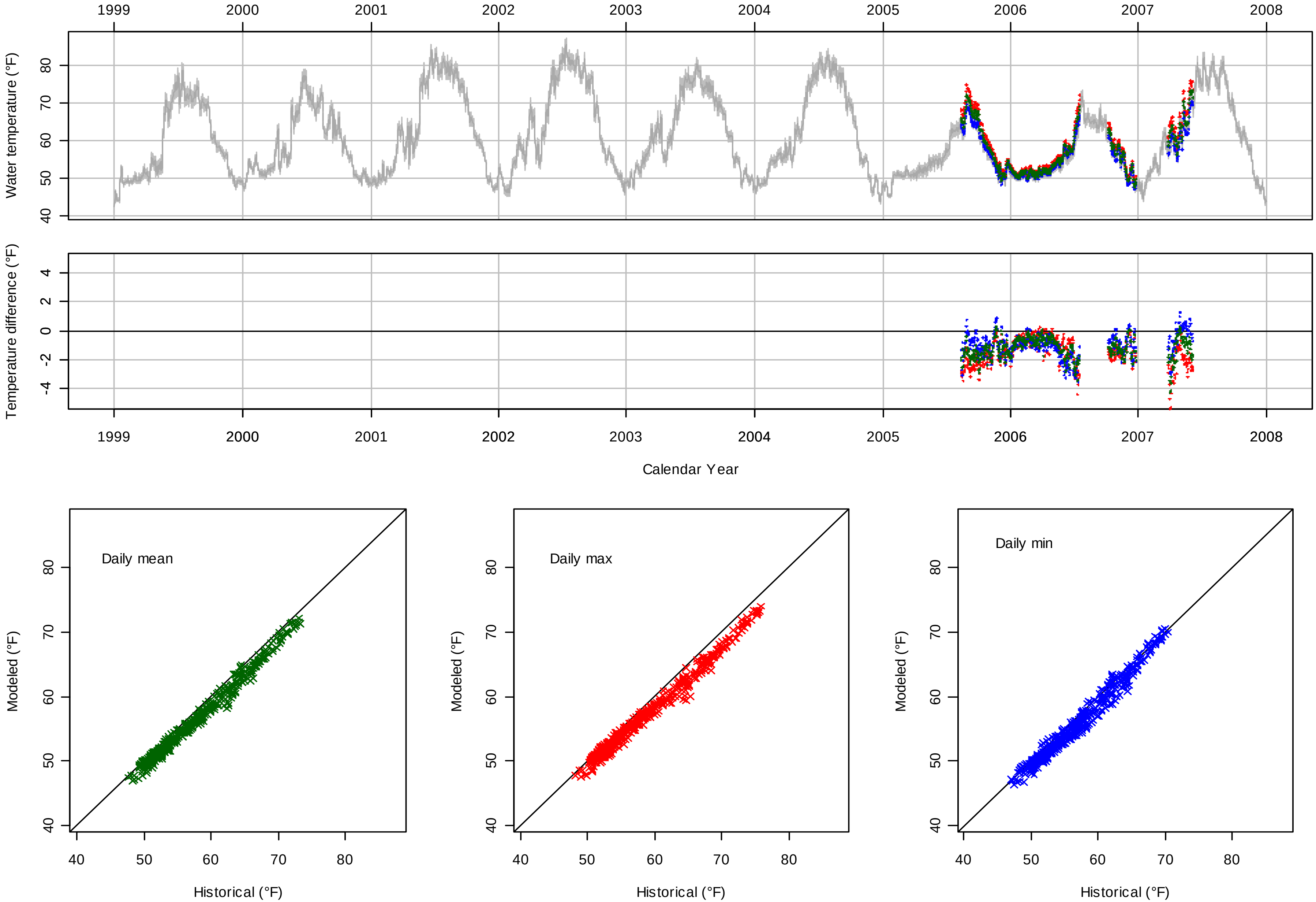

Figure A12. Model performance at Mitchell Road. Model time-series “Santa Fe Ave Br to Hwy 99 Br @ Modesto (D/S RM 16.1) Segment 3-T_cal,” historical time-series “MITCHELL_ROAD_BR_TRMRDB.”

Modesto Gage

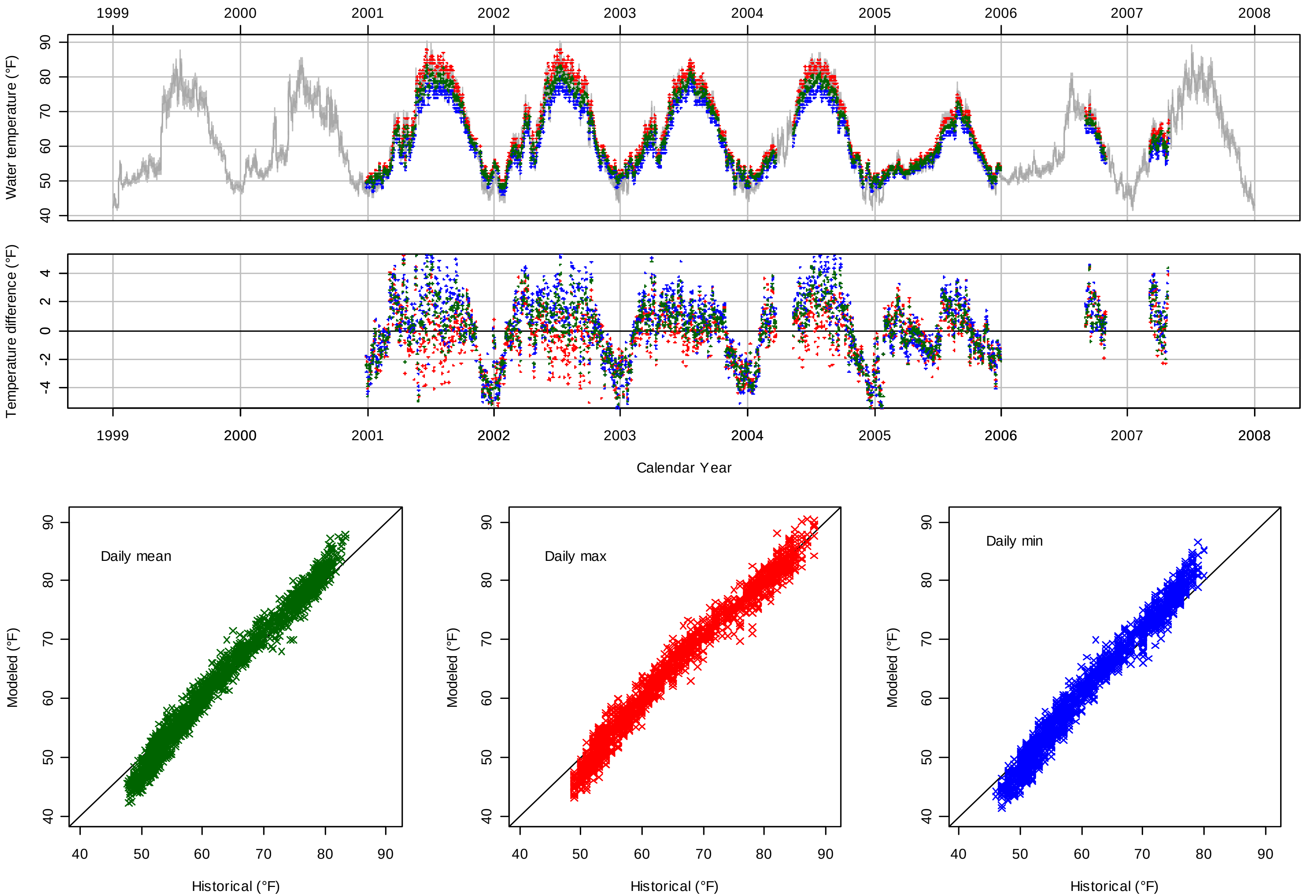

Figure A13. Model performance at Modesto Gage. Model time-series “Hwy 99 Br @ Modesto San Joaquin River (D/S RM 0.0) Segment 0-T_cal,” historical time-series “MOD_MODESTO.”

Carpenter Road

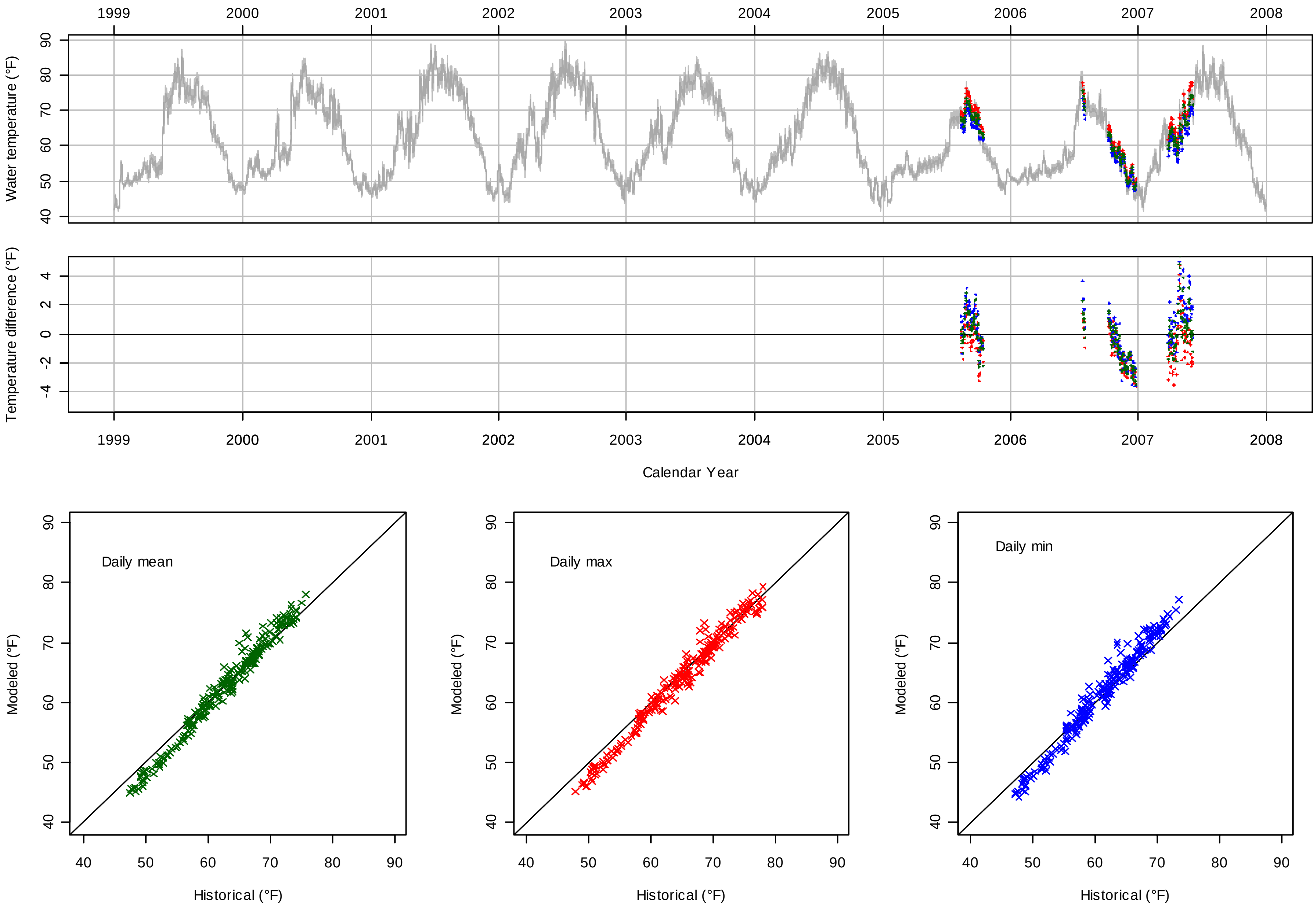

Figure A14. Model performance at Carpenter Road. Model time-series "Hwy 99 Br @ Modesto San Joaquin River (D/S RM 0.0) Segment 3-T_cal," historical time-series "CARPENTER_ROAD_BR_TRCRDB."

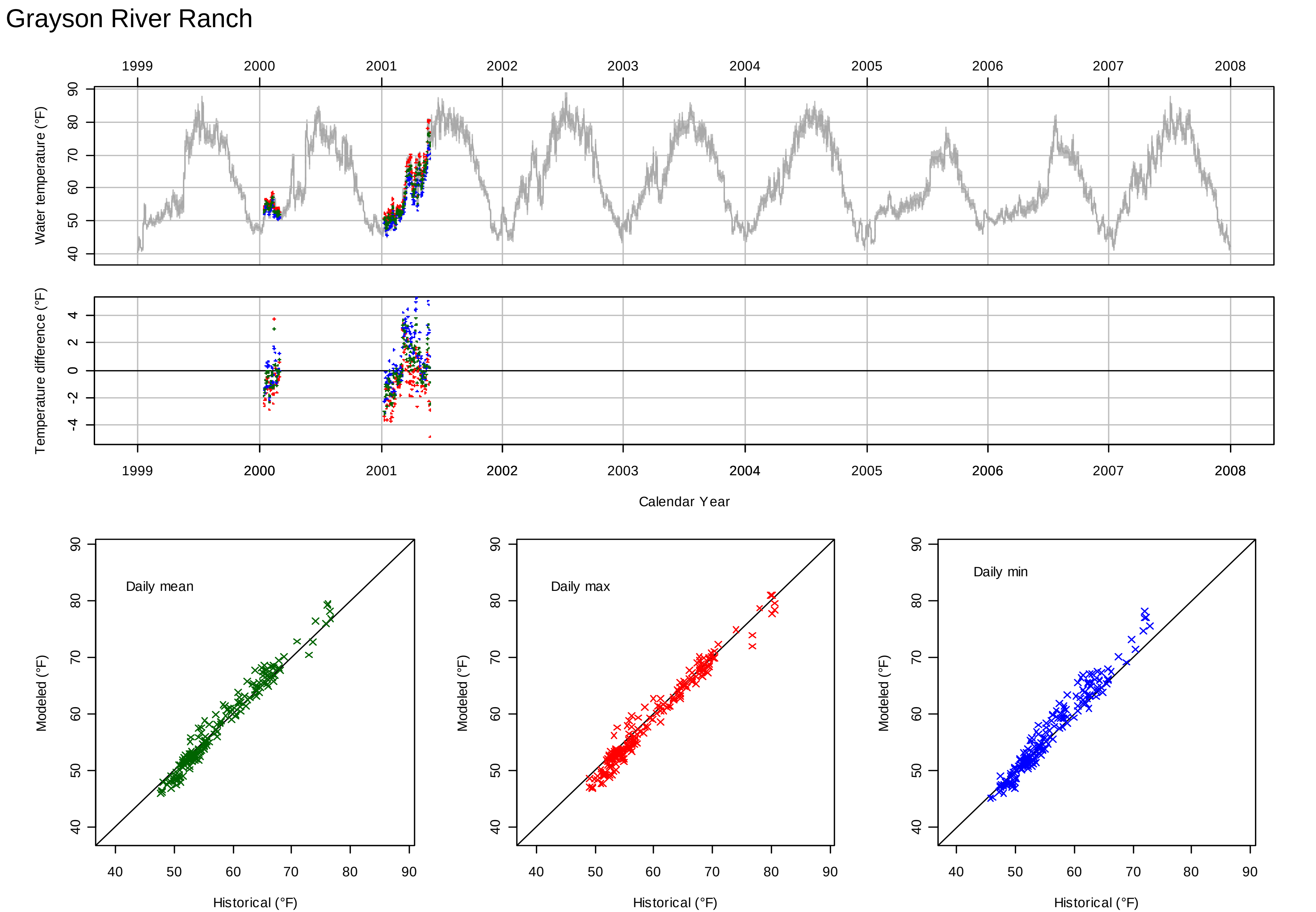

Figure A15. Model performance at Grayson River Ranch. Model time-series “Hwy 99 Br @ Modesto San Joaquin River (D/S RM 0.0) Segment 12-T_cal,” historical time-series “GRAYSON_ROTARY_RM3_TRST.”

Shiloh Bridge

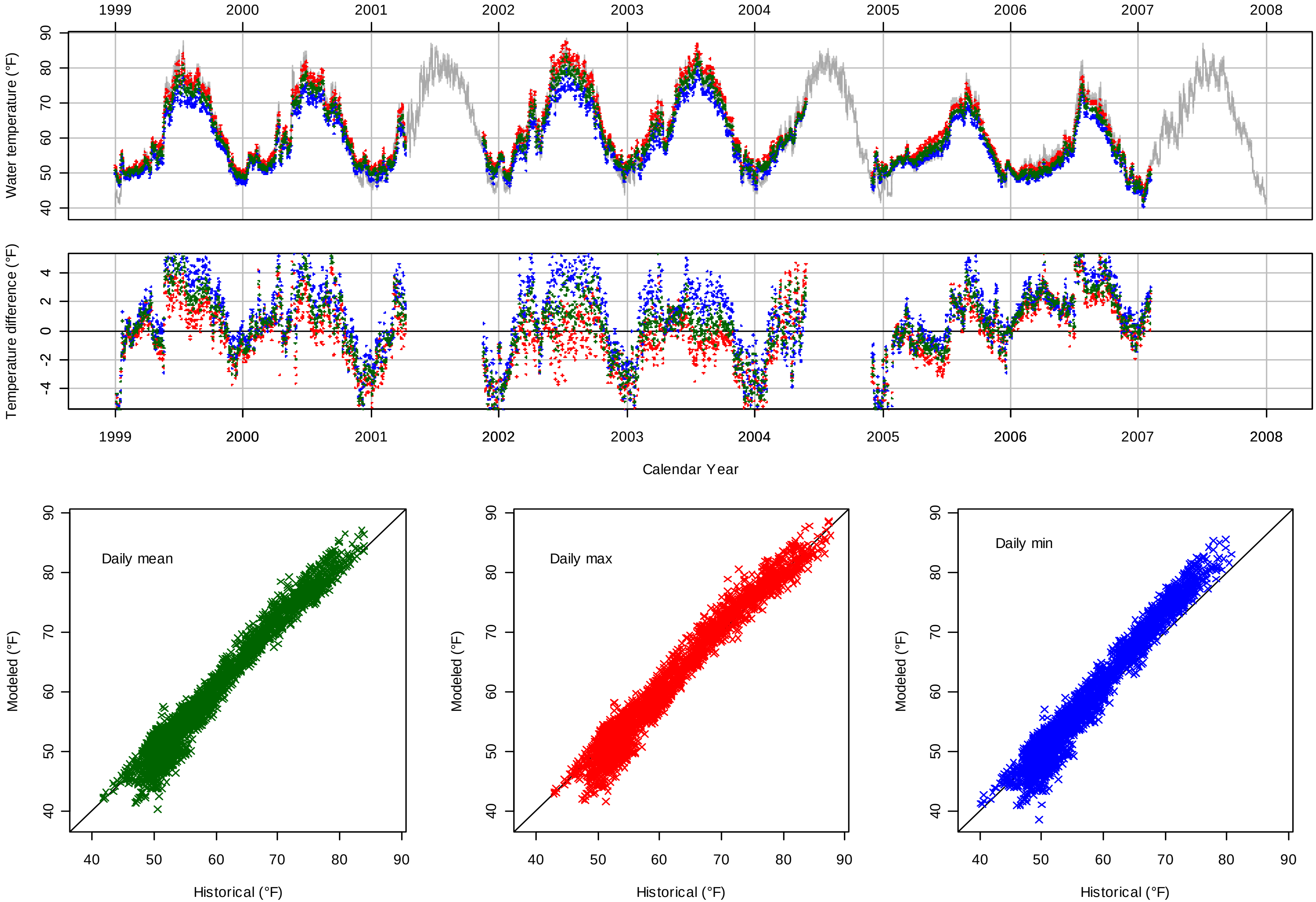

Figure A16. Model performance at Shiloh Bridge. Model time-series “Hwy 99 Br @ Modesto San Joaquin River (D/S RM 0.0) Segment 14-T_cal,” historical time-series “SHILOH_BR_RM34_TRSHILO2.”

Appendix B

HEC-5Q Modeled water temperatures (1999-2007) vs. TID/MID RTM thermograph data

La Grange

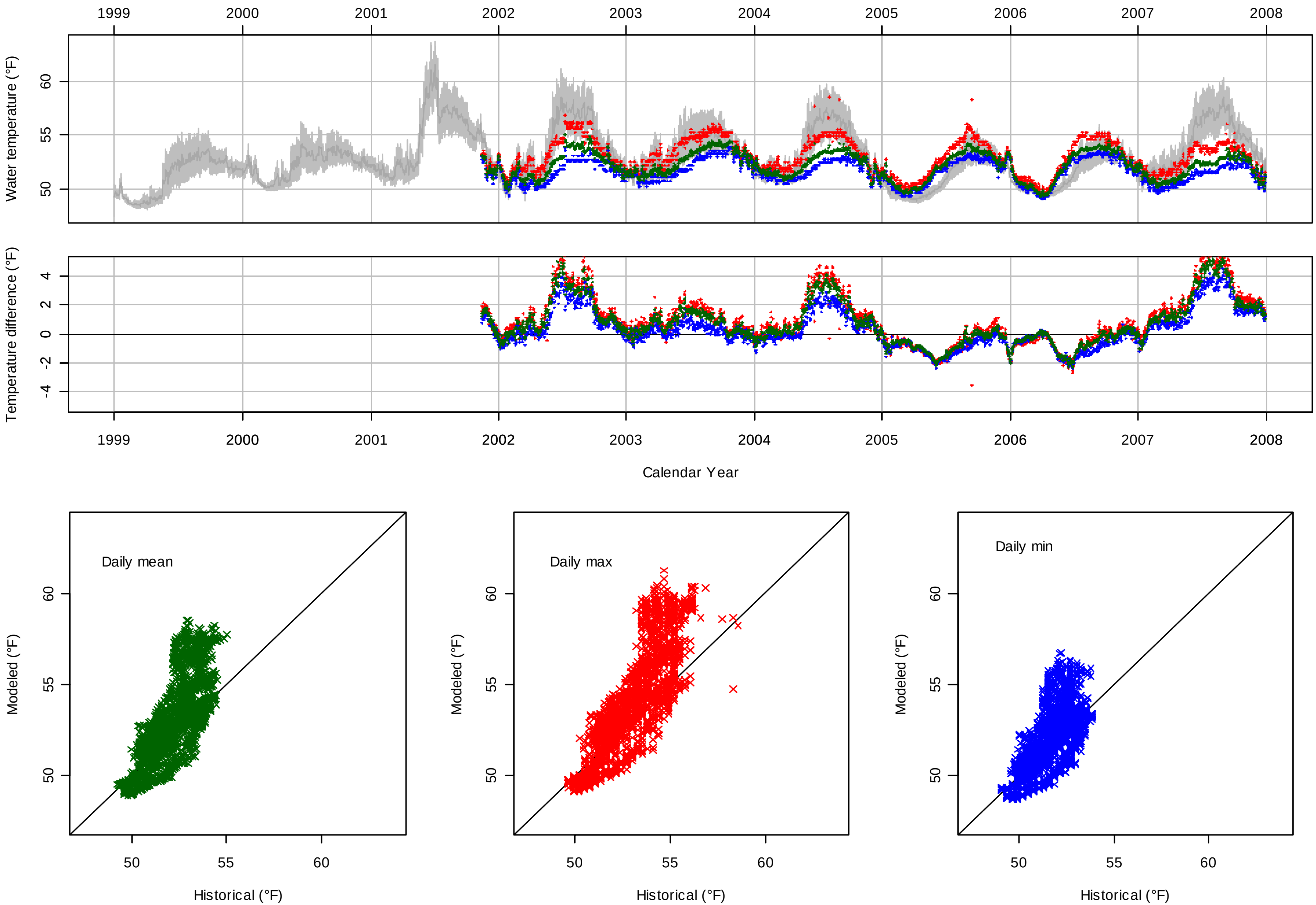

Figure B1. Model performance at La Grange Bridge. Historical time-series for RTM thermograph, modeled time-series for segment nearest river mile 51.8.

Riffle A7

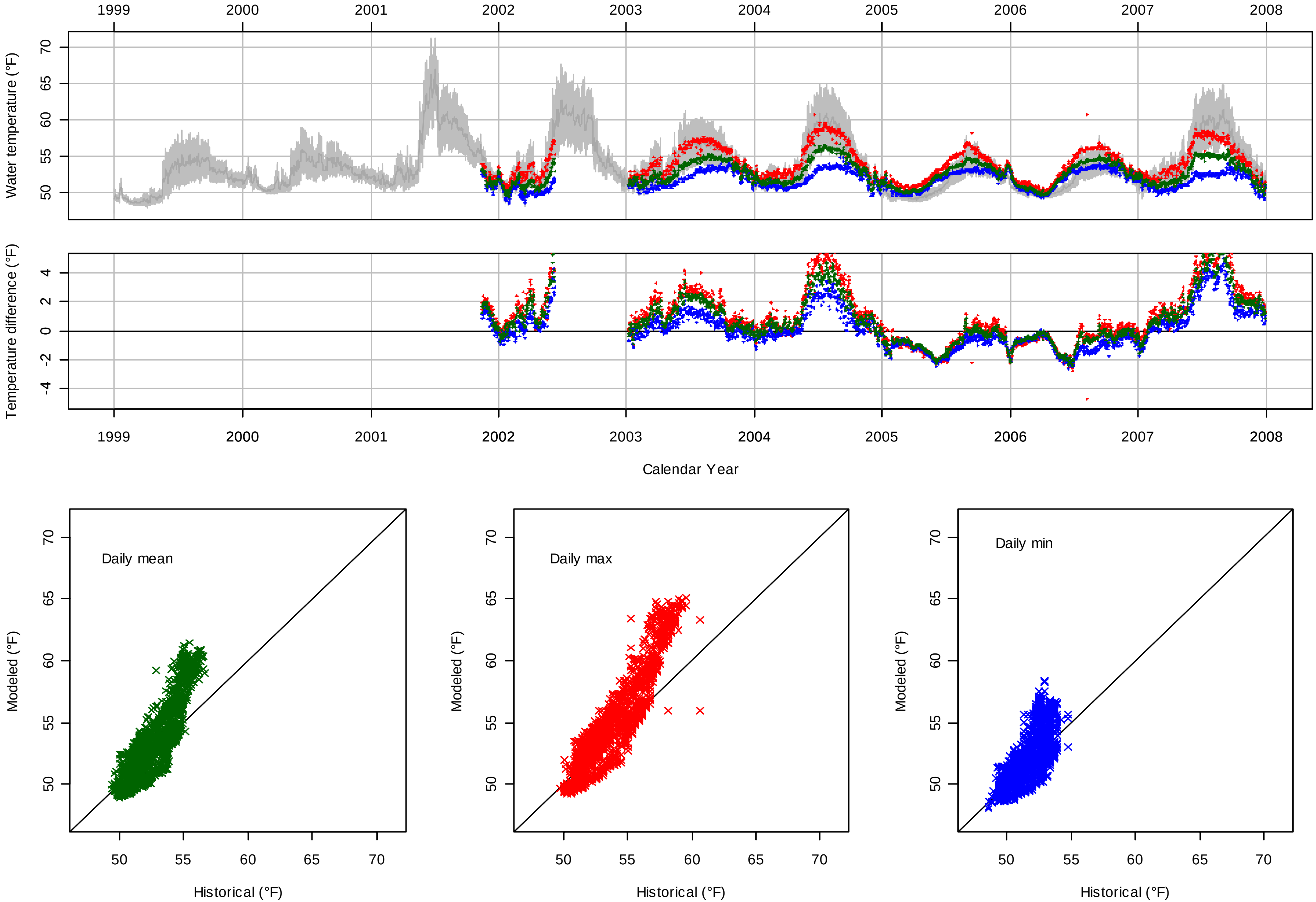

Figure B2. Model performance at Riffle A7. Historical time-series for RTM thermograph, modeled time-series for segment nearest river mile 50.7.

Riffle 3B

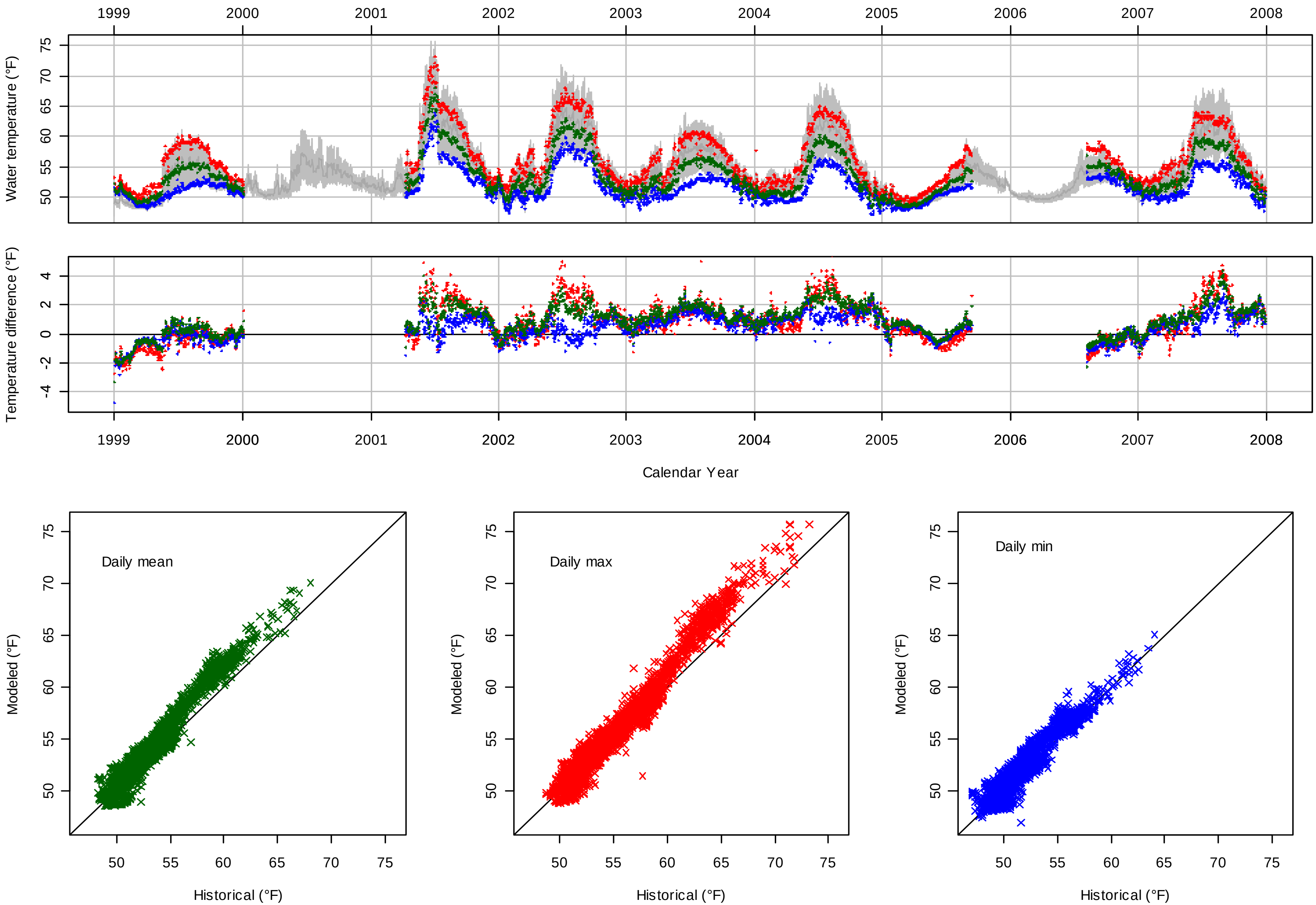

Figure B3. Model performance at Riffle 3B. Historical time-series for RTM thermograph, modeled time-series for segment nearest river mile 49.1.

Riffle 13B

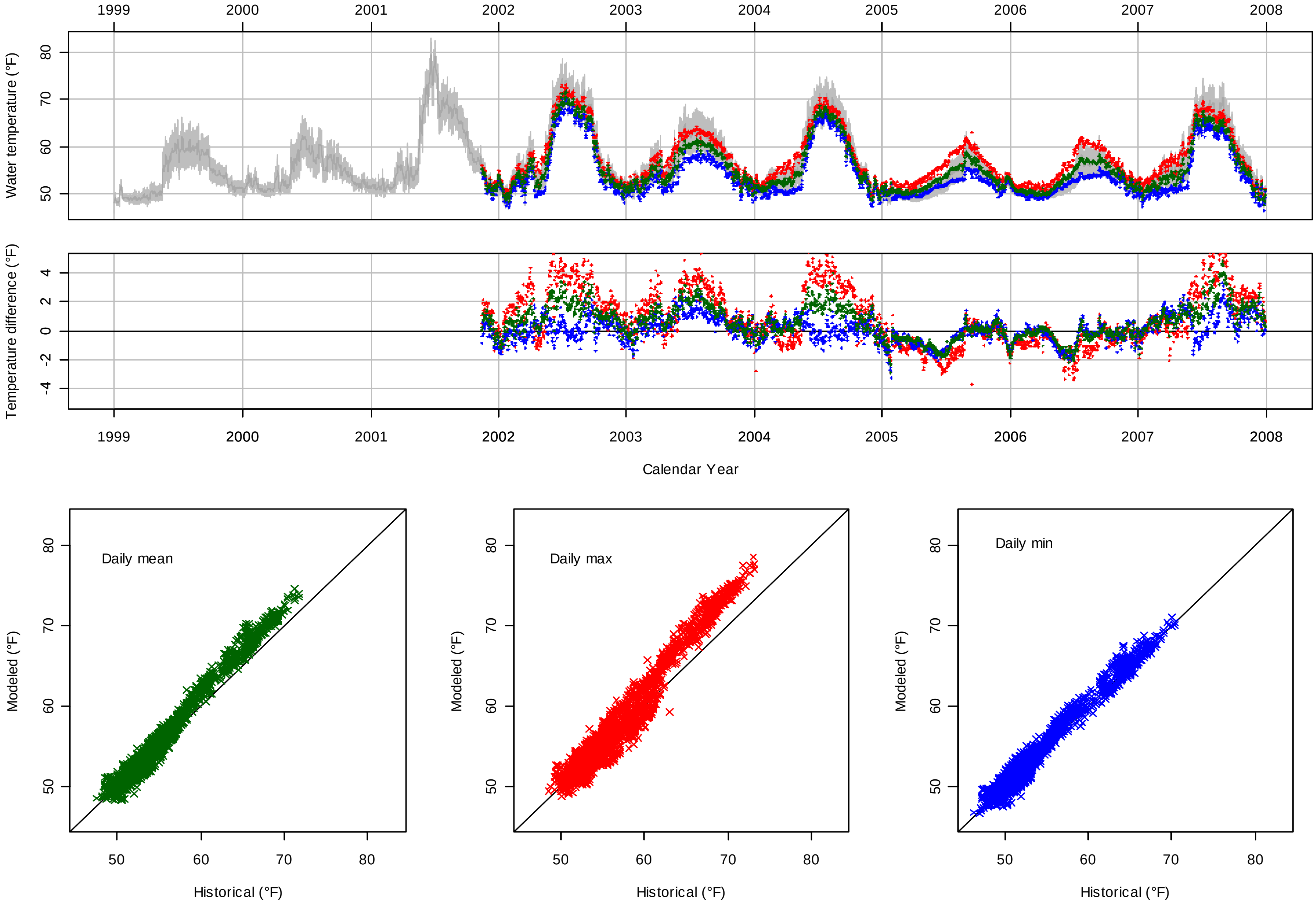

Figure B4. Model performance at Riffle 13B. Historical time-series for RTM thermograph, modeled time-series for segment nearest river mile 45.5.

Riffle 19

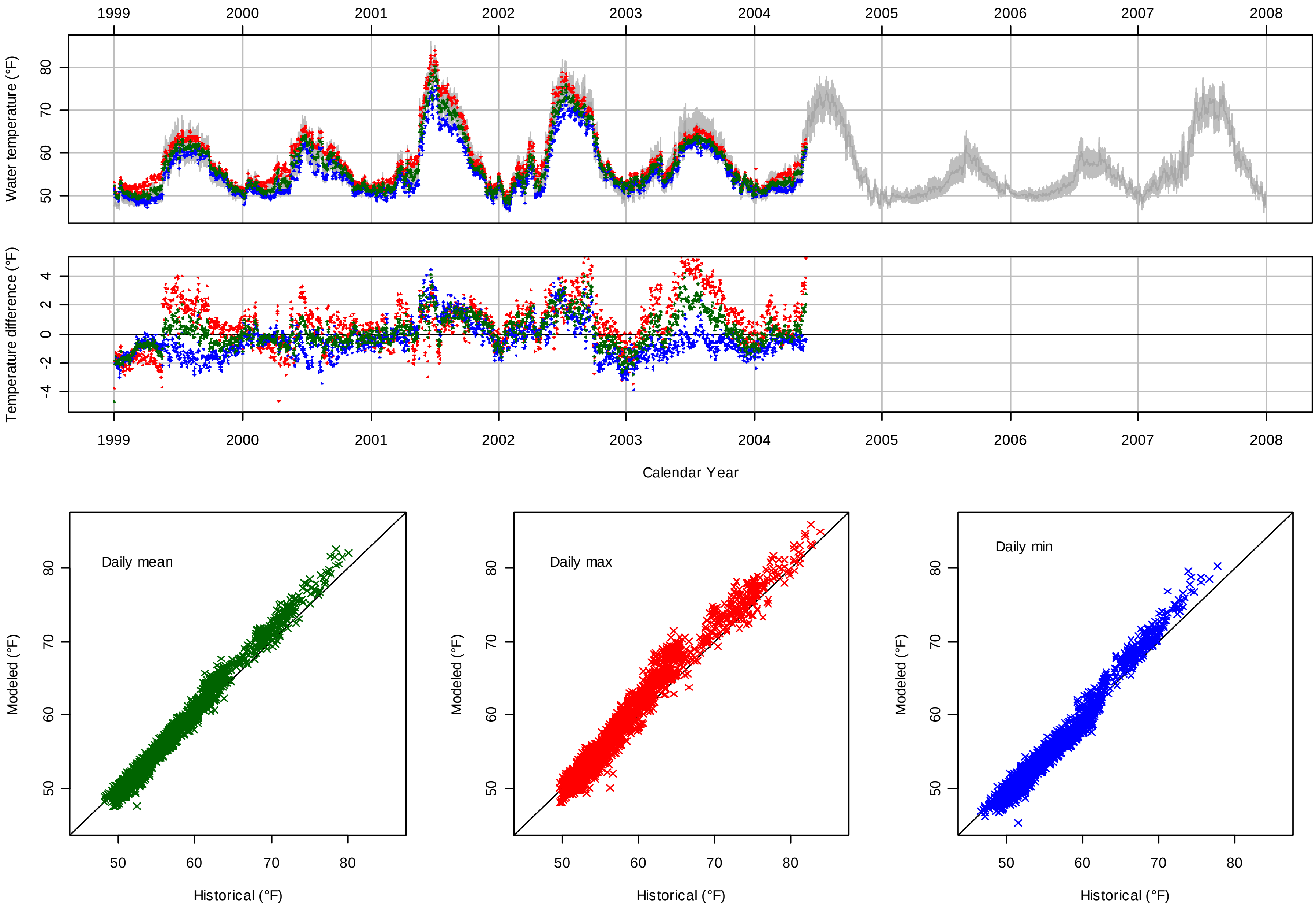

Figure B5. Model performance at Riffle 19. Historical time-series for RTM thermograph, modeled time-series for segment nearest river mile 43.3.

Riffle 21

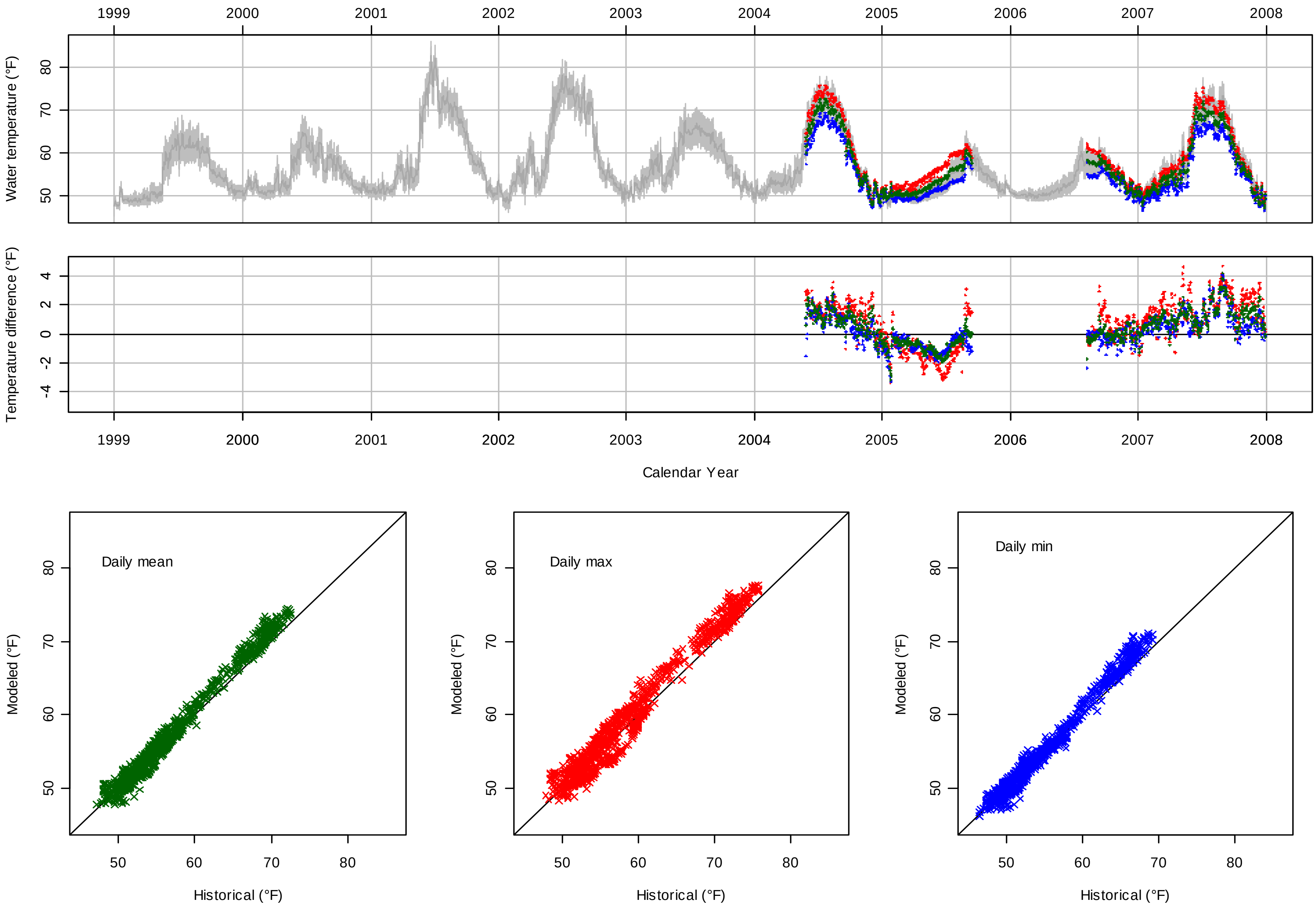

Figure B6. Model performance at Riffle 21. Historical time-series for RTM thermograph, modeled time-series for segment nearest river mile 42.9.

Roberts Ferry Bridge

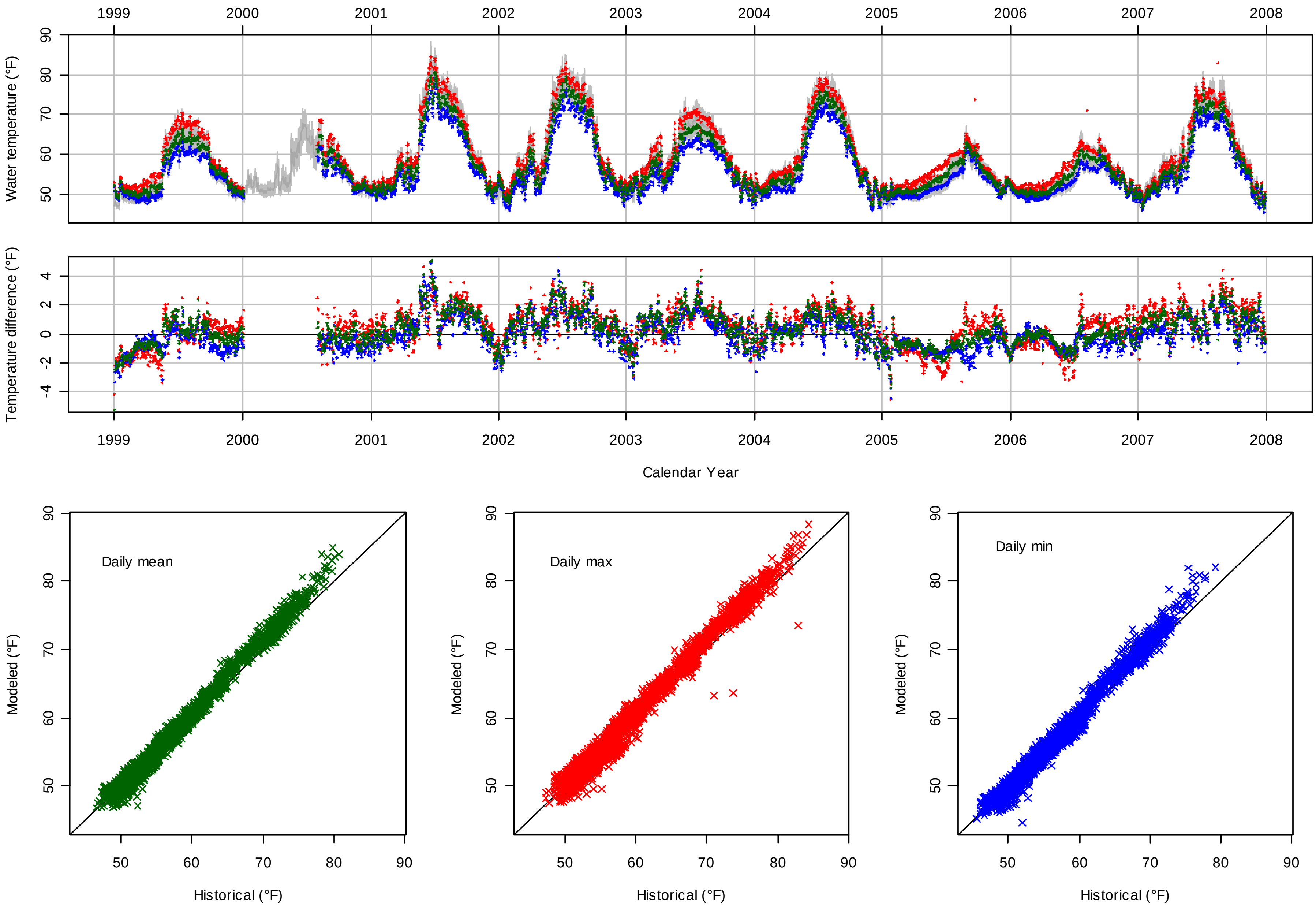

Figure B7. Model performance at Roberts Ferry Bridge. Historical time-series for RTM thermograph, modeled time-series for segment nearest river mile 39.5.

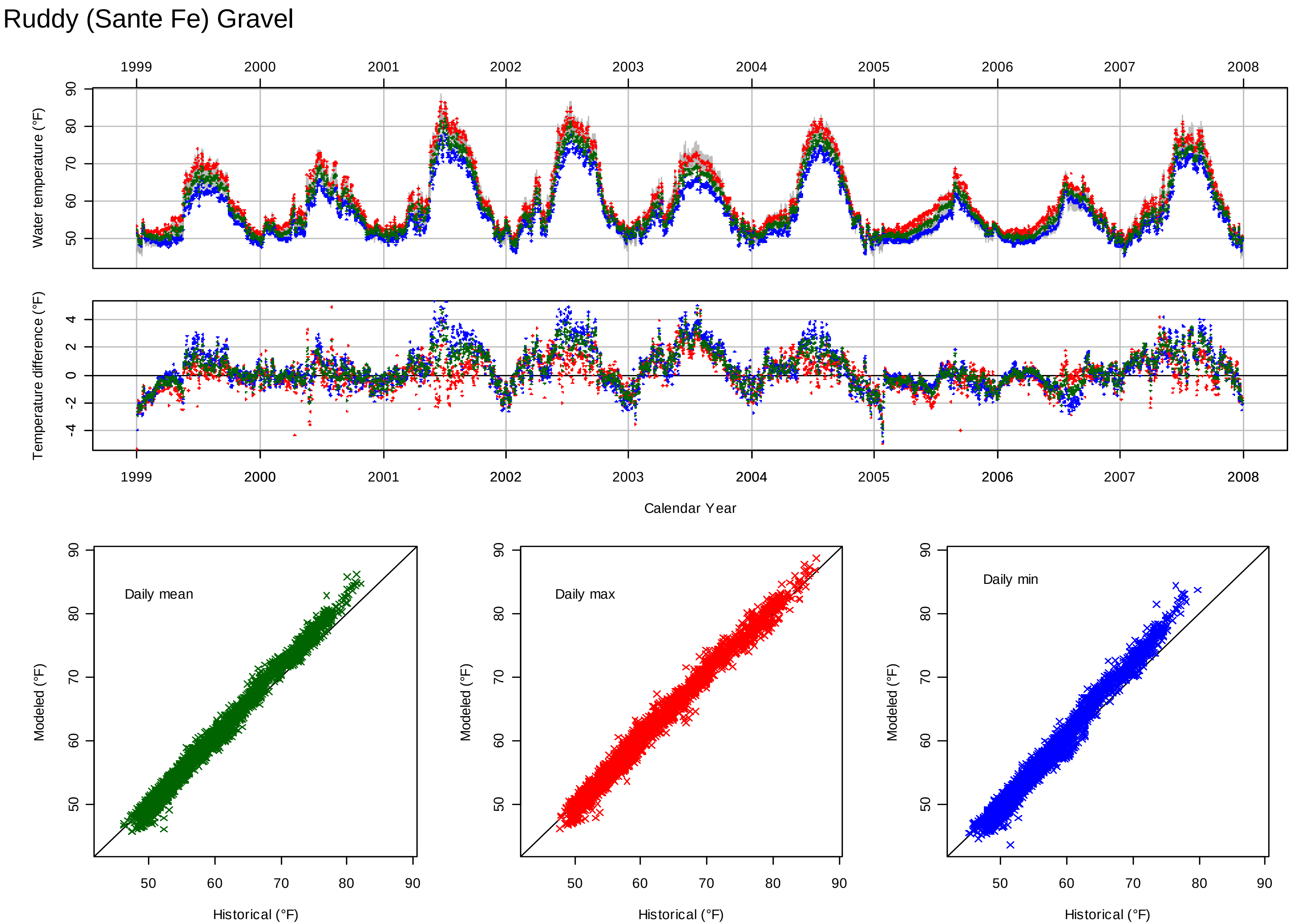

Figure B8. Model performance at Ruddy Gravel. Historical time-series for RTM thermograph, modeled time-series for segment nearest river mile 36.5.

Fox Grove

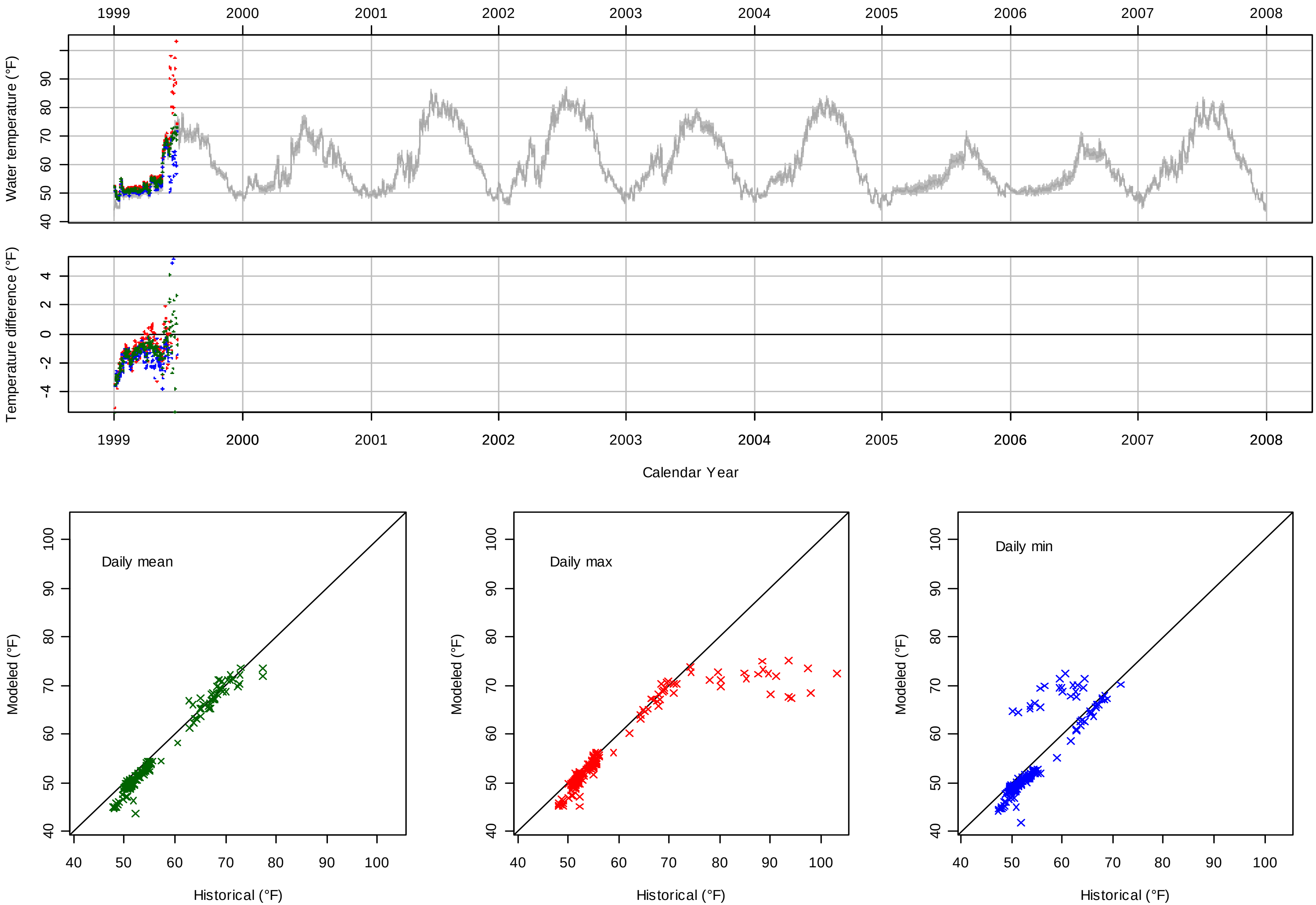

Figure B9. Model performance at Fox Grove. Historical time-series for RTM thermograph, modeled time-series for segment nearest river mile 26.1.

Hughson WWTP

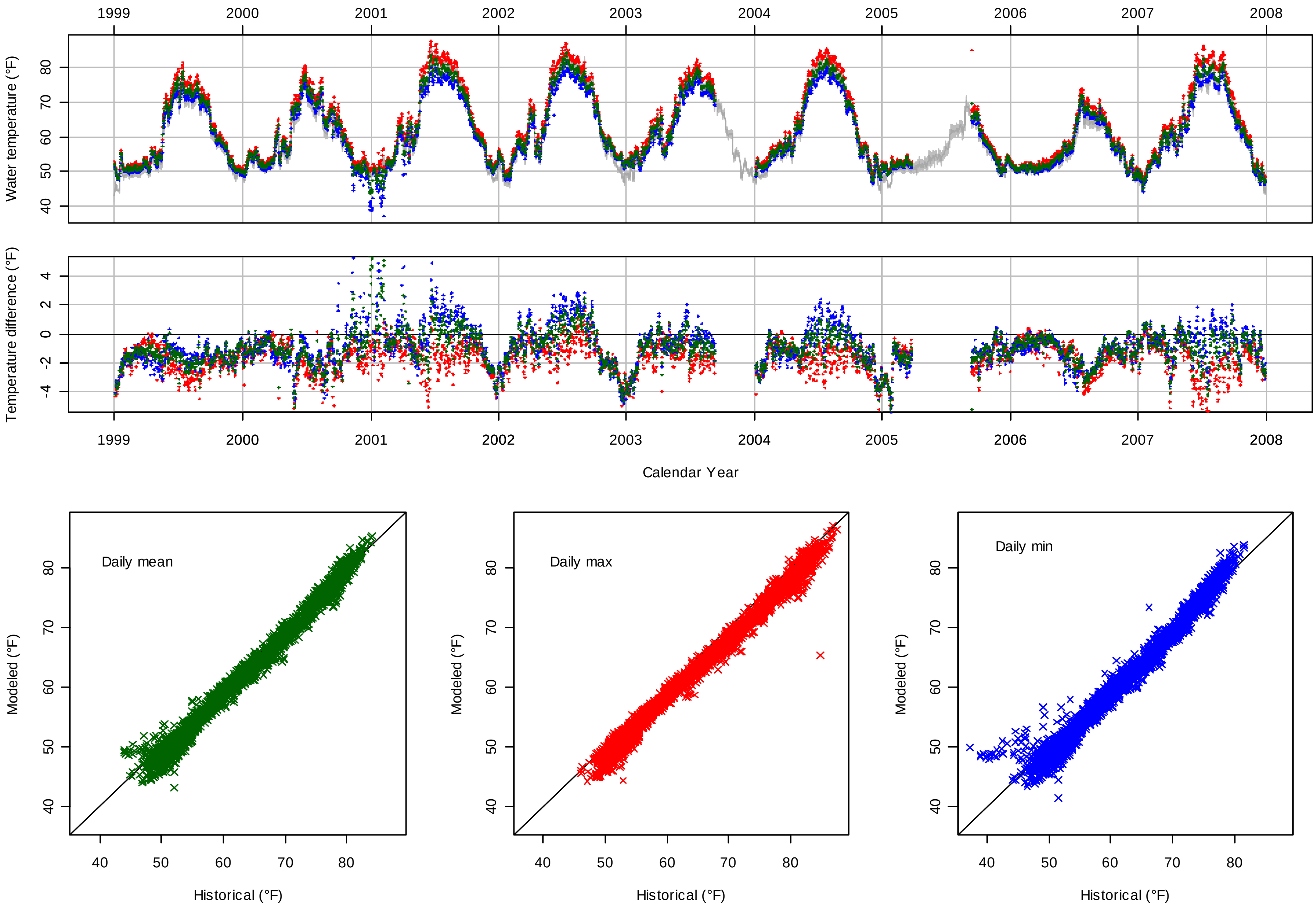

Figure B10. Model performance at Hughson WWTP. Historical time-series for RTM thermograph, modeled time-series for segment nearest river mile 23.6.

Shiloh Bridge

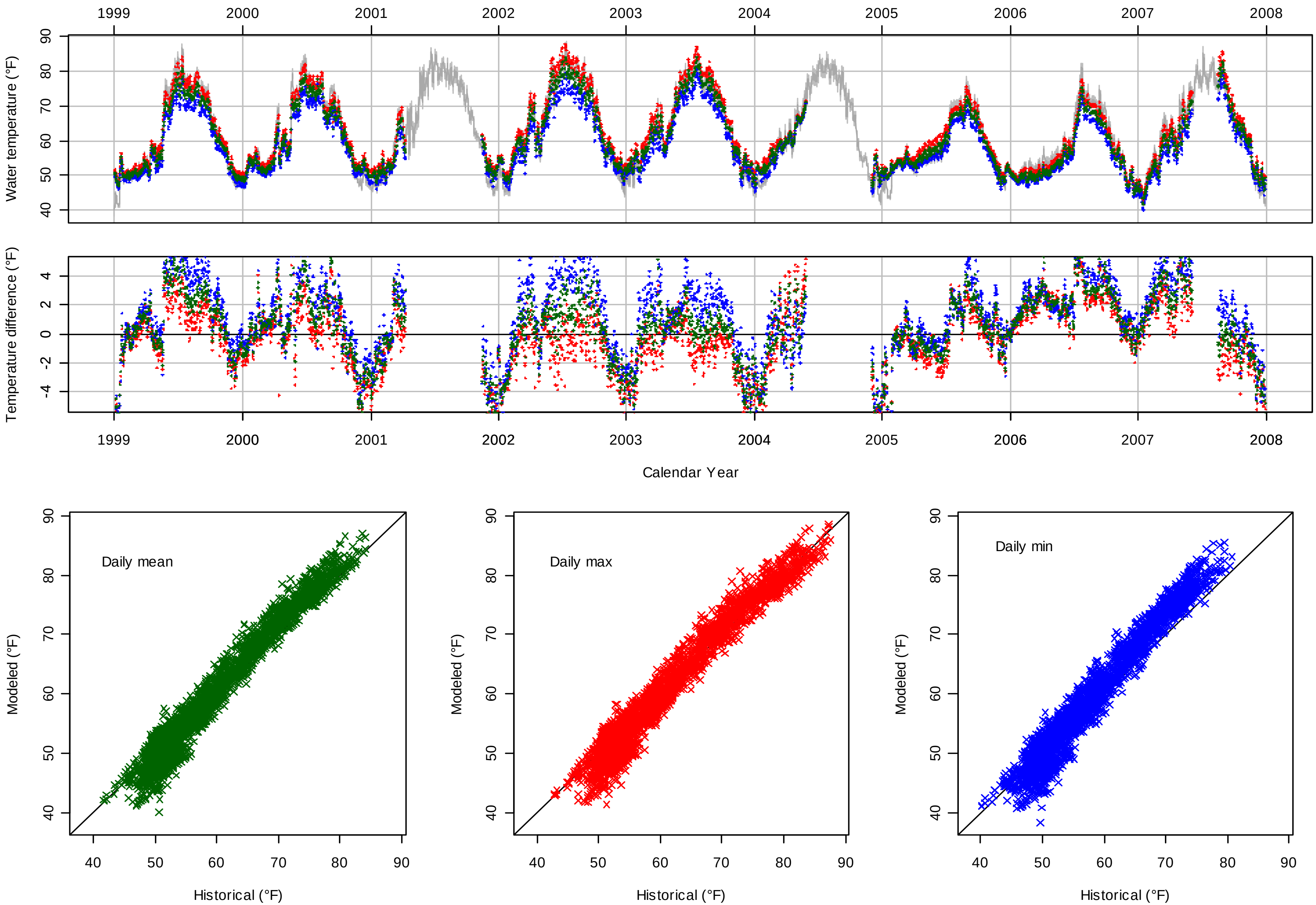

Figure B11. Model performance at Shiloh Bridge. Historical time-series for RTM thermograph, modeled time-series for segment nearest river mile 3.5.

Appendix C

Comparison of CDFG HWMS and TID/MID RTM thermograph data (1999–2007)

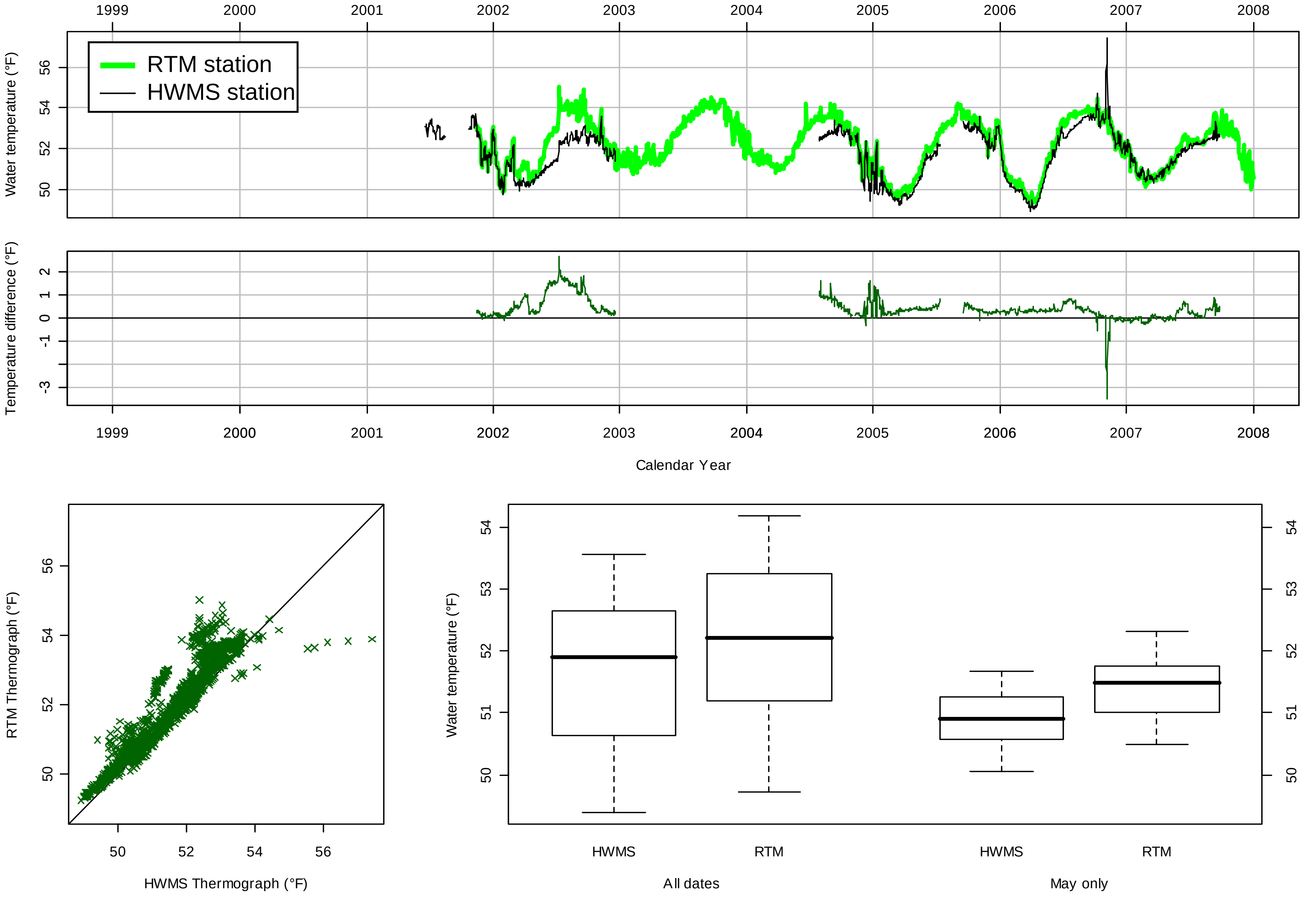

Figure C1. Comparison of thermograph records at the HWMS site “Riffle A1” (RM 51.6) and the RTM site “La Grange RTM site” (RM 51.8).

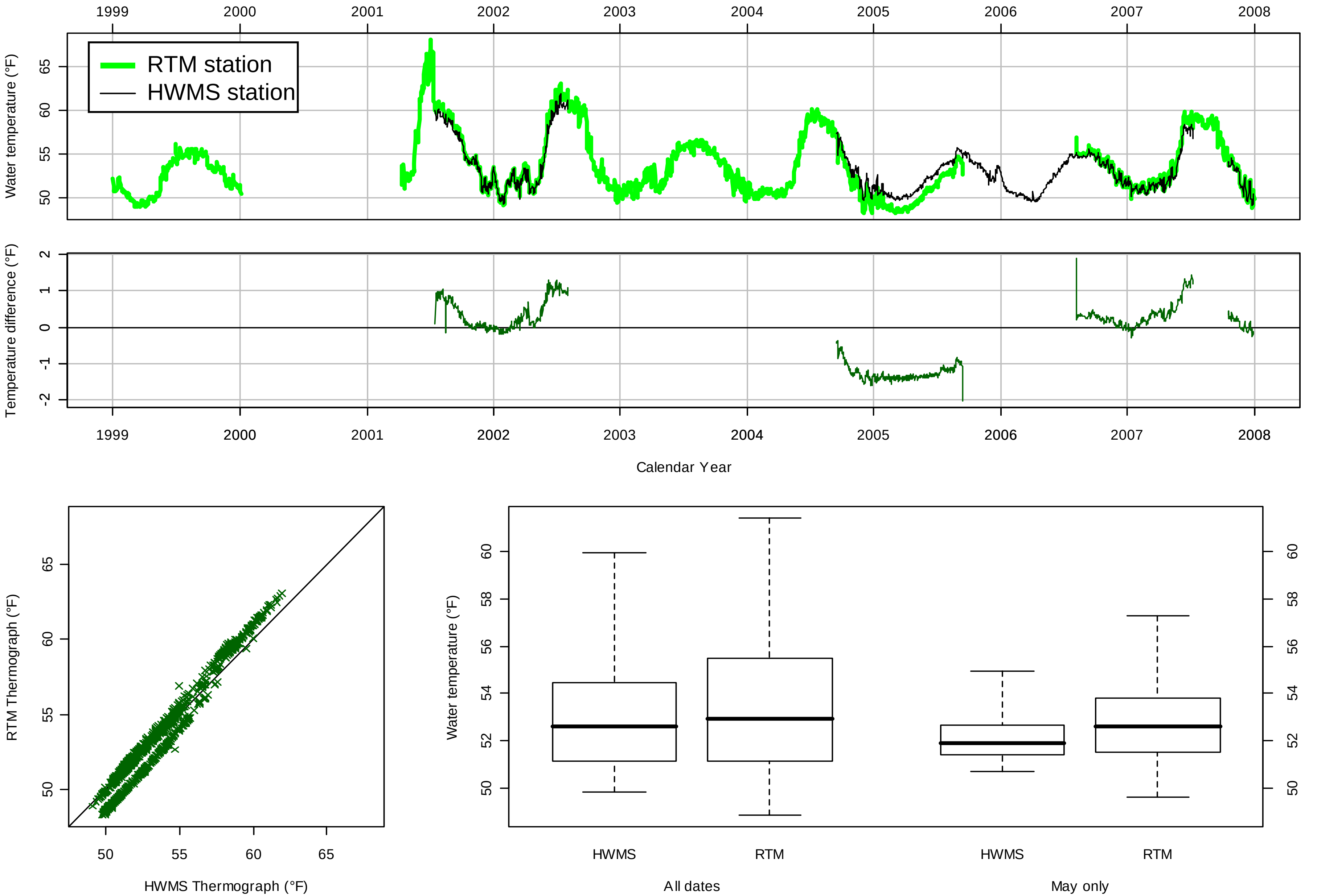

Figure C2. Comparison of thermograph records at the HWMS site “Riffle C1” (RM 49.7) and the RTM site “Riffle 3B” (RM 49.1).

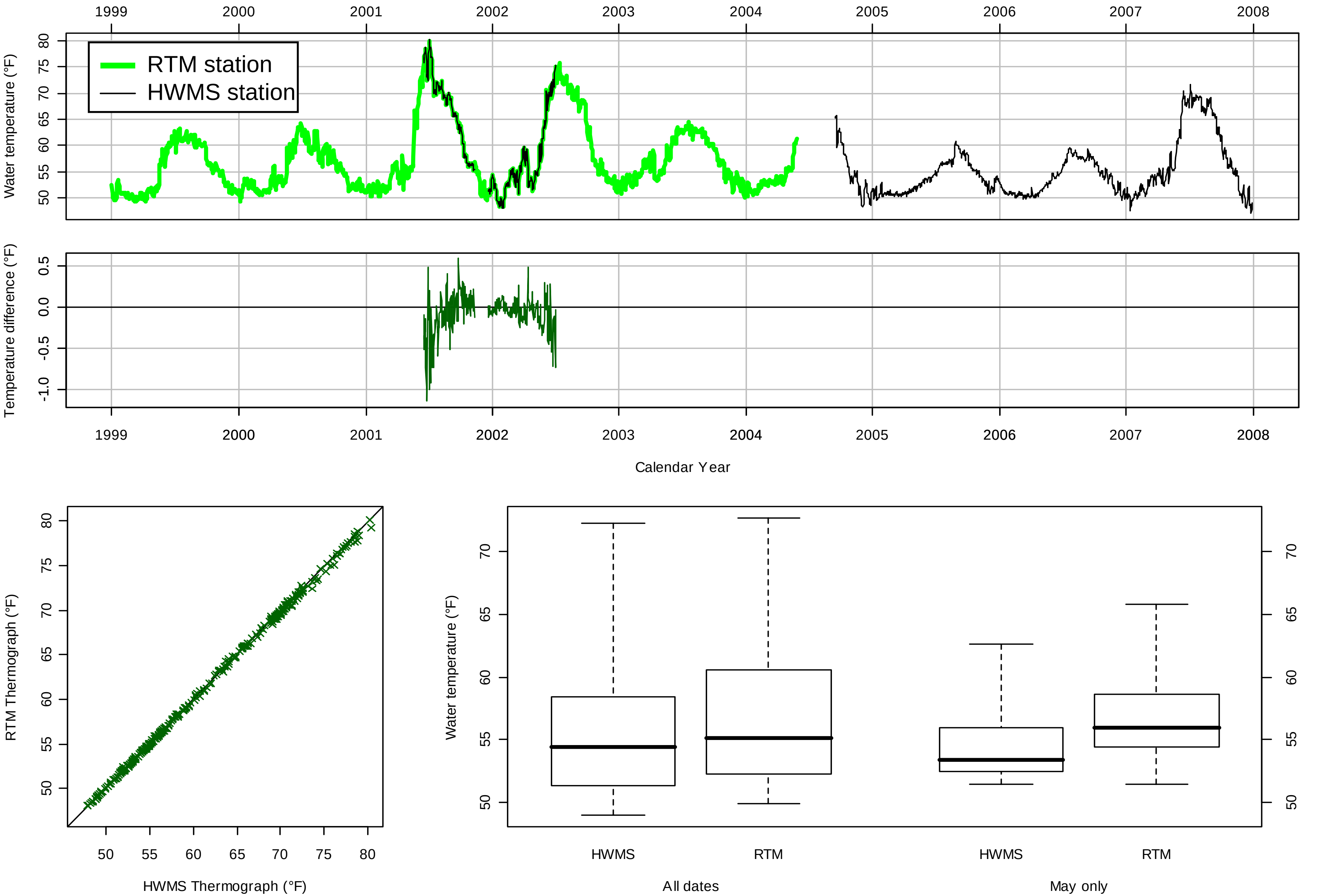

Figure C3. Comparison of thermograph records at the HWMS site “Riffle I2” (RM 43.2) and the RTM site “Riffle 19” (RM 43.3).

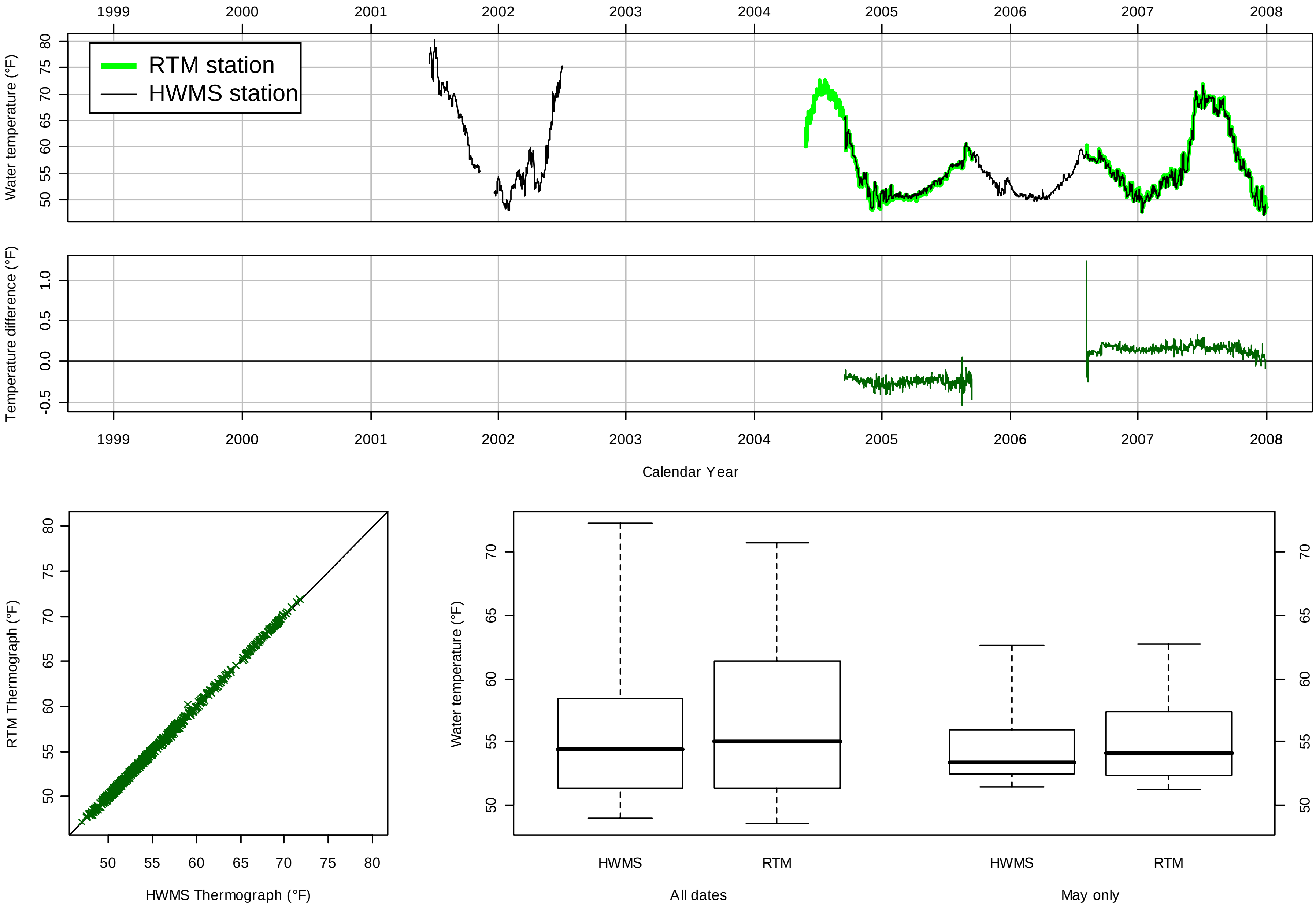

Figure C4. Comparison of thermograph records at the HWMS site “Riffle I2” (RM 43.2) and the RTM site “Riffle 21” (RM 42.9).

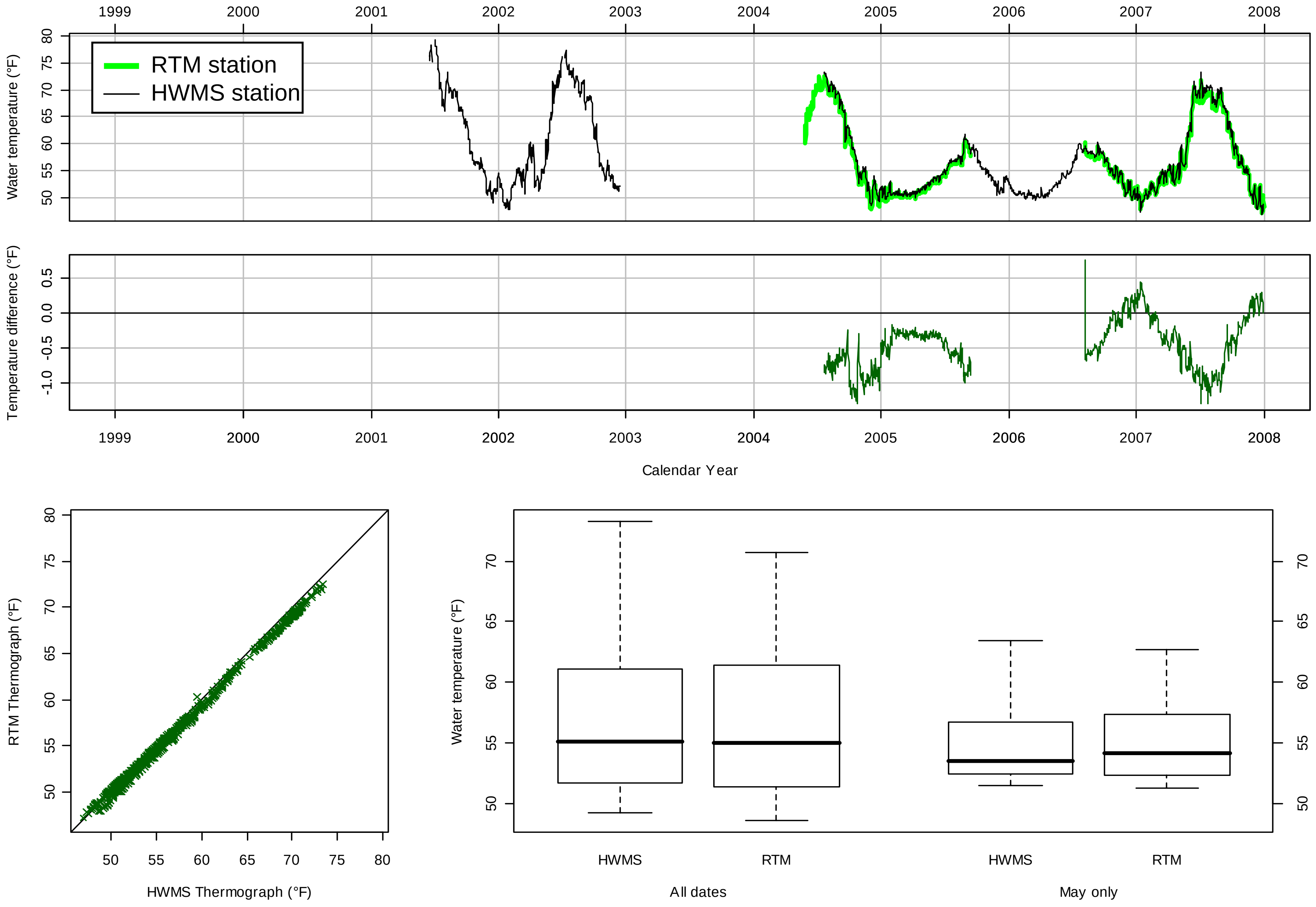

Figure C5. Comparison of thermograph records at the HWMS site “Riffle K1” (RM 42.6) and the RTM site “Riffle 21” (RM 42.9).

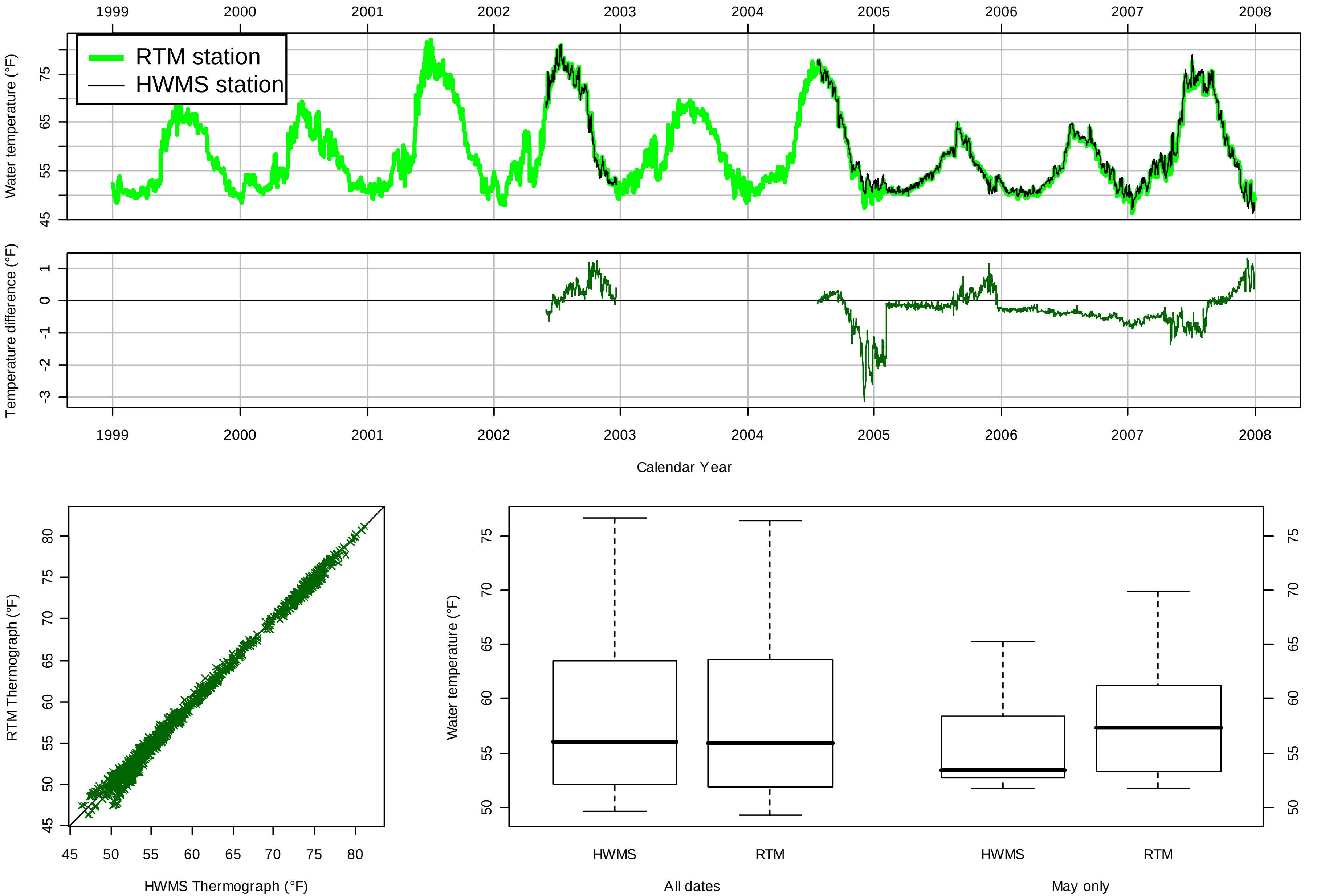

Figure C6. Comparison of thermograph records at the HWMS site “Santa Fe Gravel” (RM 36.5) and the RTM site “Ruddy (Sante Fe) Gravel” (RM 36.5).

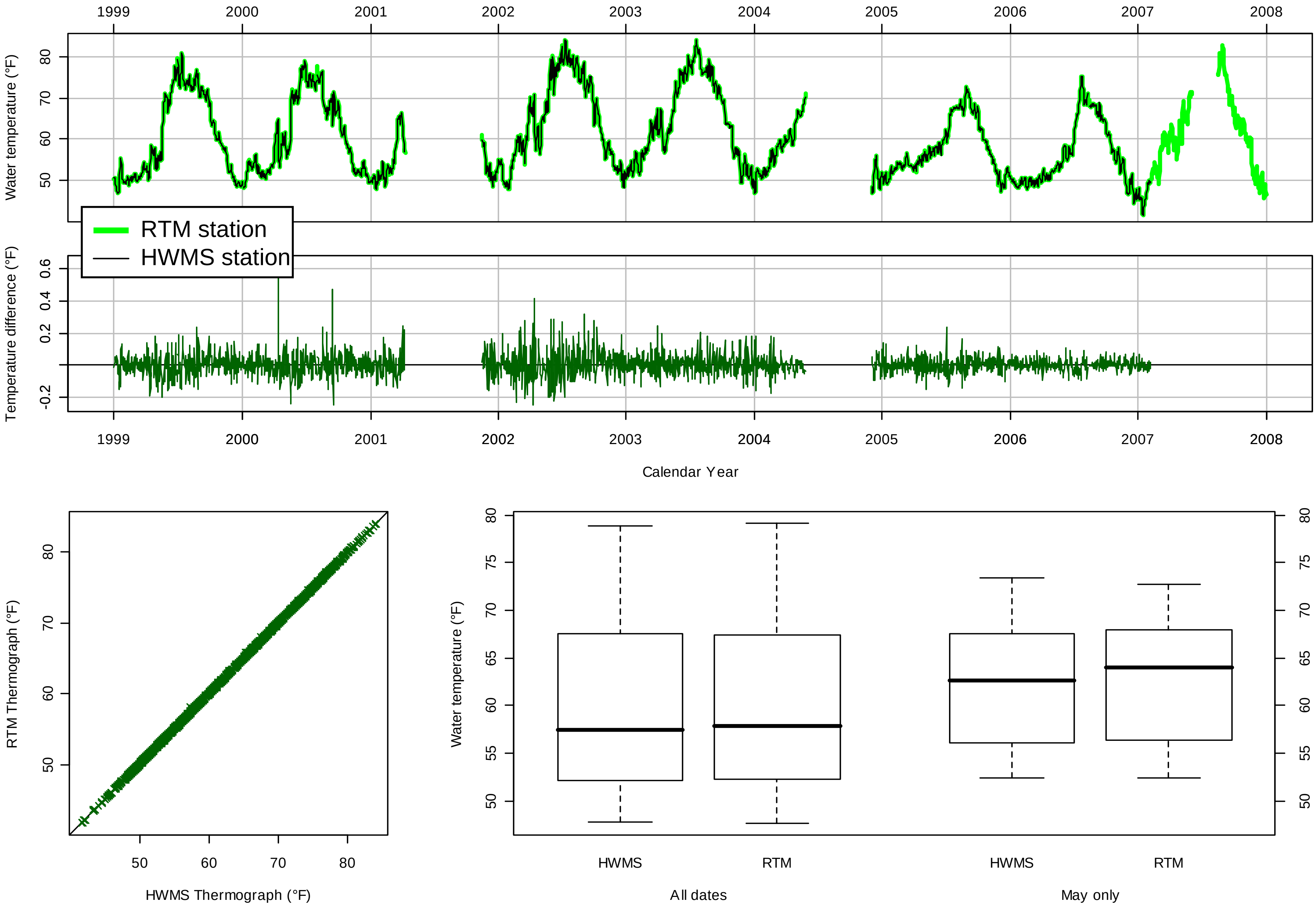

Figure C7. Comparison of thermograph records at the HWMS site “Shiloh” (RM 3.5) and the RTM site “Shiloh” (RM 3.5).

Appendix D

HEC-5Q Model prediction error by location and month (1999–2007).

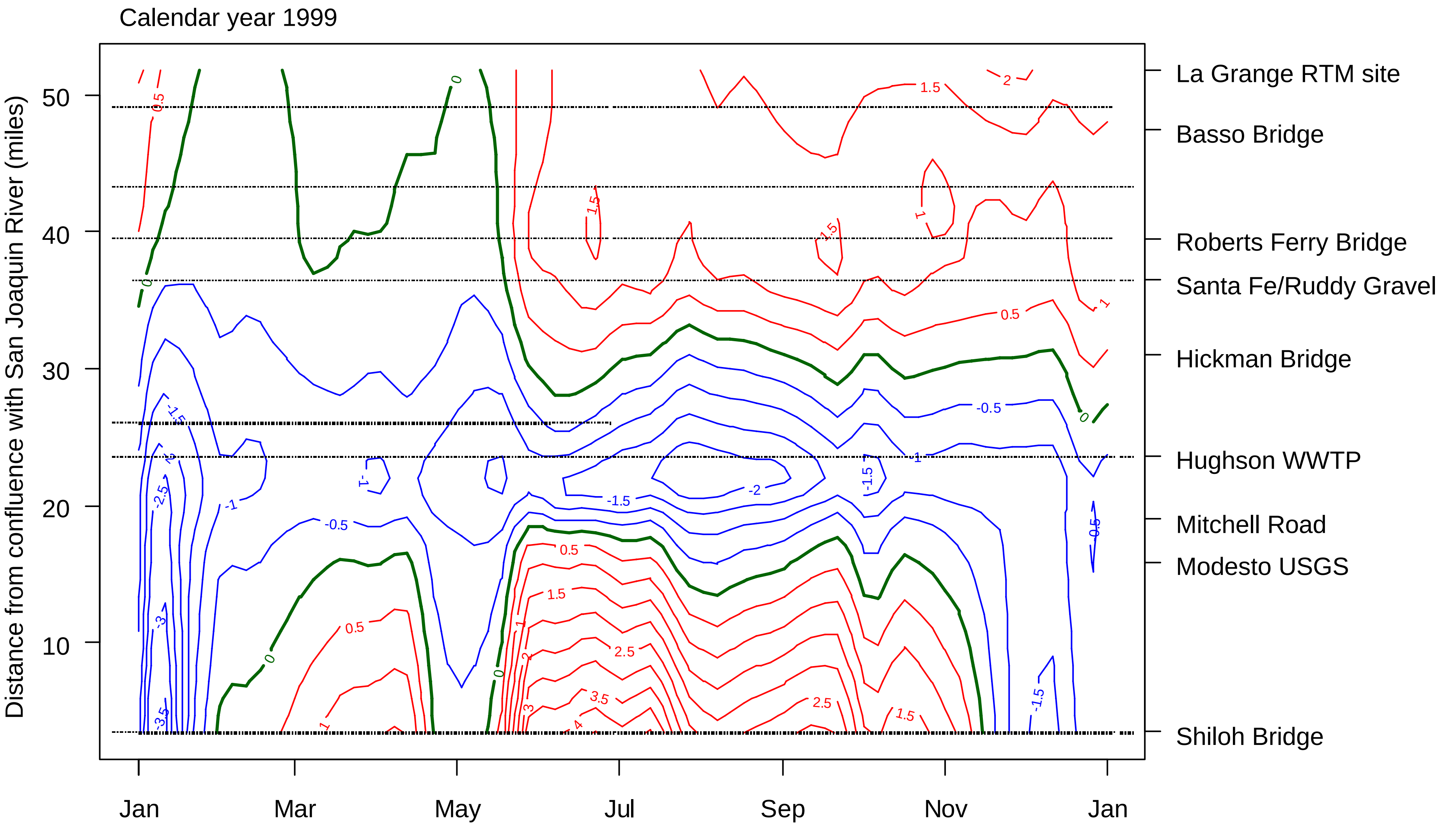

Figure D1. 1999 model prediction error (modeled minus observed) for daily mean water temperatures (°F) downstream of LaGrange Dam. Both HWMS and RTM thermograph data were used as observed data with the period of record (shown as dots). Contours show the model error obtained by kernel smoothing across a 5-day distribution of dates and a 5-mile range of river miles.

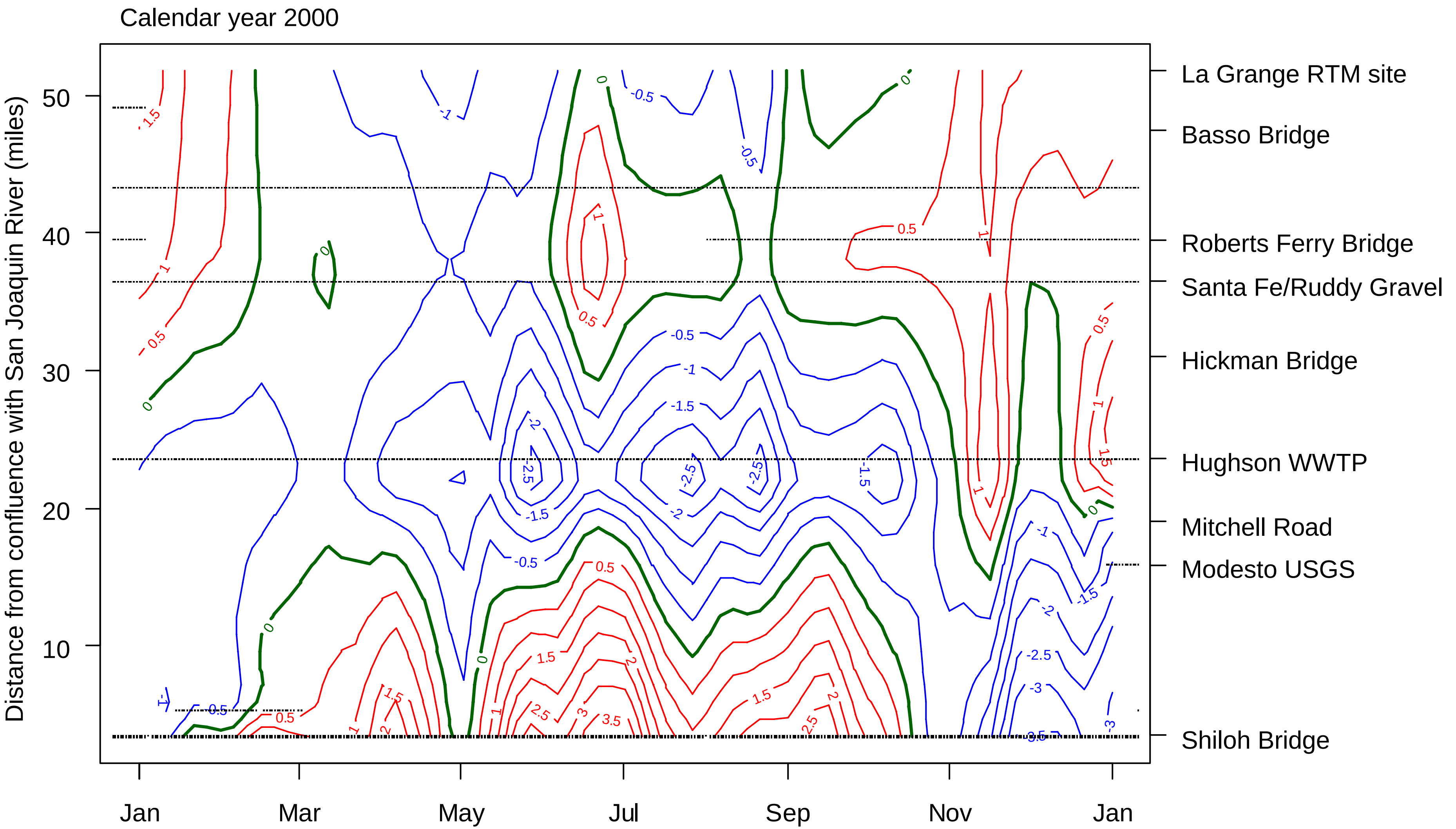

Figure D2. 2000 model prediction error (modeled minus observed) for daily mean water temperatures (°F) downstream of LaGrange Dam. Both HWMS and RTM thermograph data were used as observed data with the period of record (shown as dots). Contours show the model error obtained by kernel smoothing across a 5-day distribution of dates and a 5-mile range of river miles.

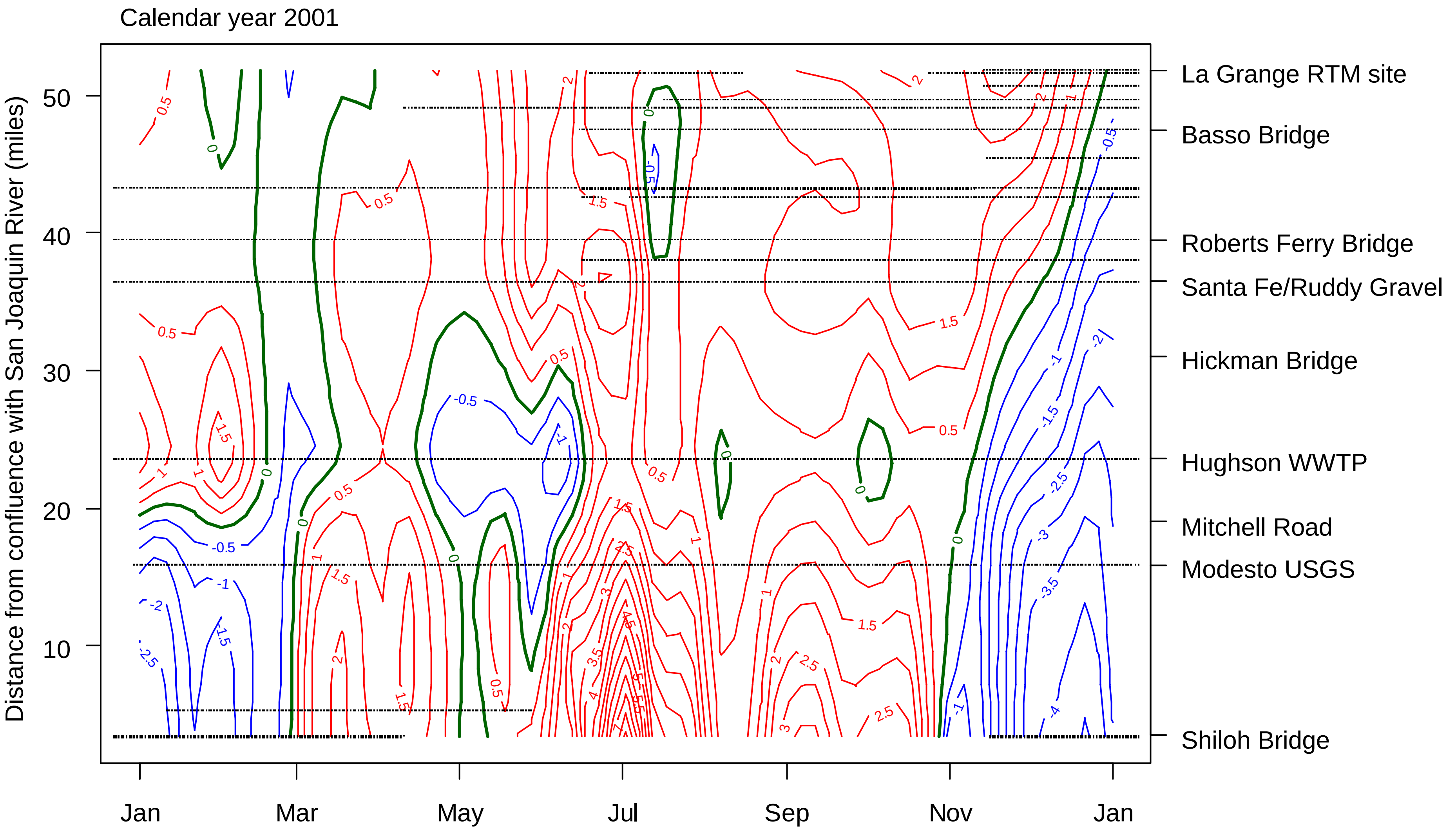

Figure D3. 2001 model prediction error (modeled minus observed) for daily mean water temperatures (°F) downstream of LaGrange Dam. Both HWMS and RTM thermograph data were used as observed data with the period of record (shown as dots). Contours show the model error obtained by kernel smoothing across a 5-day distribution of dates and a 5-mile range of river miles.

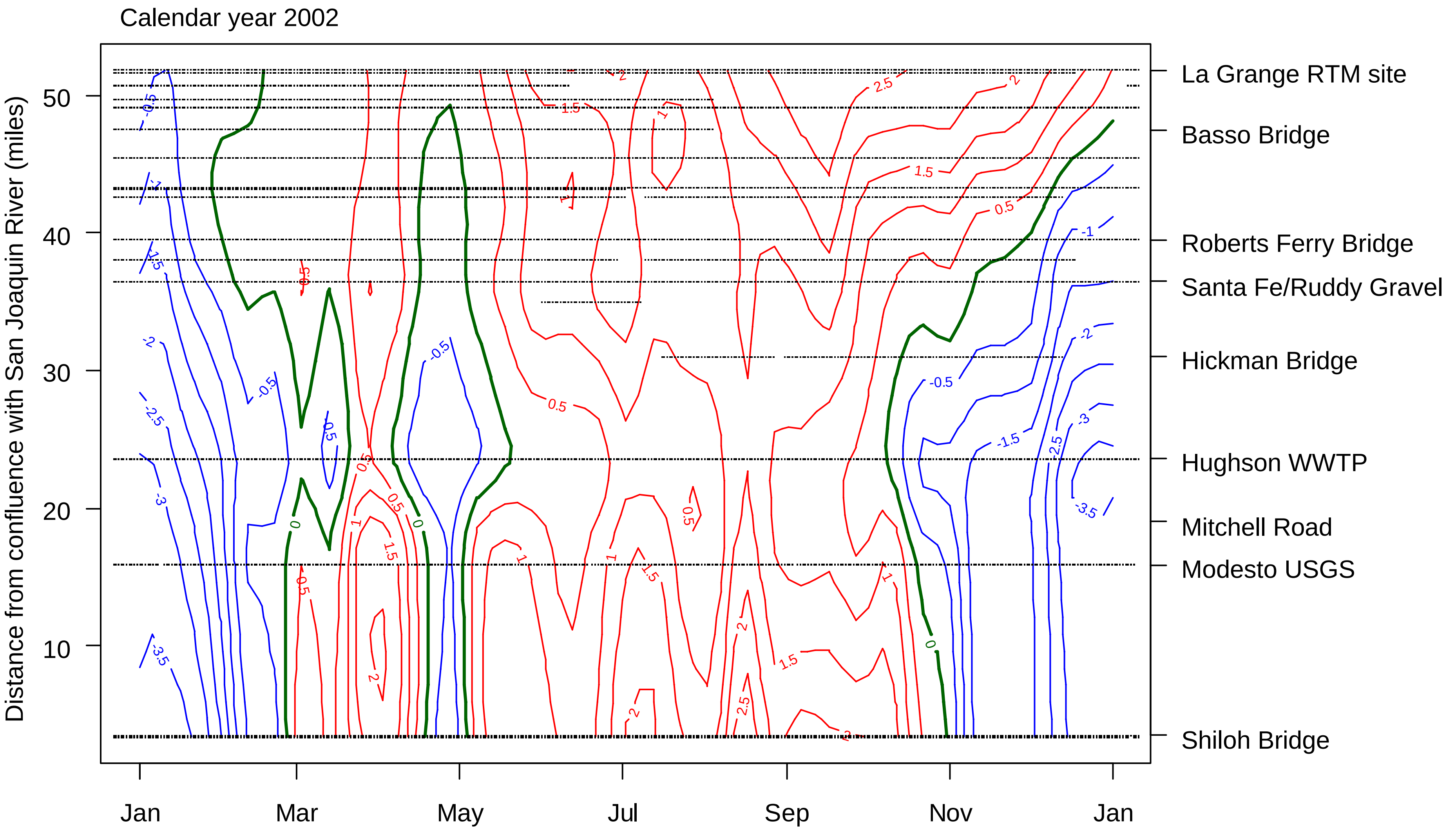

Figure D4. 2002 model prediction error (modeled minus observed) for daily mean water temperatures (°F) downstream of LaGrange Dam. Both HWMS and RTM thermograph data were used as observed data with the period of record (shown as dots). Contours show the model error obtained by kernel smoothing across a 5-day distribution of dates and a 5-mile range of river miles.

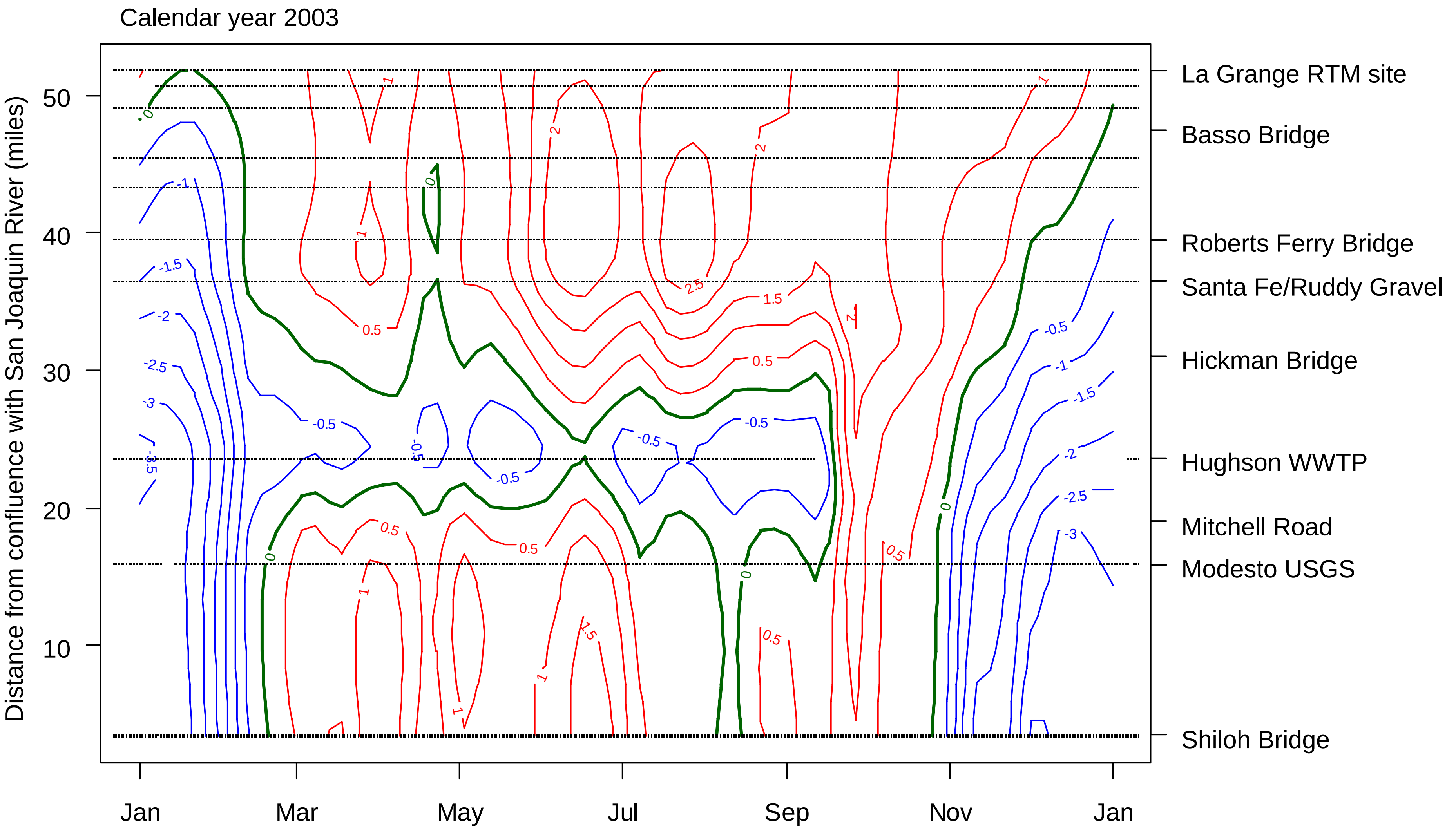

Figure D5. 2003 model prediction error (modeled minus observed) for daily mean water temperatures (°F) downstream of LaGrange Dam. Both HWMS and RTM thermograph data were used as observed data with the period of record (shown as dots). Contours show the model error obtained by kernel smoothing across a 5-day distribution of dates and a 5-mile range of river miles.

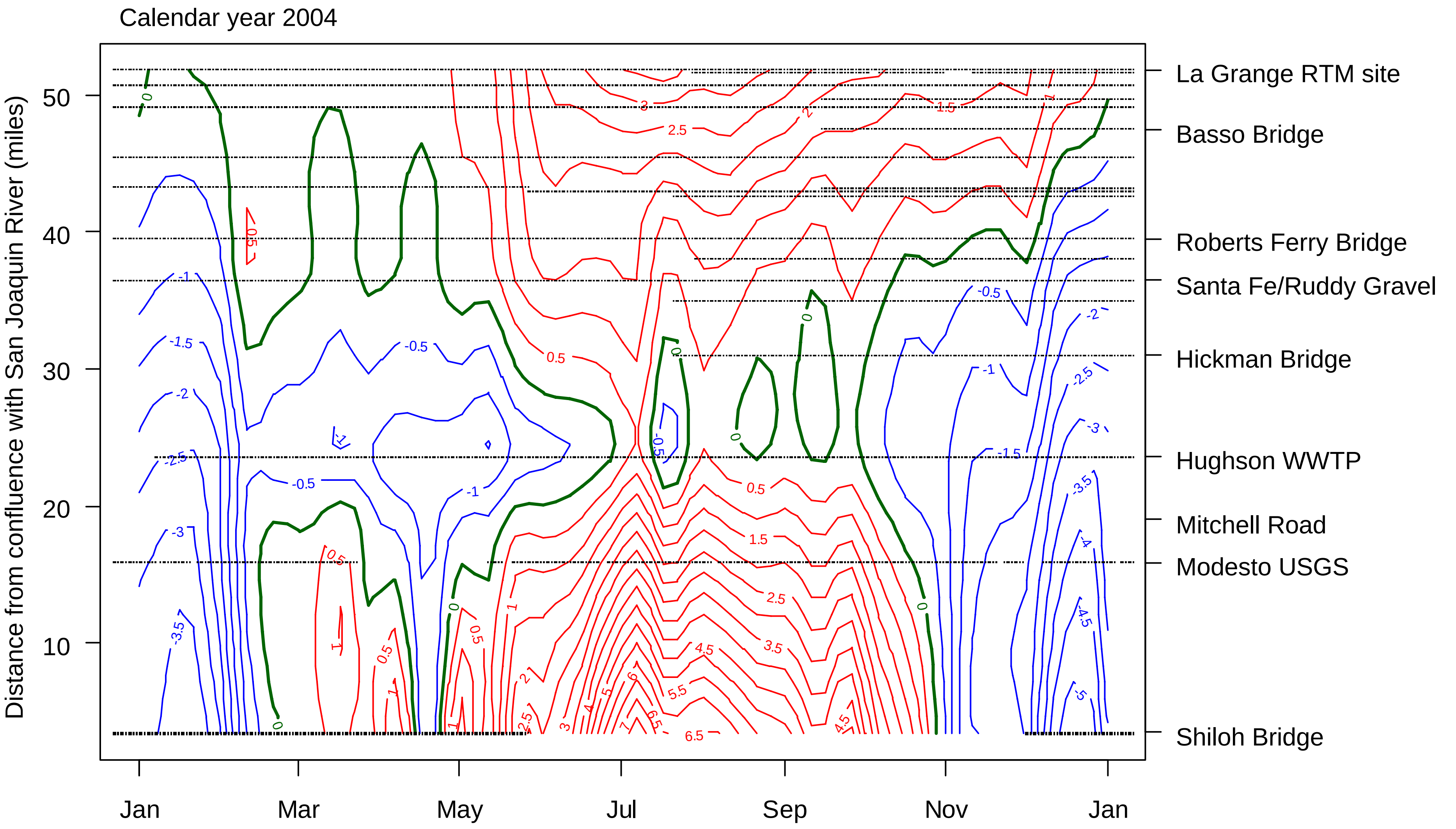

Figure D6. 2004 model prediction error (modeled minus observed) for daily mean water temperatures (°F) downstream of LaGrange Dam. Both HWMS and RTM thermograph data were used as observed data with the period of record (shown as dots). Contours show the model error obtained by kernel smoothing across a 5-day distribution of dates and a 5-mile range of river miles.

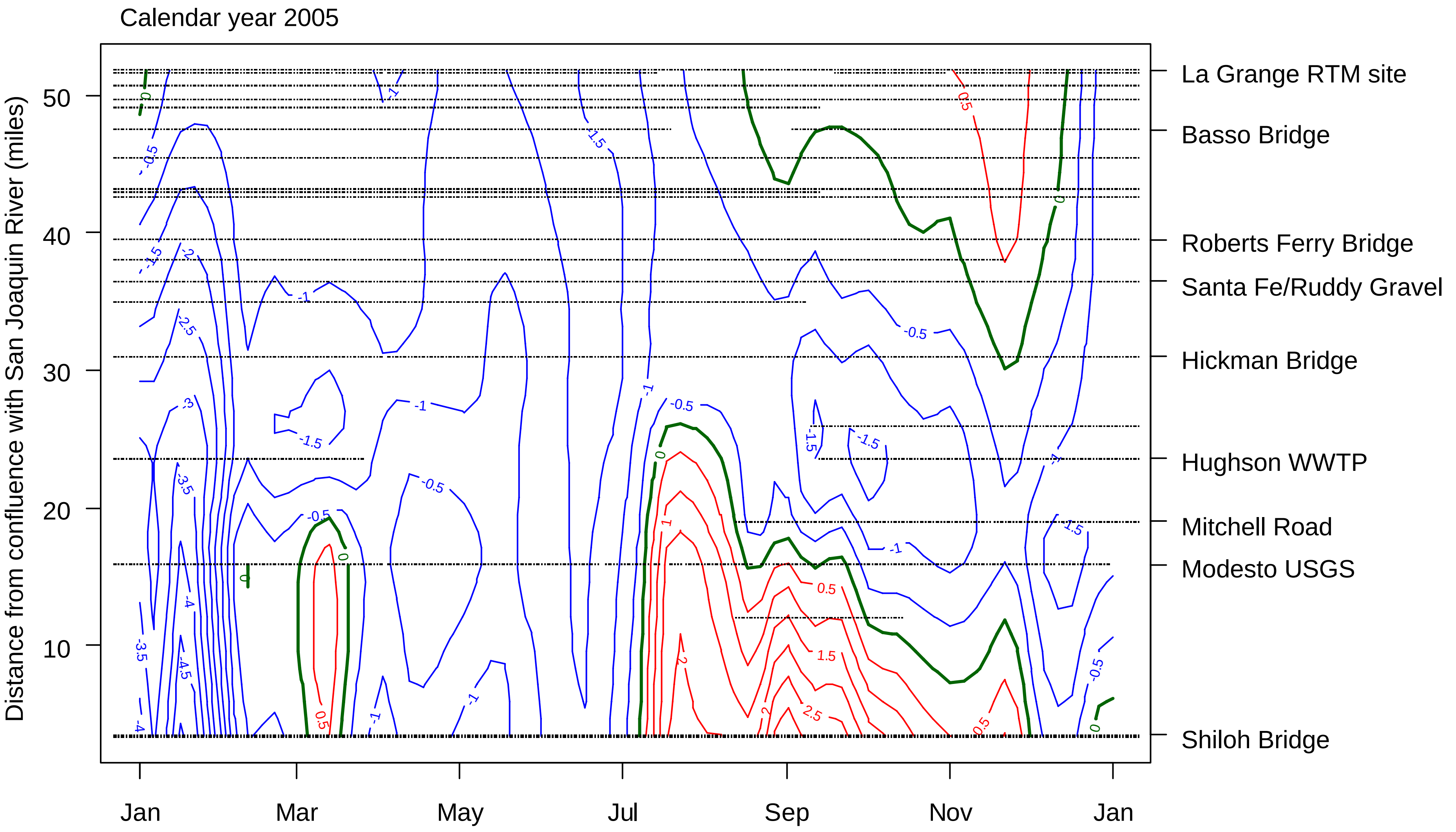

Figure D7. 2005 model prediction error (modeled minus observed) for daily mean water temperatures (°F) downstream of LaGrange Dam. Both HWMS and RTM thermograph data were used as observed data with the period of record (shown as dots). Contours show the model error obtained by kernel smoothing across a 5-day distribution of dates and a 5-mile range of river miles.

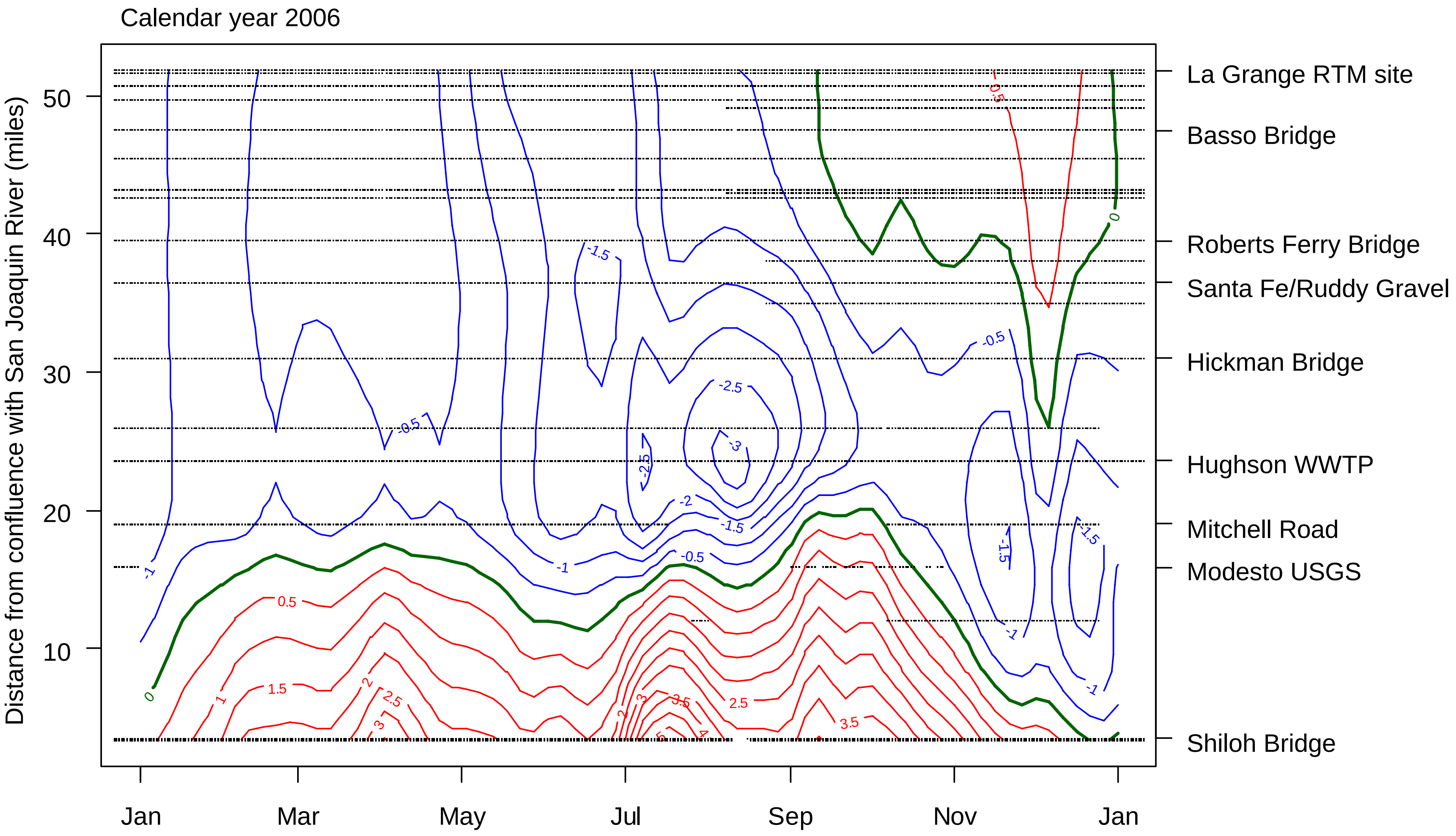

Figure D8. 2006 model prediction error (modeled minus observed) for daily mean water temperatures (°F) downstream of LaGrange Dam. Both HWMS and RTM thermograph data were used as observed data with the period of record (shown as dots). Contours show the model error obtained by kernel smoothing across a 5-day distribution of dates and a 5-mile range of river miles.

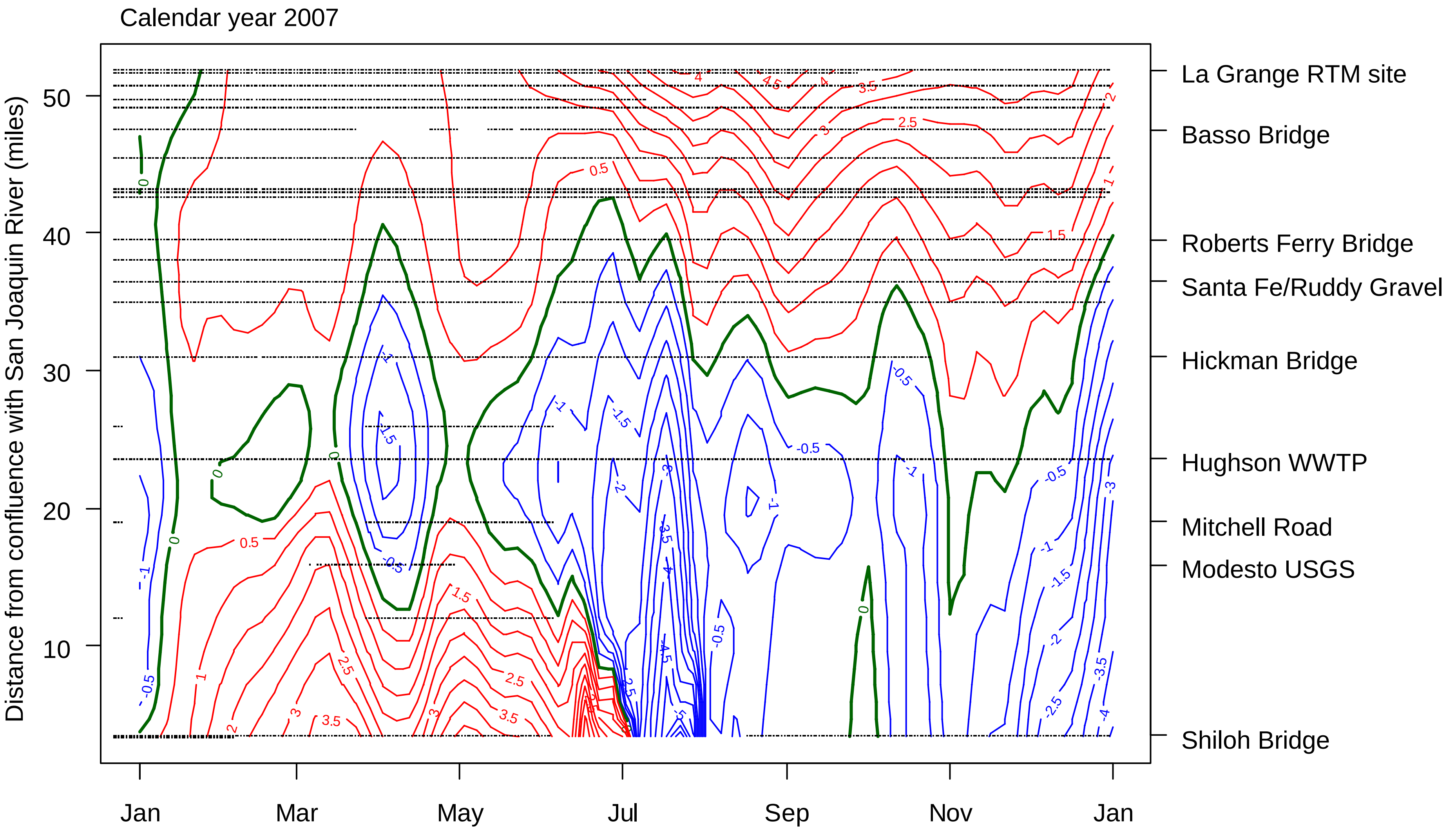

Figure D9. 2007 model prediction error (modeled minus observed) for daily mean water temperatures (°F) downstream of LaGrange Dam. Both HWMS and RTM thermograph data were used as observed data with the period of record (shown as dots). Contours show the model error obtained by kernel smoothing across a 5-day distribution of dates and a 5-mile range of river miles.