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Forebay Water Temperature Profile Studies at Libby Dam, Montana 2002 to 2004

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Introduction

Libby Dam is a United States Army Corps of Engineers (COE) project located on the Kootenai River, northwestern Montana. Construction of Libby Dam was completed in 1972, and the COE began to regulate flows on the Kootenai River below the dam for flood control and power production. The sluiceways were used to release water from the impoundment date until 1976 when several turbines came on line and the water was released using a combination of sluiceways and penstock releases. Initial penstock releases were from water deep in the reservoir and thus represented colder water similar in temperature to the sluiceways.

Beginning in 1977 Libby Dam began to operate a selective withdrawal system to supply water to the penstocks from different thermal layers in the reservoir. A string of thermistors is located on the face of the dam and measures the water temperature profile in the forebay at up to eighteen depths between the reservoir surface and bottom elevation. By utilizing a system of bulkheads to remove water from different depths in the reservoir, the selective withdrawal system attempts to produce downstream water temperatures that more closely resemble pre-impoundment conditions. These downstream temperatures are currently regulated according to a temperature rule curve established by the COE in cooperation with the Montana Department of Fish, Wildlife, and Parks (MDFWP), Idaho Department of Fish and Game (IDFG), and British Columbia Fish and Wildlife Branch (BCFW).

One objective of using the selective withdrawal system is to reduce the impact of the altered thermal regime on downstream fish habitat and populations, including the endangered Kootenai River white sturgeon. However, Whitfield and Woods (1984) concluded that impoundment substantially altered the natural thermal regime in the Kootenai River. Post-impoundment temperatures were warmer than pre-impoundment temperatures from October through February, similar in March, and cooler from April through September due to the differences in thermal properties between a deep storage reservoir and a free-flowing river. Similarly, Paragamian et al. (2002) suggested that even with the use of the selective withdrawal system Kootenai River temperatures may still be too low during the spring spawning season to promote successful recruitment of the endangered white sturgeon.

Accurate water temperature profile data are imperative for the operation of the selective withdrawal system to produce downstream river temperatures that meet the temperature rule curve and aid in the successful recruitment of sturgeon. Because the existing forebay thermal profile string is located on the face of Libby Dam, there is a concern that the temperatures measured on the dam's face may not accurately represent the temperatures in the forebay due to the following. First, the heat exchange properties of such a large mass of concrete may influence the immediate surrounding waters. For example, in the spring the concrete of the dam may have a cooling effect on the immediate surrounding waters which would result in the water at depth in the forebay being warmer than the temperature string indicates. Second, downwelling of surface water along the face of the dam in response to powerhouse operations may impact temperatures. Carroll (2004) showed that temperature strings attached to the face of several dams on the Snake River and Lower Columbia River recorded warmer temperatures than actually existed in the

river due to the downwelling of warm waters along the face of the dam. To address this concern, the COE designed a temperature profile study to quantify more precisely any longitudinal or lateral differences in temperature in the forebay of Libby Dam.

Purpose and Scope

The Seattle District Corps of Engineers conducted a forebay water temperature profile study at Libby Dam from 2002 to 2004. The purpose of the study was to collect baseline temperature data to determine the temporal and spatial gradients in water temperature in the forebay at Libby Dam. The major objectives of this study were to:

- Evaluate water temperature profiles in the forebay of Libby Dam to determine the representativeness of the current forebay temperature string location on actual forebay conditions
- Evaluate water temperatures at different depths in the reservoir to determine vertical temperature/density gradients
- Characterize the longitudinal and lateral variability of temperature in the forebay.

These objectives were addressed using automated thermal loggers and real-time water quality probes programmed to record date, time and temperature in degrees Celsius every hour. Data were collected from one real-time multiple depth temperature string located on the face of the dam and one multiple depth automated water temperature logger string located about 200 feet upstream of the face of the dam. The study was conducted from June through October 2002, April through November 2003, and May through November 2004.

Methods and Materials

Site Characterization

Libby Dam is located 18 miles northeast of Libby, Montana at river mile (RM) 221.9 of the Kootenai River (Figure 1). The dam's reservoir, Lake Koocanusa, is 90 miles long, extending 42 miles into British Columbia, Canada. The dam is a concrete gravity structure rising about 430 feet above bedrock with a top length of about 3075 feet. The reservoir has a gross storage capacity of 5.81 million acre feet (MAF), a mean depth of 126 feet, a maximum depth of 350 feet at the forebay, and a mean water residence time of about 9 months. Normal full pool and minimum regulated reservoir elevations are 2,459 and 2,287 feet, respectively. Downstream of Libby Dam, the Kootenai River flows to the south for about 3 miles to the mouth of the Fisher River and then to the northwest for about 71 miles to Bonners Ferry, Idaho through a relatively steep canyon with an average slope of about 5 feet per mile. At Bonners Ferry, the river valley widens and the river meanders to the north through a relatively flat section for about 47 miles to the Canadian Border (Figure 1).

The Lake Koocanusa watershed is dominated by high, forested, northwest trending mountain ranges separated by narrow river valleys. Elevations range from about 2,100 feet immediately downstream of Libby Dam to over 11,000 feet in the Rocky Mountains of British Columbia. The topography near Libby Dam is characterized by steep mountain slopes that plunge directly into the lake as well as relatively flat terraces that lie at intervals between the lake and the mountain slopes. The mountains rise as much as 2,000 feet per mile from the lake and vegetation is dominated by Ponderosa Pine, Douglas-fir, western larch, western redcedar, western hemlock, and lodgepole pine (USDA 1995). The lake width ranges from about 0.5 miles at Libby Dam to about 2.5 miles in the vicinity of the town of Eureka.

The climate of the study area is influenced by easterly moving weather systems from the Pacific Ocean. Winters are generally cloudy, cool, and wet, with November through March being the wettest months. Most of the snowpack in the mountains falls between November and April. Summers are typically warm and dry, with little rainfall occurring from June through September. The mean annual precipitation at Libby is about 19.4 inches (USDA 1995). Total annual snowfall varies with elevation, with about 60 inches near the dam to an estimated 300 inches in some mountain areas. The average monthly temperatures at Libby range from -5.6°C in January to 18.8°C in July, with extremes recorded in the vicinity of the dam of – 43.3 °C and 43.7°C (USCOE 1984).

Much of the annual runoff in the Kootenai River valley occurs in spring with the snowmelt. The impoundment of the Kootenai River by Libby Dam in 1972 for flood control and hydroelectric power production altered the seasonal flow patterns of the river (Bonde and Bush 1982). The annual pre-impoundment runoff conditions for the Kootenai River at the town of Libby showed high flows from April through June time period, with relatively low runoff the rest of the year,

especially in the dry late summer/fall period, and the cold winter periods (Bonde and Bush 1982). Average pre-impoundment (1912 – 1971) flows in the Kootenai River ranged from about 65,000 cubic feet per second (cfs) in late May and early June to about 4,000 cfs in January (USGS 2003). Post-impoundment conditions (1972 – 2001) have resulted in retaining water during historical high flow periods and discharging water during historical low flow periods. Since the early 1990s the COE has increased spring discharge levels to benefit downstream sturgeon survival. In general, the Kootenai River experiences reduced flows for most of the year, with peak flows of up to 26,000 cfs in late May through June for sturgeon survival.

The maximum discharge from Libby Dam through the powerhouse is about 26,000 cfs, considerably less than pre-impoundment Kootenai River peak flows. Under normal operating conditions, Libby Dam must spill water to provide flows in excess of 26,000 cfs in the Kootenai River. Because of water quality concerns associated with spilling water at Libby Dam, the dam typically does not spill water and flows have largely remained at or below powerhouse capacity since 1983. However, during 2002, the Kootenai River experienced flows up to 40,000 cfs due to the involuntary spill of water from Libby Dam in June and July.

Data Collection

Temperature data were collected using Geokon Model 4700 real-time thermal sensors and Vemco Minilog Model 8-T automated thermal loggers programmed to record date, time and temperature in degrees Celsius every hour. Real-time thermal sensors were deployed on the face of Libby Dam (Station LBTM) and the automated thermal loggers were deployed in the middle of the forebay of Libby Dam (Station LIBFB) to monitor spatial and temporal temperature regimes in Lake Koocanusa (Figure 2). Station locations and details are summarized in Tables 1 and 2.

The existing real-time water temperature sensors were anchored to the face of Libby Dam near the right bank in 1998 (Station LBTM). A total of 19 sensors were placed at fixed elevations on the dam in a vertical profile ranging from 2170 to 2450 feet with sensors concentrated in the region of more significant temperature gradients (Table 2). Because these sensors are fixed to the face of the dam, the depths of the sensors below the surface varies with the reservoir elevation. Instrumentation at the real-time stations consisted of Geokon Model 4700 thermal sensors, a Geomation 2380 DCP, a radio transmitter, and a power source. The sensors and DCP were powered by a 12-volt battery that was charged by a 120-volt AC line. Measurements were made every hour and the data were transmitted via radio directly to the Seattle District's HEC-DSS water quality database. Data were then sent out from Seattle every hour via FTP to the Columbia River Operational Hydromet Management System (CROHMS) database in Portland, Oregon.

Automated thermal loggers were deployed in the middle of the forebay about 200 feet upstream of the dam (Station LIBFB). These loggers were deployed as a string attached to a buoy in a vertical profile with loggers concentrated in the region of more significant temperature gradients

down to a depth of about 250 feet (Table 2). Because these loggers are hanging from a buoy, they represent a fixed depth below the surface regardless of reservoir elevation. These loggers recorded measurements every hour and the data were downloaded from the loggers at the end of the deployment period and entered into a database.

Data Comparison and Statistical Methods

Data collected from the fixed depth loggers at Station LIBFB were compared with data collected from the fixed elevation real-time sensors at Station LBTM using procedures outlined below. The depth of the loggers was fixed while the depths of the real-time sensors varied with reservoir elevation resulting in very few instances when the two probes depths coincided exactly. To alleviate this problem and to make the dataset more robust for statistical analysis, data from the fixed depth loggers were compared to data from the fixed elevation sensors only when the sensors were within ± 1 foot of the logger's depth for loggers deployed less than 200 feet deep, and within ± 10 feet for loggers deployed at the 200 and 250 foot depth. The use of a 10 foot range at the deeper sites was necessary due to the fewer number of times the loggers and sensors were at a similar depth.

Comparisons of temperature differences at similar depths between LIBFB and LBTM were determined statistically using a paired sample t-test and graphically using box and whisker plots (Zar 1984). The paired sample t-test is a parametric statistical test that determines the significance of the mean population difference between two pairs of data. However, because water quality data may not exhibit a normal distribution, box and whisker plots were generated to graphically compare the data. Box and whisker plots present nonparametric statistical results including the median value, 25th and 75th percentile interquartile range, 5th and 95th percentile non-outlier range, outlier values and extreme outlier values.

Quality-Assurance Procedures

Data quality control procedures for the automated thermal loggers and the real-time thermal sensors were different and are described in detail below.

Automated Thermal Loggers

Prior to field deployment, all thermal loggers were tested for accuracy in a laboratory under controlled conditions using a National Institute of Science and Technology (NIST) calibrated thermometer with a stated manufacturer's accuracy of 0.1 °C. The data loggers used in this study were Vemco Minilog 8-T and have a stated manufacturer's accuracy of 0.2 °C. These loggers were placed in an ice water bath (about 1 °C) and a room temperature water bath (about 20 °C) for at least 2 hours to test logger accuracy. These water baths were stirred every 5 minutes and the temperature recorded using the NIST calibrated thermometer. The loggers were

programmed to record temperature every minute while in the water bath. After retrieval, the difference between the logger's temperature and the thermometer's temperature were recorded and the data was compared to the manufacturers stated logger accuracy. If a logger's accuracy was different by more than 0.3 °C of the reference thermometer, the logger was not deployed in the field. A similar test for logger accuracy was completed after the loggers were retrieved from the field. Because all loggers were new in 2002, no pre-deployment calibrations were made in 2002. Statistical comparisons of the field temperature and the temperature standard are shown in Figures 3 to 7. In general, the median deference in temperature between the logger and standard were within 0.2°C for all loggers.

Real-Time Thermal Sensors

The real-time thermal sensors were permanently anchored to Libby Dam in 1998 and could not be retrieved prior to the study to perform any quality assurance testing. However, all thermal sensors used in the study were originally tested for accuracy by the manufacturer in a laboratory under controlled conditions using a National Institute of Science and Technology (NIST) calibrated thermometer with stated manufacturer's of 0.1 °C. The temperature sensors used in this study were Geokon Vibrating Wire Temperature Sensors Model 4700, and have a stated manufacturer's accuracy of 0.5°C.

Data Completeness

Data completeness and quality for data collected in 2002, 2003 and 2004 are summarized in Tables 3 to 5. The percentage of temperature monitoring data received was calculated from the number of missing hourly values versus the number of planned hourly values. The percent of real-time temperature data passing quality assurance represents the percent of data that was received and passed the quality assurance review of data described below. As seen in Tables 3 to 5, two automated thermal loggers deployed in the field during the 2003 monitoring season and one logger deployed during the 2004 season failed to collect any data.

Once the data were received and missing data were flagged, the following quality assurance review procedures occurred. First, tables of raw data were visually inspected for erroneous data resulting from logger and probe malfunctions or improper transmission of data value codes. Second, data tables were reviewed for sudden increases in temperature that could not be correlated to any hydrologic event and therefore may be a result of mechanical problems. Third, graphs of the data were created and analyzed in order to identify unusual spikes in the data. These spikes were then further investigated in order to identify the causes of error. Suspect data was then corrected if possible. For instance, data where drift occurred can be easily adjusted through software programs. Data that could not be corrected were flagged as rejected and deleted from the database.

As shown in Tables 3 to 5, problems with receiving real-time hourly temperature data were encountered during the study. Missing data for the real-time station LBTM were largely due to

DCP malfunctions and programming problems. Missing data for the automated thermal loggers at station LIBFB were due to logger malfunctions resulting in no data being collected. No data were rejected for the water quality probes and automated thermal loggers.

Results and Discussion

Hydrological and Meteorological Characterization

Hydrographs of average daily discharge and reservoir elevations for Libby Dam for the period April through November 2002, 2003, and 2004 are presented in Figure 8, while post-impoundment river flow statistics for the period 1984-2001 are presented in Figure 9. Compared to the post-impoundment median river flow conditions, the Kootenai River in 2002 experienced a substantially higher peak flow in July and an extended period of higher than average flows from June through August. High inflows and limited reservoir storage capacity in 2002 necessitated Libby Dam to begin to involuntarily spill water starting on June 25, 2002 for flood control operations. The flood control operations resulted in flows in the Kootenai River over the powerhouse capacity of 26,000 cfs from June 25 through July 7, and from July 13 through July 17, 2002. Peak flows of 40,000 cfs were measured on July 4, 2002 (Figure 8). Kootenai River flows remained higher than normal throughout the months of July and August. Flows in 2003 were substantially less than in 2002, but were still greater than the post-impoundment median flow with a peak flow of about 25,000 cfs in June. Flows in 2004 were the lowest of the three sampling seasons with a peak flow of about 15,000 cfs in early June, similar to the post-impoundment median flows. No spillway flows were recorded in 2003 or 2004. Reservoir elevations reflect the yearly differences in flows, with higher forebay elevations experienced in 2002 and 2003 compared to 2004 (Figure 8).

The weather station chosen to represent conditions in the study area was the National Weather Service's Libby Dam weather station number 245009. Daily maximum and minimum air temperatures for the 2002, 2003, and 2004 sampling seasons and average daily historical (1971-2000) maximum and minimum temperatures are presented in Figure 10. These data show that temperatures at Libby Dam during each of the sampling seasons were variable with periods of warmer than normal weather followed by cooler than normal weather. The highest temperatures recorded at Libby Dam generally occurred during the latter part of July, with air temperatures exceeding 35°C. The lowest temperatures typically occurred in November with air temperatures below – 5°C.

Temporal and Spatial Patterns

Temporal patterns for water temperature collected at stations LIBFB and LBTM are presented in Figures 11 to 13. Temperatures at both sites followed a similar pattern of warming from spring through summer and cooling in the fall, with the warmest temperatures experienced during July and August. Temperature patterns at both LIBFB and LBTM were dynamic with daily fluctuations in surface water temperatures ranging from about 3 °C to 10 °C seen at both stations. The timing and duration of these fluctuations were similar between both stations and tended to closely follow weather conditions (See Figure 10). Periods of rapid surface temperature changes

at LIBFB and LBTM appeared to be related to changes in air temperatures seen in Figure 10 suggesting that weather systems (wind, temperature, cloud cover) play an important role in the formation and breakup of temperature stratification at Libby Dam. Unfortunately, wind speed and direction data were not collected at Libby Dam during the study.

Strong vertical thermal gradients were evident at forebay stations LIBFB and LBTM as indicated by the temperature profile time histories presented in Figures 11 to 13. The forebay stratification and thermal gradient was strong during the sampling seasons likely due to the relatively long reservoir residence time and the large input of solar radiation during the warm summer months. However, this stratification was periodically broken down resulting in the mixing of warmer surface waters with cooler waters at depth (Figures11 to 13).

The dynamic nature of the temporal temperature pattern in the forebay of Libby Dam was similar at the middle of the forebay (LIBFB) and at the face of the dam (LBTM) suggesting that the downwelling of warm surface waters along the face of the dam due to being pulled down by the powerhouse was likely not responsible for the dynamic nature of the temperature regime. Because Lake Koocanusa is a 90 plus mile long narrow reservoir wind is likely the major external source responsible for the periodic mixing seen in the forebay. Wind can impact thermal stratification by creating internal seiches, which result in the breakdown of thermal stratification. Internal seiches are generated when winds blow consistently from one direction, driving surface waters downwind and piling up water on the lee shore until the wind subsides. When wind speeds decrease, the force of the water is released resulting in the mass of water moving back and forth and the mixing of surface waters with waters at depth, resulting in thermocline movement and the disruption of the thermal gradient.

Lateral Bias Evaluation

Comparisons were made between the forebay stations water temperatures recorded at the middle of the forebay (LIBFB) and at the face of the dam (LBTM) to determine if any lateral bias existed (see Figure 2). The potential for temperature differences exists at these stations because the existing forebay thermal profile located on the face of the dam may be influenced by the heat exchange characteristics of the large mass of concrete and downwelling of warmer surface waters in response to powerhouse operations.

Comparisons of temperature differences at similar depths between LIBFB and LBTM were determined statistically using a paired sample t-test. The paired sample t-test is a parametric statistical test that determines the significance of the mean population difference between two pairs of data. Paired t-tests were conducted by pairing depth and time between stations LIBFB and LBTM and calculating the temperature difference by subtracting LBTM temperatures from LIBFB temperatures. Table 5 shows the results of these tests during the 2002-2004 sampling period. The paired t-test calculates the mean difference for each pair and determines if this difference is statistically significant from zero. These data show that for all depths, the pairs were significantly different. However, the maximum mean difference and standard deviation for

each pair was 0.331°C and 0.425°C, respectively, for the 2 foot pair. These values are less than the manufactures stated accuracy for the real time thermal sensors of (± 0.5 °C), suggesting that only minor bias (± 0.5 °C) occurred between LIBFB and LBTM that could be accounted for by instrument accuracy, slight differences in instrument depths, or internal seiche activity.

Comparisons of temperature differences at similar depths between LIBFB and LBTM by subtracting LBTM temperatures from LIBFB temperatures were also determined graphically using box and whisker plots (Figure 14). Box and whisker plots present nonparametric statistical results including the median value, 25th and 75th percentile interquartile range, 5th and 95th percentile non-outlier range, outlier values and extreme outlier values. Although outlier temperature differences up to 3.0 °C were recorded, the median difference between the LIBFB and LBTM ranged from 0.322°C at 2-feet to 0.06°C at 130 feet (Table 6). The interquartile spread of the data ranged from 0.14°C to 0.5°C at 2-feet to 0.12°C to 0.16°C at 250 feet, while the 95th percentile spread of the data ranged from –0.26°C to 0.94°C at 2 feet to 0.09°C to 0.17°C at 250 feet. These data suggest that the vast majority of temperature differences between LIBFB and LBTM could be accounted for by the instrument accuracy (± 0.5 °C) as well as slight differences in instrument depths.

The greatest temperature differences between LIBFB and LBTM were measured in the upper 80 feet (Figure 14), likely due to the dynamic nature of the thermal structure in the forebay at Libby Dam (see Figures 11 to 13). Solar radiation, wind and internal seiches appear to play a role in the setup and breakdown of the thermal structure in the forebay. As seen in Figures 11 to 13, temperatures in the upper layers of the forebay are dynamic, likely due to internal seiches. Thus, some of the temperature differences noted at the same depth between LIBFB and LBTM are likely a consequence of the dynamic nature of thermal stratification at Libby Dam or the elevation differences of the paired temperature instruments. The stronger correlation between temperatures below about 80 feet is likely due to the inherent stability of the thermal regime at depth.

Interestingly, the median temperature differences between LIBFB and LBTM at all depths were positive values (Table 6). Moreover, the interquartile range and 95th percentile range of the data was skewed towards positive values at all depths indicating that the vast majority of temperatures recorded at LBTM were greater than at LIBFB. These data indicate that temperatures for a specific depth along the face of the dam recorded at LBTM were slightly less than in the middle of the forebay at LIBFB. However, as noted above, these temperature differences were minor and within the range of probe accuracy.

Conclusions

Evaluation of the temperature monitoring results yielded the following conclusions:

- Temperatures at both sites followed a similar pattern of warming from spring through summer and cooling in the fall, with the warmest temperatures experienced during July and August. Temperature patterns at both LIBFB and LBTM were dynamic with daily fluctuations in surface water temperatures ranging from about 3 °C to 10 °C seen at both stations. The timing and duration of these fluctuations were similar between both stations and tended to closely follow weather conditions.

- Strong vertical thermal gradients were evident at forebay stations LIBFB and LBTM likely due to the relatively long reservoir residence time and the large input of solar radiation during the warm summer months However, this stratification was periodically broken down resulting in the cooling of surface waters.

- The dynamic nature of the temporal temperature pattern in the forebay of Libby Dam was similar at the middle of the forebay (LIBFB) and at the face of the dam (LBTM) suggesting that internal seiches may be responsible for the dynamic nature of the temperature regime.

- Only minor bias (± 0.5 °C) was associated between the fixed monitoring station on the face of the dam (LBTM) and the temperature string in the middle of the forebay (LIBFB), which could be accounted for by instrument accuracy, internal seiches or slight differences in instrument depths.

- The median temperature differences between LIBFB and LBTM at all depths were positive values. Moreover, the interquartile range and 95th percentile range of the data was skewed towards positive values at all depths indicating that temperatures for a specific depth recorded in the middle of the forebay at LIBFB were slightly greater than along the face of the dam at LBTM.

Recommendations

Evaluation of the temperature monitoring results yielded the following recommendation:

- The minor differences noted between stations LIBFB and LBTM suggest that the existing monitoring station location on the face of the dam at LBTM is generally representative of forebay conditions. However, future thermal trend monitoring and operation strategies will likely require temperature accuracy greater than the existing ± 0.5 °C. Therefore, it is recommended to continue to monitor the more accurate temperature string in the middle of the forebay and investigate the feasibility of installing more accurate thermal sensors at the fixed monitoring station.

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Tables

Table 1. Temperature station locations and sampling period, years 2002, 2003 and 2004.

Site Identifier	Station Name	Latitude	Longitude	Location	Total Depth at Station at Full Pool (feet)	Temperature Monitoring Method	Sampling Periods
LBTM	Libby Dam Forebay Right Bank	48.41170	115.31770	On Face of Dam	350	Real Time Thermal Sensors	06/11/03 - 11/19/03 04/18/03 - 11/17/03 05/19/04 - 10/31/04
LIBFB	Libby Dam Forebay Middle	48.41125	115.31167	In Middle of Forebay	350	Automated Thermal Loggers	06/11/03 - 11/19/03 04/18/03 - 11/17/03 05/19/04 - 10/31/04

Table 2. Temperature data completeness for 2002.

Station Name and Abbreviation	Field Probe Number	Sensor Elevation (feet)	Probe Depth (feet)	Planned monitoring hours	Number of missing hourly values	Percentage of temperature monitoring data received	Percentage of temperature data passing quality assurance
Real Time Thermal Sensors (LBTM)							
LBTM-2450	—	2450	—	3360	268	92.0	92.0
LBTM-2440	—	2440	—	3360	268	92.0	92.0
LBTM-2430	—	2430	—	3360	268	92.0	92.0
LBTM-2420	—	2420	—	3360	268	92.0	92.0
LBTM-2410	—	2410	—	3360	268	92.0	92.0
LBTM-2400	—	2400	—	3360	268	92.0	92.0
LBTM-2390	—	2390	—	3360	268	92.0	92.0
LBTM-2380	—	2380	—	3360	268	92.0	92.0
LBTM-2370	—	2370	—	3360	268	92.0	92.0
LBTM-2360	—	2360	—	3360	268	92.0	92.0
LBTM-2350	—	2350	—	3360	268	92.0	92.0
LBTM-2340	—	2340	—	3360	268	92.0	92.0
LBTM-2330	—	2330	—	3360	268	92.0	92.0
LBTM-2320	—	2320	—	3360	268	92.0	92.0
LBTM-2310	—	2310	—	3360	268	92.0	92.0
LBTM-2300	—	2300	—	3360	268	92.0	92.0
LBTM-2275	—	2275	—	3360	268	92.0	92.0
LBTM-2225	—	2225	—	3360	268	92.0	92.0
LBTM-2170	—	2170	—	3360	268	92.0	92.0
Automated Thermal Loggers (LIBFB)							
LIBFB-2	7518	—	2	3360	0	100.0	100.0
LIBFB-10	7519	—	10	3360	0	100.0	100.0
LIBFB-20	7520	—	20	3360	0	100.0	100.0
LIBFB-30	7521	—	30	3360	0	100.0	100.0
LIBFB-40	7522	—	40	3360	0	100.0	100.0
LIBFB-50	7523	—	50	3360	0	100.0	100.0
LIBFB-60	7524	—	60	3360	0	100.0	100.0
LIBFB-70	7525	—	70	3360	0	100.0	100.0
LIBFB-80	7526	—	80	3360	0	100.0	100.0
LIBFB-90	7527	—	90	3360	0	100.0	100.0
LIBFB-100	7529	—	100	3360	0	100.0	100.0
LIBFB-115	7528	—	115	3360	0	100.0	100.0
LIBFB-130	7530	—	130	3360	0	100.0	100.0
LIBFB-150	7531	—	150	3360	0	100.0	100.0
LIBFB-160	7532	—	160	3360	0	100.0	100.0
LIBFB-175	7533	—	175	3360	0	100.0	100.0
LIBFB-200	7534	—	200	3360	0	100.0	100.0
LIBFB-250	7535	—	250	3360	0	100.0	100.0

Table 3. Temperature data completeness for 2003

Station Name and Abbreviation	Field Probe Number	Sensor Elevation (feet)	Probe Depth (feet)	Planned monitoring hours	Number of missing hourly values	Percentage of temperature monitoring data received	Percentage of temperature data passing quality assurance
Real Time Thermal Sensors (LBTM)							
LBTM-2450	—	2450	—	4992	108	97.8	97.8
LBTM-2440	—	2440	—	4992	108	97.8	97.8
LBTM-2430	—	2430	—	4992	108	97.8	97.8
LBTM-2420	—	2420	—	4992	108	97.8	97.8
LBTM-2410	—	2410	—	4992	108	97.8	97.8
LBTM-2400	—	2400	—	4992	108	97.8	97.8
LBTM-2390	—	2390	—	4992	108	97.8	97.8
LBTM-2380	—	2380	—	4992	108	97.8	97.8
LBTM-2370	—	2370	—	4992	108	97.8	97.8
LBTM-2360	—	2360	—	4992	108	97.8	97.8
LBTM-2350	—	2350	—	4992	108	97.8	97.8
LBTM-2340	—	2340	—	4992	108	97.8	97.8
LBTM-2330	—	2330	—	4992	108	97.8	97.8
LBTM-2320	—	2320	—	4992	108	97.8	97.8
LBTM-2310	—	2310	—	4992	108	97.8	97.8
LBTM-2300	—	2300	—	4992	108	97.8	97.8
LBTM-2275	—	2275	—	4992	108	97.8	97.8
LBTM-2225	—	2225	—	4992	108	97.8	97.8
LBTM-2170	—	2170	—	4992	108	97.8	97.8
Automated Thermal Loggers (LIBFB)							
LIBFB-2	7518	—	2	4992	0	100.0	100.0
LIBFB-10	7519	—	10	4992	0	100.0	100.0
LIBFB-20	7520	—	20	4992	0	100.0	100.0
LIBFB-30	7521	—	30	4992	4992	0.0	0.0
LIBFB-40	7522	—	40	4992	0	100.0	100.0
LIBFB-50	7523	—	50	4992	0	100.0	100.0
LIBFB-60	7524	—	60	4992	0	100.0	100.0
LIBFB-70	7525	—	70	4992	0	100.0	100.0
LIBFB-80	7526	—	80	4992	0	100.0	100.0
LIBFB-90	7527	—	90	4992	0	100.0	100.0
LIBFB-100	7528	—	100	4992	0	100.0	100.0
LIBFB-125	7529	—	125	4992	0	100.0	100.0
LIBFB-150	7530	—	150	4992	0	100.0	100.0
LIBFB-175	7531	—	175	4992	4992	0.0	0.0
LIBFB-200	7532	—	200	4992	0	100.0	100.0
LIBFB-250	7533	—	250	4992	0	100.0	100.0

Table 4. Temperature data completeness for 2004.

Station Name and Abbreviation	Field Probe Number	Sensor Elevation (feet)	Probe Depth (feet)	Planned monitoring hours	Number of missing hourly values	Percentage of temperature monitoring data received	Percentage of temperature data passing quality assurance
Real Time Thermal Sensors (LBTM)							
LBTM-2450	—	2450	—	3983	20	99.5	99.5
LBTM-2440	—	2440	—	3983	20	99.5	99.5
LBTM-2430	—	2430	—	3983	20	99.5	99.5
LBTM-2420	—	2420	—	3983	20	99.5	99.5
LBTM-2410	—	2410	—	3983	20	99.5	99.5
LBTM-2400	—	2400	—	3983	20	99.5	99.5
LBTM-2390	—	2390	—	3983	20	99.5	99.5
LBTM-2380	—	2380	—	3983	20	99.5	99.5
LBTM-2370	—	2370	—	3983	20	99.5	99.5
LBTM-2360	—	2360	—	3983	20	99.5	99.5
LBTM-2350	—	2350	—	3983	20	99.5	99.5
LBTM-2340	—	2340	—	3983	20	99.5	99.5
LBTM-2330	—	2330	—	3983	20	99.5	99.5
LBTM-2320	—	2320	—	3983	20	99.5	99.5
LBTM-2310	—	2310	—	3983	20	99.5	99.5
LBTM-2300	—	2300	—	3983	20	99.5	99.5
LBTM-2275	—	2275	—	3983	20	99.5	99.5
LBTM-2225	—	2225	—	3983	20	99.5	99.5
LBTM-2170	—	2170	—	3983	20	99.5	99.5
Automated Thermal Loggers (LIBFB)							
LIBFB-2	7740	—	2	3983	3983	0.0	0.0
LIBFB-10	7741	—	10	3983	0	100.0	100.0
LIBFB-20	7743	—	20	3983	0	100.0	100.0
LIBFB-30	7744	—	30	3983	0	100.0	100.0
LIBFB-40	7745	—	40	3983	0	100.0	100.0
LIBFB-50	7746	—	50	3983	0	100.0	100.0
LIBFB-60	7747	—	60	3983	0	100.0	100.0
LIBFB-70	7748	—	70	3983	0	100.0	100.0
LIBFB-80	7751	—	80	3983	0	100.0	100.0
LIBFB-90	7753	—	90	3983	0	100.0	100.0
LIBFB-100	7754	—	100	3983	0	100.0	100.0
LIBFB-125	7755	—	125	3983	0	100.0	100.0
LIBFB-150	7756	—	150	3983	0	100.0	100.0
LIBFB-200	7757	—	200	3983	0	100.0	100.0

Table 5. Paired t-test evaluation of LIBFB minus LBTM temperature for specific depths using years 2002 to 2004 data.

Paired t-test Sample Depths	N	Mean Difference	Standard Deviation	t-test (t)	Degrees of Freedom (df)	Significance (r)
2 foot	1249	0.331	0.425	27.535	1248	0.000
10 feet	2015	0.121	0.389	13.99	2014	0.000
20 feet	1994	0.131	0.358	16.29	1993	0.000
30 feet	1441	0.253	0.316	30.32	1440	0.000
40 feet	2015	0.198	0.365	24.37	2014	0.000
50 feet	2014	0.215	0.318	30.06	2013	0.000
60 feet	2015	0.182	0.278	29.37	2014	0.000
70 feet	2015	0.181	0.258	31.45	2014	0.000
80 feet	2015	0.135	0.214	28.27	2014	0.000
90 feet	2015	0.148	0.206	32.08	2014	0.000
100 feet	2015	0.111	0.216	23.12	2014	0.000
115 feet	148	0.234	0.202	14.09	147	0.000
125 feet	2066	0.169	0.192	40.09	2065	0.000
130 feet	680	0.083	0.153	14.08	679	0.000
150 feet	930	0.116	0.17	20.71	929	0.000
160 feet	388	0.114	0.19	15.01	387	0.000
175 feet	380	0.177	0.207	16.66	379	0.000
200 feet	1346	0.183	0.171	39.24	1345	0.000
250 feet	392	0.139	0.026	104.89	391	0.000

Table 6. Box plot evaluation of LIBFB minus LBTM temperature for specific depths using years 2002 to 2004 data.

Depth	N	Median	25th percentile	75th percentile	5th percentile	95th percentile
2 feet	1249	0.32	0.14	0.50	-0.26	0.94
10 feet	2015	0.07	-0.06	0.29	-0.45	0.79
20 feet	1994	0.17	-0.04	0.29	-0.41	0.69
30 feet	1441	0.21	0.09	0.39	-0.22	0.83
40 feet	2015	0.20	0.01	0.36	-0.38	0.78
50 feet	2014	0.20	0.05	0.38	-0.28	0.71
60 feet	2015	0.18	0.02	0.33	-0.26	0.64
70 feet	2015	0.17	0.04	0.31	-0.21	0.61
80 feet	2015	0.12	0.00	0.26	-0.19	0.49
90 feet	2015	0.13	0.02	0.27	-0.18	0.50
100 feet	2015	0.12	-0.02	0.26	-0.26	0.44
115 feet	148	0.22	0.11	0.35	-0.09	0.58
125 feet	2066	0.17	0.04	0.29	-0.14	0.49
130 feet	680	0.07	-0.02	0.17	-0.14	0.37
150 feet	930	0.12	0.00	0.22	-0.15	0.39
160 feet	388	0.12	0.02	0.21	-0.14	0.35
175 feet	380	0.17	0.04	0.32	-0.16	0.53
200 feet	1346	0.14	0.07	0.28	-0.04	0.50
250 feet	392	0.14	0.12	0.16	0.09	0.17

Figures

Figure 1. Location of Libby Dam and watershed.

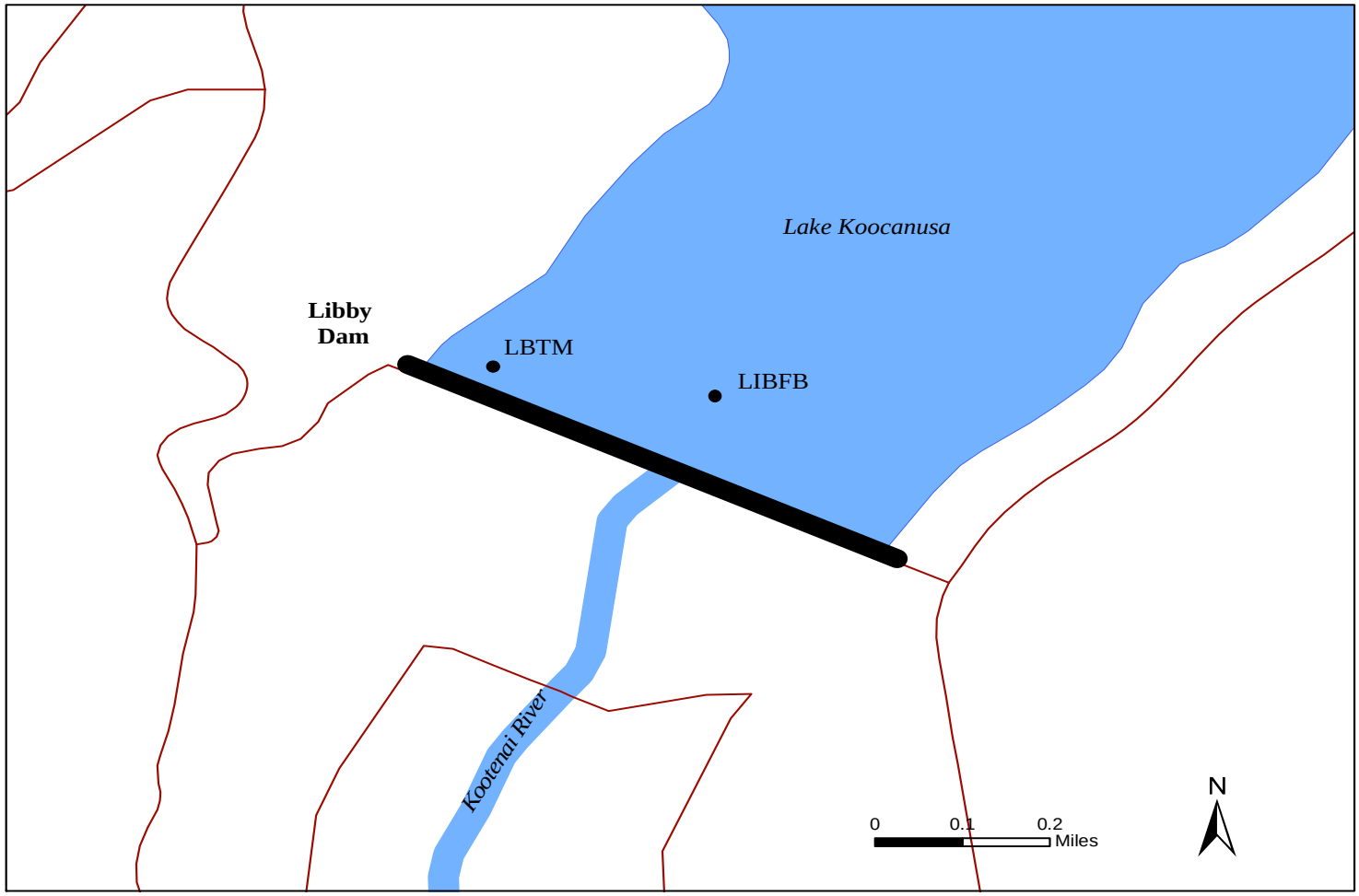


Figure 2. Locations of forebay temperature monitoring stations at Libby Dam, Montana.

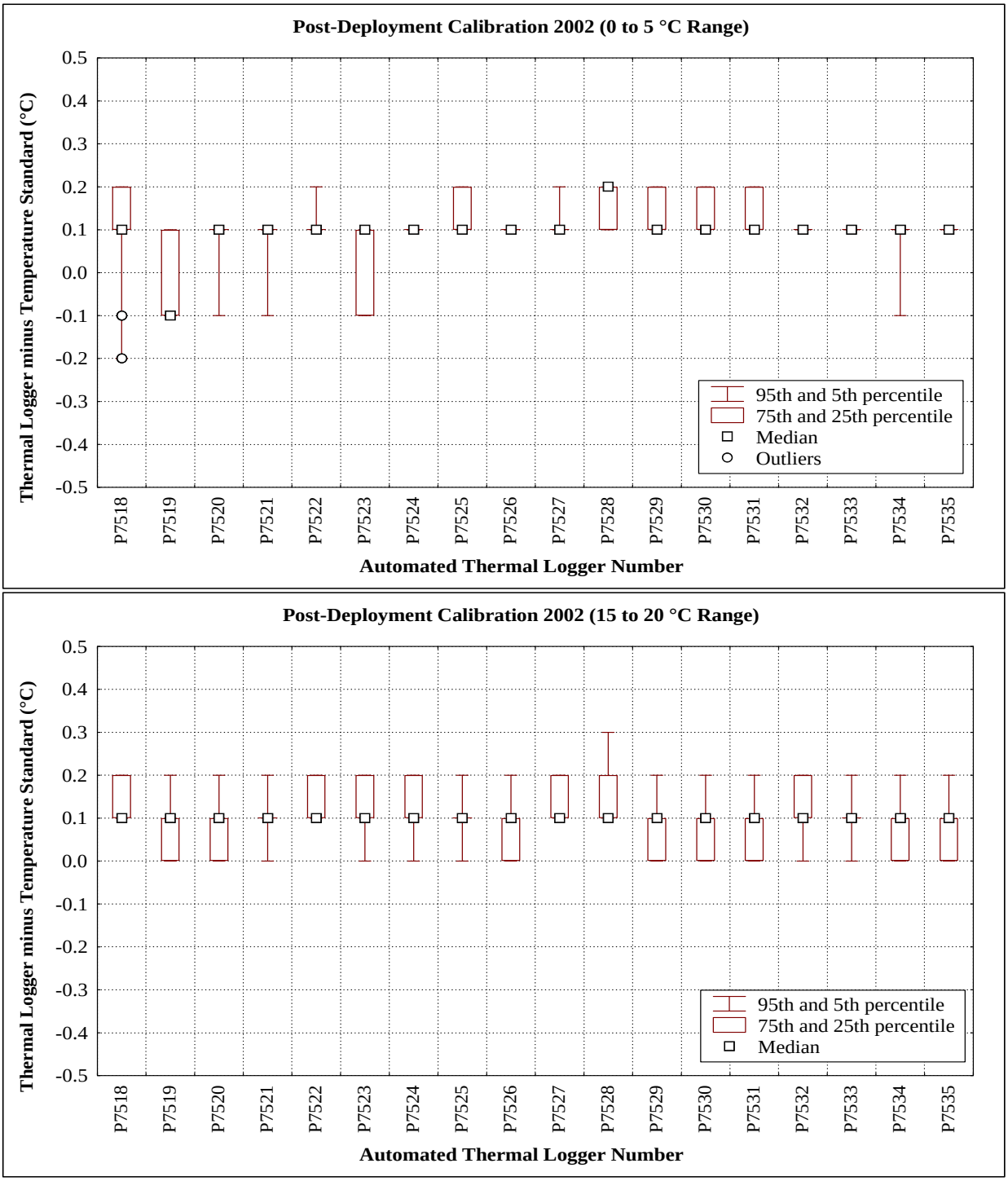


Figure 3. Difference between the automated thermal logger temperature and the NIST temperature standard for the 0 to 5 °C and 15 to 20 °C range in 2002.

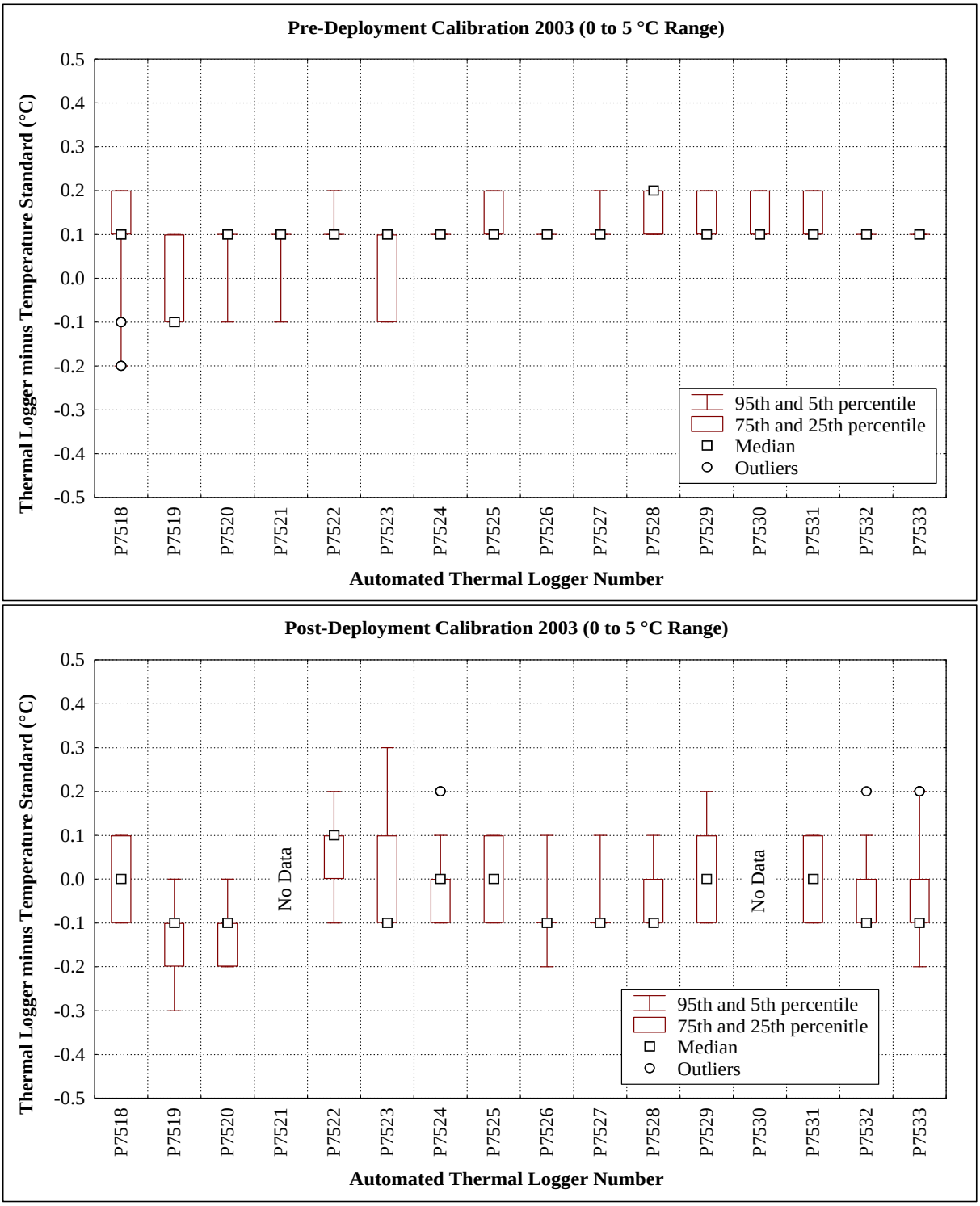


Figure 4. Difference between the automated thermal logger temperature and the NIST temperature standard for the 0 to 5 °C range in 2003.

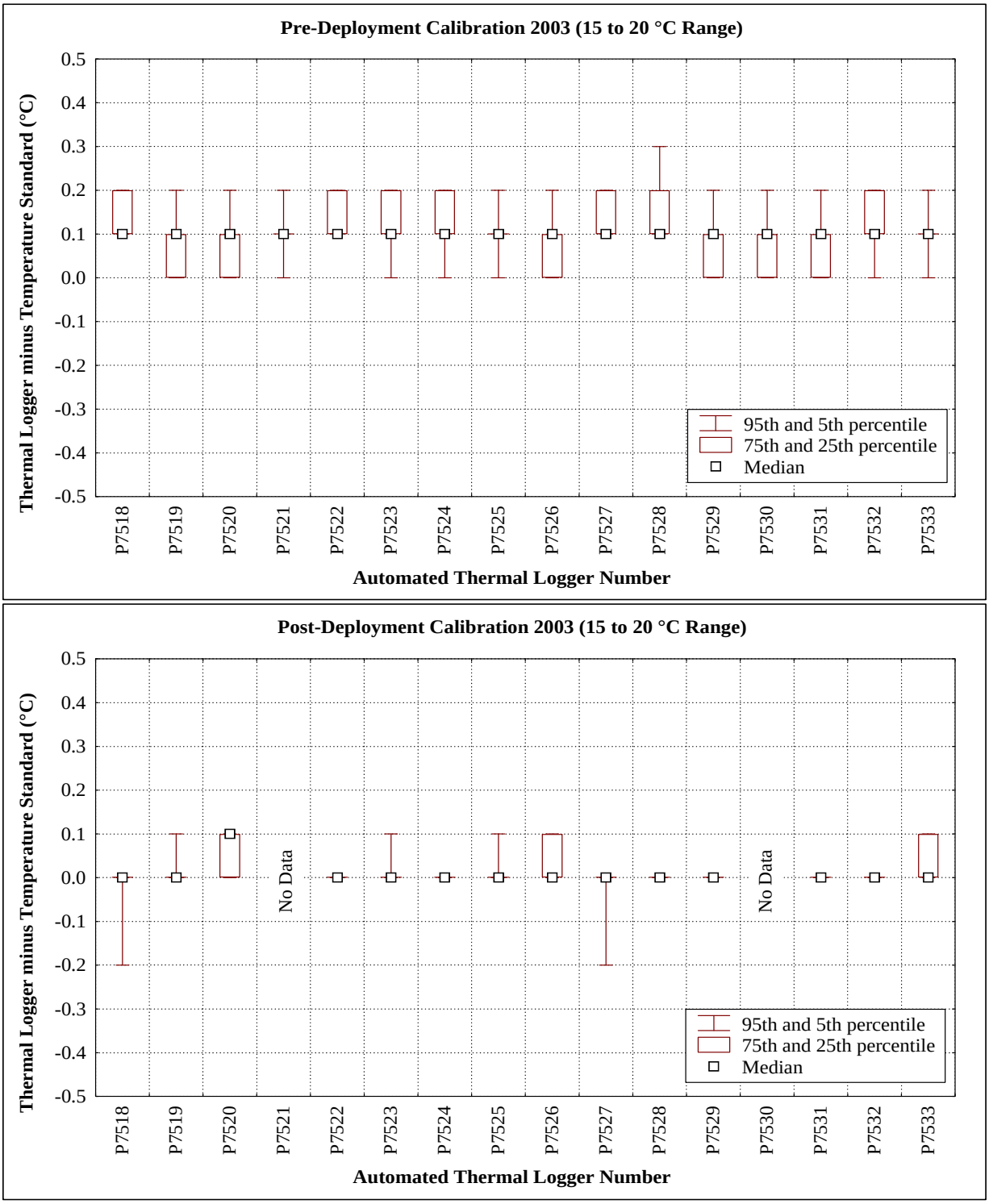


Figure 5. Difference between the automated thermal logger temperature and the NIST temperature standard for the 15 to 20 °C range in 2003.

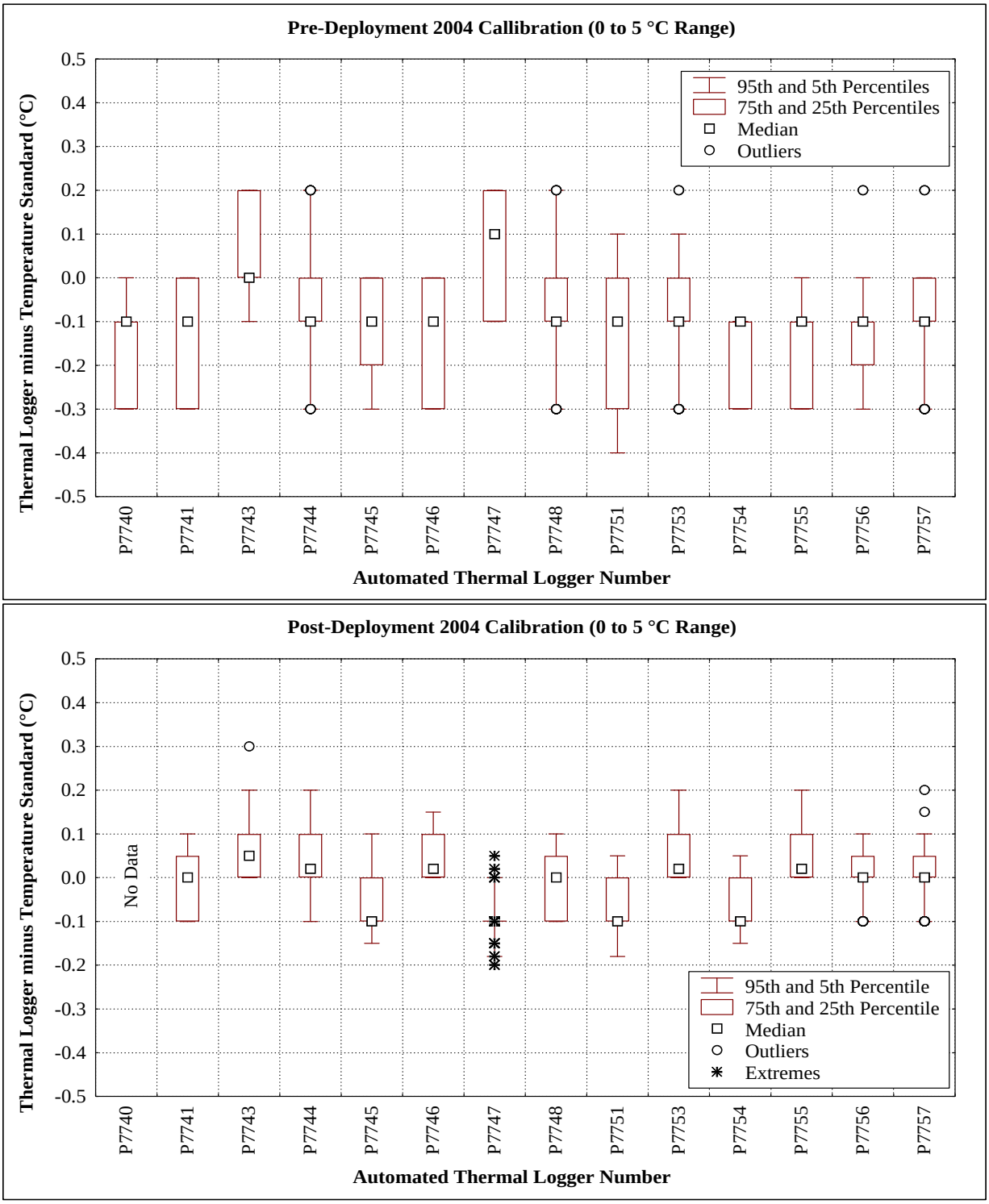


Figure 6. Difference between the automated thermal logger temperature and the NIST temperature standard for the 0 to 5 °C range in 2004.

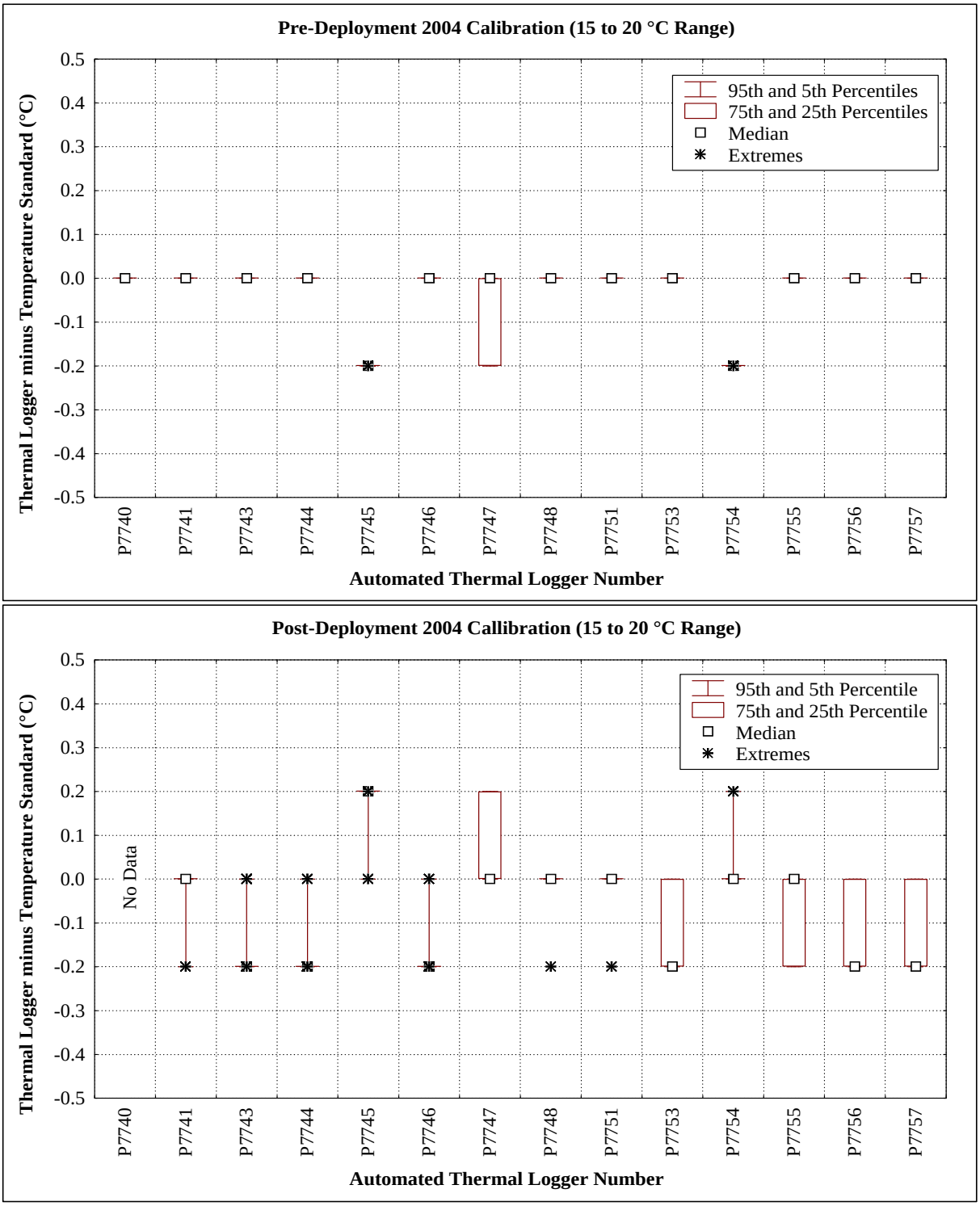


Figure 7. Difference between the automated thermal logger temperature and the NIST temperature standard for the 15 to 20 °C range in 2004.

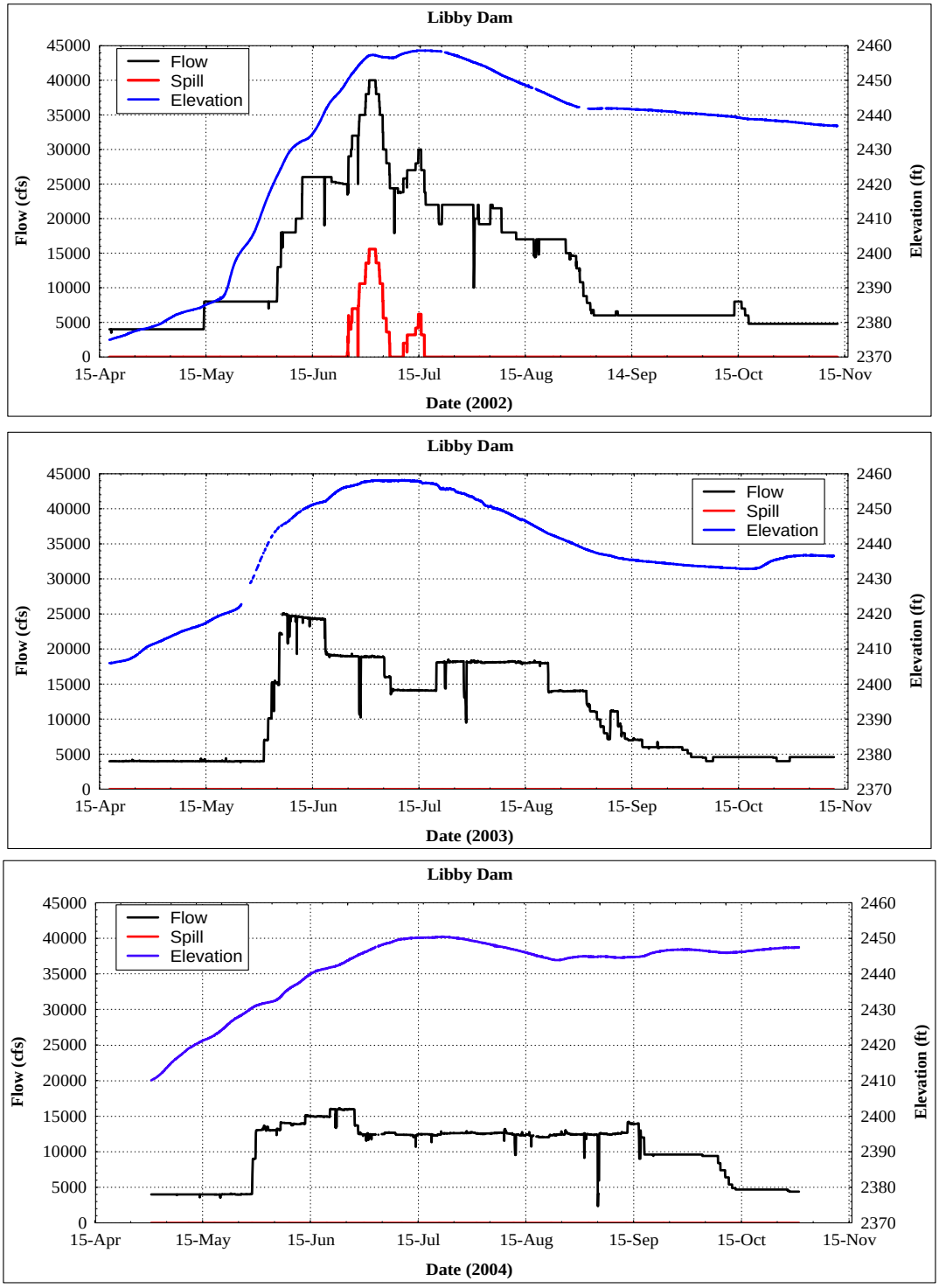


Figure 8. Outflow, spillway discharge, and forebay elevation at Libby Dam from April 15 to November 15 2002, 2003, and 2004.

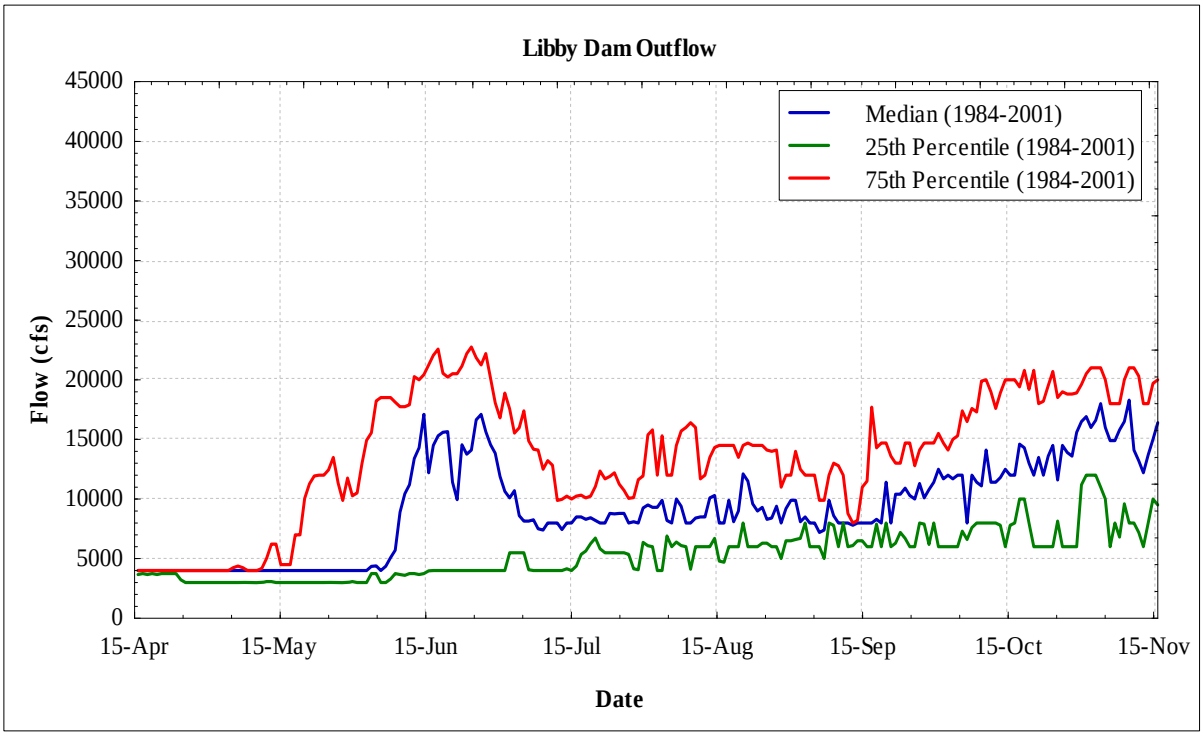


Figure 9. Historical (1984 – 2001) flows for the Kootenai River below Libby Dam.

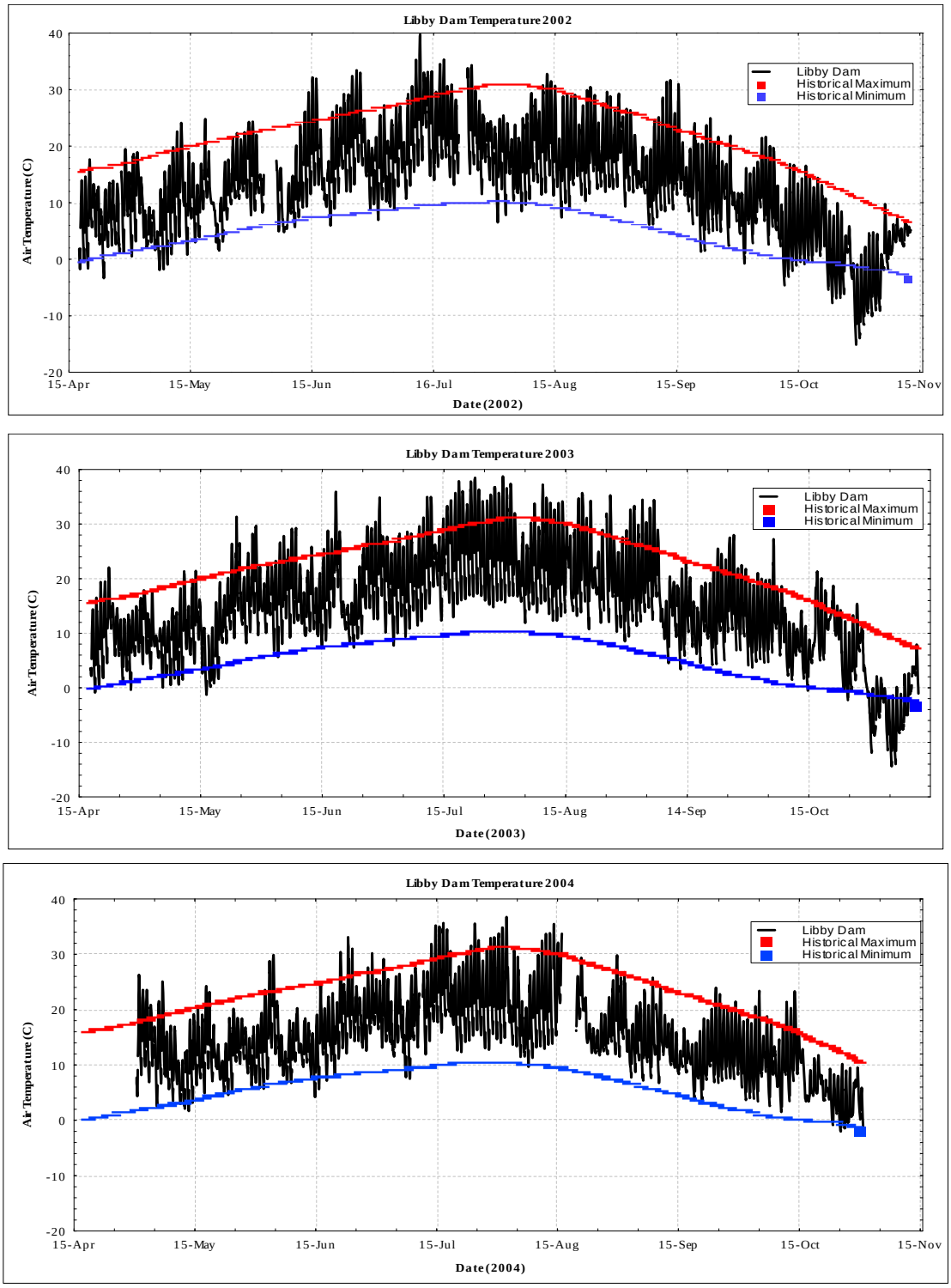
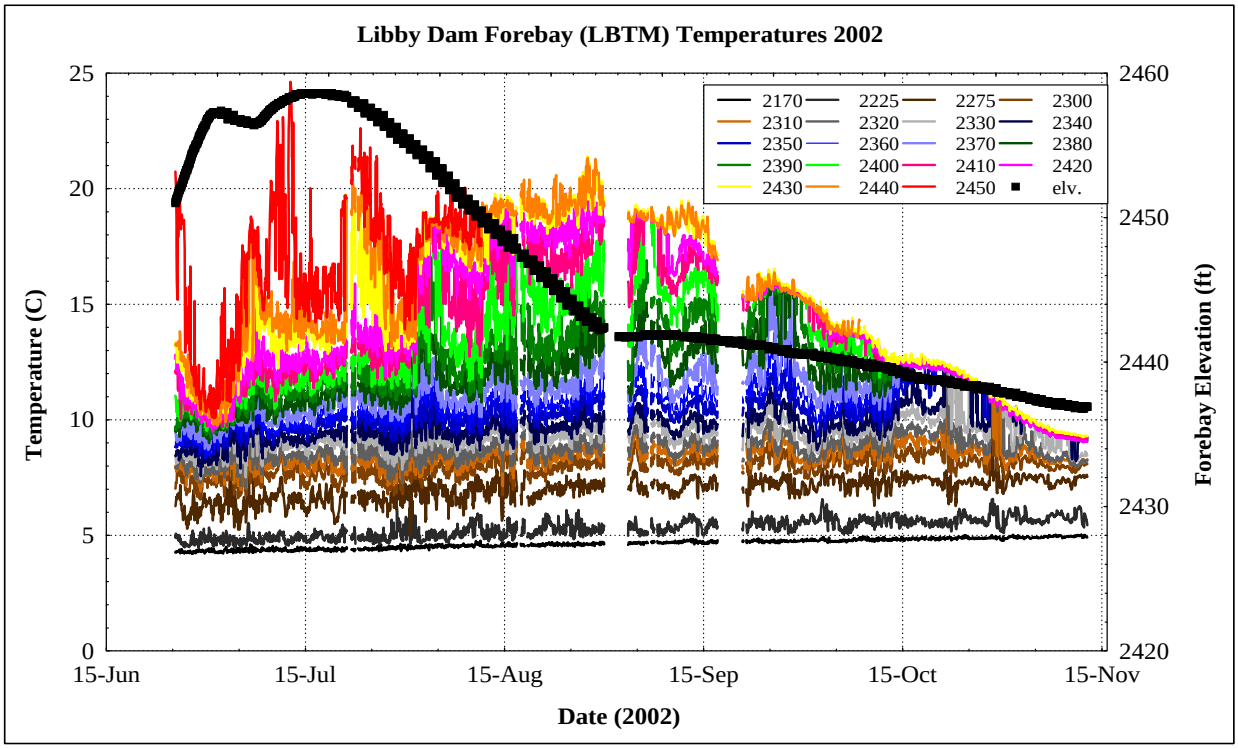


Figure 10. Historical and years 2002, 2003, and 2004 meteorological data for Libby Dam.



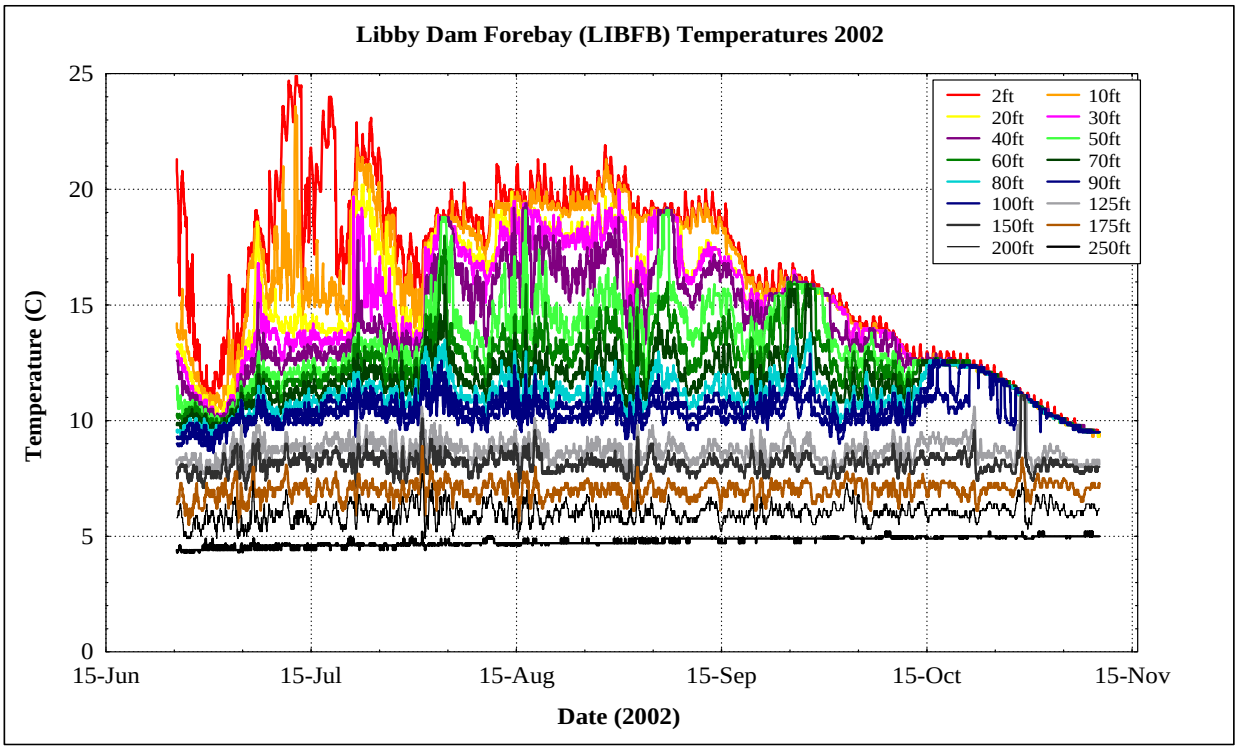


Figure 11. Temporal variation of temperature in 2002 at stations LBTM and LIBFB.

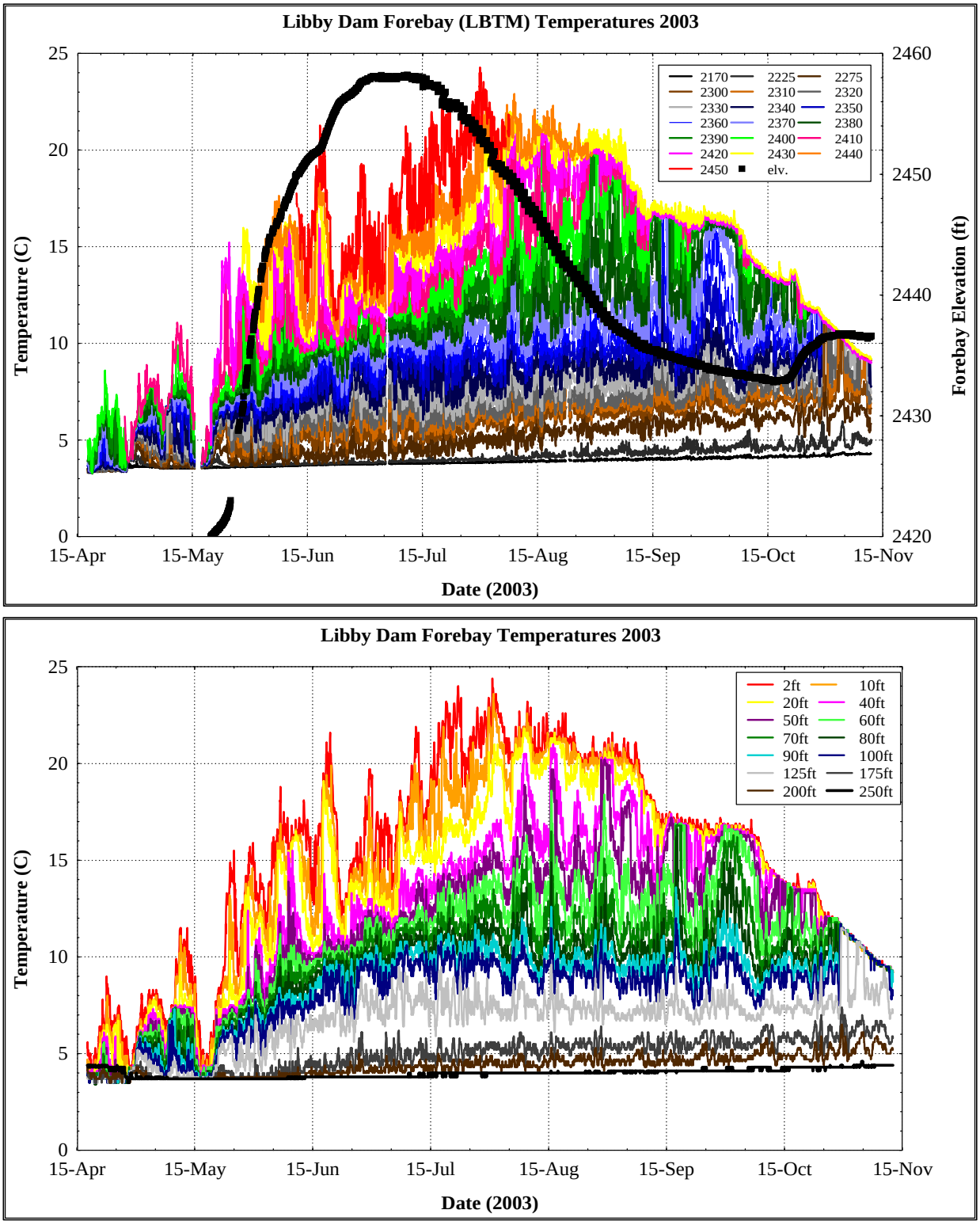
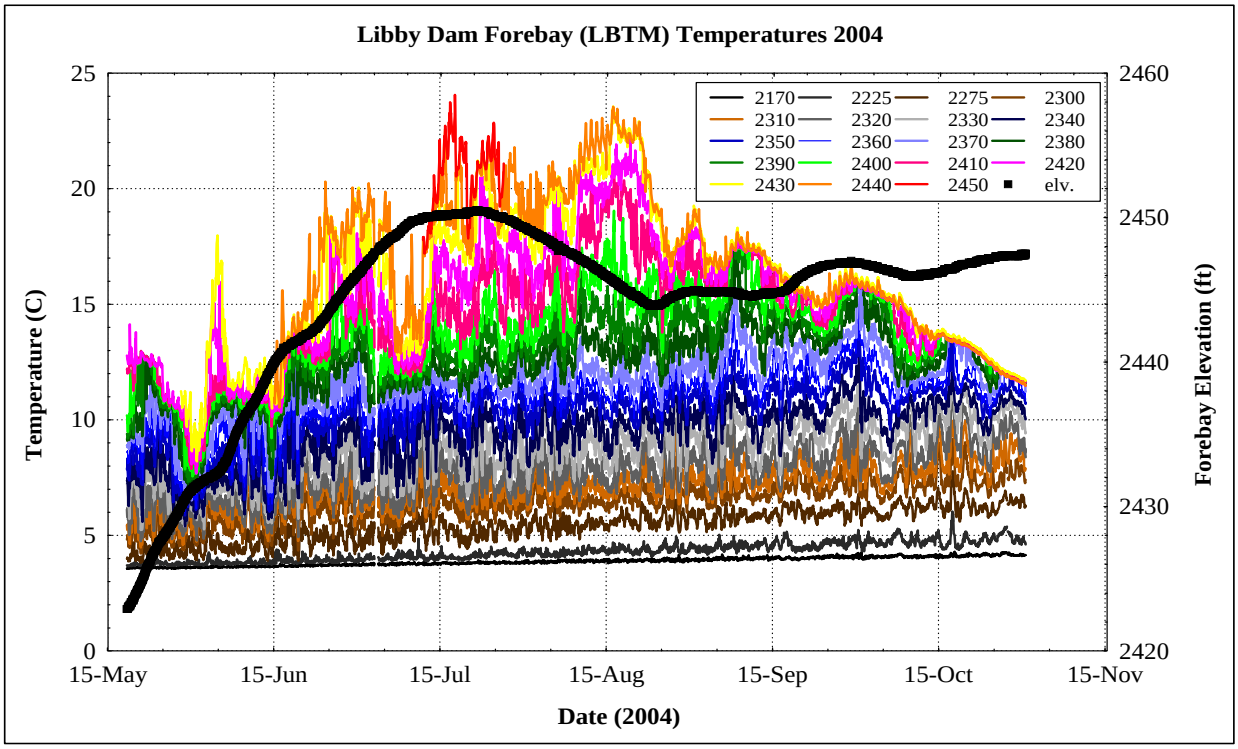


Figure 12. Temporal variation of temperature in 2003 at stations LBTM and LIBFB.



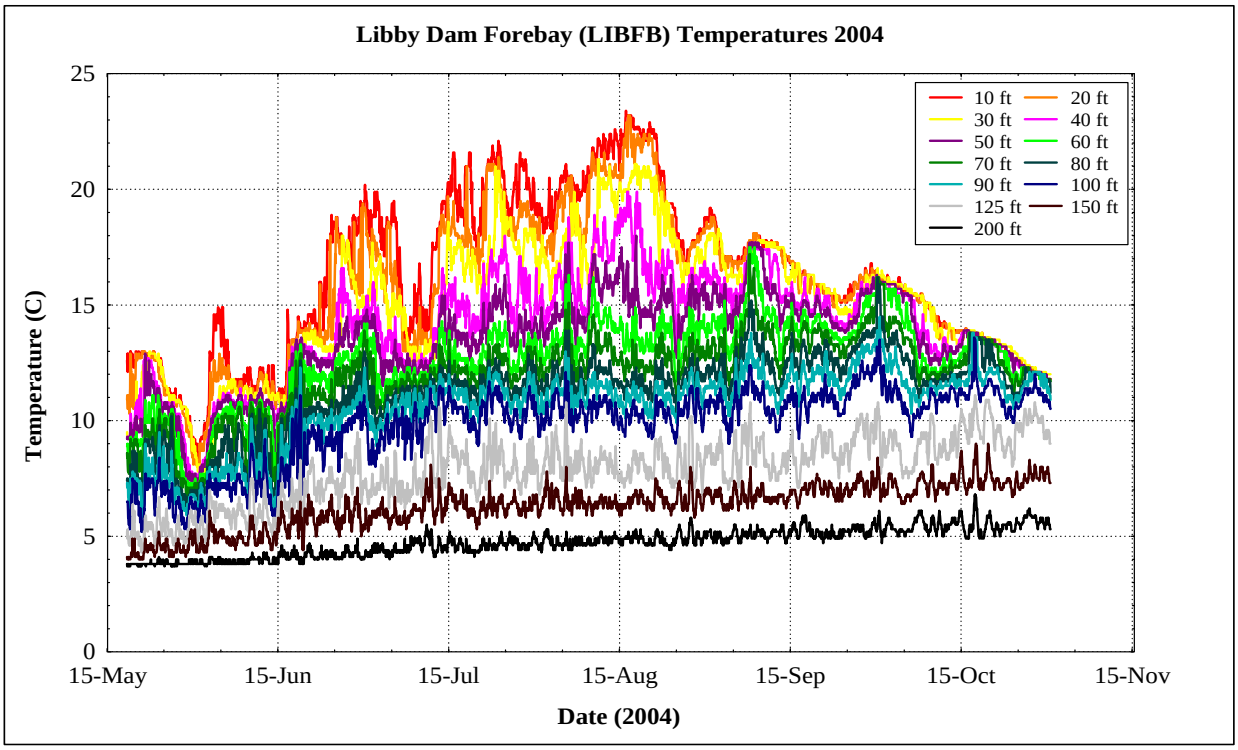


Figure 13. Temporal variation of temperature in 2004 at stations LBTM and LIBFB.

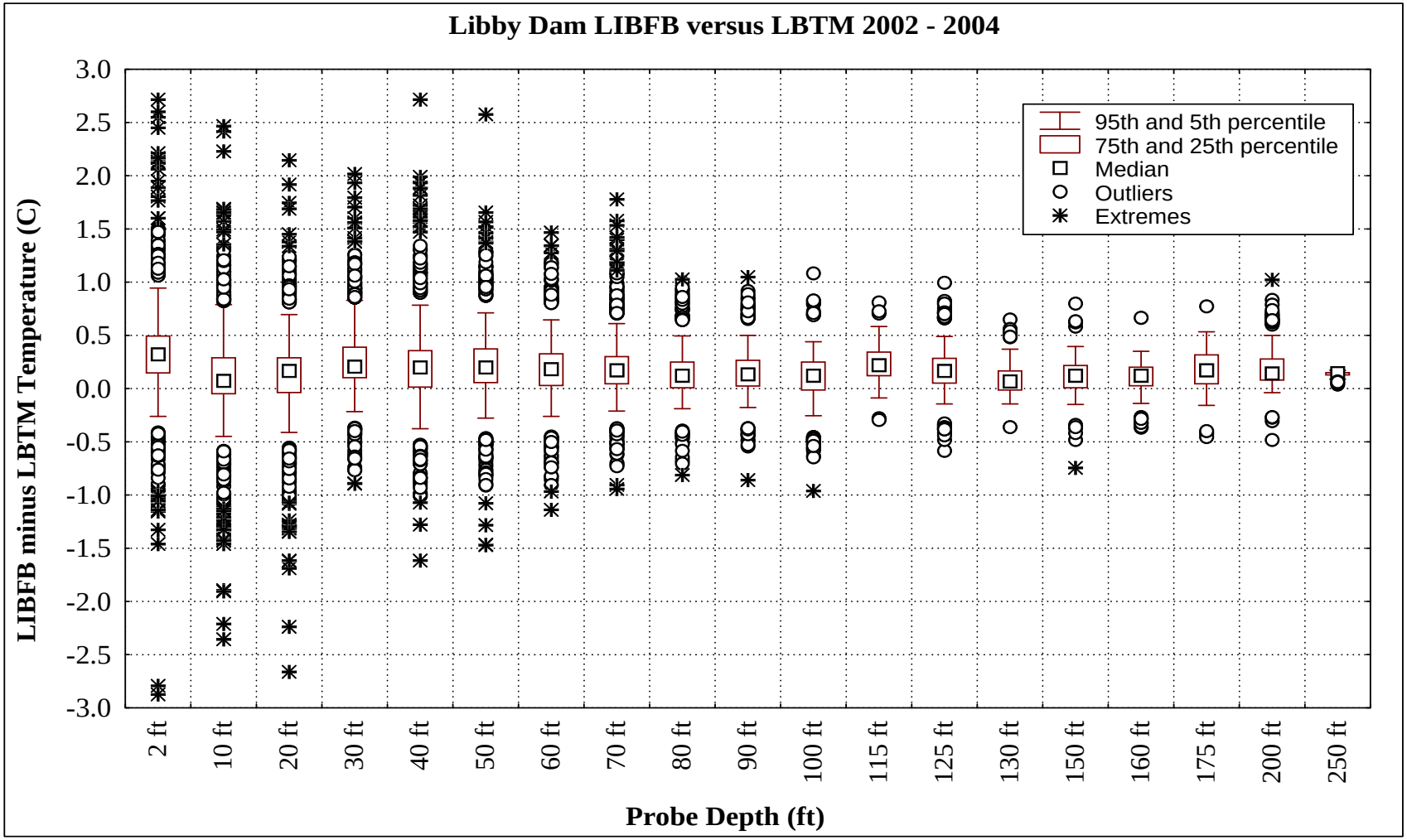


Figure 14. Temperature difference between stations LIBFB and LBTM for specific depths using 2002 through 2004 data.