EVALUATION OF TEMPERATURE COMPENSATION FOR DOMESTIC GAS METERS

FINAL REPORT: TASK 2 – TEMPERATURE ZONE DEVELOPMENT AND TASK 3 – EXPERIMENTAL PROGRAM

SwRI® Project No. 18-11111

Prepared for:

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Salt Lake City, Utah 84145

July 2007

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1. EXECUTIVE SUMMARY

The purpose of this project was to assess the potential to improve meter accuracy using temperature correction factors based on representative ambient temperature measurements made in zones within the Questar service area. The zone approach would be implemented using a single weather station, providing temperatures representative of the temperatures throughout the zone. The maximum and minimum temperatures during a given billing period would be used to calculate an "average" temperature, $(T_{high} + T_{low})/2$, for that billing period. The resulting temperature would be used to adjust the flow rates based on the relationship, if confirmed, between the ambient temperature and the flowing gas temperature. The project was organized into three tasks: Task 1 - *Review Current State of Knowledge*, Task 2 – *Temperature Zone Development* and Task 3 – *Experimental Program*. The results of Task 1 are presented in a separate report. This report covers Tasks 2 and 3.

A temperature zone, encompassing the Ogden, Salt Lake City and Provo areas was selected based on historical climate data. Sixteen sites (fifteen single-family homes and one fast food restaurant) had remote data acquisition systems installed. The systems were instrumented to measure flowing gas temperature, ground temperature, ambient temperature, meter surface temperature, solar radiation flux, flow rate from a standard diaphragm meter and flow rate from a temperature-compensating diaphragm meter. (For a complete discussion of the methods used, see 4.4.3.2.) Data was collected from April 2006 through March 2007. The study concluded that:

- Ambient temperature data can be used to select zone boundaries and to predict intra-zone temperature variability. "Average" ambient temperature data at a single location (the SLC airport in this study) can be used to represent the temperature throughout a zone. The temperature zone approach can be used to provide improved flow measurement.

- The accuracy of the "average" ambient temperature methods improved during the winter months, relative to the summer months. This is because 1) solar radiation exposure is greater during the summer months and 2) the effect of solar radiation on the correlation between ambient temperature and gas temperature is more pronounced during the summer months, when solar radiation tends to be high, and becomes secondary during the winter months, when solar radiation tends to be low. This is significant because more gas is consumed during the winter months.

- The Fixed Factor method performed poorly. The error, relative to the reference measurement, ranged from +6 to -7 %. Errors were greater during mid-summer (July through August) and mid-winter (December through January). Errors were lowest during spring and fall. The effect of the percent error on total volume for a given site was impacted by seasonal load variations. Over the course of the year, the Fixed Factor method produced a net undermeasurement.

- Temperature-compensating meters performed significantly better than the fixed factor method. The percent difference in flow rate, relative to the reference, of the temperature-compensating meters, was approximately in the middle of the group of methods tested (excluding the fixed-factor method). The results of the temperature-compensating meter tests were comparable to the accuracy produced by the “average” ambient temperature methods.

- Overall, performance of the TC meters was steady over the course of the year, with the bulk of the comparisons showing a difference of about +/- 1 to 2 percent. Stations 1, 5, 11 and 13 showed greater variability over the course of the year, increasing the percent difference for all TC meters to about +/- 3%.Measurement precision worsened during the winter months. In comparison, both of the “average” ambient methods (Figure 24 and Figure 25) showed improved precision during the winter months (see 4.4.3.2).

- In contrast to the “average” ambient temperature methods, the precision of temperature-compensating meters worsened during October, November, December, and January. For all the remaining months, the precision performance of the TC meter was not statistically different from the precision performance of the two “average” ambient methods. The cause of the worsening precision was not studied because it was outside the scope of the project.

- The use of meter surface temperature stood out as the most accurate indicator of flowing gas temperature, producing differences in flow rate of +/- 1%. This is because of the “plenum” effect of the meter, which facilitates heat transfer to/from the meter body to/from the gas.

- Figure 19 suggests that the effect of solar radiation on the correlation between ambient temperature and gas temperature is greater during the summer months, when solar radiation and ambient temperatures are higher and that the effect is lower during the winter months, when solar radiation and ambient temperatures are lower. This observation may help explain the difference in the performance of the “average” ambient temperature methods during summer versus winter. The effect could be reduced by using a more reflective meter finish.

- The use of the statistical average ambient temperature, or daily high and low temperatures, at the SLC airport may improve the accuracy of the zone method.

2. INTRODUCTION

Most of Questar's domestic gas meters do not compensate for variations in the gas flowing temperature from the assumed 60°F fixed billing temperature. Because of the climate in Questar's service area, this practice contributes to unaccounted-for gas. This problem could be corrected by installing new temperature compensated (TC) meters or retrofitting existing meters with temperature correctors, but the required capital expenditure is significant, particularly if done in a short period of time. An alternative method would allow Questar to begin adjusting volumes for actual gas temperature, while gradually phasing-in the use of temperature-compensating meters.

A sensitivity analysis was conducted to determine the impact of the constant temperature assumption on flow rate measurement. The results of the sensitivity analysis showed that significant measurement errors occur if the flowing gas temperature differs from the assumed gas temperature of 60°F. Figure 1 shows the relationship. When the actual gas temperature is 10°F from the assumed gas temperature, errors in measurement of as much as 2 percent are possible. The error increases significantly as the temperature difference increases. The average slope, based on a linear curve fit is 0.17%/°F.

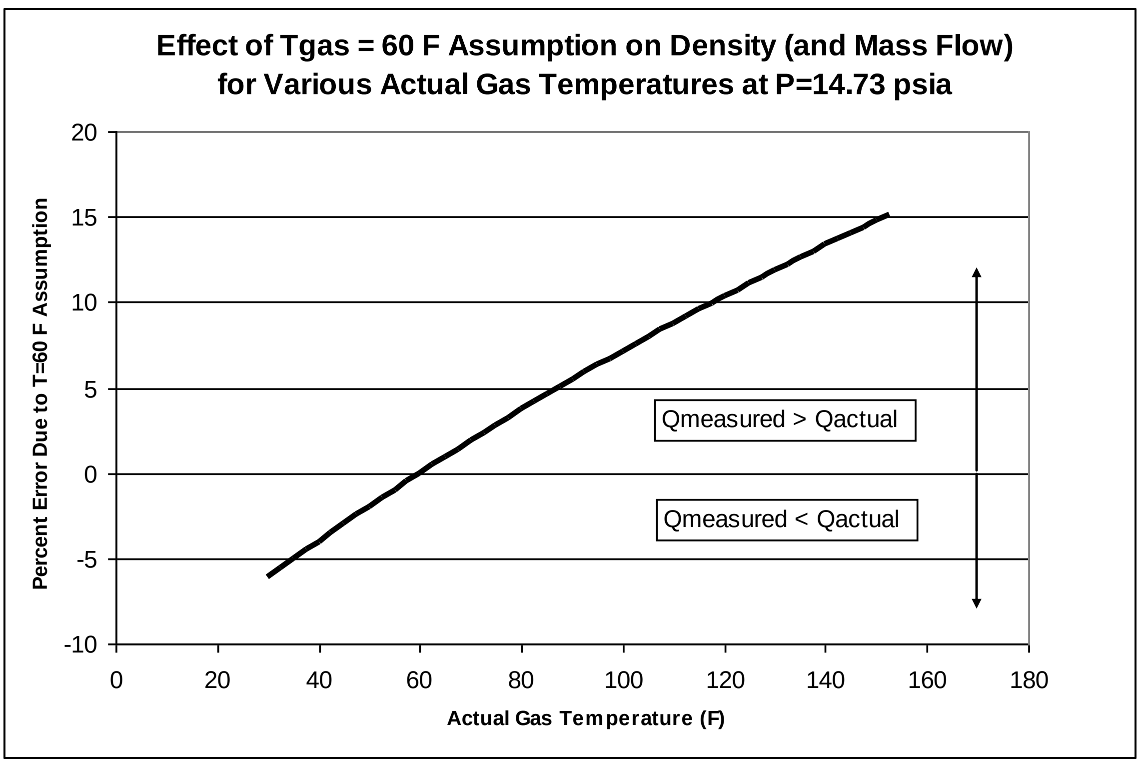

Figure 1. Effect of constant gas temperature assumption on measurement accuracy.

The purpose of this project was to assess the potential to improve meter accuracy by using temperature correction factors based on representative ambient temperature measurements made in zones within the Questar service area. The zone approach would be implemented using a single weather station, providing temperatures representative of the temperatures throughout the zone. The maximum and minimum temperatures during a given period would be used to calculate an "average" temperature, $(T_{high} + T_{low})/2$, for that period. The resulting temperature would be used to adjust the flow rates based on the relationship between the ambient temperature and the flowing gas temperature. The project was organized into three tasks: Task 1 - *Review Current State of Knowledge*, Task 2 – *Temperature Zone Development* and Task 3 – *Experimental Program*.

The objective of the first task was to assess the current state-of-the-art related to temperature compensation. This was accomplished by conducting a literature search and a benchmark survey of local gas distribution companies (LDCs) in the US and Canada. Also part of the first task was a brief review and comparison of Questar's current temperature compensation practices to that of the other LDCs. The results of the first task were presented in a separate report[1]. The report concluded that:

- <u>It is common practice among some LDCs to temperature compensate using temperature correction factors that are based on ambient temperature readings.</u> Implementation of this technique varies, but the general methods are similar. Some LDCs develop a single compensation factor for their entire service area, while others divide the service area into geographic zones and apply individual factors for each zone based on weather data from those zones. Most LDCs use local weather station data to estimate the temperature in their regions, however, a few LDCs use temperature measurements taken by the company, for instance at gate stations, to estimate the temperature in their regions.

- <u>In general, the literature showed that the flowing gas temperature at outdoor meter installations closely agreed with the local ambient temperature. The literature also pointed out that the meter size, solar exposure, and other installation factors are secondary effects and do not significantly affect this relationship between ambient and gas temperature.</u> One study by Columbia Gas did point out that in cold weather, the actual flowing gas temperature is higher than the ambient temperature and in hot weather, the actual flowing gas temperature is lower than the ambient temperature. As a result, Columbia Gas recommended adding 4°F to the ambient temperature to provide a conservative temperature compensation factor and slightly bias the unaccounted-for gas in the customers' favor.

- Better correction factor accuracy can be achieved by using a flow-weighted average temperature rather than a simple temperature average. The flow-weighted average takes into account the fact that the load at typical residential installations is higher when the temperature is lower. The literature did not

[1] *Task 1 Report - Review Current State of Knowledge*, Walter D.B., Svedeman, S.J., Kelner, E. SwRI Project No. 18.11111.

provide enough information to show whether this flow-weighting needs to be done on an hourly basis to capture load changes during the day or whether it is sufficient to perform the weighting based on cumulative monthly meter readings.

Tasks 2 and 3 were conducted with these conclusions in mind. It is important to note that confirming or rejecting the reported correlation of ambient temperature to gas temperature and the "secondary effect" of solar radiation were two objectives of the experimental portion of the study. The effect of a flow-weighted temperature correction was outside the scope of this study.

Tasks 2 and 3 were intended to develop and test a method for adjusting gas flow measurement, using the ambient temperature in a zone. Tasks 2 and 3 were complementary, in that Task 2 used historical climate data to select temperature zones and Task 3 used experimental measurements within a test zone to confirm that the historical data provided a reliable means for selecting temperature zones. Task 3 was also intended to investigate the dependence of flowing gas temperature on parameters such as ambient temperature and solar radiation flux, and to compare the performance of temperature compensating (TC) meters.

3. TASK 2 - TEMPERATURE ZONE DEVELOPMENT

3.1 Objective

The objective of this task was to provide the basis for the establishment of temperature zones in the Questar Gas service area, to select temperature zones and to select sites for the experimental program.

3.2 Review of Historical Climate Data

Prior to this project, WeatherBank, Inc of Edmund Oklahoma, conducted a study of historical climate data for the Questar Weather Normalization Adjustment program[2]. Since this work had already been done, Questar requested that SwRI review the final report to determine if the results could be used in this study. The temperature zone information was reviewed and found to be insufficient for this project. However, WeatherBank agreed to perform an additional study, based on guidance from Questar and SwRI, under their existing contract with Questar.

3.2.1 WeatherBank Data

WeatherBank provided monthly maximum and minimum temperatures covering a thirty-year period (1975-2004) from 179 weather stations in Utah, Colorado, Arizona, Nevada, Idaho and Southwest Wyoming. Monthly "averages" were computed from these data by averaging the minimum and maximum temperatures. WeatherBank also provided plots of isotherms for the Questar service area, using a software package called SURFER-7 and a technique called "kriging," a geostatistical approach to modeling based on the spatial correlation structure of the raw temperature data. Figure 2 and Figure 3 are examples of the average temperature plots provided by WeatherBank for August and January. The complete set of plots is included as Appendix A.

In Figure 2, temperature zones are apparent in the region west of the Wasatch Mountains, in Southwest Wyoming, in Eastcentral and Southeast Utah, and along the mountain ranges. In Figure 3, possible temperature zones are apparent from the Wasatch Mountains, moving east and north into Wyoming, west of the mountains and in the southern third of the state, excluding mountainous regions.

3.2.2 Descriptive Statistics and Temperature Trends

The 30-year temperature weather station data obtained from WeatherBank was examined for possible trends in the temperature profiles by weather station. Initially, a grouping of weather stations by three city areas was defined: Salt Lake City, Ogden and Logan. Table 1 lists the weather stations, by Weather Station ID Code, considered in this early investigation of the temperature data.

[2] WeatherBank, Inc. Report Number: QGC-SLC-02212003

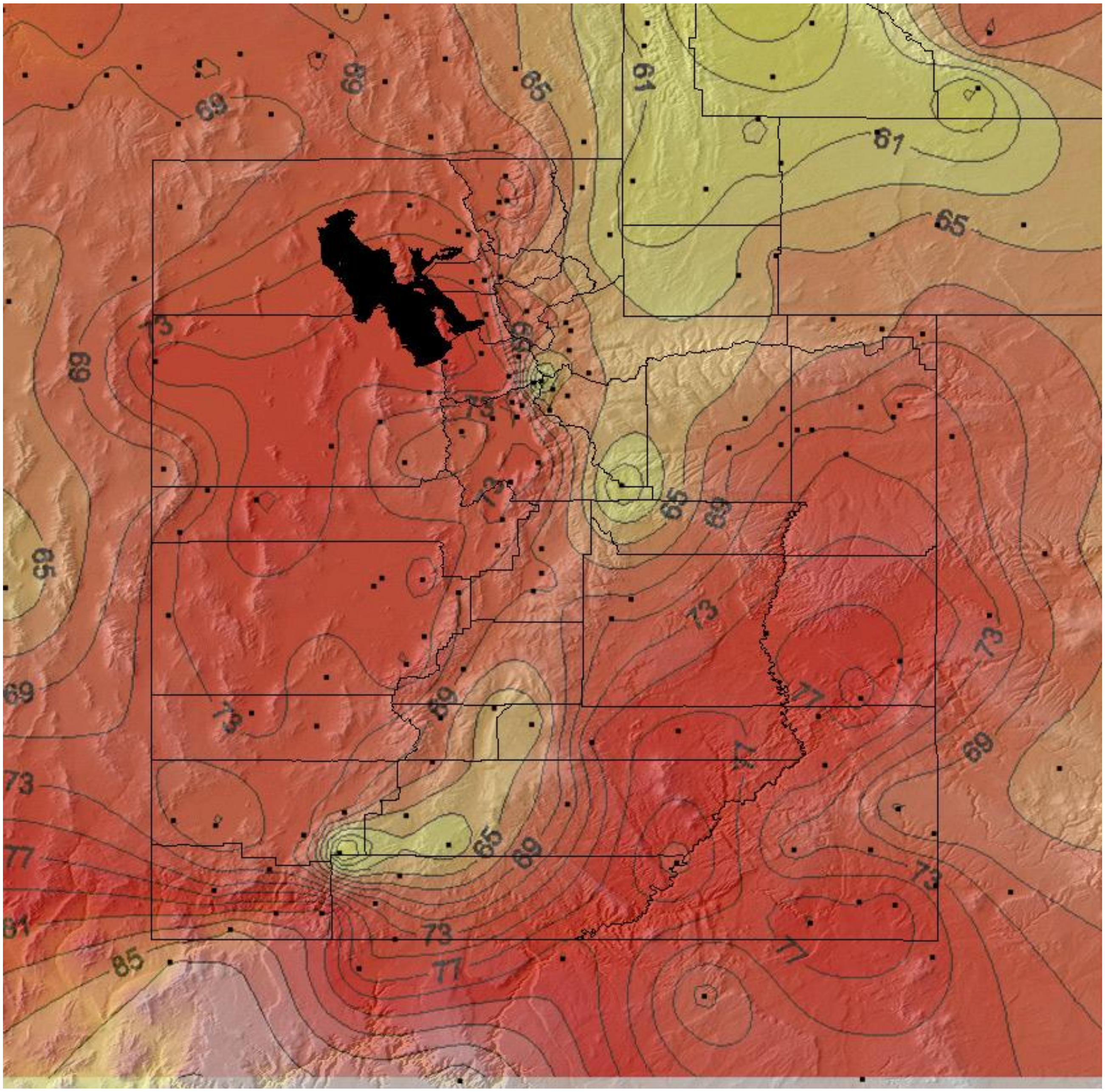

Figure 2. Average August temperature contour map for Questar service area based on a 30-year period.

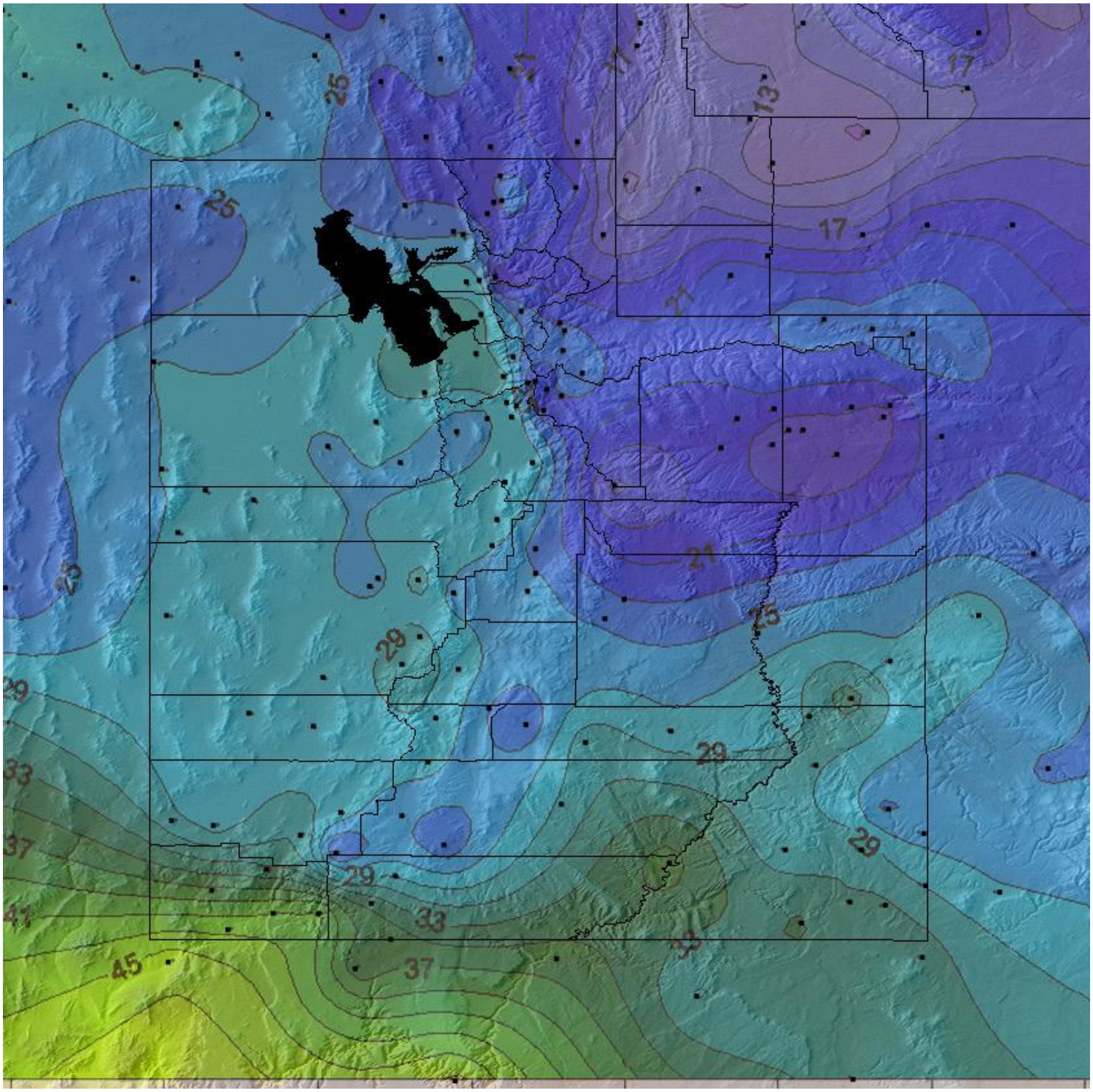

Figure 3. Average January temperature contour map for Questar service area based on a 30-year period.

City/Area	Weather Stations
SLC	0061, 0072, 1588, 1759, 2057, 2385, 3097, 3809, 4467, 5892, 6919, 7598, 7846, 7909, 8733, 8771, 8973, 9165
Ogden	2726, 5826, 6404, 6414, 6869
Logan	0928, 1731, 5182, 5186, 5194

Table 1. Salt Lake City, Logan and Ogden Area Weather Stations

Temperature descriptive statistics were computed for the three city areas on a monthly basis for the 30-year period. The standard deviations ranged from a low of 2.75°F in Logan in August to a high of 6.66°F in Logan in January.

Monthly average temperature plots were produced for each city area from 1975-2004. These plots helped to provide insight into (a) weather stations which did not exhibit the same temperature trend within a city area and (b) whether the entire 30-year temperature profile was different from a 10-year (1995-2004) temperature profile. In other words, were the temperatures during the last 10 years different from the last 30 years?

Figure 4 represents the April 30-year temperature data for Salt Lake City. The 18 weather stations identified are plotted individually from 1975-2004. The year-to-year average April temperatures are connected by straight lines (i.e., no curve fitting was performed). Note that for this particular month two stations are considerably cooler than the remaining stations: station #72 (pink) and #7846 (red). These two stations are located near Alta, Utah in the Wasatch Mountains. Thus, these stations should not be included in a Salt Lake City area temperature zone. Also note that the variation in temperatures across the years is somewhat large from 25°F to 60°F.

An analysis of variance (ANOVA) comparing the average monthly temperatures for Salt Lake City, Ogden and Logan areas over 30 years and over 10 years was performed. There was no significant difference (at the 5% significance level) in the average monthly temperature between the 30-year average and the 10-year average, indicating that no recent (over the last 10 years) trends in surface temperatures are being masked by the 30-year statistics.

3.2.3 Comparison of Average Temperatures Across Four Cities

Weather station data from the areas including Salt Lake City, Ogden, Provo and Logan were compared across cities to determine if the monthly average temperature over 30 years was significantly different. This was done in order to determine if the four city areas could be combined into one temperature zone. Topography and area maps, generated by WeatherBank, were used to determine comparable geographical temperature areas. Table 2 lists the weather stations included in each of the four city areas.

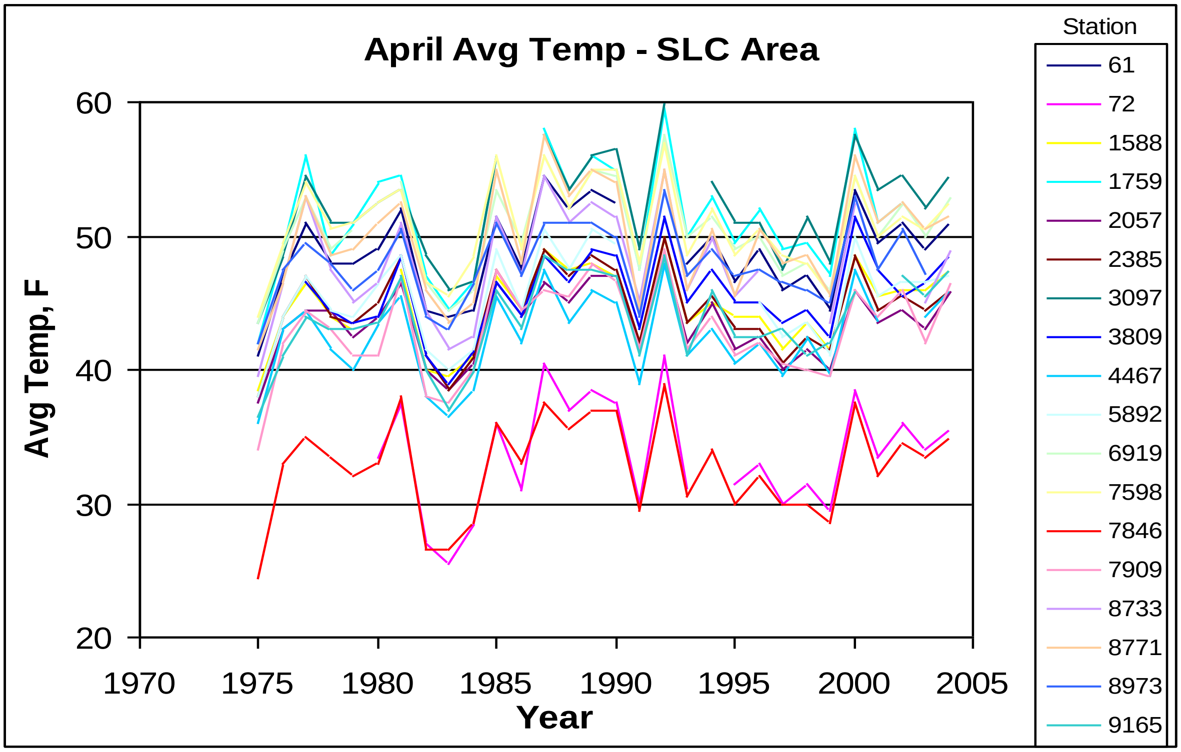

Figure 4. Average April temperature for 18 Salt Lake City Area weather stations over a 30-year period.

City/Area	Weather Stations
SLC	1759, 3097, 5892, 7598, 8771
Ogden	2726, 6404, 6414
Provo	6919, 8119, 8973
Logan	928, 1731, 5182, 5186, 5194

Table 2. City/Area and associated weather stations.

An ANOVA was performed in order to compare the average temperature using all weather stations within a city across the four defined city areas. All statistical tests were made at the 5% level of significance. Table 4 lists the results of the ANOVA. Each month was compared independently. Cities with the same letter are areas in which the average temperatures are not significantly different. For example, in January over the 30-year temperature history the average temperatures in SLC, Ogden and Provo are not significantly different from one another. But all three areas are significantly different from the average temperature in the Logan area. In 8 of the 12 months, the average temperatures for SLC, Ogden and Provo are not significantly different from one another. In addition, the variation in the temperature data by city ranged from standard deviation of 2.26 to 6.66°F. Therefore, a temperature zone chosen using those areas was investigated

3.2.4 Combining SLC, Provo and Ogden Weather Stations

The 11 weather stations identified in Table 2 from SLC, Provo, and Ogden were analyzed to determine the average "*delta temperature*" (i.e., maximum average temperature – minimum average temperature). This was done to confirm that the largest difference in the average temperatures across the 11 stations was less than or equal to 5°F. This requirement was suggested by Questar and was based on an estimated measurement error associated with gas temperature of approximately 0.2%/°F. Table 3 lists the maximum *delta temperature* by month across the 11 stations using the 30-year temperature average by station.

Month	Maximum Temperature		Minimum Temperature		Delta Temperature
	City/Station	Avg. Temp	City/Station	Avg. Temp	
Jan	SLC/1759	30.73	SLC/5892	26.12	4.61
Feb	SLC/1759	35.73	SLC/5892	29.84	5.89
Mar	SLC/3097	44.43	SLC/5892	37.60	6.83
Apr	SLC/3097	52.39	SLC/5892	45.68	6.71
May	SLC/3097	61.30	SLC/5892	53.79	7.51
Jun	SLC/3097	72.04	SLC/5892	62.96	9.08
Jul	SLC/3097	80.81	SLC/5892	70.92	9.89
Aug	SLC/3097	78.61	SLC/5892	69.20	9.41
Sep	SLC/3097	67.83	SLC/5892	60.44	7.39
Oct	SLC/1759	55.20	SLC/5892	48.83	6.37
Nov	SLC/3097	41.44	SLC/5892	36.43	5.01
Dec	SLC/3097	32.68	SLC/5892	27.96	4.72

Table 3. Delta temperature (°F) across 11 weather stations by month.

Note that 10 of the 12 months had temperature deltas greater than 5°F. Upon examination of the locations of the temperature stations it was noted that station #5892 was located near Mountain Dell reservoir along I-80, east of Salt Lake City. This station provided the lowest average temperature for all 12 months. Thus, station #5892 was deleted from the group and the *delta temperature* based on the remaining 10 stations was computed. The results from this analysis are provided in Table 5.

Therefore, in the development of a temperature zone for weather monitoring it was possible to base the zone selection on a combination of several city areas in which the delta temperatures were near the targeted 5°F differential. The weather stations selected as an example zone in this section were based entirely on geographic areas and temperature profiles. Density of residential Questar customers was not considered.

Month	Average Temp For Weather Stations in Each City/Area			
	SLC	Ogden	Provo	Logan
Jan	29.46	29.01	28.54	23.97
	A	*A*	*A*	
				B
Feb	34.06	34.06	33.38	28.87
	A	*A*	*A*	
				B
Mar	42.58	43.09	41.99	39.3
	A	*A*	*A*	
				B
Apr	50.23	51.13	50.00	47.46
	A	*A*	*A*	
				B
May	58.99	59.34	58.29	55.66
	A	*A*	*A*	
				B
Jun	69.05	69.11	67.76	64.73
	A	*A*		
			B	
				C
Jul	77.33	76.92	75.21	72.48
	A	*A*		
			B	
				C
Aug	75.61	75.07	73.41	70.95
	A	*A*		
			B	
				C
Sep	65.72	65.53	64.26	61.4
	A	*A*		
			B	
				C
Oct	53.25	53.16	52.25	49.51
	A	*A*	*A*	
				B
Nov	39.62	39.57	38.87	35.91
	A	*A*	*A*	
				B
Dec	31.05	30.89	30.29	26.26
	A	*A*	*A*	
				B

Table 4. ANOVA comparison of average temperature (°F) across city/areas.

3.3 Temperature Zone Selection

To complement the analysis, Questar proposed fourteen temperature zones based on the historical temperature data, number of customers, and available weather stations. A summary of the proposed zones is listed in Table B in Appendix B. Thirty-year monthly temperature averages were obtained from the WeatherBank summary tables for each individual weather station. Based on these zone definitions, the maximum and minimum average monthly temperatures across the weather stations were identified and used to compute the *delta temperature*. Those *delta temperatures* greater than 5°F are highlighted in yellow. Also included for each zone are the weather station averages sorted by temperature (lowest to highest) for each month. In future applications, this information can be used to identify the stations Questar may want to consider for temperature monitoring purposes (i.e., highest temperature, lowest temperature, midrange temperature).

Month	Maximum Temperature		Minimum Temperature		Delta Temperature
	City/Station	Avg. Temp	City/Station	Avg. Temp	
Jan	SLC/1759	30.73	Provo/8973	26.20	4.53
Feb	SLC/1759	35.73	Provo/8973	31.14	4.59
Mar	SLC/3097	44.43	Provo/8973	39.21	5.22
Apr	SLC/3097	52.39	Provo/8973	48.07	4.32
May	SLC/3097	61.30	Provo/8973	56.43	4.87
Jun	SLC/3097	72.04	Provo/8973	66.11	5.93
Jul	SLC/3097	80.81	Provo/8973	73.65	7.16
Aug	SLC/3097	78.61	Provo/8973	71.62	6.99
Sep	SLC/3097	67.83	Provo/8973	61.85	5.98
Oct	SLC/1759	55.20	Provo/8973	49.85	5.35
Nov	SLC/3097	41.44	Provo/8973	36.57	4.87
Dec	SLC/3097	32.68	Provo/8973	28.33	4.35

Table 5. Delta temperature (°F) across 10 weather stations by month.

Based on the analysis of the historical 30-year average temperature data and the preliminary zone definitions suggested by Questar, a single zone was selected for the Task 3 experimental program. Zone 6, representing the Wasatch Front region was chosen because (1) it encompassed a relatively large geographical area, (2) there were many residential homes near the weather stations currently being monitored, (3) the area included a large residential population, and (4) the eight original stations identified by Questar had delta temperature values considerably less than 5°F. After closer examination of the locations of the original eight stations it was decided to add two more stations, Utah Lake (#8973) and Cottonwood (#1759) to Zone 6 to broaden the geographical area. Table B in Appendix B includes the monthly average 30-year temperatures for all 10 weather stations. Subsequently there were now four months with delta temperatures greater than 5°F: July, August, September and October. However, since the largest delta was 5.8°F the decision was made by Questar and SwRI to include all 10 weather stations in the Zone 6 definition for comparing the historical data with the experimental data obtained in Task 3.

4. TASK 3 - EXPERIMENTAL PROGRAM

4.1 Objective and Approach

The experimental program had three objectives. The first was to confirm or reject historical temperature profiles for the zone that was selected in Task 2. The second was to provide data to confirm or reject the relationship between ambient temperature and flowing gas temperature that was suggested in an article by Columbia Gas of Ohio[3]. The third objective was to provide data comparing the accuracy of flow measurements using various flowing gas temperature assumptions and to compare the performance of TC meters.

Tests were conducted at sixteen field sites in the SLC/Ogden/Provo area (Zone 6 - Wasatch Front) selected during the temperature zone selection task. Sixteen field sites were needed in order to provide an acceptable level of confidence in the statistical comparison of the average monthly temperatures across the field sites within the experimental temperature zone[4] and to provide back-up data in case of equipment failure. In addition, the field tests were positioned throughout the zone to assess the statistical validity of using a single ambient temperature measurement location to represent the ambient temperature throughout the whole zone. Last, the assumption that the zone temperature variation in the historical data was not statistically different from the zone temperature variation in the field data was also tested.

In addition to the ambient temperature data, ground temperature, flowing gas temperature, meter surface temperature and solar radiation flux were measured in order to understand the variables that impact flowing gas temperature. This is critical for successful implementation of the temperature zone approach, since it relies on ambient temperature as an estimate of flowing gas temperature.

The flow rate comparisons were accomplished using the non-TC meter flow rate, adjusted for flowing gas temperature, as the reference flow measurement. The flowing gas temperature was calculated using the "average" of the non-TC meter's inlet and outlet gas temperatures ($(T_{in} + T_{out})/2$). Certain simplifying assumptions were made because of the lack of gas composition data at each site and because of standard distribution flow measurement practices. The assumptions were:

- Compressibility Factor, $Z = 1$
- Specific Heats, C_p and C_v = Constant
- $P_{std} = P_{flow} = 14.73$ psia (no pressure compensation)[5]

[3] "Outsourcing Meter Repair May Lower Distribution System Costs," Monte, Dave. Pipeline & Gas Industry, January, 2000, pp. 63-66.

[4] The number of field sites required depends on the standard deviation of the historical temperature data, the statistical acceptance region, the probability of rejecting the hypothesis when it is true (Type I error) and the probability of accepting the hypothesis when it is false (Type II error).

[5] In practice, Questar corrects flow to 12.85 psia. Pressure compensation was not necessary for the relative comparisons of this study.

- P = constant through both meters

Since these are relative comparisons and the assumptions are applied equally to all methods under comparison, any biases associated with the first three assumptions will cancel out. The fourth assumption, P = constant through both meters, could have some effect on the results. However, calculations estimated the effect to be no more than 0.16%.

The compressibility factor assumption allowed use of the Ideal Gas relationship to separate the effect of pressure from the effect of temperature. This is a common practice in distribution measurement and allows for the use of factors to correct for temperature and pressure. In Questar's case, the pressure is corrected using elevations and the temperature factor is fixed, using an assumed gas temperature of 60°F. The net effect due to these assumptions is that the flow rate can be calculated using $Q = Q_{flow} (T_{std}/T_{flow})$, where "std" implies 60°F and "flow" implies flowing gas temperature. For the experimental program, the flow rate equation was modified to $Q = Q_{NTC} (T_{std}/T_{test})$, where Q_{NTC} was the output of the non-temperature-compensating meter and T_{test} was the temperature associated with the method being tested. Using this convention, the following flow rate equations were used for the flow rate comparisons:

- Reference flow rate: $Q_{ref} = Q_{NTC} (T_{std}/T_{ref})$, where $T_{ref} = (T_{in}+T_{out})/2$
- Fixed Factor: $Q_{fixed} = Q_{NTC} (T_{std}/60^{O}F)= Q_{NTC}$
- Ambient Temperature: $Q_{amb} = Q_{NTC} (T_{std}/T_{ambient})$
- Meter Surface Temperature: $Q_{surf} = Q_{NTC} (T_{std}/T_{meter\ surface})$
- Temperature-Compensating Meter: $Q = Q_{TC}$

The net effect of these equations is that if a particular method assumes the gas temperature is lower than the reference temperature, the method will result in a flow rate measurement that is biased high. Likewise, if the gas temperature is assumed higher than the reference temperature, the method will result in a measurement that is biased low. This argument can be recast in terms of mass flow rate and the constant temperature (i.e. fixed-factor) approach. Mass flow rate is the product of density and volumetric flow rate, ρQ. An assumption of constant temperature, given our previous assumptions regarding pressure and compressibility, implicitly assumes constant density. However, if the actual flowing temperature is higher than the assumed constant temperature, the actual density will be lower and, correspondingly, the actual mass flow rate will be lower. The end result will be that the mass flow rate calculated using the assumed constant temperature will be higher than the actual mass flow rate. In the case of the temperature-compensating meter, placed in series with the reference meter, the mass flow rate through both meters should be approximately equal, assuming steady flow. In this analysis, all methods are compared to the reference flow rate using the percent difference.

The tests were conducted for 12 months, beginning April 2006. Questar Gas graciously provided the following support:

- Protective enclosures for data acquisition equipment.
- Data acquisition system installation.
- Ongoing technical support and instrumentation maintenance.

- Data downloads from dataloggers.
- Data forwarded via a dedicated FTP site on the SwRI server.

4.2 Measurement Site Selection

During the proposal phase, a cursory examination of the potential number of sites, based on several assumptions[6], suggested that the number of field sites required in a given zone would range from less than five to sixteen. The one assumption that was truly unknown was the estimate of the monthly temperature variation in a weather station. Using the 30-year monthly historical temperature data from the 10 weather stations in Zone 6 it was determined that the largest temperature standard deviation was 5.82°F which occurred at the Santaquin weather station (#7686) during January. This represents the highest variation in monthly temperature data for the selected weather stations based on the 30-year database. This value was used as a conservative estimate of the variation in the weather station temperature. In order to detect a change in the average temperature of 5°F across the 10 weather stations, the number of field sites required would be 13. The probability of a Type I Error was assumed to be 0.05 and the probability of a Type II Error was assumed to be 0.20. Since the project could financially allow up to sixteen stations for the experimental phase, it was decided to include all sixteen stations in the Zone 6 region. This would allow a buffer in the sample size in case of data-acquisition problems.

Questar Gas employees provided access to their properties in order to install and maintain the measurement systems. The locations of available sites was limited due to the population density and due to the reliance on Questar Gas employees, so site selection was based on the best available sites, combined with the zone temperature historical data. Sixteen locations were selected in order to provide a reasonable statistical comparison and representation of the ambient conditions throughout the zone. The selected sites are listed in Table 6. Their respective locations are shown in Figure 5. Map with locations of the 16 stations and SLC Airport Photos of the measurement systems at each site are included in Appendix C.

4.3 Measurement System

The measurement system components were selected for accuracy, stability and suitability for operation in a harsh environment. Onset, a manufacturer of weather monitoring equipment, was selected to provide the dataloggers, the solar radiation sensor, and the thermistors. Weed was selected to provide the resistance temperature devices used to measure gas temperature. Riotronics was selected to provide the meter pulsers. The flowmeters and temperature devices were calibrated to ensure traceability to national standards.

[6] Assumptions: Normal distribution, $0.75 \le |\delta|/\sigma \le 3.0$, P(Type I) = 0.05 (double-sided), and P(Type II) = 0.2, using Table A.8, from Probability and Statistics for Engineers and Scientists, 6th Ed., Walpole, Myers and Myers, Prentice Hall

4.3.1 *Instrumentation and Data Acquisition*

The test sites included a temperature compensated meter installed in series with the existing meter. The data acquisition system included:

- Inlet and outlet gas temperature measurement devices
    - 4-wire Resistance Temperature Devices, Weed 203-01B-A-4-C-004.0-A2-Z006
    - 4-20 mA transmitters, Weed 4HQT3U+000+0250F
    - Connection Head, Weed 7A00D1
    - Analog/Digital adapters compatible with datalogger, Onset S-CIA-CM14
- Ground, ambient and surface temperature measurement devices
    - Thermisters, Onset S-TMB-M006
    - Solar radiation shield for ambient temperature measurement, Onset M-RSA

Test Station Information											
		Location						Meters			
Station #	Name	Address	City	Lat.	Long.	Elev.	Dir.	Std Meter #	Beg. Read	TC meter #	Beg. Read
1	Rick Ferlin	2109 N 520 W	West Bountiful	40.91221	-111.893	4253	N	361-44253	0	560-31174	9504
2	Shari Quarnberg	117 W 2800 S	Bountiful	40.858927	-111.883	4606	W	361-44250	5154	560-31187	9030
3	Kelly Bytheway	1432 W. 6415 S.	Taylorsville	40.63488	-111.932	4279	E	361-44252	7393	560-31175	2930
4	Justin Withers	380 S 1500 W	Lehi	40.3832197	-111.873	4539	S	361-44246	4826	560-31188	5995
5	Rayce Townsend	233 E 600 S	Farmington	40.970495	-111.883	4339	W	361-44244	6889	560-31183	1150
6	Ester McCray	426 N 1300 W	Salt Lake City	40.77875	-111.928	4220	N	361-44247	9565	560-31179	2859
7	Ryan Whittekiend	783 N 1120 E	Spanish Fork	40.1198436	-111.636	4622	N	361-44255	8305	560-31184	9716
8	Verl Hovey	1432 S 235 W	Orem	40.2712015	-111.701	4714	SW	361-44254	7381	560-31189	8858
9	McDonalds Restaurant	1780 W 7800 S	West Jordan	40.610104	-111.941	4387	N	156-00187	78389	156-00539	58431
10	Byron Davis	5292 W Stockton St	Kearns	40.66143	-112.018	4420	N	361-44248	5833	560-31185	5716
11	Manny Torres	450 N 400 E	Santaquin	39.9831368	-111.777	4884	SE	361-44243	0	560-31176	3705
12	Rob Shick	1588 Wood Glen Rd	Sandy	40.56326	-111.845	4812	W	361-44257	2326	560-31182	376
13	Mike Jaynes	13991 S. Sage Hollow Dr.	Draper	40.497531	-111.839	5143	N	361-44256	9197	560-31178	2937
14	Rob Anderson	10831 N 5600 W	Highland	40.4287838	-111.793	4902	S	361-44242	6871	560-31193	4202
15	Clark VanWagner	1440 W Harrisville Rd	Ogden	41.2886352	-112.016	4279	W	361-44227	2240	560-31190	46
16	Steve Stuart	916 E 2100 N	Ogden	41.2964268	-111.951	4433	N	361-44249	3310	560-31180	8508

Table 6. Test stations within the SLC/Odgen/Provo zone.

- Flow pulsers
    - Riotronics *PulsePoint* Retrofit Gas Meter Pulse Device
    - Two types: 10 pulses/cubic foot and 2 pulses/cubic foot (used at the Mc Donald's site.
    - Pulse input adapters compatible with datalogger, Onset S-UCA-M006
- Solar radiation sensor
    - Sensor, Onset S-LIB-M003
    - Leveling device to ensure consistent sensor orientation relative to the earth, Onset M-LLA
- Datalogger, Onset H21-001
    - A sample frequency of 5 minutes was selected in order to balance the need for capturing very low flow rates with limited datalogger memory.
- 12 volt battery

The system configuration for each site is shown in Figure 6. A schematic of all system elements is shown in Figure 7. Photos of the system installed on-site are shown in Figure 8 and Figure 9. A protective cover was added to isolate the power supply and wiring from the elements. The radiation sensor and radiation sensor leveling process are shown in Figure 10 and Figure 11, respectively.

The non-TC meter was used as the reference. It was located upstream of the TC meter. Temperature measurements were made at the inlet and outlet of the reference meter, to capture any changes in gas temperature as the gas flowed through the meter. The reference meter gas temperature was measured as the average of the inlet and outlet gas temperatures. Since each meter provided an independent measurement, the relative locations of the meters should have had no effect on the results.

4.3.2 Instrument Calibration

Temperature instrumentation was calibrated using a Standard Platinum Resistance Thermometer submerged in a variable temperature water bath, and controlled by a LabView application. The calibration system is capable of providing stable temperatures traceable to the SwRI Calibration Lab. The SwRI Calibration Lab is ISO 17025 compliant and accredited by the American Association of Laboratory Accreditation.

Example temperature instrument calibration curves are shown in Figure 12 and Figure 13. "End-to-end" calibrations were performed for all temperature devices. This means that the temperature devices were calibrated by comparing the temperature indicated by the datalogger to the reference temperature. This was done to remove any bias associated with the logger and other analog to digital conversion. Thermistor residuals were typically much less than +/- 0.5°F prior to calibration. After calibration, the uncertainties in the thermistor and RTD measurements were approximately 0.05°F at the 95% confidence level.

Instrument failures were anticipated due to the duration of the test program. Therefore, it was necessary to determine the reproducibility of the calibrations. If the calibrations were found reproducible, then replacement devices could be installed without impacting the accuracy level. Figure 14 and Figure 15 show the reproducibility of the temperature calibrations. In all cases tested, changes in calibration were no more than +/- 0.5 percent, indicating good reproducibility.

The meters were calibrated using Questar Gas' SNAP prover. The estimated uncertainty of the SNAP prover is +/- 0.15%. During data reduction, flow rates were adjusted using the average calibration factor for each meter. Figure 16 and Figure 17 show the calibration curves for the non-temperature-compensating meters and the temperature-compensating meters, respectively. Table 7 shows the average calibration factors used in the data reduction.

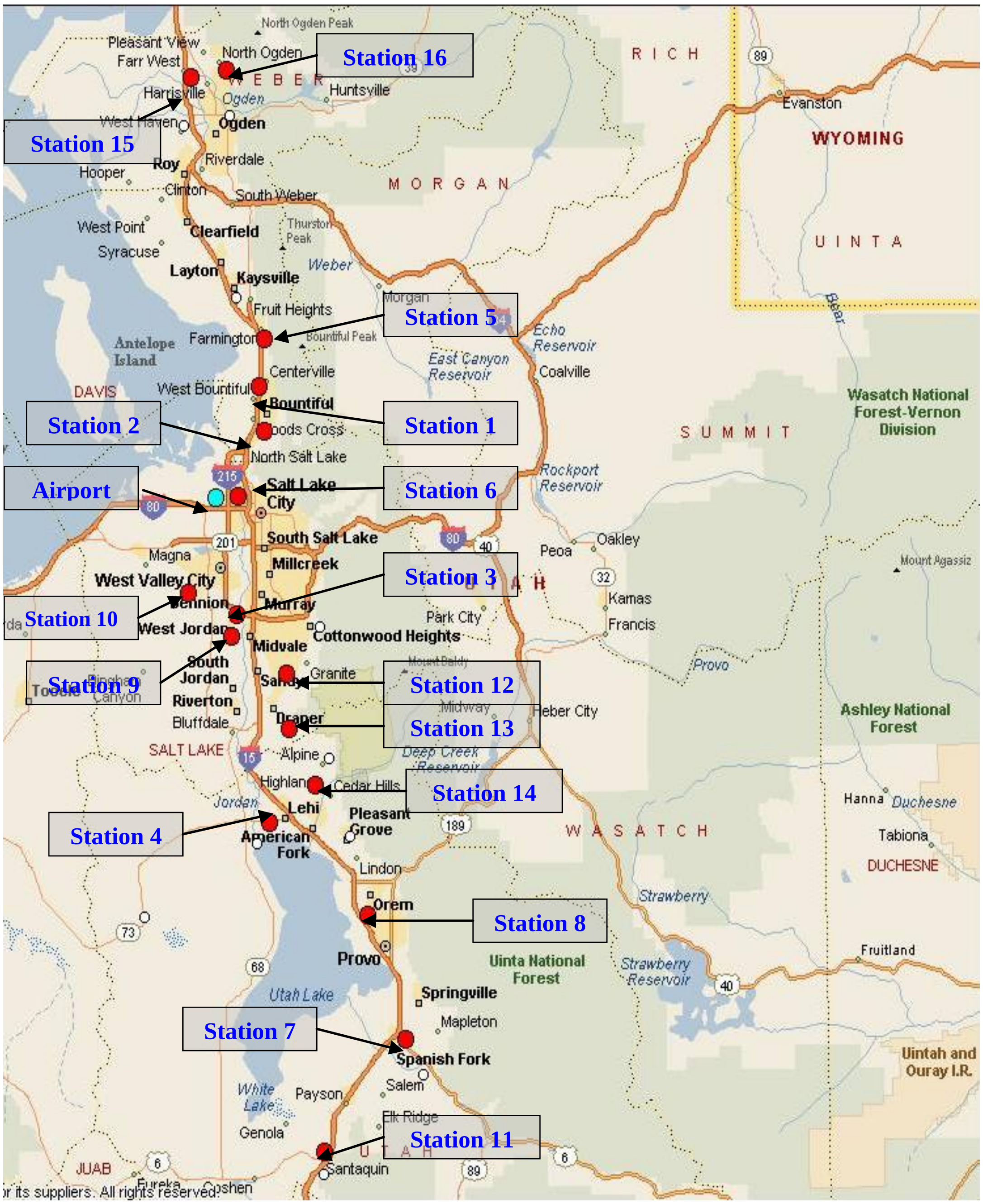

Figure 5. Map with locations of the 16 stations and SLC Airport.

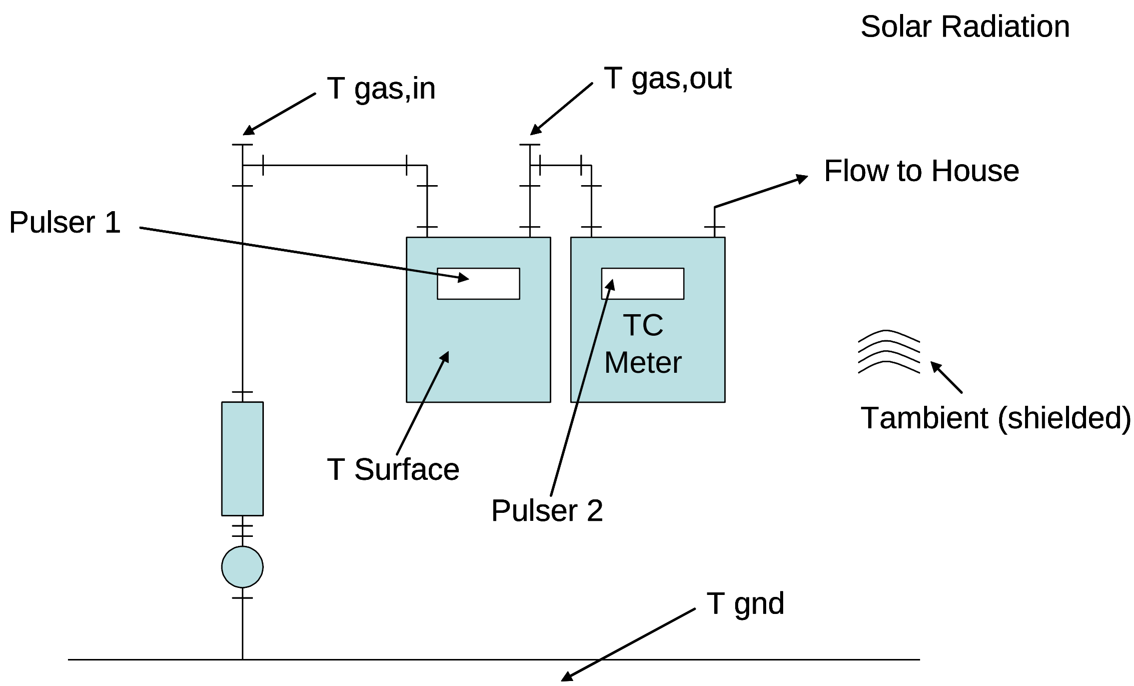

Figure 6. Sketch of data acquisition system.

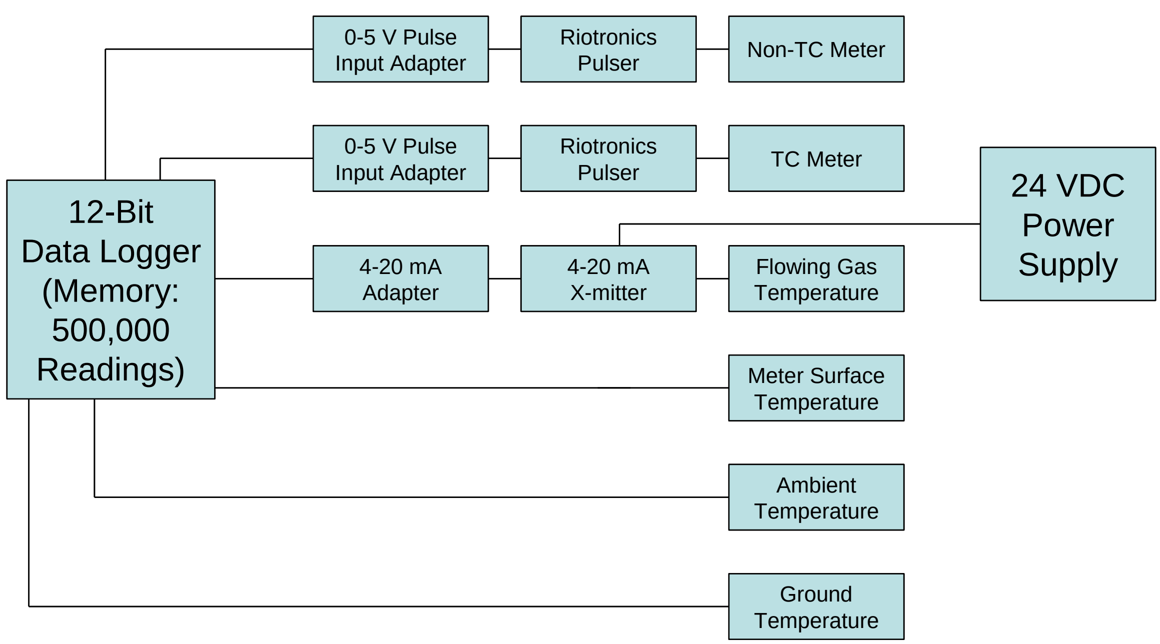

Figure 7. Data acquisition system schematic.

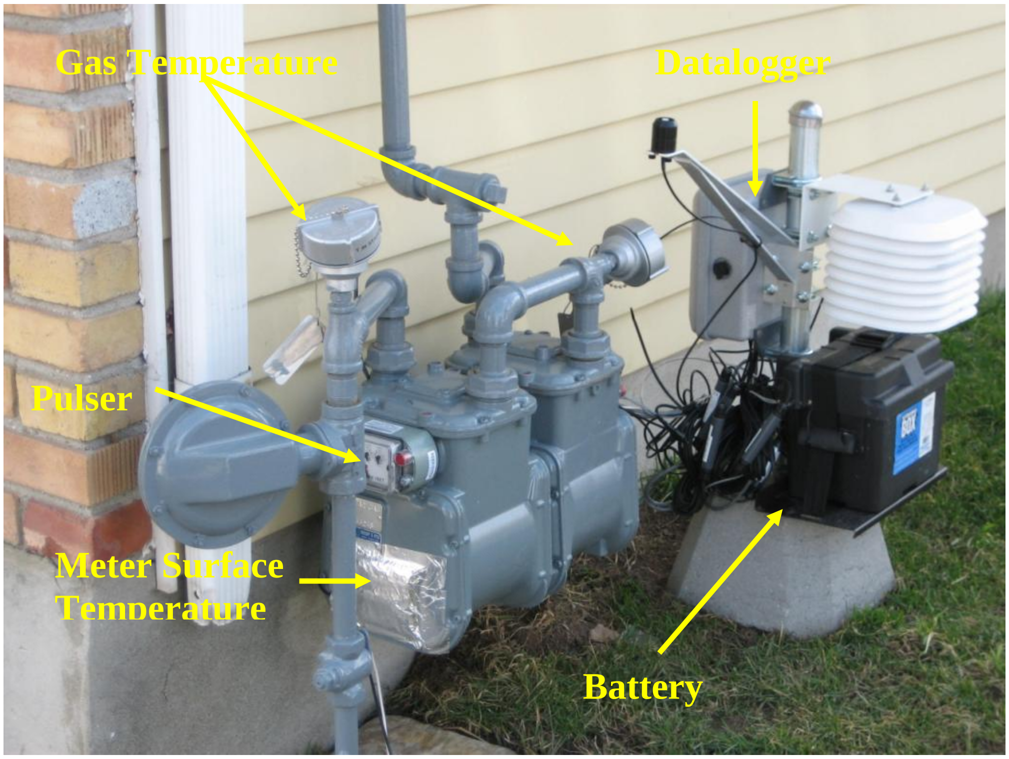

Figure 8. Site measurement setup showing components.

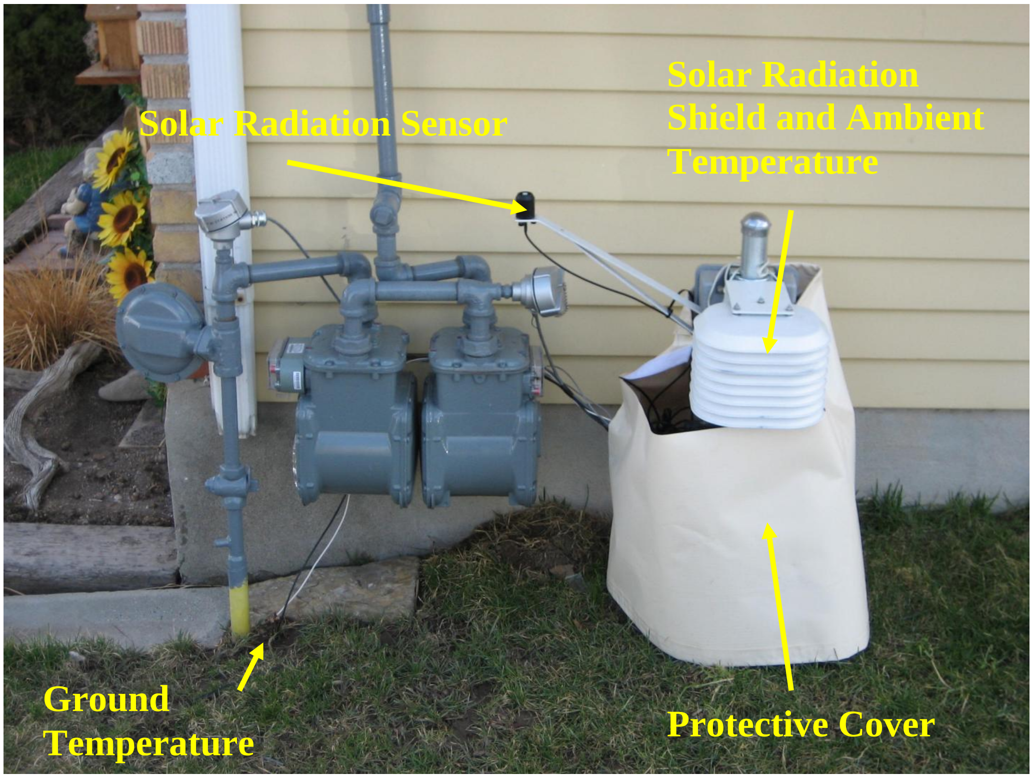

Figure 9. Site measurement setup showing protective cover.

Figure 10. Radiation sensor.

Figure 11. Leveling the radiation sensor.

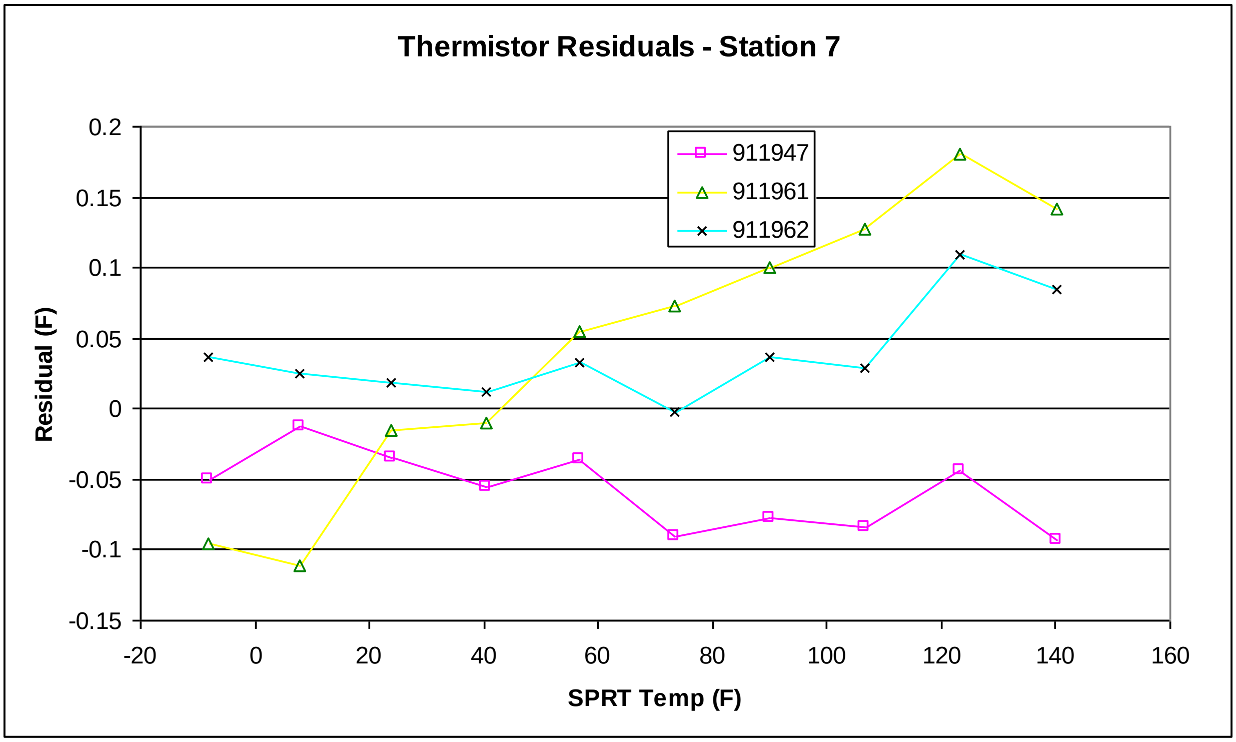

Figure 12. As-found residuals from calibration of three thermistors. The estimated uncertainty after calibration is +/- 0.05°F.

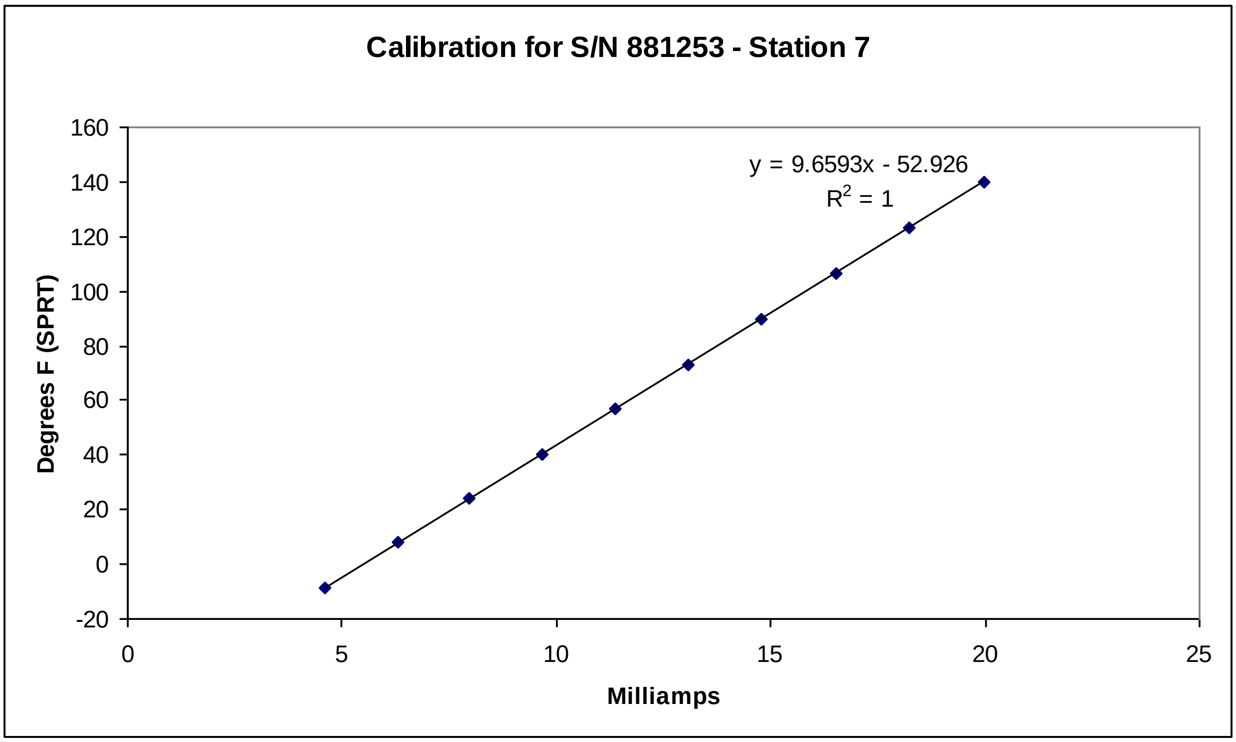

Figure 13. Representative calibration curve for a resistance temperature device.

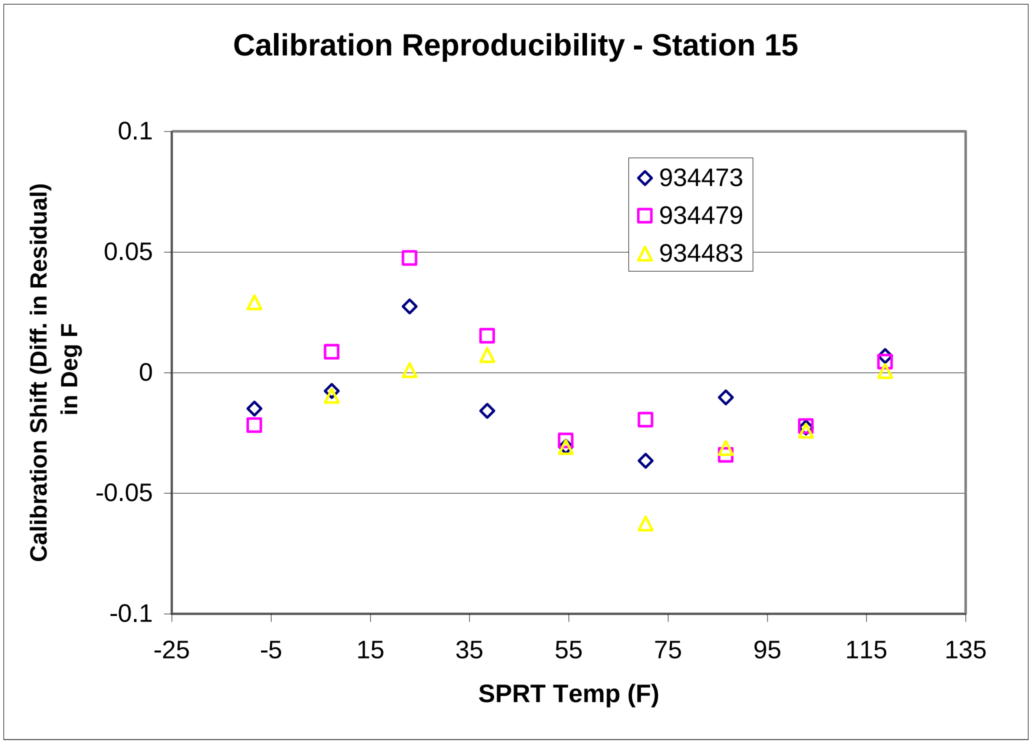

Figure 14. Calibration reproducibility when calibrated on two consecutive days.

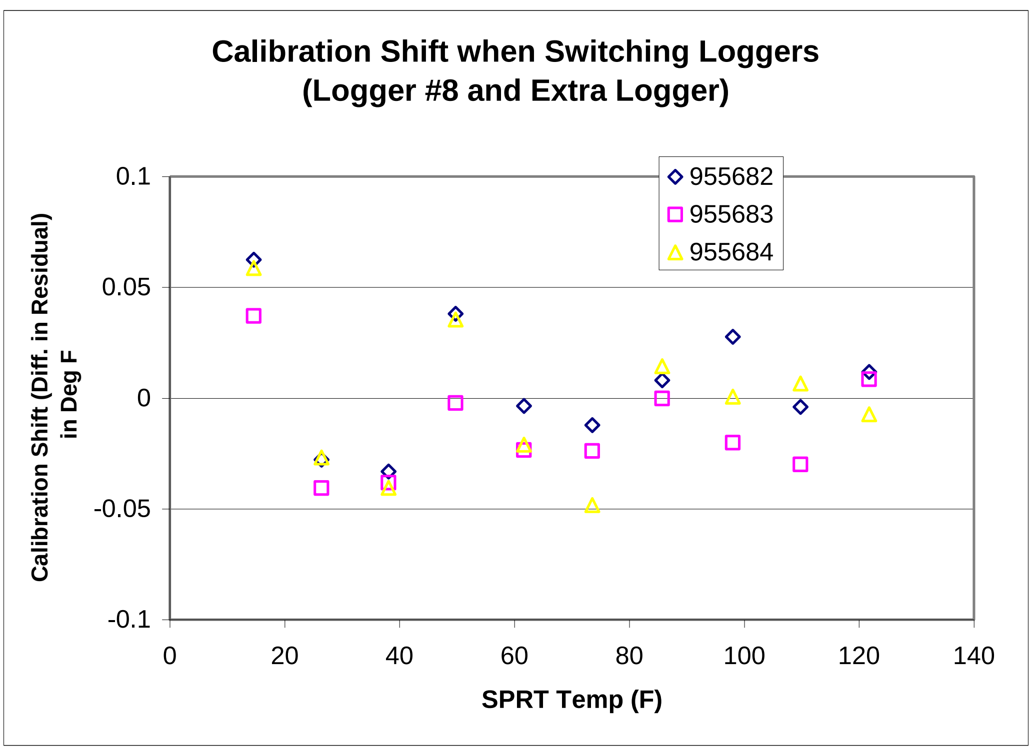

Figure 15. Calibration shift when using different dataloggers.

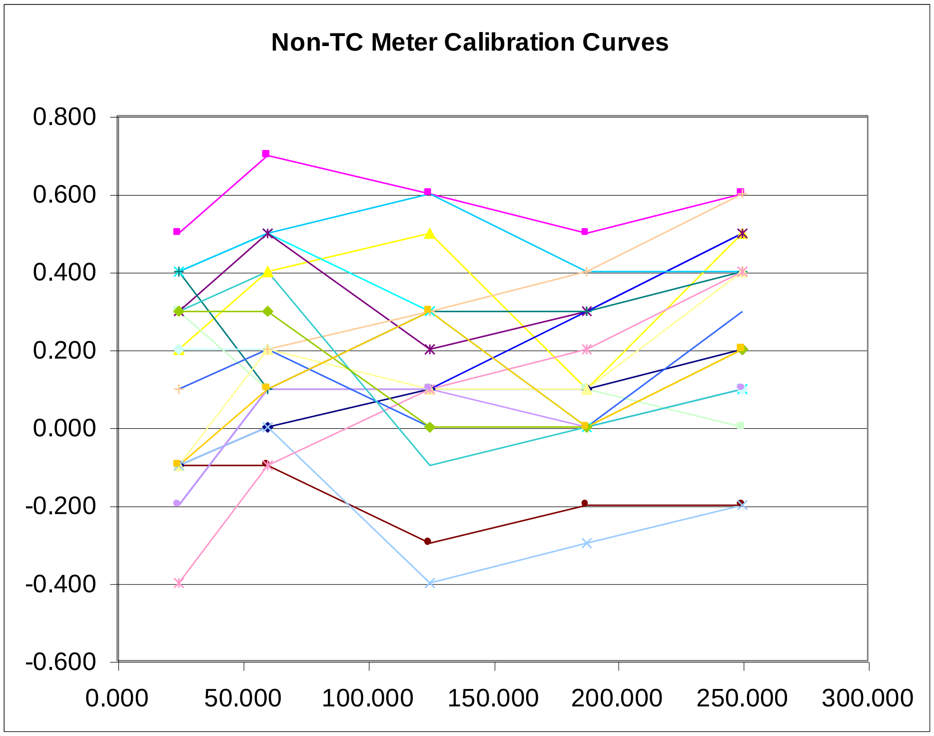

Figure 16. Non-temperature-compensating meter calibration curves. Calibrations performed using Questar gas SNAP prover.

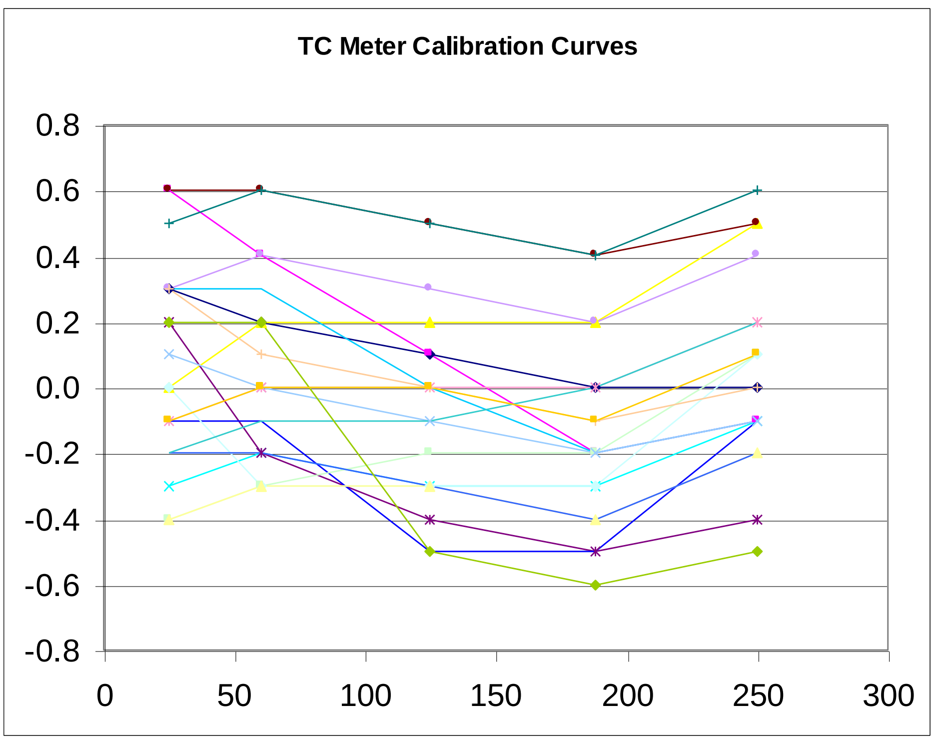

Figure 17. Temperature-compensating meter calibration curves. Calibrations performed using Questar Gas SNAP prover.

Meter Number	Station	TC/NonTC	Average Calibration Factor
361-44253	1	NonTC	0.140
560-31174	1	TC	0.200
361-44250	2	NonTC	0.460
560-31187	2	TC	0.000
361-44252	3	NonTC	0.120
560-31175	3	TC	0.100
361-44246	4	NonTC	0.360
560-31188	4	TC	0.300
361-44244	5	NonTC	0.260
560-31183	5	TC	-0.200
361-44247	6	NonTC	-0.180
560-31179	6	TC	0.500
361-44255	7	NonTC	0.040
560-31184	7	TC	-0.200
361-44254	8	NonTC	-0.200
560-31189	8	TC	0.100
156-00187	9	NonTC	-0.200
156-00539	9	TC	-0.150
361-44248	10	NonTC	0.300
560-31185	10	TC	-0.300
361-44243	11	NonTC	0.340
560-31176	11	TC	0.200
361-44257	12	NonTC	0.320
560-31182	12	TC	0.100
361-44256	13	NonTC	0.020
560-31178	13	TC	-0.300
361-44242	14	NonTC	0.580
560-31193	14	TC	0.000
361-44227	15	NonTC	0.060
560-31190	15	TC	0.300
361-44249	16	NonTC	0.160
560-31180	16	TC	0.500

Table 7. Average calibration factors for flow meters.

4.4 Results of Experimental Program

The experimental program kicked-off on April 1, 2006. Data collection was completed on March 31, 2007. After reviewing the complete data set, it was decided to exclude Station 3 from the study due to numerous data acquisition problems. However, as discussed in 4.2, this reduction in the number of stations does not compromise the sample size of 13 field sites required for statistical comparisons.

4.4.1 Objective 1- Confirm or Reject the Historical Temperature Profiles

This project objective included two important comparisons. First, the data collected at the 15 test sites was analyzed in order to determine if it was representative of the historical temperature data from Zone 6. Second, the 1-year temperature data from the SLC Airport was compared to the temperatures from the 15 test sites to determine whether a single weather station could represent a larger geographical area.

Table 8 summarizes the monthly temperature average, standard deviation and delta temperature for both the 30-year Zone 6 data and the 1-year experimental data collected from the 15 test sites within Zone 6. The delta temperature is the difference between the 30-year average temperature and the 1-year test site average temperature. Note that the test year average temperature was within ±5°F of the historical average temperature for all months except January and September. Both of these months recorded warmer temperatures during the test year. Also, note that the variability (standard deviation) of the 15-site monthly temperatures was consistent with the 30-year historical data. Since the temperature at the test sites was collected during a one year time span it was not surprising that the variation in the temperatures was less than the 30-year data. The primary purpose was to determine if the variation across the 15 sites was within the variation seen from the 30-year history of the same geographical area.

Month	30-yr Historical Zone 6		1-yr 15 Test Sites		Delta Temperature
	Avg. Temp °F	Std. Dev. °F	Avg. Temp °F	Std. Dev. °F	Historical Avg. – Test Site Avg.
Apr	50.36	3.77	51.86	2.78	-1.50
May	58.78	3.31	62.71	2.33	-3.93
Jun	68.51	3.39	71.30	1.87	-2.79
Jul	76.34	3.08	79.06	1.85	-2.72
Aug	74.57	2.74	73.31	2.47	1.25
Sep	65.05	3.14	58.89	1.66	6.16
Oct	52.84	3.22	48.84	1.60	4.00
Nov	39.27	3.82	41.30	1.17	-2.03
Dec	30.71	3.76	30.04	1.42	0.67
Jan	29.08	5.22	21.31	2.53	7.77
Feb	33.88	4.71	35.86	1.06	-1.98
Mar	42.59	3.64	43.38	4.25	-0.79

Table 8. Temperature descriptive statistics for historical data and test year data.

To statistically compare the 15-site temperature data to the historical database from Zone 6, prediction intervals were computed using the historical data as the sample population. A two-sided 95% simultaneous prediction interval was computed for each month to contain the values of all 15 site temperatures selected from the same zone. The 15 test site temperatures were then compared to the prediction interval to see if they were contained within the temperature prediction bounds for Zone 6. Table 9 lists each prediction interval by month in addition to the minimum and maximum temperature from the 15-site average monthly temperature. All 15 site temperatures fell within the 95% prediction intervals for all months except August, September, January and March. For these four months, a single station in the 15-site test area had a cooler monthly temperature than the lower limit on the prediction interval. Also, for each of these four months the site with the minimum temperature was not the same. For August, September and January, the test site minimum temperature was within 0.6°F of the lower limit. The commercial site at McDonald's had an average monthly temperature in March of 29.49°F which was 2.32°F cooler than the lower limit on the prediction interval. In general, the temperature data from the 15 test sites appears consistent with the temperature profiles of the 30-year historical data within the defined Zone 6 geographical area. Therefore, historical temperature data may be used to select appropriate temperature zones.

Month	30-yr Historical Zone 6 Temperature		95% Prediction Interval		1-yr 15 Test Site Temperatures	
	Average °F	Std Deviation °F	Lower Limit °F	Upper Limit °F	Minimum °F	Maximum °F
Apr	50.36	3.77	39.20	61.52	43.69	55.71
May	58.78	3.31	48.98	68.59	60.45	68.38
Jun	68.51	3.39	58.47	78.55	69.21	75.18
Jul	76.34	3.08	67.21	85.48	77.08	82.93
Aug	74.57	2.74	66.44	82.70	66.39	76.79
Sep	65.05	3.14	55.74	74.37	55.68	62.32
Oct	52.84	3.22	43.30	62.37	44.10	51.36
Nov	39.27	3.82	27.96	50.59	39.09	43.19
Dec	30.71	3.76	19.56	41.85	27.99	32.03
Jan	29.08	5.22	13.59	44.57	13.02	23.43
Feb	33.88	4.71	19.92	47.84	34.01	37.59
Mar	42.59	3.64	31.81	53.37	29.49	47.59

Table 9. 95% Prediction intervals for 15 site temperature selections.

To compare the monthly temperature average across the 15 test sites to the monthly temperature at the SLC Airport, prediction intervals were computed using the test site data as the representative population. Two-sided 95% prediction intervals to contain a single site observation (SLC Airport) were computed for each month. The results are summarized in Table 10. The average monthly temperatures for the SLC Airport were computed during the same test site experimental period. In all months except September, the SLC Airport temperature average fell within the 95% prediction interval limits. In September, the average temperature at the airport was 0.86°F warmer than the upper limit on the prediction interval. Figure 18 depicts the monthly averages by sampling stations in addition to the SLC Airport average. The temperature at the SLC Airport can be used as a representative temperature of the 15-site test zone area.

Month	1-yr Test Site Temperatures		95% Prediction Interval		SLC Airport Temperature °F
	Average, °F	Std Deviation °F	Lower Limit °F	Upper Limit °F	
Apr	51.86	2.78	45.70	28.02	53.23
May	62.71	2.33	57.54	67.88	63.11
Jun	71.30	1.87	67.16	75.45	73.20
Jul	79.06	1.85	74.96	83.16	83.00
Aug	73.31	2.47	67.84	78.79	76.46
Sep	58.89	1.66	55.20	62.57	63.43
Oct	48.84	1.60	45.28	52.39	50.55
Nov	41.30	1.17	38.71	42.89	40.97
Dec	30.04	1.42	26.89	33.20	30.73
Jan	21.31	2.53	15.71	26.91	21.08
Feb	35.86	1.06	33.52	38.20	36.84
Mar	43.38	4.25	33.97	52.80	46.27

Table 10. 15-Site 95% prediction intervals compared to SLC airport.

4.4.2 Objective 2 – Investigate the Presumed Correlation between Ambient Temperature and Flowing Gas Temperature

To investigate the possible correlation between ambient temperature and gas inlet temperature, a linear regression was fit independently for each of the 15 test sites by month using the daily temperatures collected during each month. Thus, an R^2 value representing the amount of variation explained by the linear relationship between the ambient temperature and gas inlet temperature was computed for each site by month. R^2 values near 0 indicate no linear relationship while R^2 values near 1.0 signify strong linear associations.

Figure 19 illustrates the comparison of the R^2 values from the ambient temperature and gas inlet temperature correlations with the maximum radiation at each test site and month. Although there is a large spread in the data some general observations can be made:

- Nearly all R^2 values for the maximum radiation values less than 600 W/m^2 were greater than 0.80.
- The majority of R^2 values less than 600 W/m^2 occurred during the November-February time frame.

- The R^2 values for the maximum radiation values greater than 1000 W/m^2 were generally < 0.90.
- R^2 values for maximum radiation between 600 W/m^2 and 1000 W/m^2 ranged from 0.60 to 0.90.

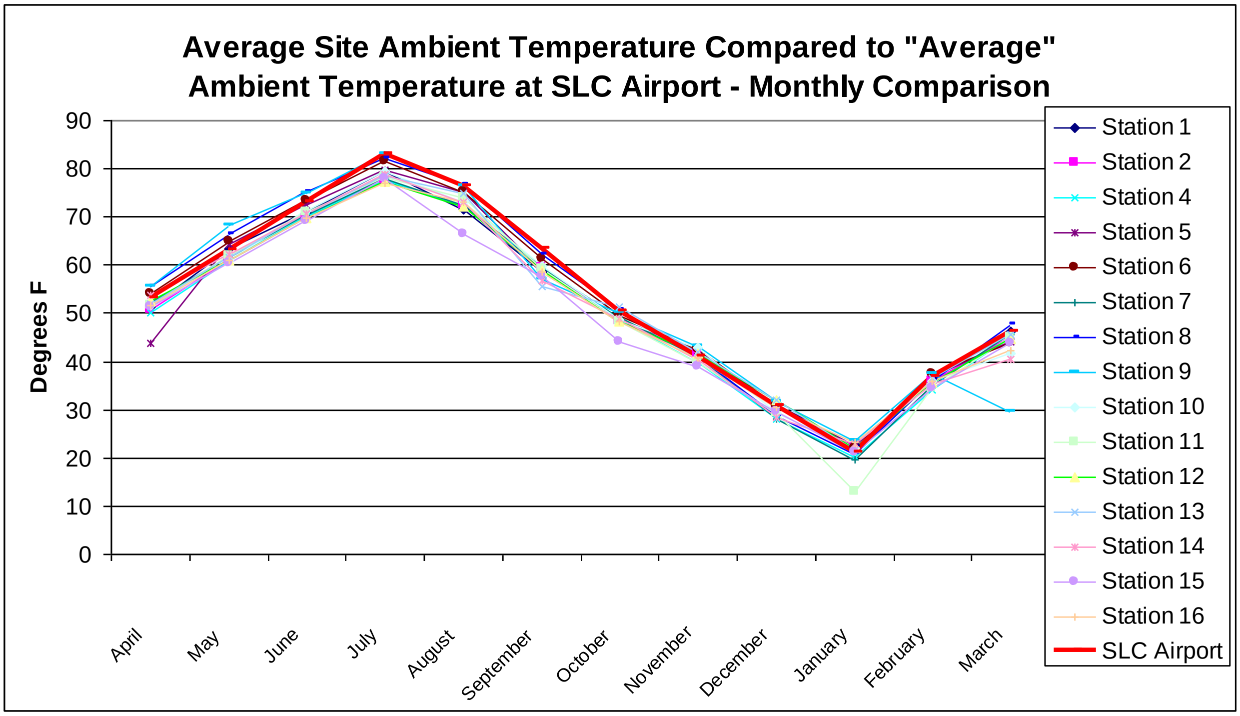

Figure 18. Site ambient temperatures compared to "average" ambient temperature at SLC airport.

There is a significant downward trend in the R^2 values as the maximum radiation increases. This suggests that the correlation is weakened when the solar radiation is above approximately 600 W/m^2. The prediction is very poor because of the large range in the R^2 data. Perhaps the most relevant observation is that the majority of the low radiation (less than 600 W/m^2) corresponds to the winter months and that during those months, the correlation between ambient temperature and gas temperature is generally greater than 0.8. While there are some higher levels of radiation and correspondingly low values of R^2 during those months, it appears that in general, the correlation is stronger during the winter months than during the summer months. The effect of solar radiation could be controlled to some extent by using a more reflective finish on the meters. The impact on flow measurement accuracy is discussed in 4.4.3.2

Figure 20 shows the solar radiation levels observed at each site over the course of the field tests. For a given station, lower levels of radiation occurred during the winter months. During the summer months, nearly all stations observed radiation levels just below or above 600 W/m^2, indicating that the correlation between ambient temperature and gas temperature was weakened by the presence of radiation. During the winter months, many of the stations observed solar radiation levels below 600 W/m^2, indicating that the correlation between ambient temperature and flowing gas temperature was relatively strong.

In conclusion, radiation impacts the correlation between gas temperature and ambient temperature. However, it appears that the extent of the impact depends on the level of radiation. If it is high, such as during the summer months, the effect is considerable, and controls the gas temperature (i.e. weakens the correlation). If it is low, such as during the winter months, the effect is secondary and the ambient temperature/gas temperature correlation is stronger. This is important for the application of the ambient temperature correction method because considerably more gas is consumed during the winter months than during the summer months. Based on this discussion, one can infer that the ambient temperature/gas temperature correlation can be strengthened further, particularly during the summer months, by using a more reflective finish. This study did not address the effect of meter finish.

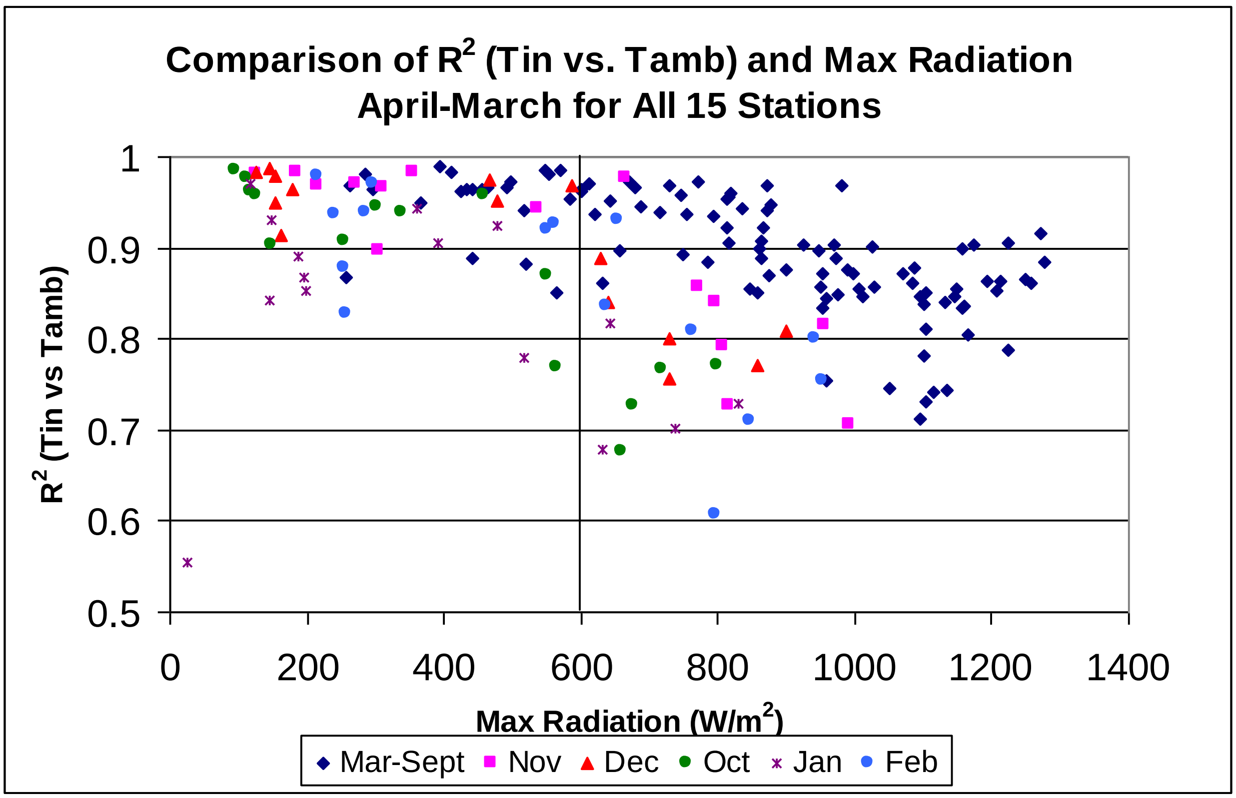

Figure 19. R^2 (Ambient Temperature and Flowing Gas Temperature) as a function of maximum solar radiation for all 15 stations in the test zone.

4.4.3 Objective 3 – Flow Measurement Comparisons

4.4.3.1 Data Reduction

The experimental program generated a tremendous amount of data. In order to manage data quality and provide meaningful summary information, the data was reduced in stages. The first stage involved reviewing the data for completeness. This was followed by an initial analysis, which reduced the data to plots showing flow rates, percent differences, temperature profiles and possible temperature correlations. In the third and final step, the data for all stations and months was summarized in a separate spreadsheet for statistical and other analyses. Summarized plots are included in Appendix D.

As part of the data quality control, pulser output from the TC and non-TC (reference) meters were plotted against each other to confirm their correlation. Correlated data forms a 45 degree line when plotted on the same scale. Data that fell outside the 45 degree line was reviewed and removed if justified. Justifiable reasons for removing data included: dropped pulses, dead battery, failed pulse-input adapter, failed *PulsePoint* device, logger failure and reasons determined by experience as unrelated to flow. Because of this process, load profiles showing actual gas consumed were not developed. Instead, data is presented in terms of percent error, relative to the reference. The percent error can be used to calculate the error in terms of gas volume.

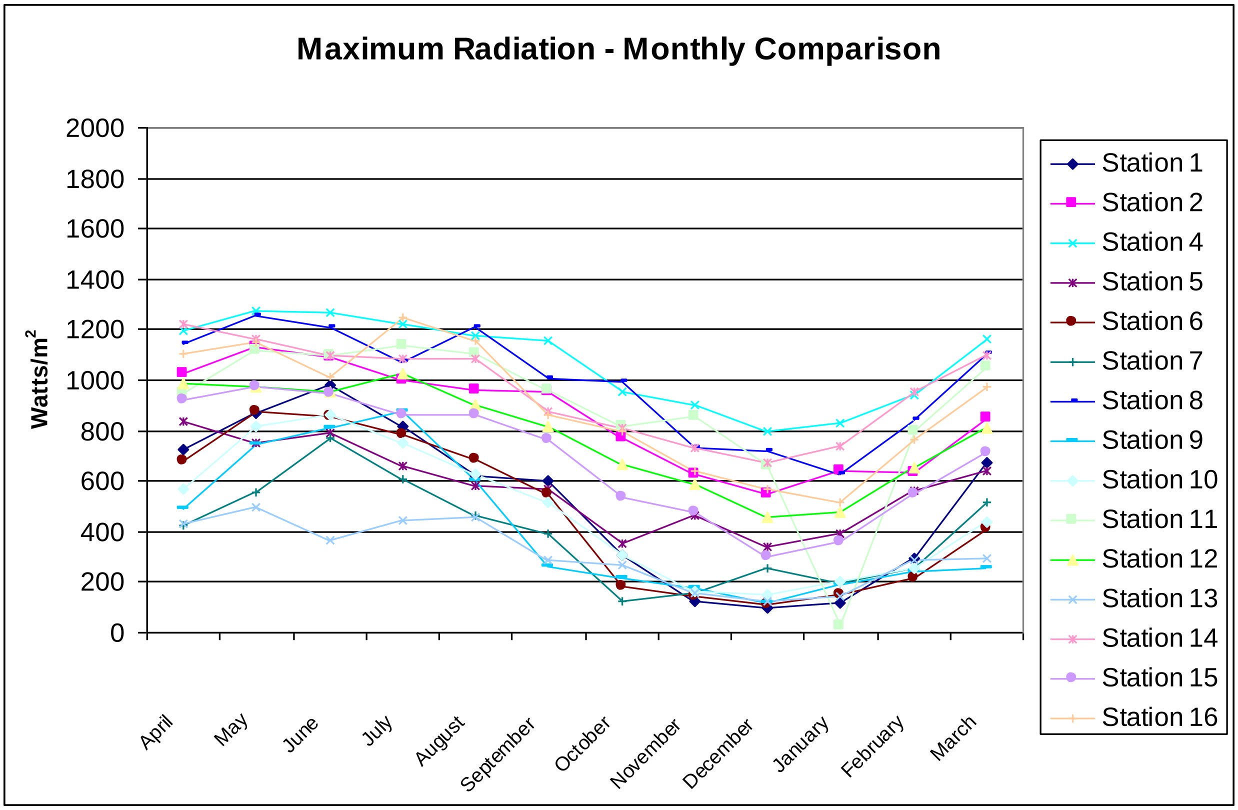

Figure 20. Solar radiation levels.

4.4.3.2 Results

Six flow measurement methods were compared to the reference flow rate on a relative percentage basis (i.e. %Diff = 100(Q_{test}-Q_{ref})/Q_{ref}):

1. Fixed Factor (T_{gas} = 60°F)
2. Meter Surface (T_{gas} = $T_{meter\ surface}$)

3. Ambient at Site ($T_{gas} = T_{amb,site}$)
4. "Average" Ambient at Site ($T_{gas} = (T_{max,site}+T_{min,site})/2$)
5. "Average" Ambient at Airport ($T_{gas} =(T_{max,airport}+T_{min,airport})/2$)
6. Temperature Compensating Meter

The data acquisition system was designed to provide enough information to calculate flow every five minutes. The reference flow rate, and Methods 1, 2, 3, and 6 were compared by summing the five minute volumes, after correcting for temperature ($Q_{tot} = \sum(Q_i \cdot Tcorrect_i)$ over a period of approximately one calendar month. This minimized the chance of "masking" ambient or radiation effects that might occur if volumes were corrected based on average temperatures for a given month ($Q_{tot} = Tcorrect_{avg}\sum Q_i$). The total volumes for Methods 4 and 5 were calculated using the "average" shown above. TC meter flow rates were calculated using the total pulses recorded, multiplied by the pulse factor, in cubic feet/pulse.

Table 11 shows the results of the flow measurement comparison tests. The most accurate approach, in terms of percent difference relative to the reference, was the meter surface temperature approach. The "averaging" methods, from data collected at the airport and at the sites, performed similarly to the TC meter. The least accurate method was the Fixed Factor method.

Method	Mean	Max	Min	Range
Fixed Factor	-1.45%	6.28%	-7.67%	13.95%
Meter Surface	0.08%	0.46%	-0.46%	0.92%
Ambient at Site	0.46%	1.82%	-0.45%	2.27%
"Average" Ambient at Site	-0.24%	2.92%	-2.43%	5.35%
"Average" Ambient at Airport	-0.16%	2.39%	-2.95%	5.34%
Temperature Compensating Meter	0.54%	3.23%	-3.10%	6.33%

Table 11. Summary of flow measurement comparisons showing percent difference, relative to the reference flow rate.

Summary results are plotted in Figure 21 through Figure 26 for all stations, all months and all methods. The fixed factor method (Figure 21) produced the largest errors, relative to the reference. This was due to the wide seasonal variation in ambient temperature in the Questar Gas service area. Actual gas temperatures were near 60°F during the spring and fall, but significantly above and below 60°F during summer and winter, respectively. As discussed previously, this introduces significant errors.

Figure 22 shows the percent error when the gas temperature was assumed equal to the meter body surface temperature. This method was the most accurate and indicated that the gas temperature was controlled by the meter body temperature, which was influenced by exposure to solar radiation, as discussed in Section 4.4.2.

Figure 23 shows the percent error when the gas temperature was assumed equal to the ambient temperature at the site. The overall performance was not as good as the Meter Surface method, but was a significant improvement over the Fixed Factor method.

Figure 24 shows the percent error when the gas temperature was assumed equal to the "average" ambient temperature at the site. The method performed differently from late spring to early fall, than during early fall to early spring. The difference was associated with the effect of solar radiation, which rose to a maximum in mid-summer and fell to a minimum in mid-winter. As discussed in 4.4.2, the effect of radiation was more pronounced during the summer months, and became a secondary effect during winter months. Despite the influence of solar radiation, the mean, maximum, minimum and range improved, relative to the Fixed Factor method.

Figure 25 shows the percent error when the gas temperature was assumed equal to the "average" ambient temperature at the airport. This is the site that would be used to adjust gas temperature in the implementation of the temperature zone method. The method also performed differently from late spring to early fall, than during early fall to early spring. This was not surprising, since both methods rely on ambient temperature. As with the previous method, despite the influence of solar radiation, the mean, maximum, minimum and range improved, relative to the Fixed Factor method.

An ANOVA was run for each month to compare the average percent difference across three calculation methods: "Average" Ambient at Site, "Average" Ambient at Airport, and TC Meter. All tests were made at the 5% level of significance. The average percent difference results are shown in Table 12. For May, June, July and August there was no significant difference in the average percent difference among the three methods. For all the remaining months except January, the average percent difference for the TC meter method was significantly higher than the other two calculation methods. In January, the average percent difference for the TC meter was not significantly different than the average ambient at the airport, but both methods showed significantly higher average differences compared to the average ambient at site method.

Month	Method		
	Average Ambient at Site	**Average Ambient at Airport**	**Temperature Compensating Meter**
April	-0.6234	-0.4345	0.6259
May	0.0211	0.1943	0.4314
June	0.6076	0.4668	0.4225
July	0.5403	0.1293	0.5015
August	0.7586	0.1940	0.2610
September	-0.8802	-0.9099	0.4280
October	-1.1838	-0.5934	0.4129
November	-0.3290	-0.2143	0.4975
December	-0.8550	-0.0365	0.7608
January	-0.2304	0.5669	0.9583
February	-0.4497	-0.2286	0.5040
March	-0.2587	-0.9848	0.6923

Table 12. Average percent difference by method by month.

Figure 26 shows the performance of the TC meter, relative to the reference meter. Overall, performance of most TC meters was steady over the course of the year, with the bulk of the comparisons showing a difference of about +/- 1 to 2 percent. Stations 1, 5, 11 and 13 showed greater variability over the course of the year, increasing the percent difference for all TC meters to about +/- 3%. Measurement precision worsened during the winter months. In comparison, both of the “average” ambient methods (Figure 24 and Figure 25) showed improved precision during the winter months. A statistical comparison of the standard deviations among the TC meter, “average” ambient at site and the “average” ambient at the airport methods showed that the standard deviation for the TC meter method was significantly greater than the standard deviation for the other two “ambient” methods for the months of October, Novermber, December, and January (Table 13). This is important because of the increased gas consumption during the winter. For all the remaining months, the precision performance of the TC meter was not statistically different from the precision performance of the two “average” ambient methods. The ambient temperature methods performed better, in terms of precision during the cold months because of the improved correlation between ambient temperature and gas temperature observed during the colder months, when solar radiation is relatively low. The cause of the higher variations for Stations 1, 6, 11, and 13 is unknown, but may be associated with manufacturing variability.

Month	**Method**		
	Average Ambient at Site	**Average Ambient at Airport**	**Temperature Compensating Meter**
April	0.575345	0.753695	0.884650
May	0.723516	0.929159	0.609497
June	0.836565	0.900682	0.627328
July	0.722232	0.676949	0.866741
August	0.850278	0.933439	0.941785
September	0.800057	0.896812	1.048330
October	**0.490162**	**0.569942**	**1.155130**
November	**0.388285**	**0.424323**	**0.665619**
December	**0.474305**	**0.357154**	**0.793552**
January	**0.353364**	**0.550462**	**1.083020**
February	0.486311	0.521489	0.782643
March	0.499158	0.774332	0.925939

Table 13. Standard deviation by method by month.

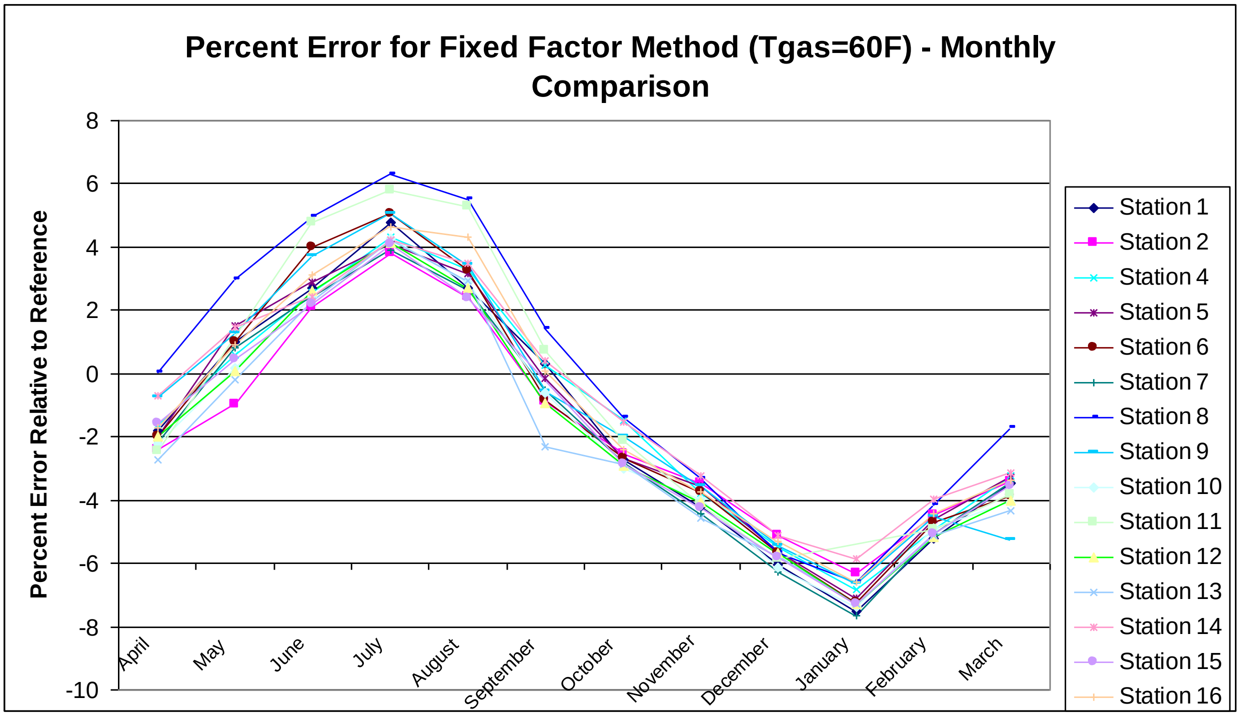

Figure 21. Flow measurement comparison for Fixed Factor method, all stations and all months.

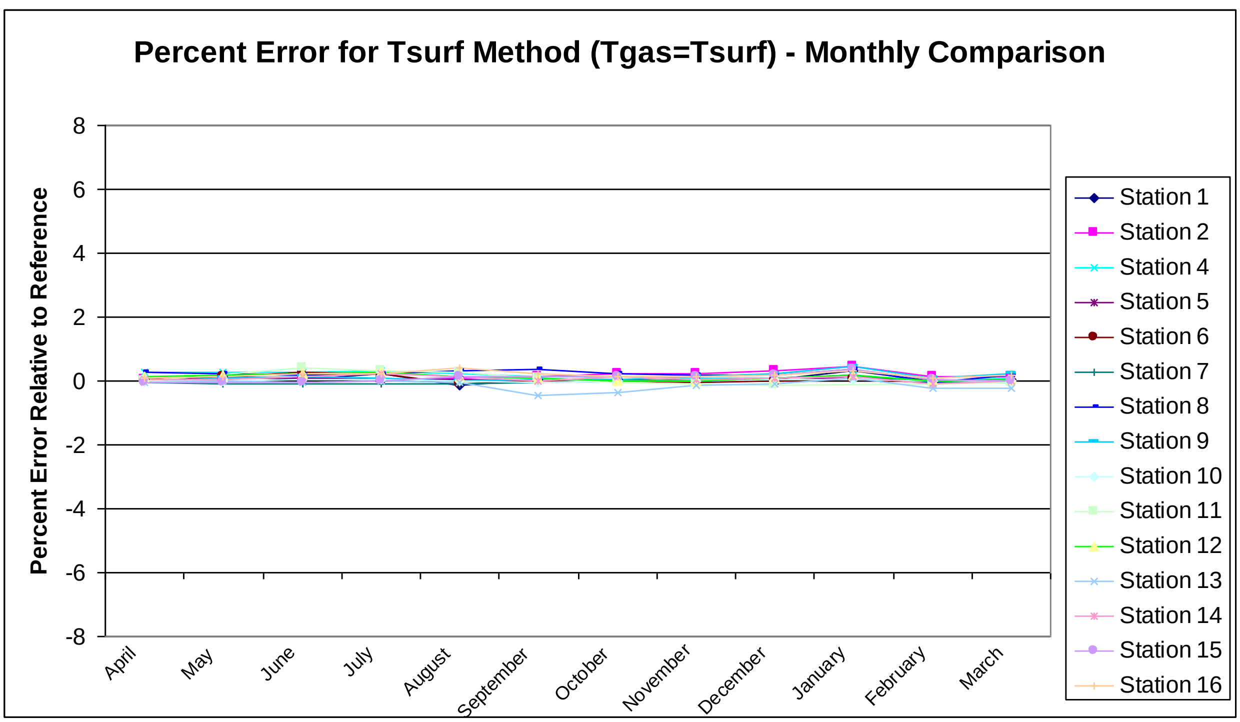

Figure 22. Flow measurement comparison for Meter Surface method, all stations and all months.

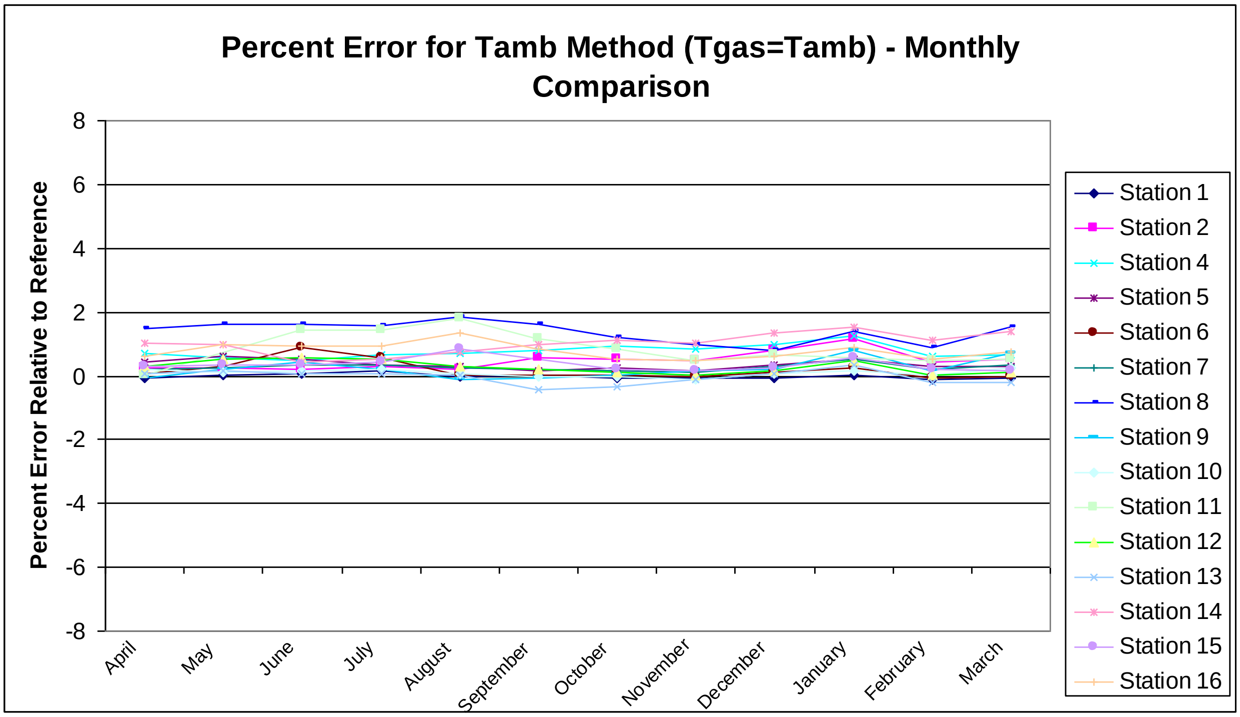

Figure 23. Flow measurement comparison for Ambient at Site method, all stations and all months.

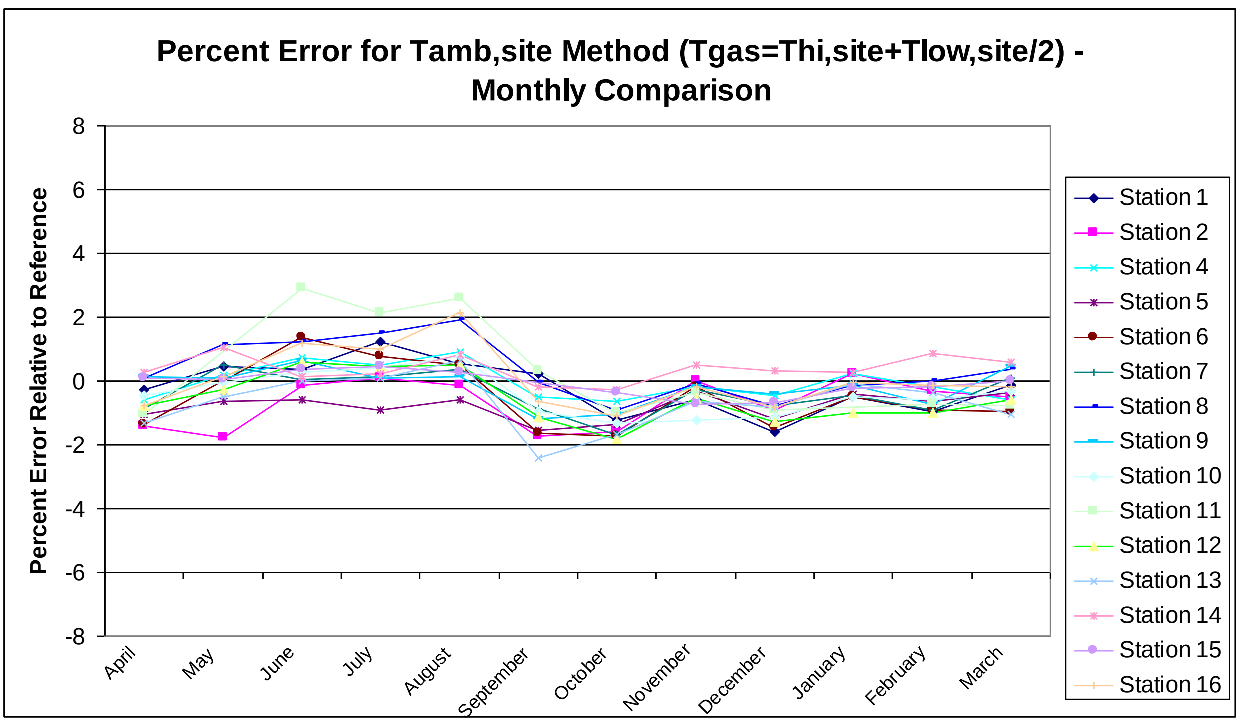

Figure 24. Flow measurement comparison for "Average" Ambient at Site method, all stations and all months.

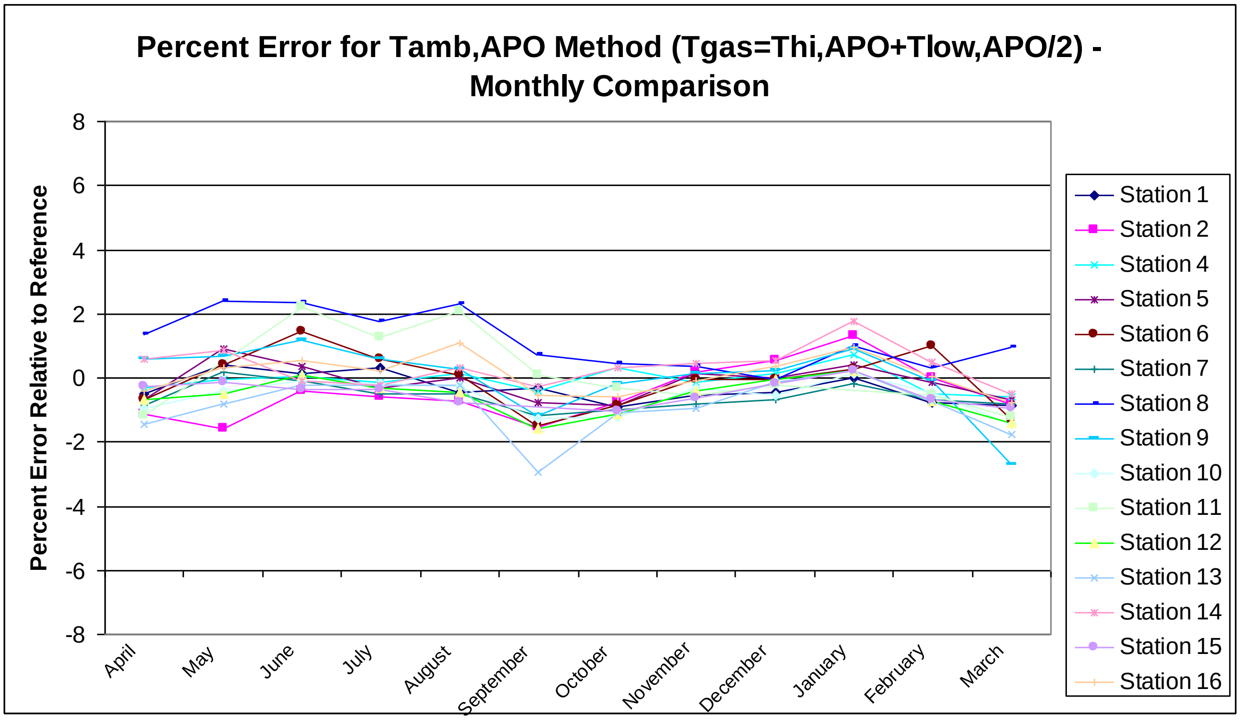

Figure 25. Flow measurement comparison for "Average" Ambient at Airport method, all stations and all months.

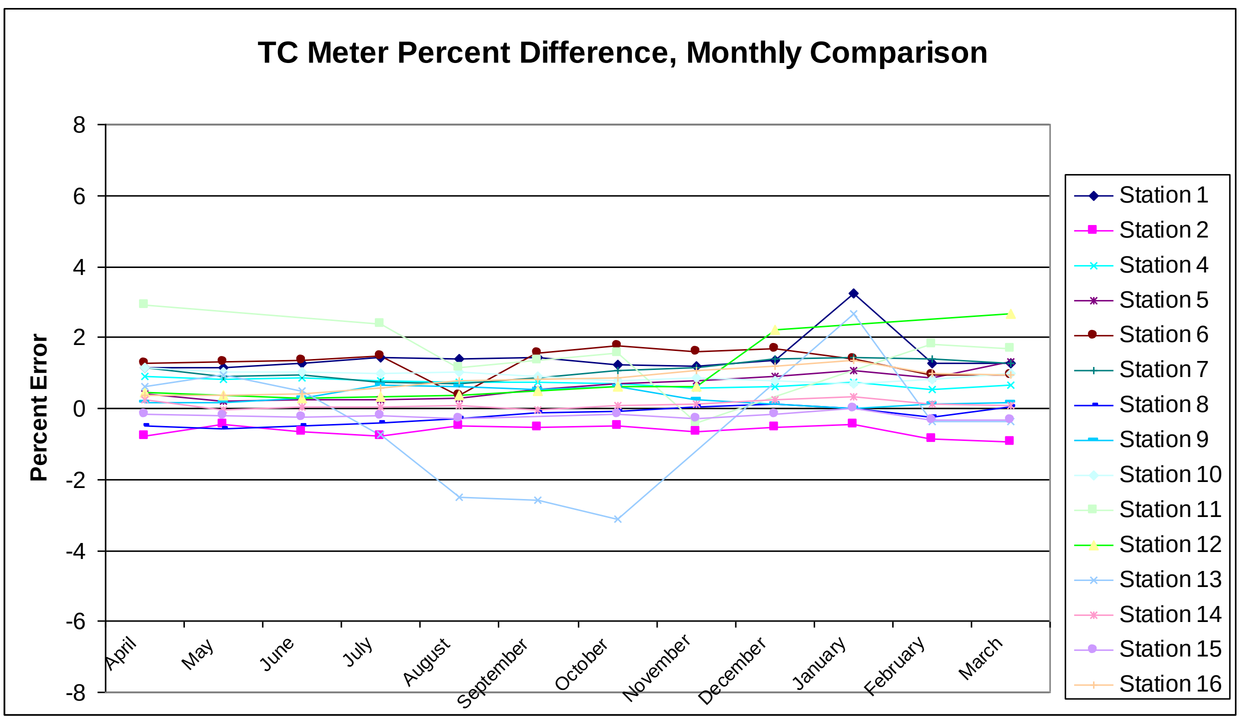

Figure 26. Flow measurement comparison for the Temperature Compensating meter, all stations and all months.

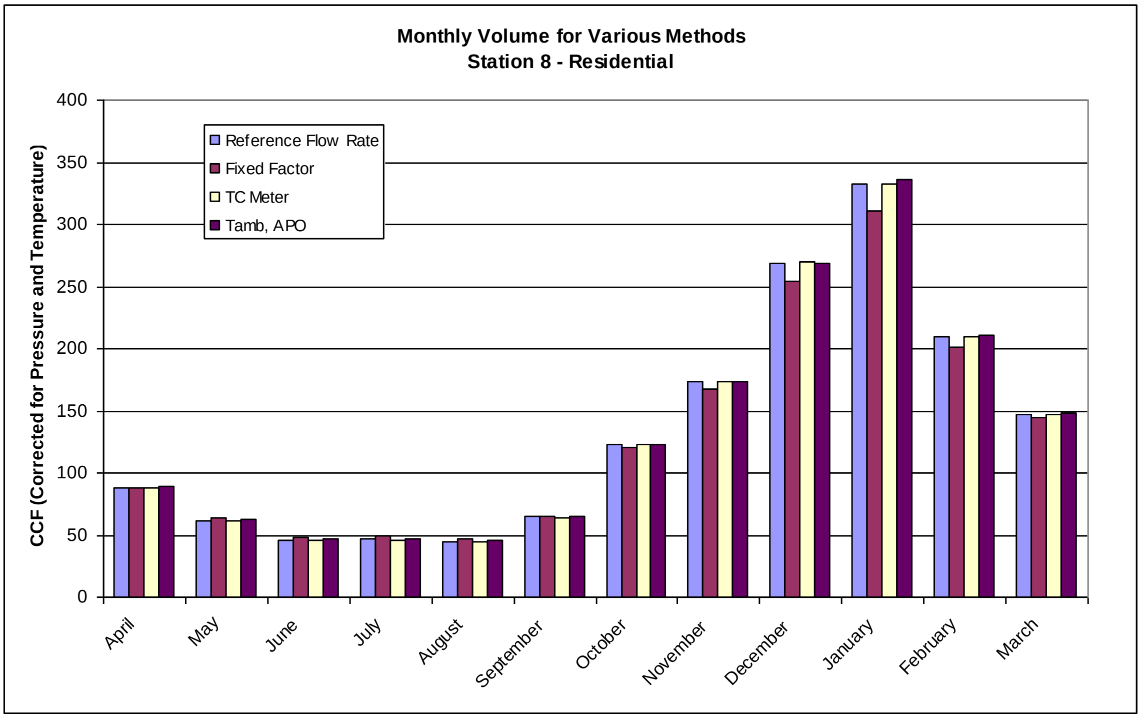

Figure 27. Monthly volume for various methods - Station 8.

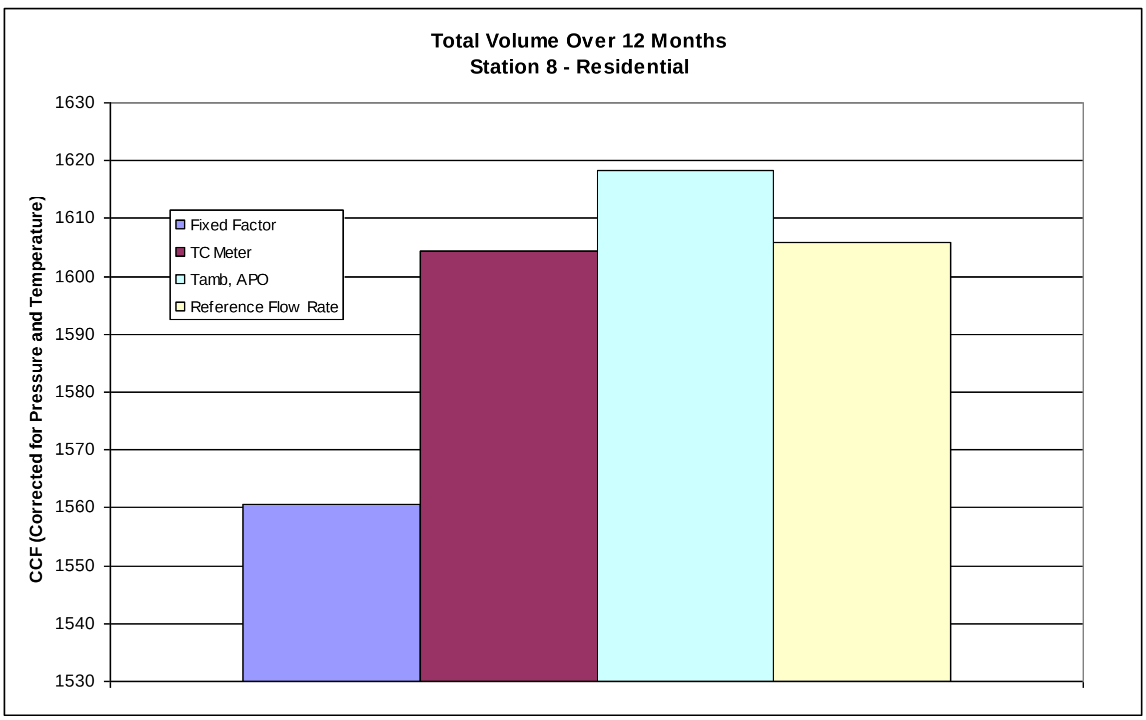

Figure 28. Total volume over 12 months - Station 8.

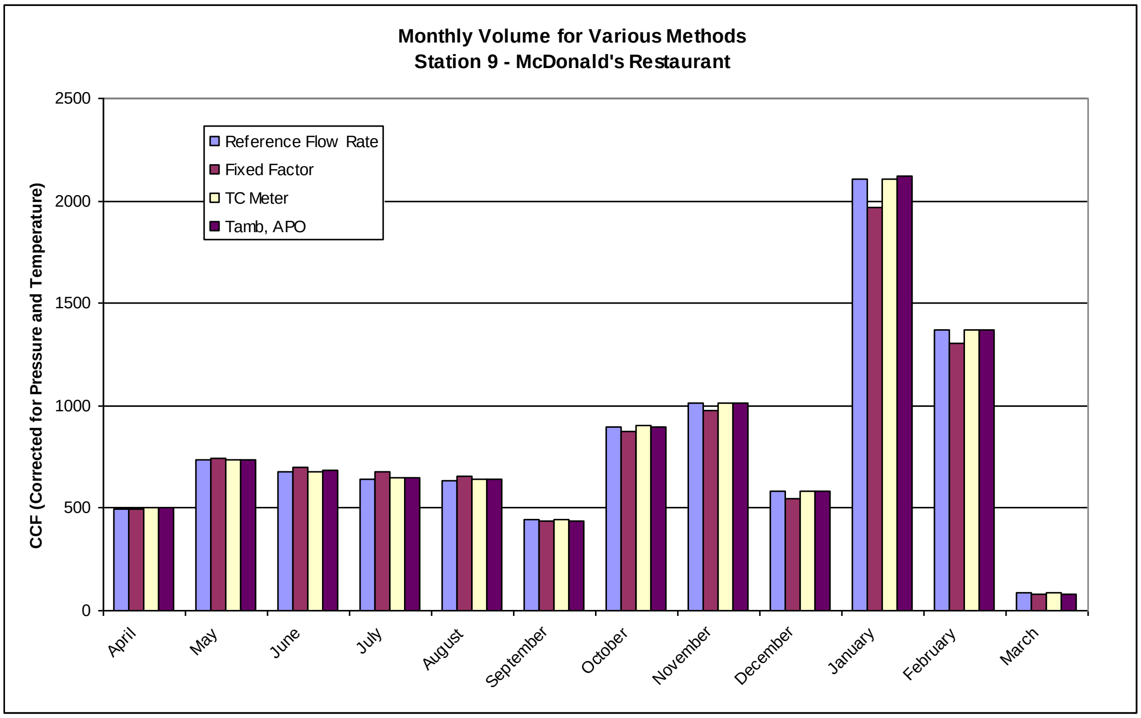

Figure 29. Monthly volumes for various methods - Station 9 (McDonald's Restaurant).

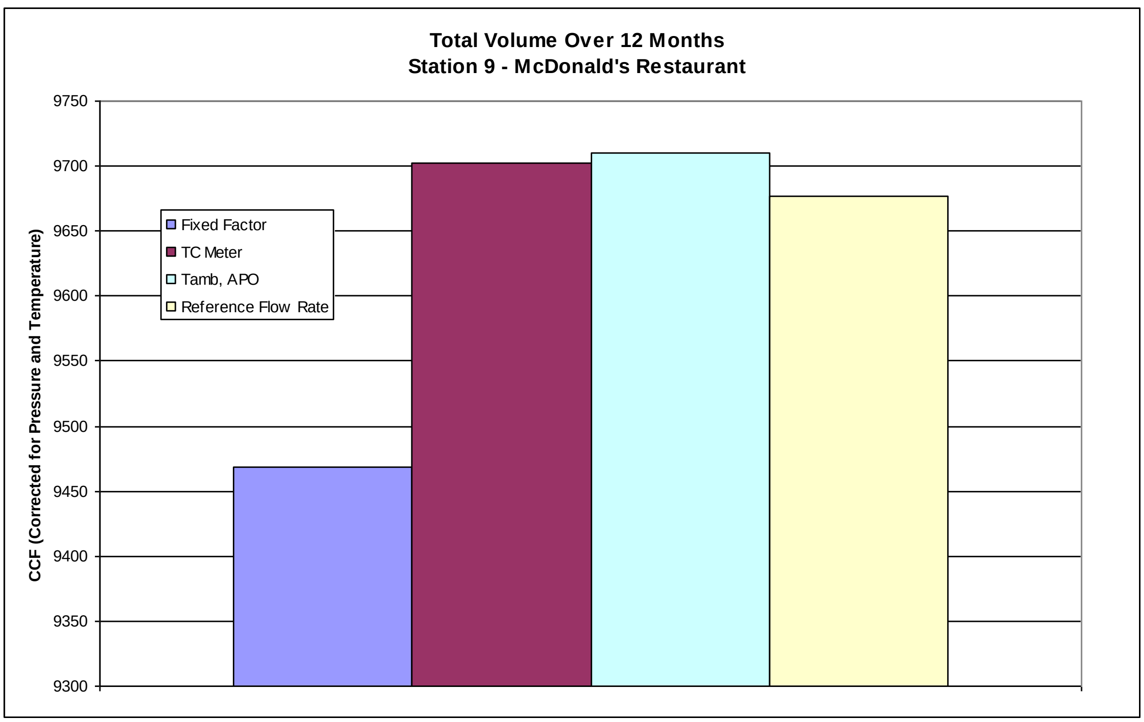

Figure 30. Total volume over 12 months - Station 9 (McDonald's Restaurant).

Figures 27 through 30 show the effect on total volume for four methods (Fixed Factor, TC Meter, “Average” Ambient at Airport, and the Reference) each month and totalized over the year for a single residential customer and a single industrial customer (a McDonald’s restaurant). During the summer months, the Fixed Factor method tended to overmeasure, and during the winter months, it tended to undermeasure (Figures 27 and 29. In Figures 28 and 30, the total flow over the year (accounting for summer and winter loads) was underestimated by the Fixed Factor method, while the TC meter and the zone method each provided results much closer to the reference.

4.5 Conclusions from the Experimental Program

- Historical Temperature Profiles
    - The test year average temperature across the 15 test sites was representative of historical data for all months (i.e., within the ±5 degrees on average) except for January and September which recorded warmer temps during the test period.
    - Variability in the test year temperatures was consistent with historical variability.
    - Historical data can be used to select temperature zones.
    - The temperature at the SLC Airport can be used to represent the temperature throughout the selected zone.
- Correlation between Ambient Temperature and Gas Temperature
    - The correlation between ambient temperature and inlet gas temperature is generally good with average R^2 from 0.8 to 0.90 for most months.
    - The relationship between maximum solar radiation and R^2 (for ambient temperature and inlet gas temperature) is not well defined; however, lower levels of maximum solar radiation (less than 600 W/m^2) demonstrated high R^2 values while higher levels of max radiation (greater than 1000 W/m^2) demonstrated slightly lower R^2 values. In general, higher levels of radiation were observed during the summer months and lower levels during the winter months.
    - The correlation appears to be dependent on solar radiation in that it is stronger when solar radiation levels are lower and it is weaker when solar radiation levels are higher. The correlation could be strengthened by using a more reflective meter finish.

- Flow Rate Comparisons for Various Gas Temperature Assumptions[7] and Temperature-Compensating Meter

  - The fixed factor method accuracy was between about +6/-7%.
  - The $T_{gas} = T_{ambient}$ method provided accuracy within about -1/+2%.
  - The $T_{gas} = T_{surface}$ method provided accuracy within about +/- 1%.
  - The $T_{gas} = T_{ambient,site}$ method provided accuracy within about +/- 3%.
  - The $T_{gas} = T_{ambient,zone}$ method provided accuracy within about +/- 3%.
  - Temperature-compensating meters provided accuracy in the range of approximately +/-3% for all stations.
  - In general, all methods provided improved accuracy over the fixed-factor method.
  - The use of daily high and low temperatures would likely improve the $T_{ambient}$ methods by reducing the impact of a single, extreme ambient temperature that could occur during a given period.
  - The McDonald's test site showed nothing unusual, compared to the other test sites. However, the load during the summer is considerably higher than the load at a typical residential site.
  - The variation in the results for $T_{gas} = T_{ambient,site}$ and $T_{gas} = T_{ambient,zone}$ dropped during the period September through January, suggesting better predictability in the method's results over the zone during the colder months of the year.
  - Temperature compensating meters provided generally stable performance throughout the year. However, some of the meters showed relatively high variations. The cause of the high variations is not known, but may be related to manufacturing variability.
  - The use of meter surface temperature offered improved accuracy at sites with relatively high solar radiation exposure. This is consistent with the observation that the ambient temperature/gas temperature correlation is affected by solar radiation (which affects meter surface temperature).
  - There was little difference between results using ambient temperature and meter surface temperature at sites with relatively low solar radiation exposure. This is consistent with the observation that the ambient temperature/gas temperature correlation is affected by solar radiation (which affects meter surface temperature).

[7] See 4.4.3.2 for an explanation of the various gas temperature assumptions.

- The use of meter surface temperature stood out as the most accurate indicator of flowing gas temperature, producing differences in flow rate of +/- 1%. This is because of the "plenum" effect of the meter, which facilitates heat transfer from the meter body to the gas.

5. CONCLUSIONS AND RECOMMENDATIONS FROM TASKS 2 AND 3

- Ambient temperature data can be used to select zone boundaries and to predict intra-zone temperature variability. "Average" ambient temperature data at a single location (the SLC airport in this study) can be used to represent the temperature throughout a zone. The temperature zone approach can be used to provide improved flow measurement.

- The accuracy of the "average" ambient temperature methods improved during the winter months, relative to the summer months. This is because 1) solar radiation exposure is greater during the summer months and 2) the effect of solar radiation on the correlation between ambient temperature and gas temperature is more pronounced during the summer months, when solar radiation tends to be high, and becomes secondary during the winter months, when solar radiation tends to be low. This is significant because more gas is consumed during the winter months.

- The Fixed Factor method performed poorly. The error, relative to the reference measurement, ranged from +6 to -7 %. Errors were greater during mid-summer (July through August) and mid-winter (December through January). Errors were lowest during spring and fall. The effect of the percent error on total volume for a given site was impacted by seasonal load variations. Over the course of the year, the Fixed Factor method produced a net undermeasurement.

- Temperature-compensating meters performed significantly better than the fixed factor method. The percent difference in flow rate, relative to the reference, of the temperature-compensating meters, was approximately in the middle of the group of methods tested (excluding the fixed-factor method). The results of the temperature-compensating meter tests were comparable to the accuracy produced by the "average" ambient temperature methods.

- Overall, performance of the TC meters was steady over the course of the year, with the bulk of the comparisons showing a difference of about +/- 1 to 2 percent. Stations 1, 5, 11 and 13 showed greater variability over the course of the year, increasing the percent difference for all TC meters to about +/- 3%.Measurement precision worsened during the winter months. In comparison, both of the "average" ambient methods (Figure 24 and Figure 25) showed improved precision during the winter months (see 4.4.3.2).

- In contrast to the "average" ambient temperature methods, the precision of temperature-compensating meters worsened during October, November, December, and January. For all the remaining months, the precision performance of the TC meter was not statistically different from the precision performance of the two "average" ambient methods. The cause of the worsening precision was not studied because it was outside the scope of the project.

- The use of meter surface temperature stood out as the most accurate indicator of flowing gas temperature, producing differences in flow rate of +/- 1%. This is because of the "plenum" effect of the meter, which facilitates heat transfer to/from the meter body to/from the gas.

- Figure 19 suggests that the effect of solar radiation on the correlation between ambient temperature and gas temperature is greater during the summer months, when solar radiation and ambient temperatures are higher and that the effect is lower during the winter months, when solar radiation and ambient temperatures are lower. This observation may help explain the difference in the performance of the "average" ambient temperature methods during summer versus winter. The effect could be reduced by using a more reflective meter finish.

- The use of the statistical average ambient temperature, or daily high and low temperatures, at the SLC airport may improve the accuracy of the zone method.

APPENDIX A

WEATHERBANK PLOTS

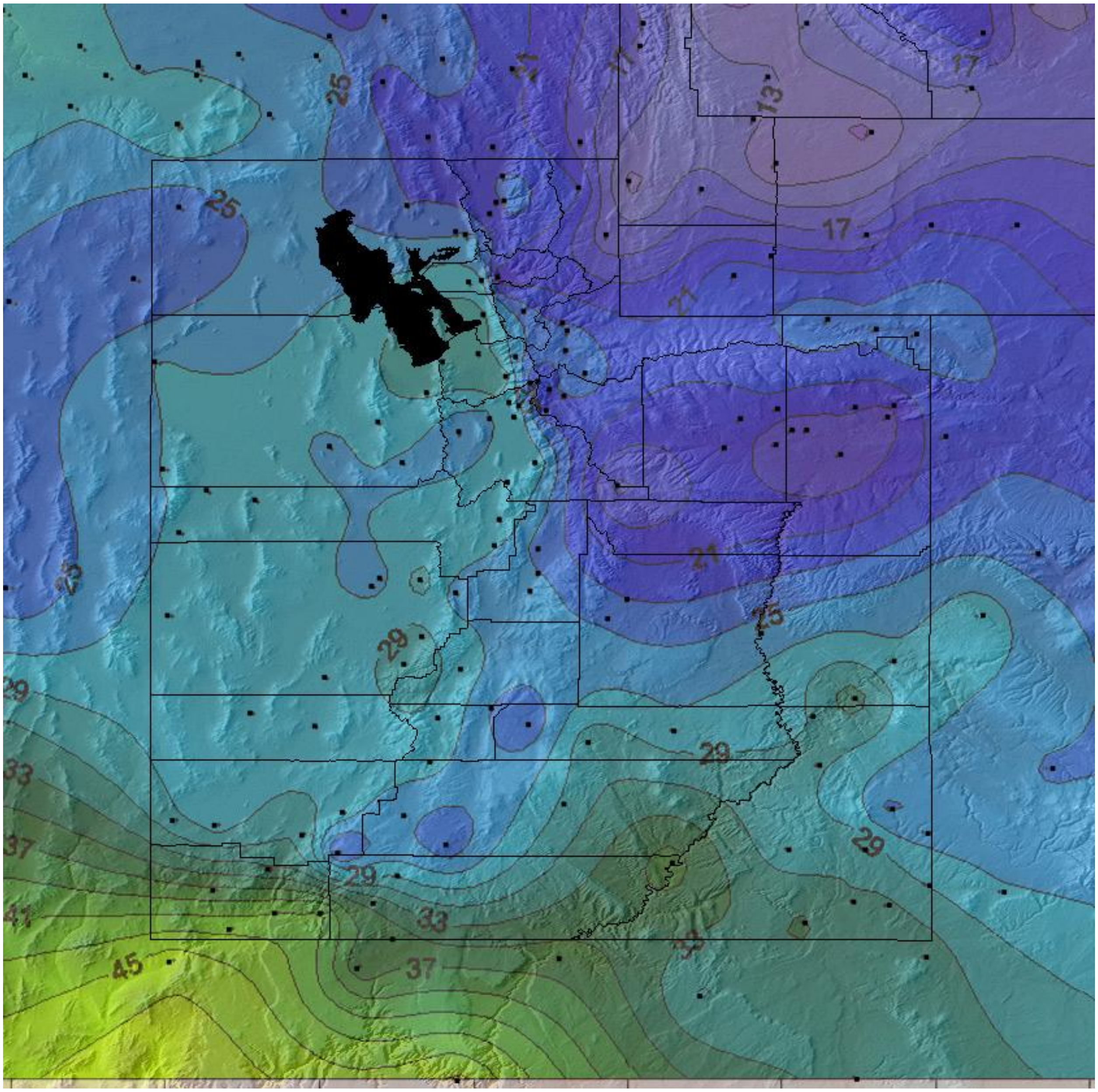

Figure A1. January temperature contours and topography for Questar Gas service area.

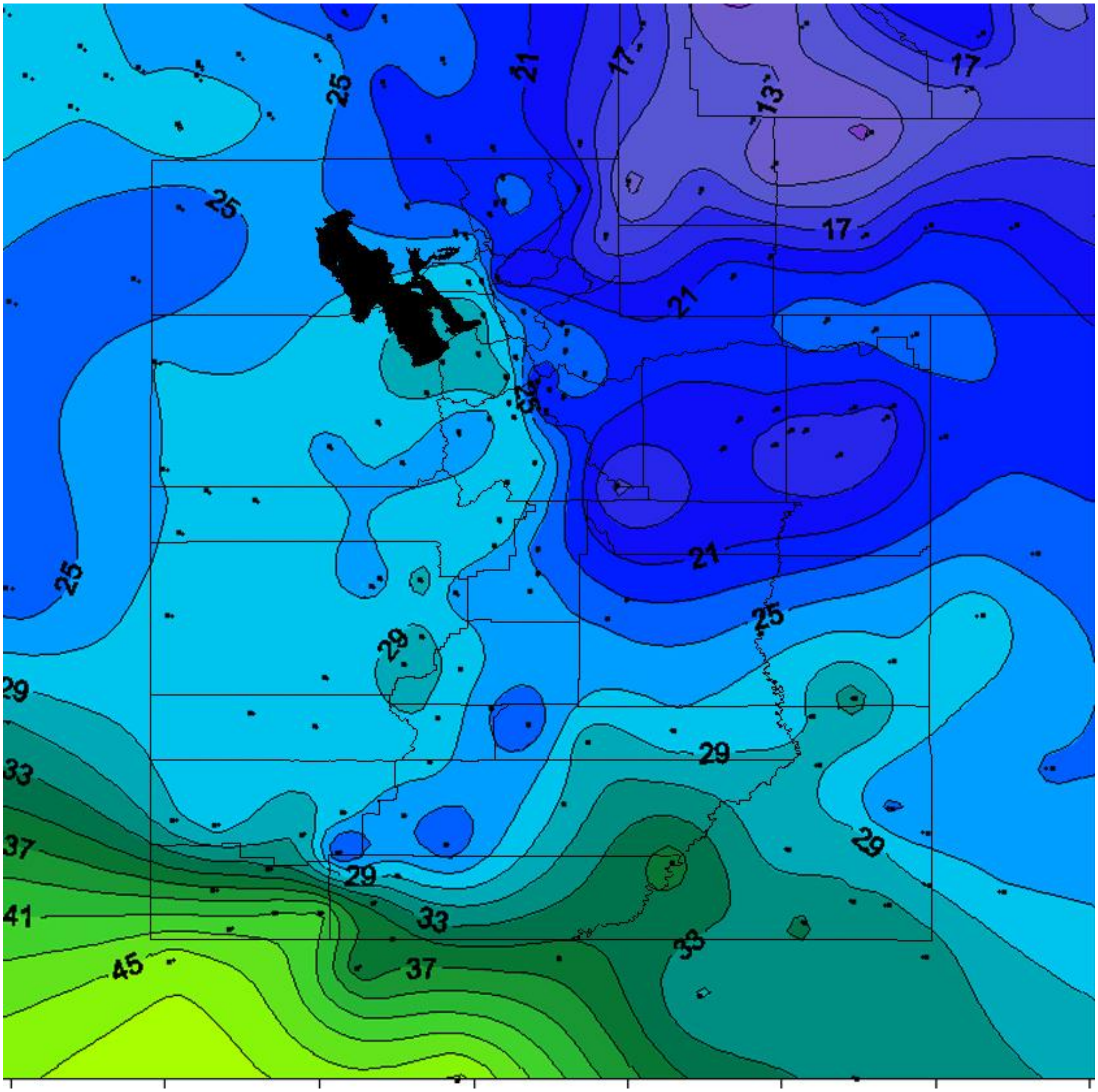

Figure A2. January temperature contours for Questar Gas service area.

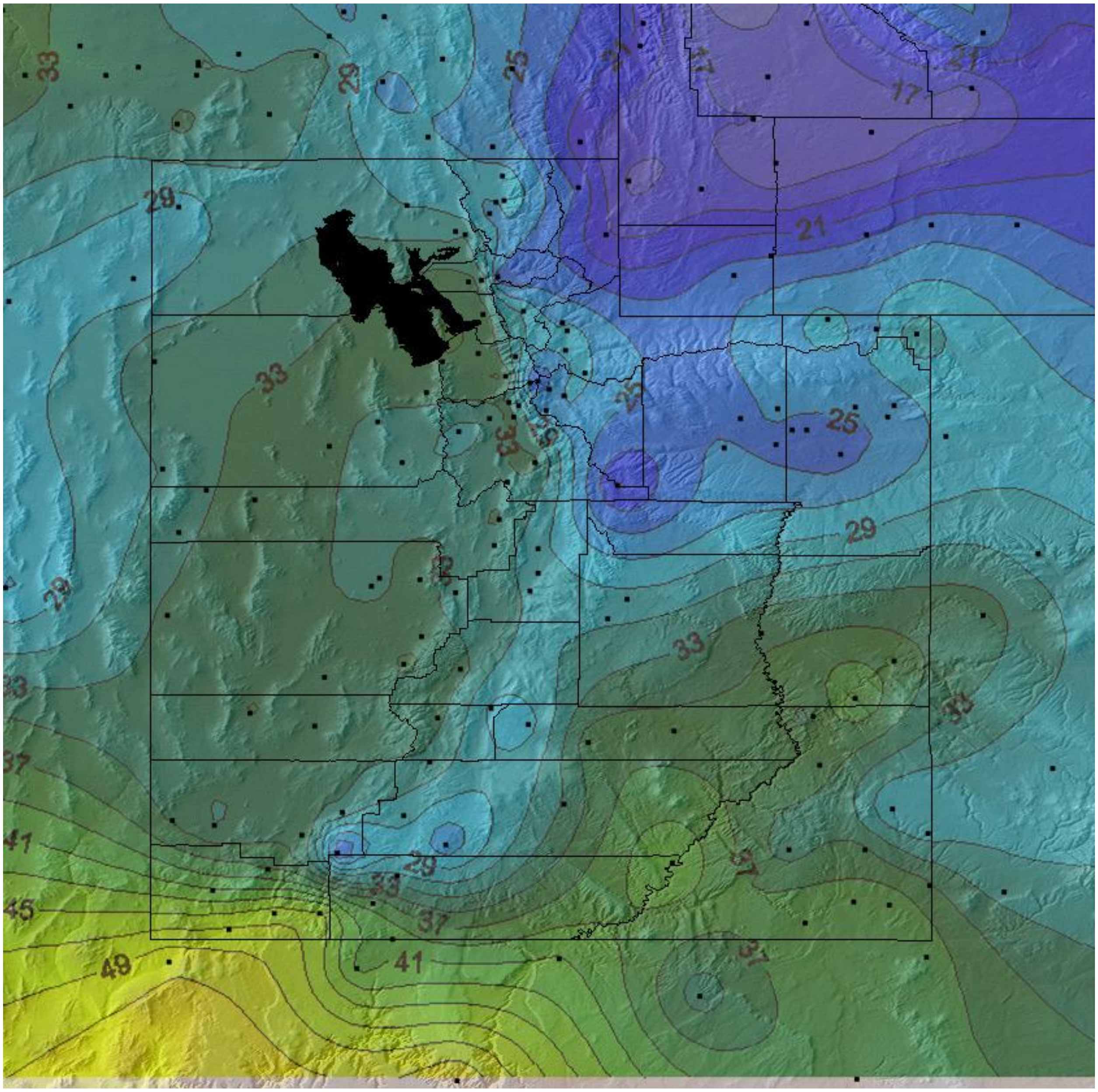

Figure A3. February temperature contours and topography for Questar Gas service area.

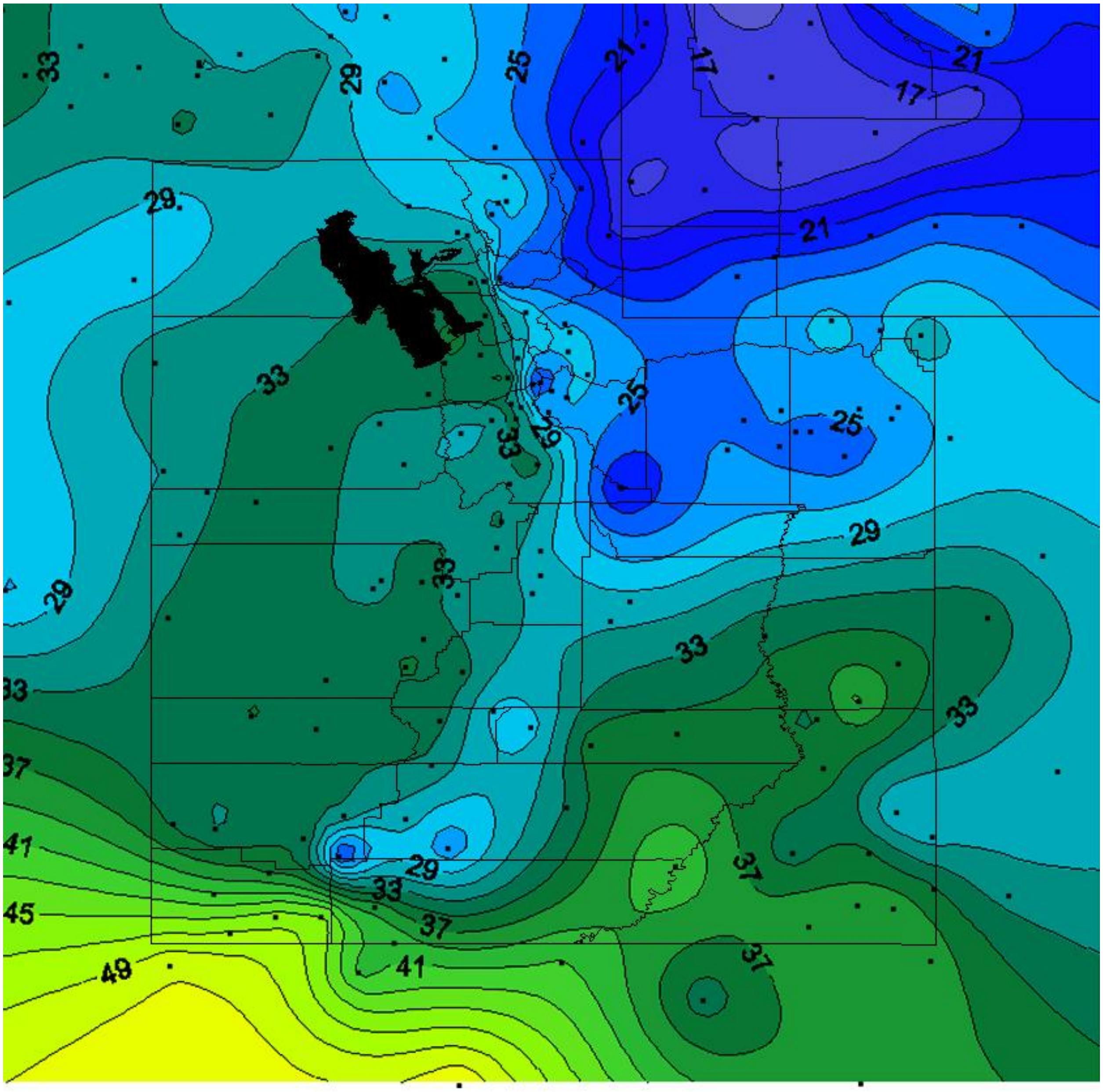

Figure A4. February temperature contours for Questar Gas service area.

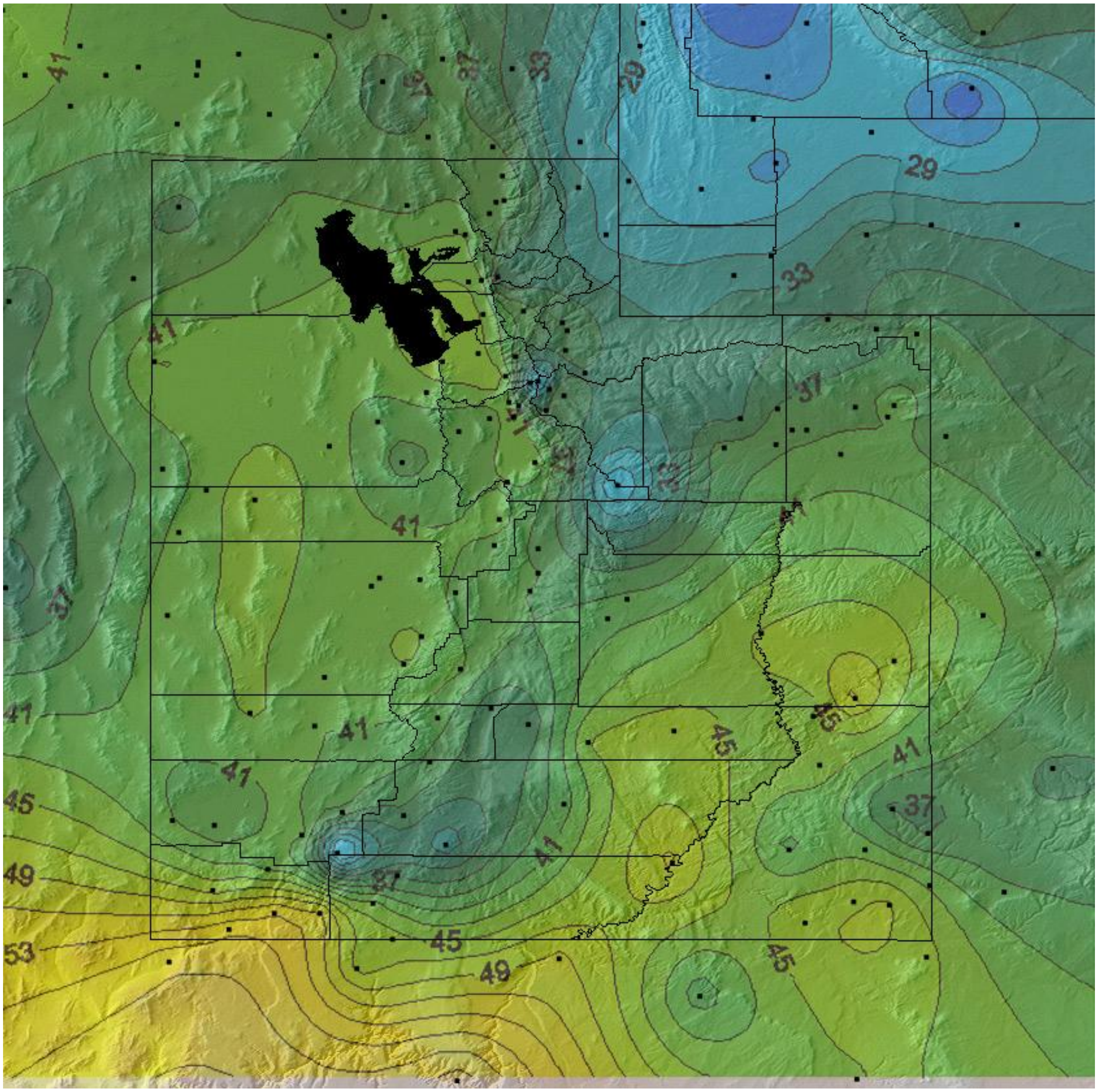

Figure A5. March temperature contours and topography for Questar Gas service area.

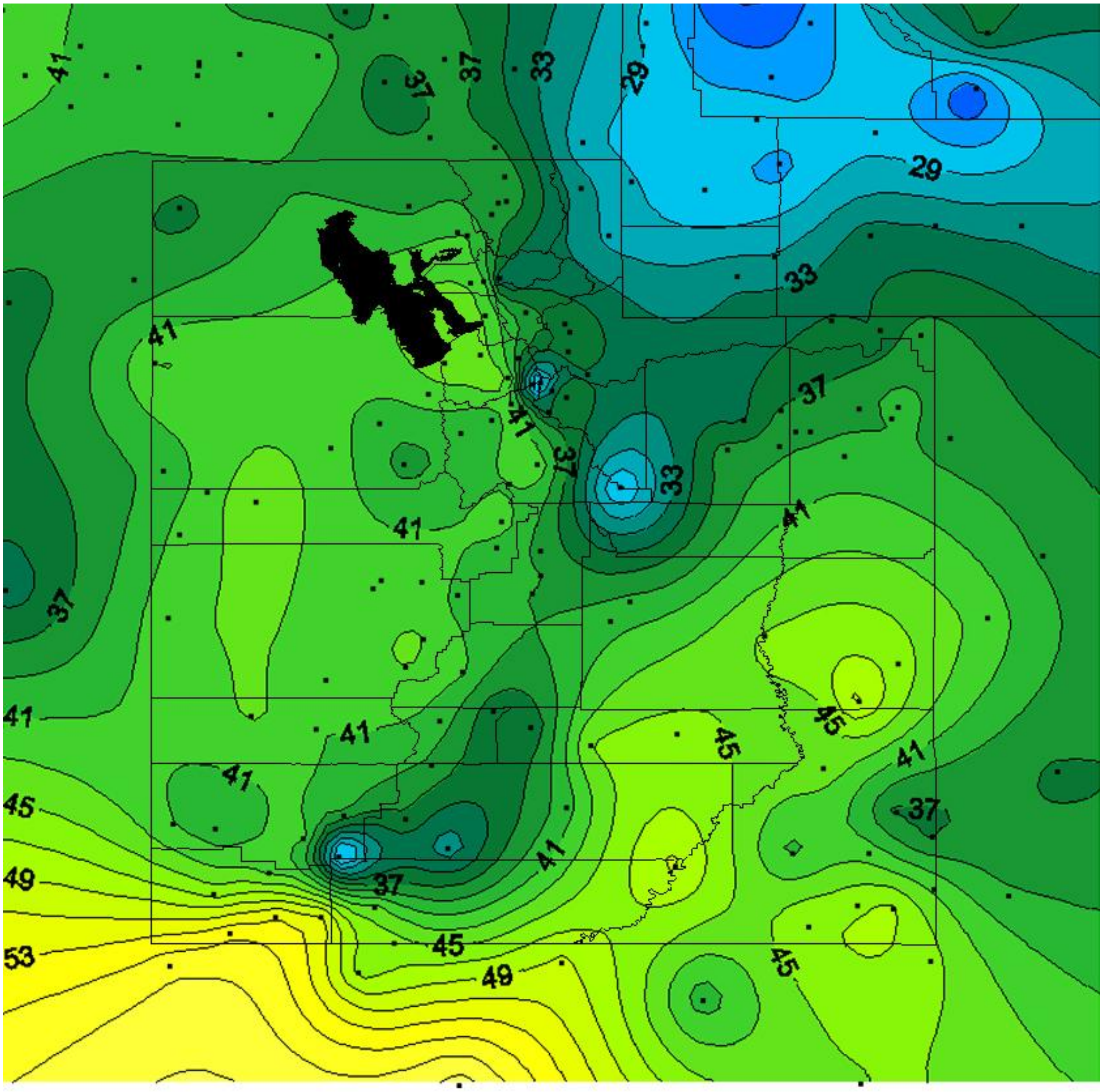

Figure A6. March temperature contours for Questar Gas service area.

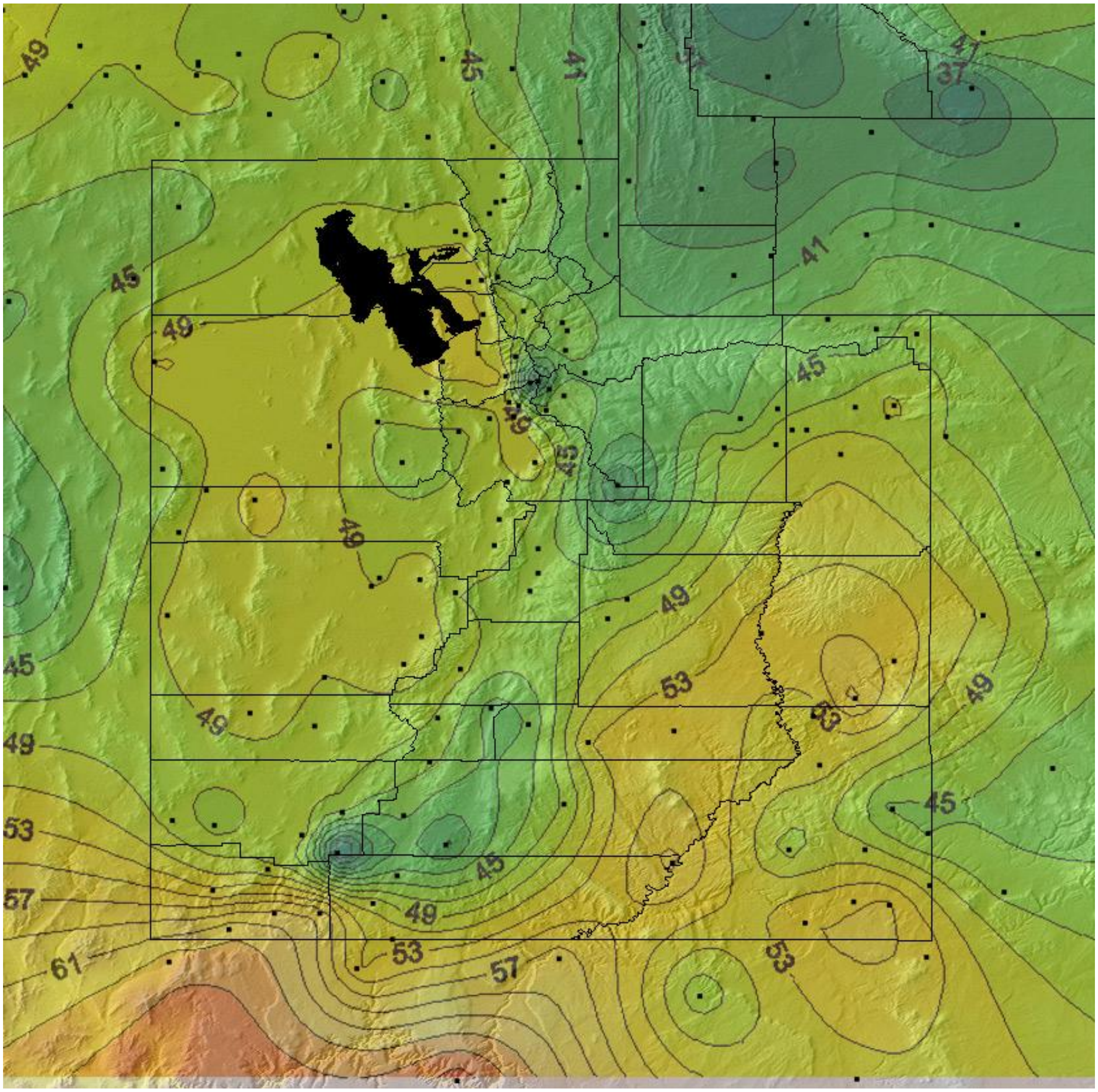

Figure A6. April temperature contours and topography for Questar Gas service area.

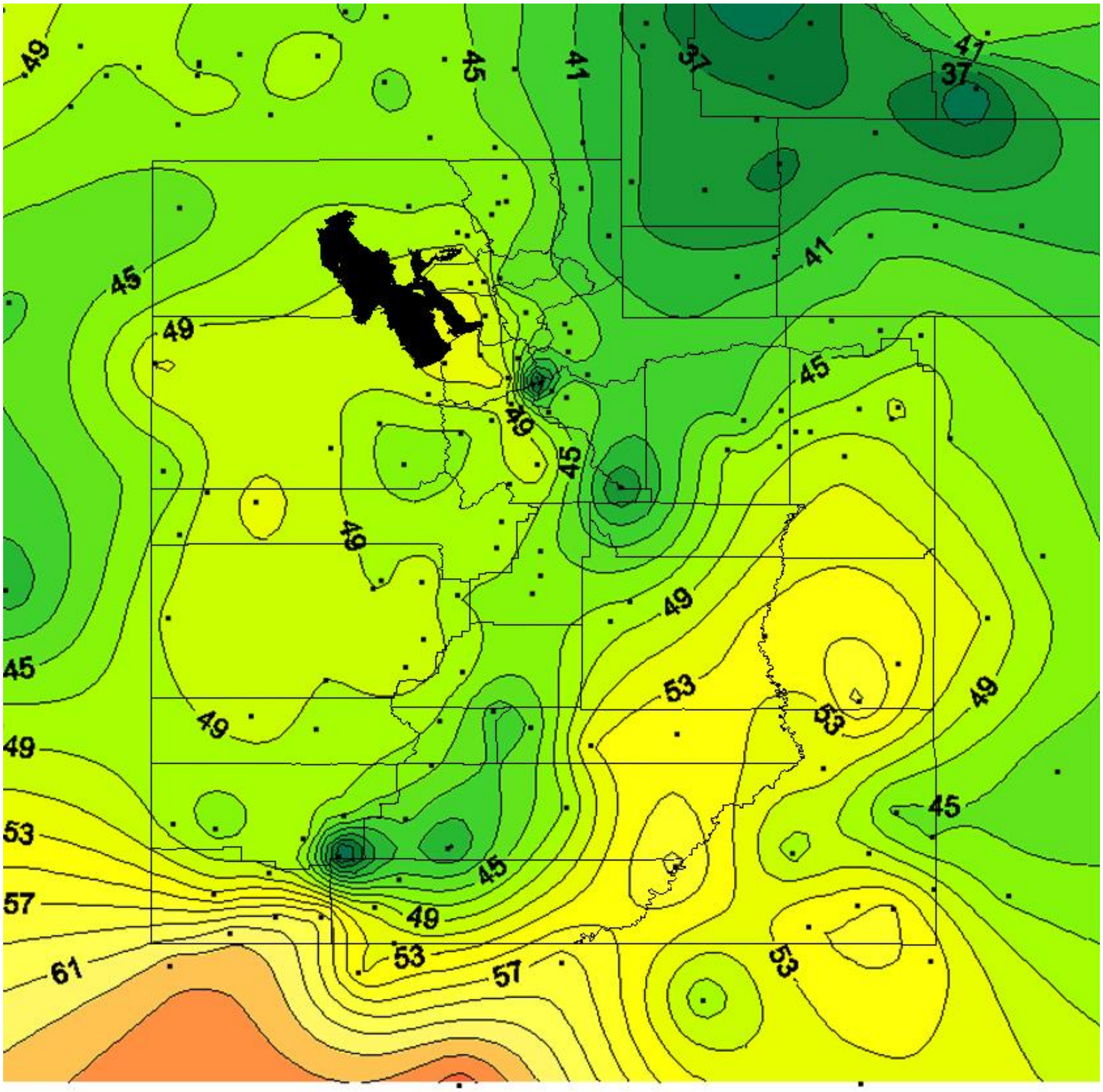

Figure A8. April temperature contours for Questar Gas service area.

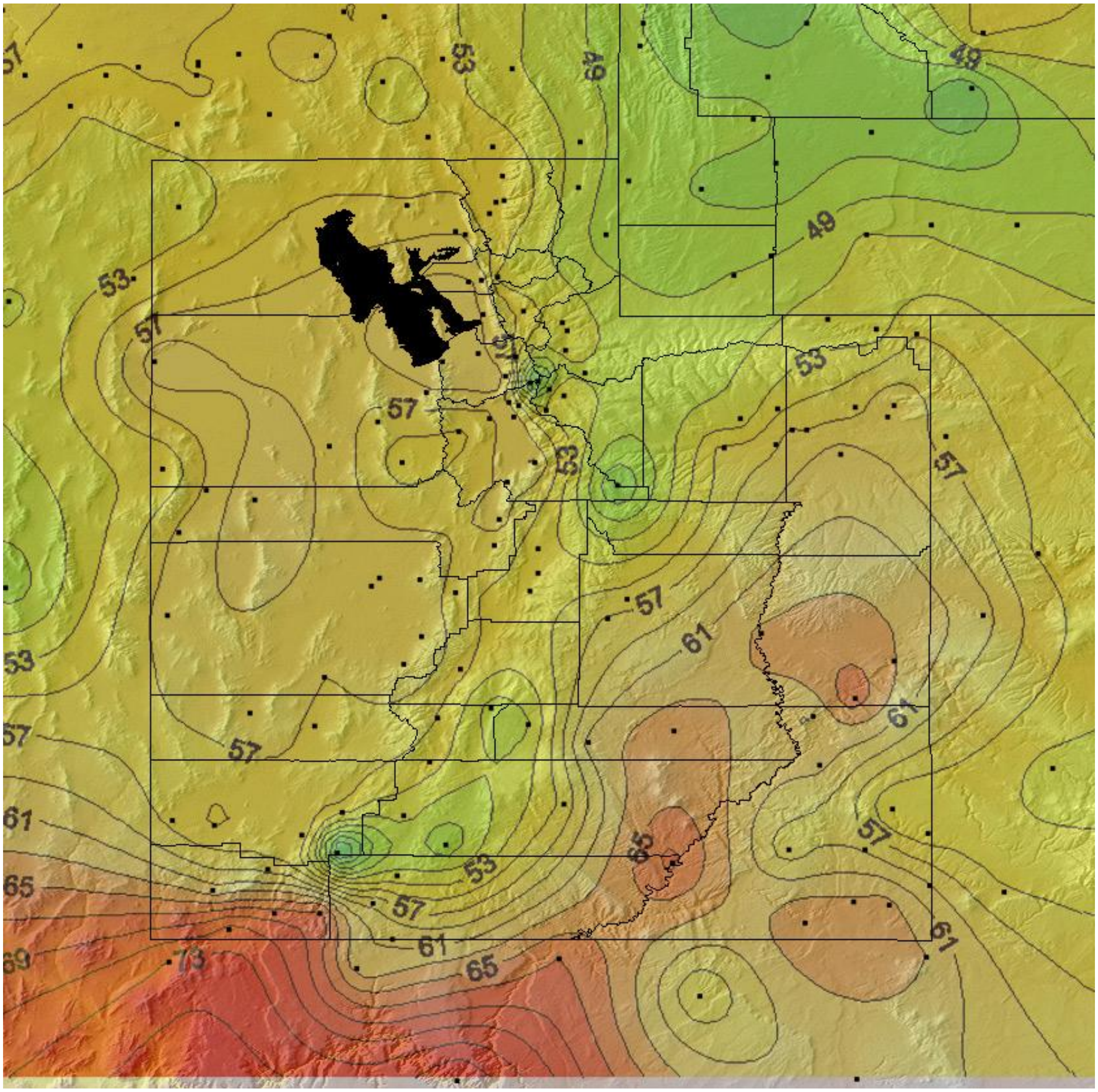

Figure A9. May temperature contours and topography for Questar Gas service area.

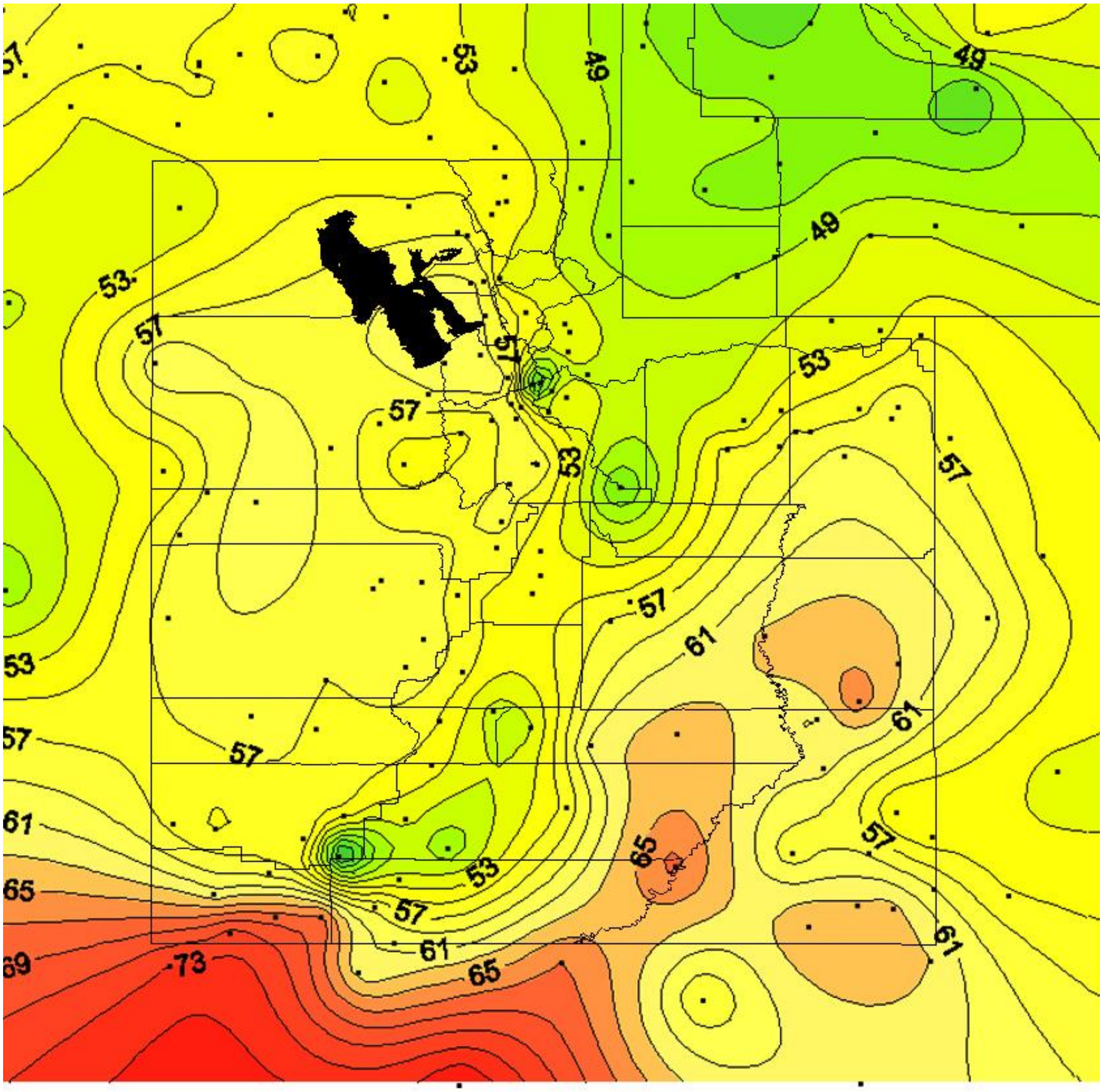

Figure A10. May temperature contours for Questar Gas service area.

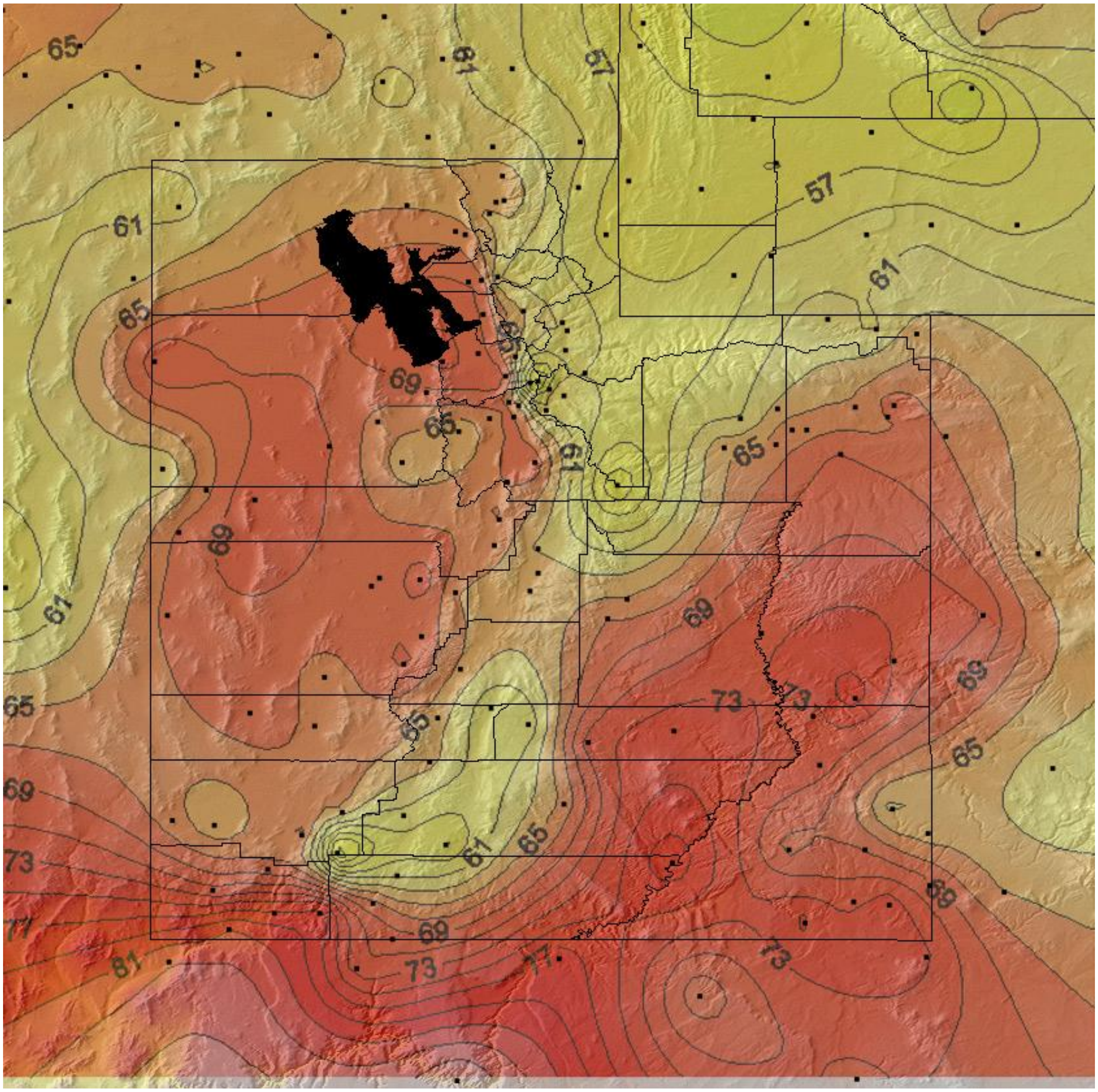

Figure A11. June temperature contours and topography for Questar Gas service area.

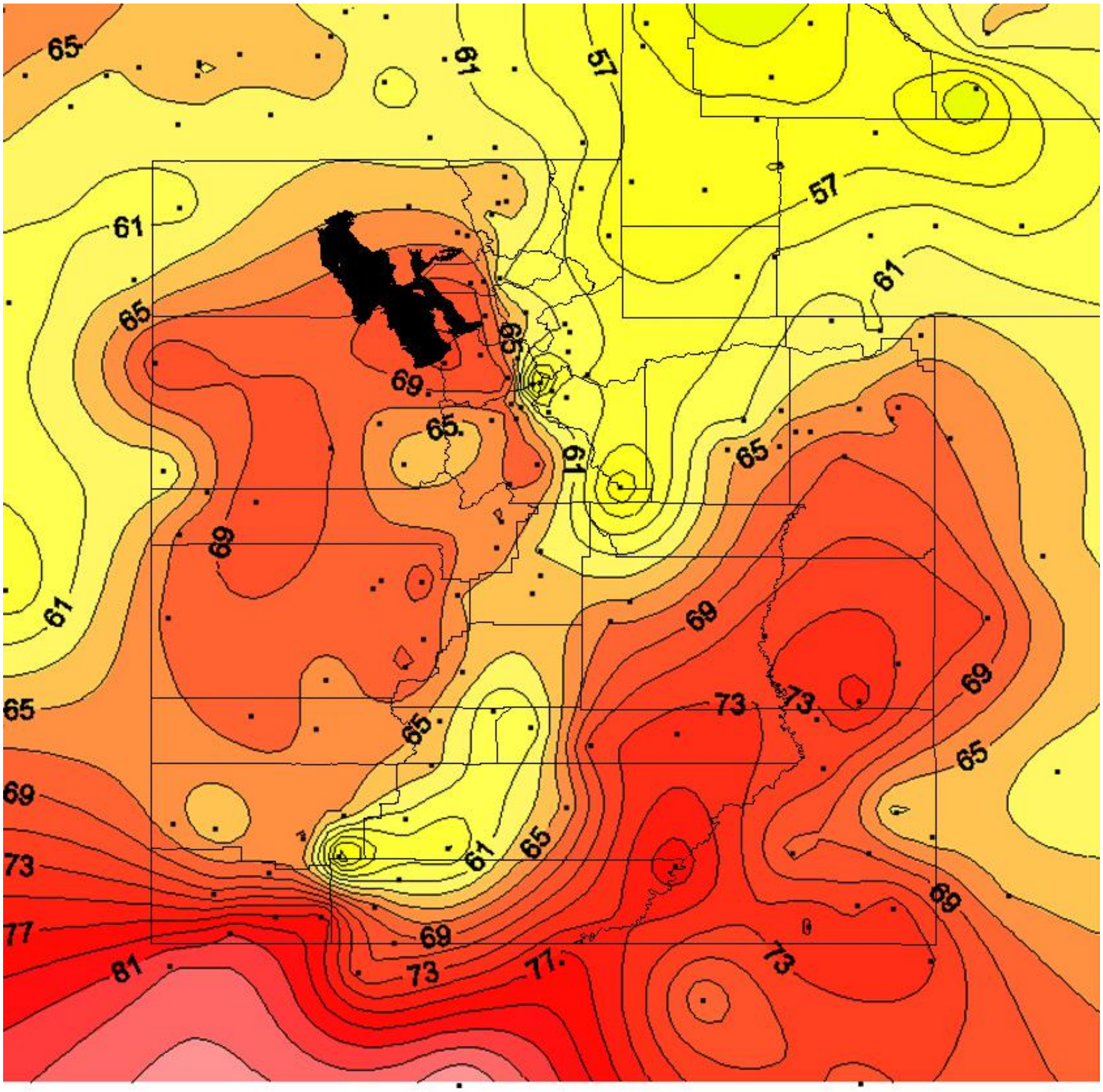

Figure A12. June temperature contours for Questar Gas service area.

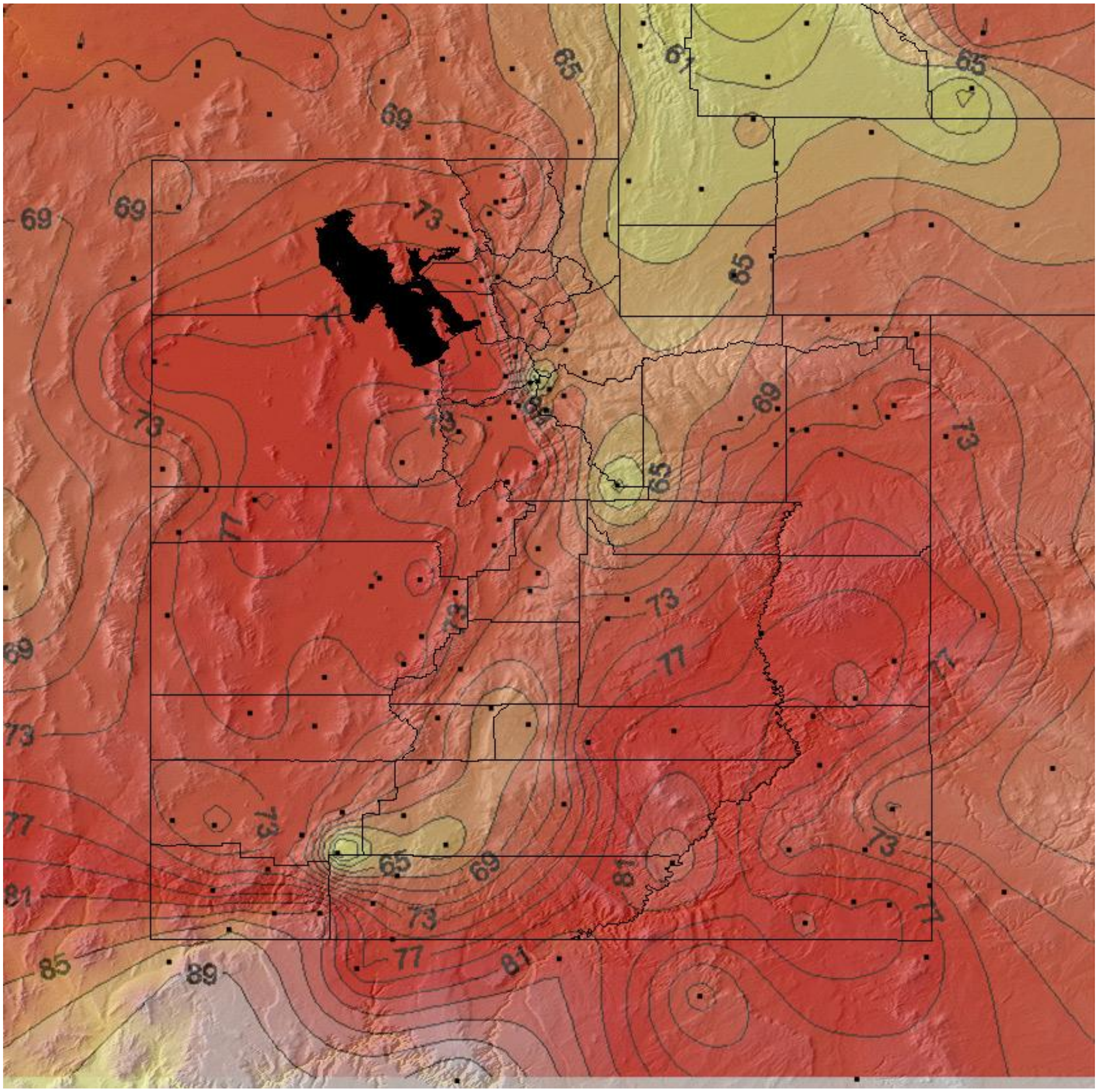

Figure A13. July temperature contours and topography for Questar Gas service area.

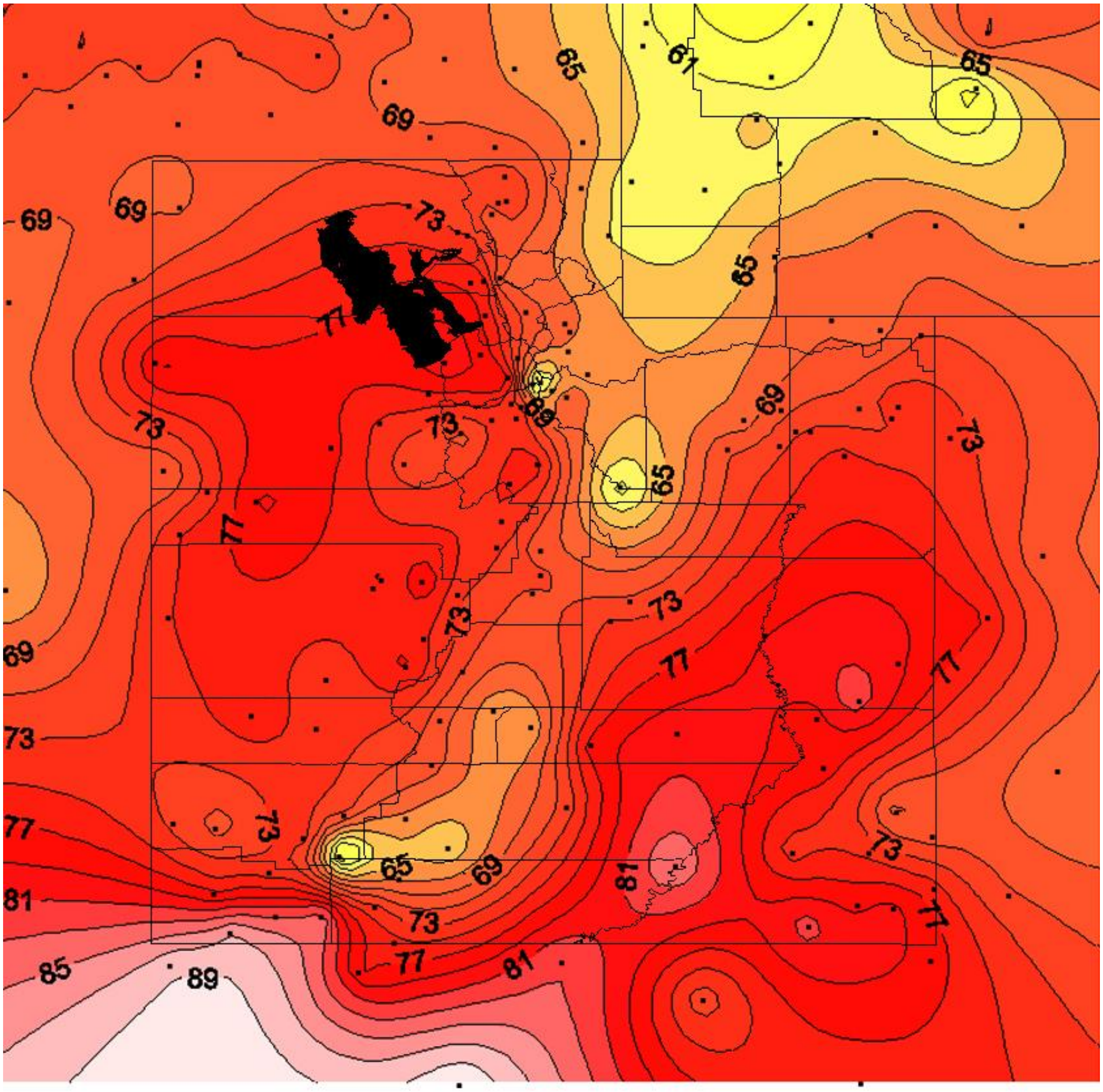

Figure A14. July temperature contours for Questar Gas service area.

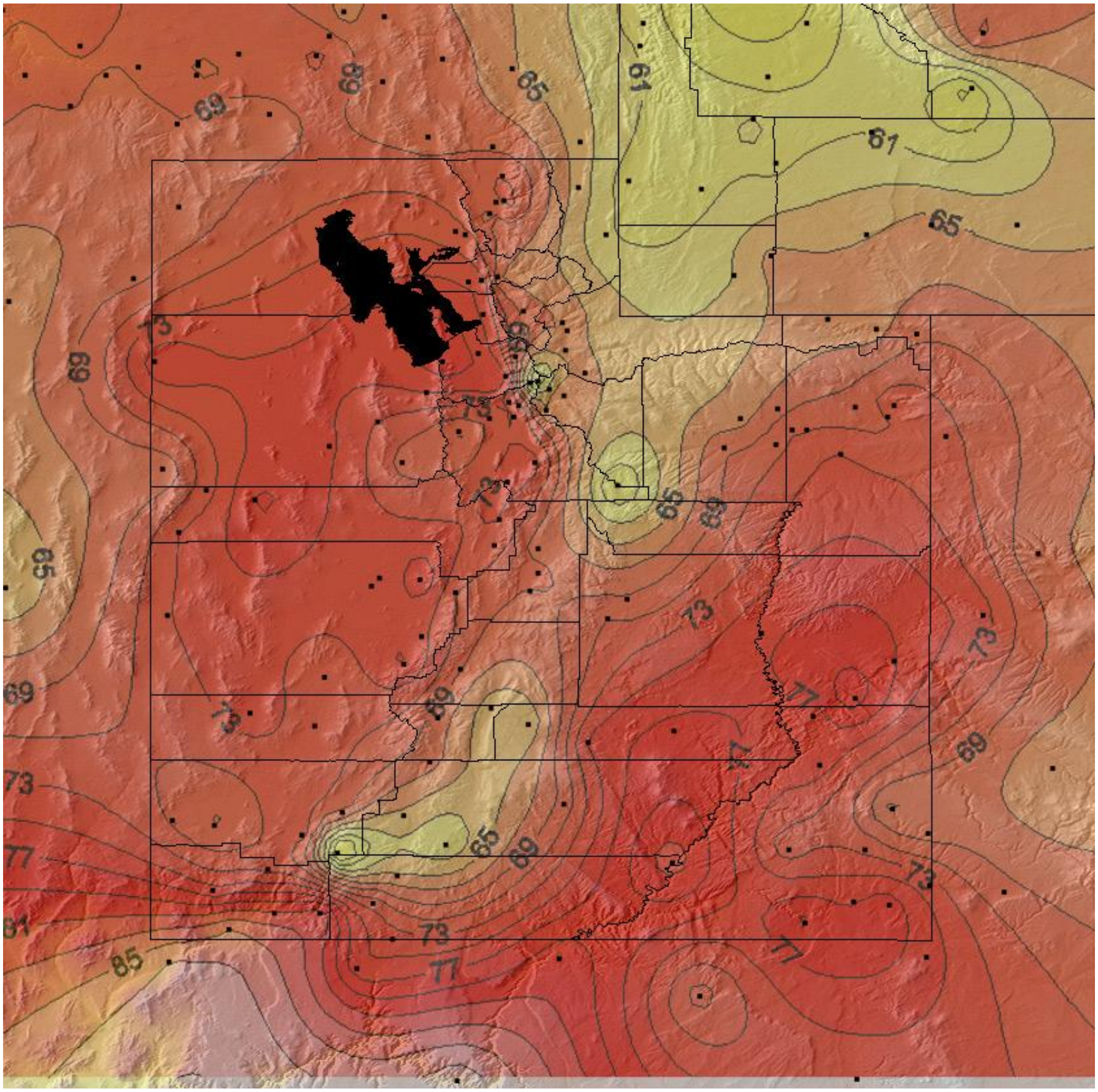

Figure A16. August temperature contours and topography for Questar Gas service area.

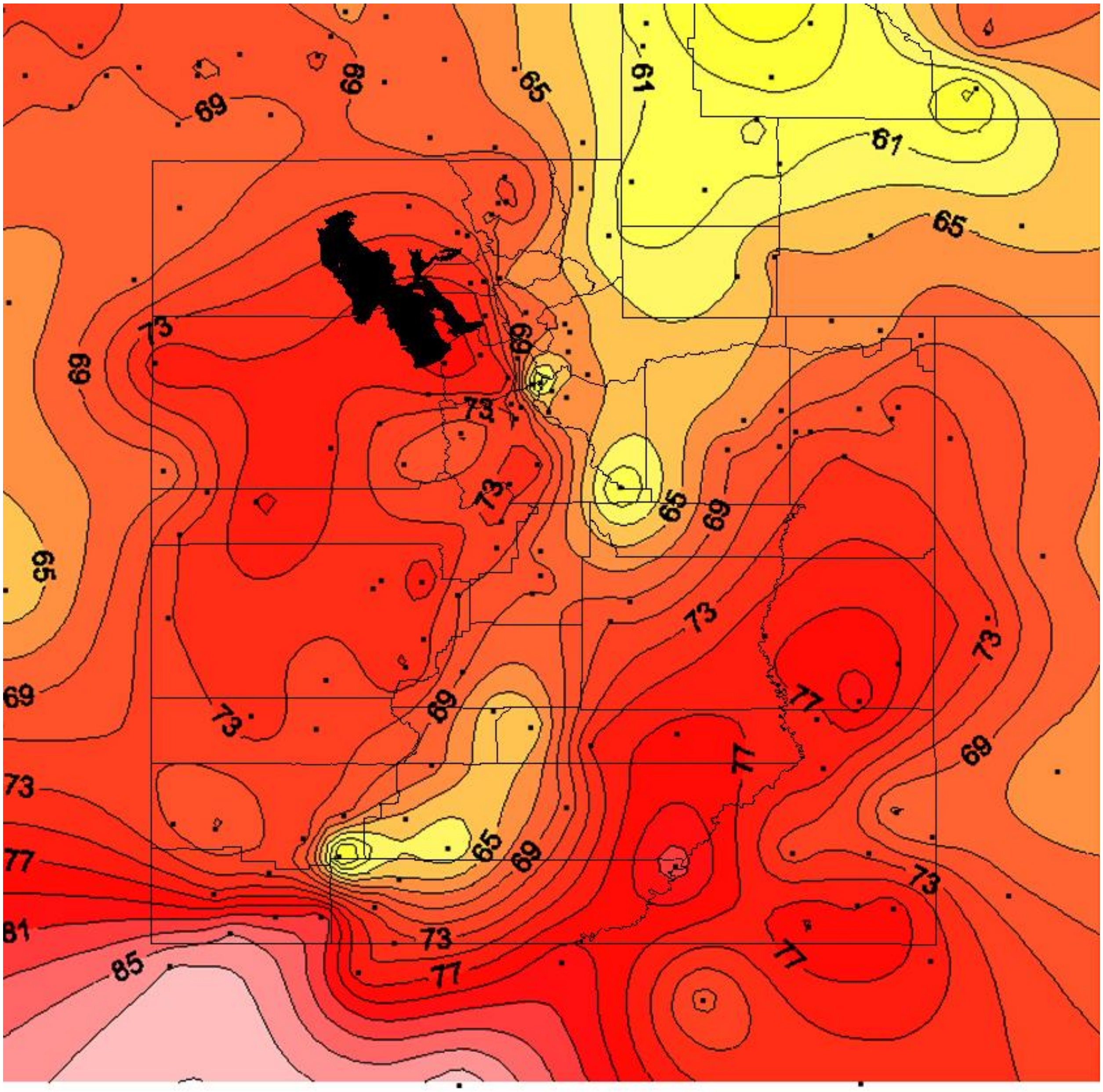

Figure A16. August temperature contours for Questar Gas service area.

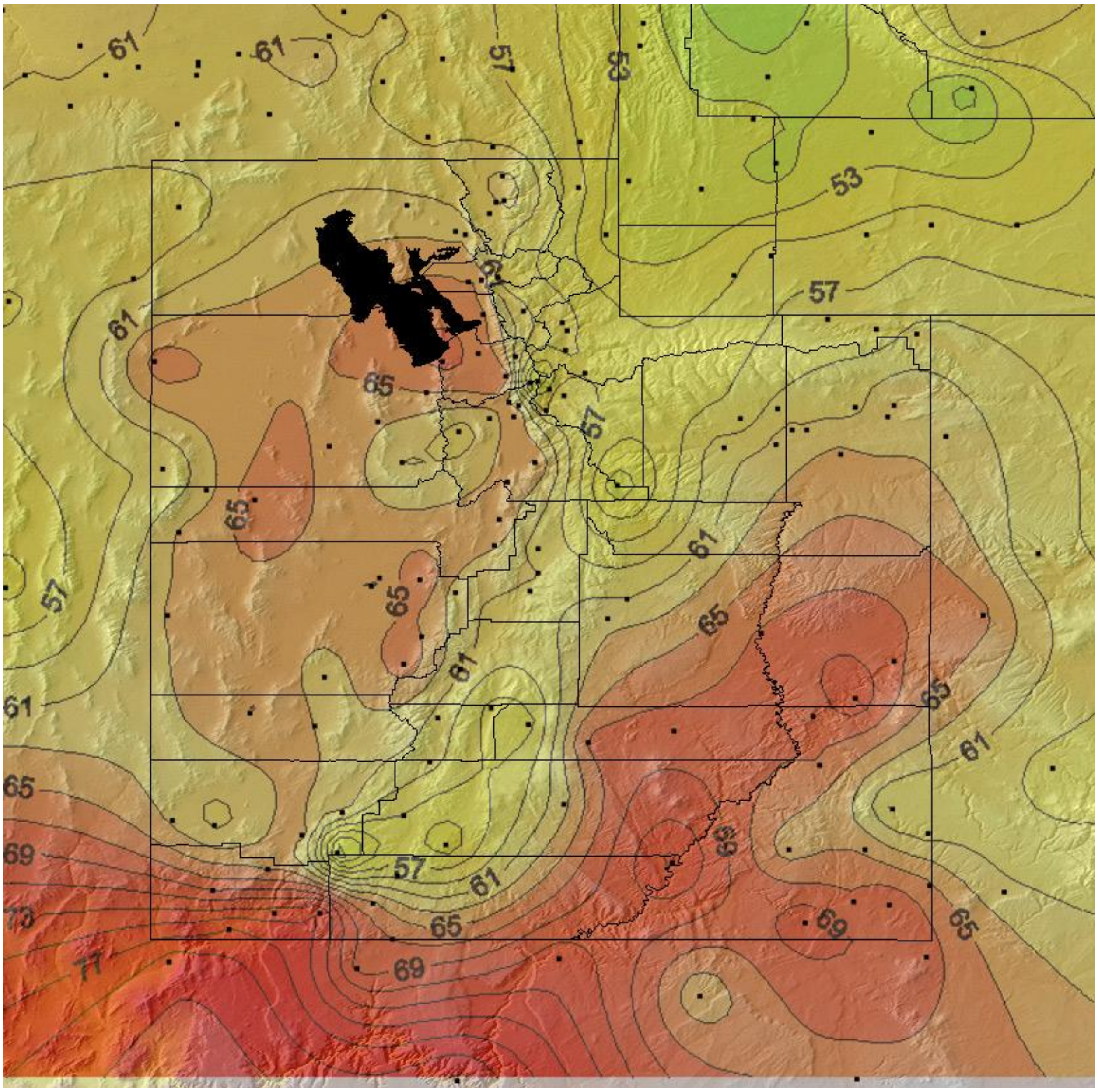

Figure A17. September temperature contours and topography for Questar Gas service area.

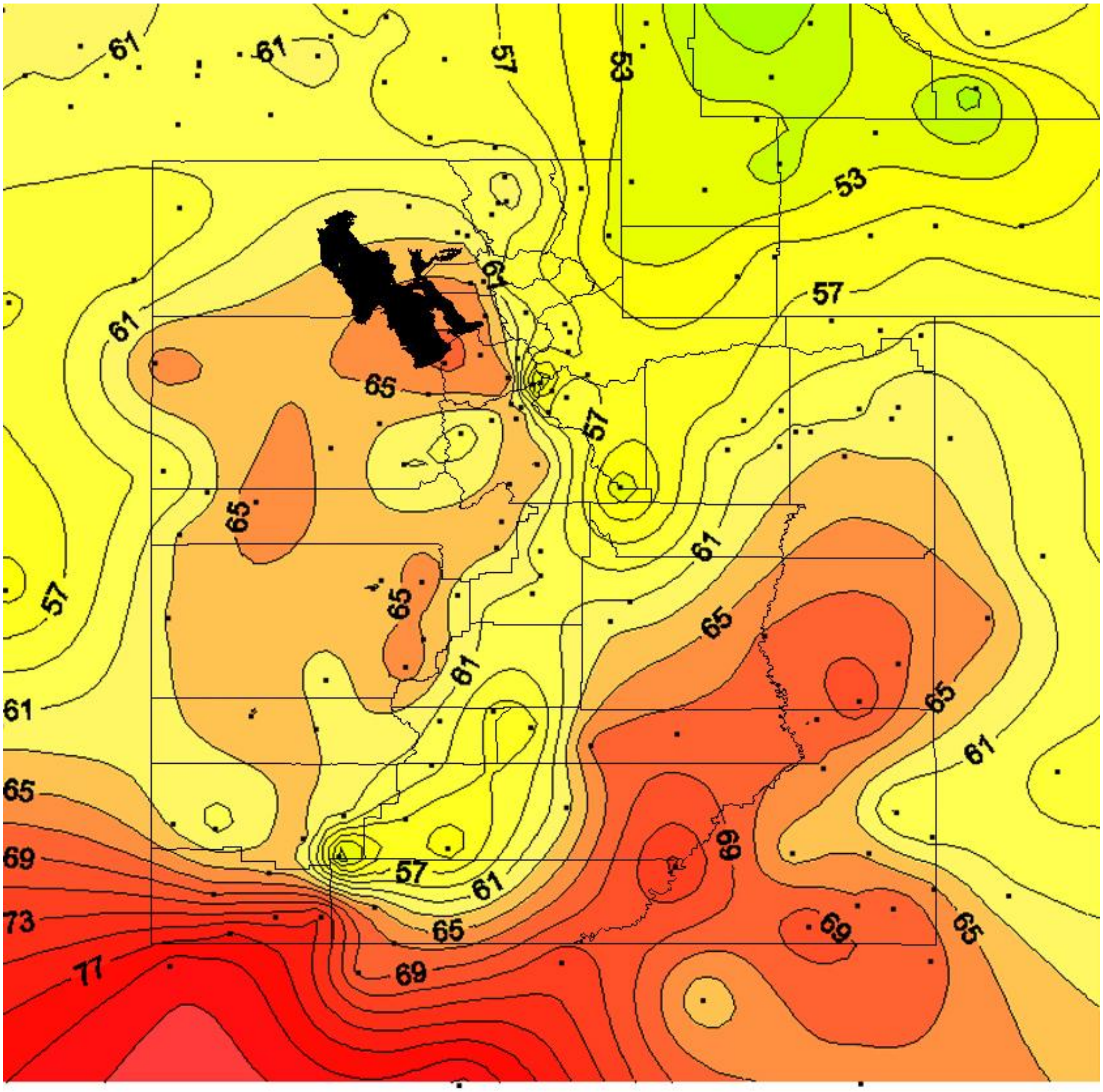

Figure A18. September temperature contours for Questar Gas service area.

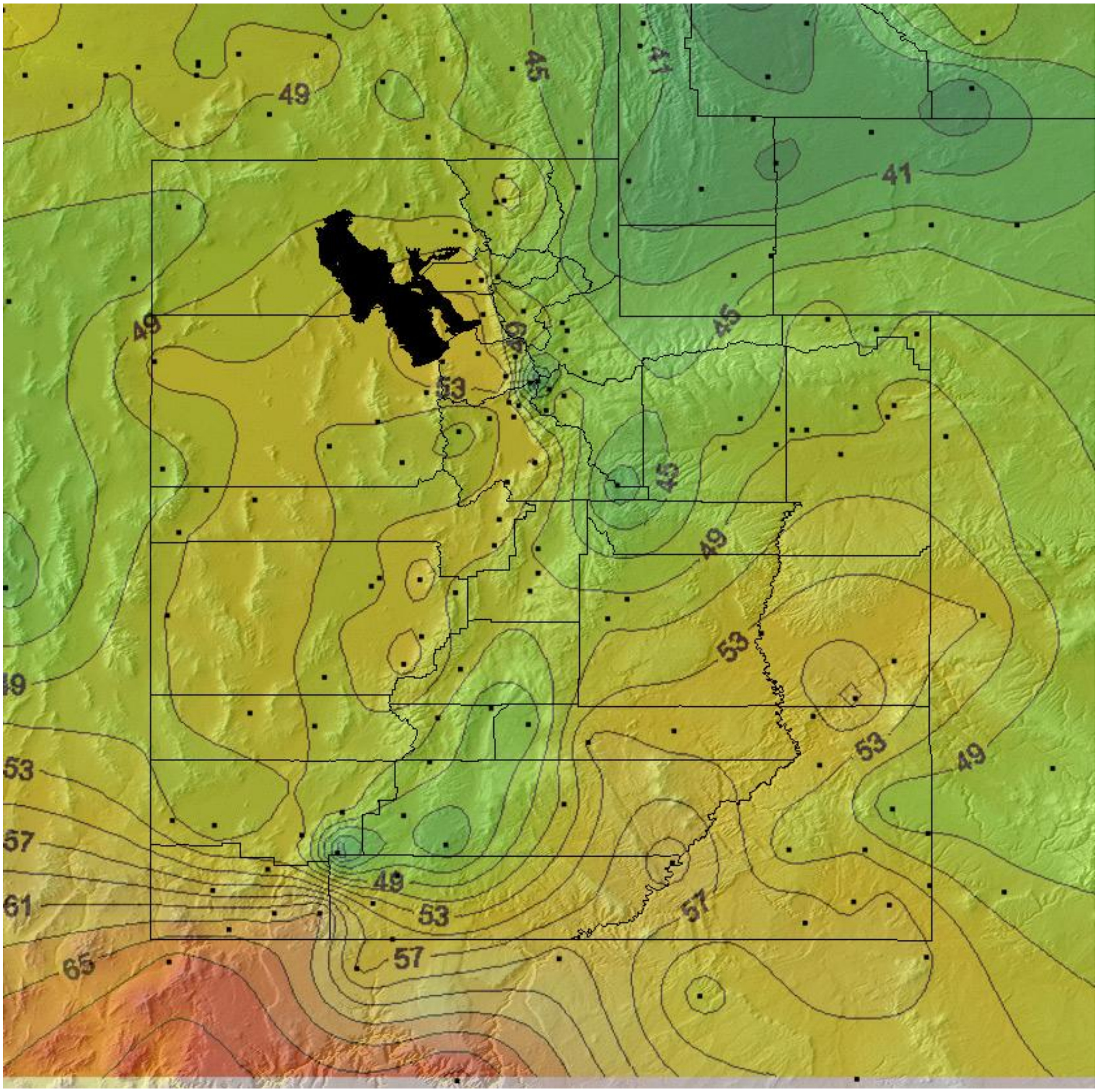

Figure A19. October temperature contours and topography for Questar Gas service area.

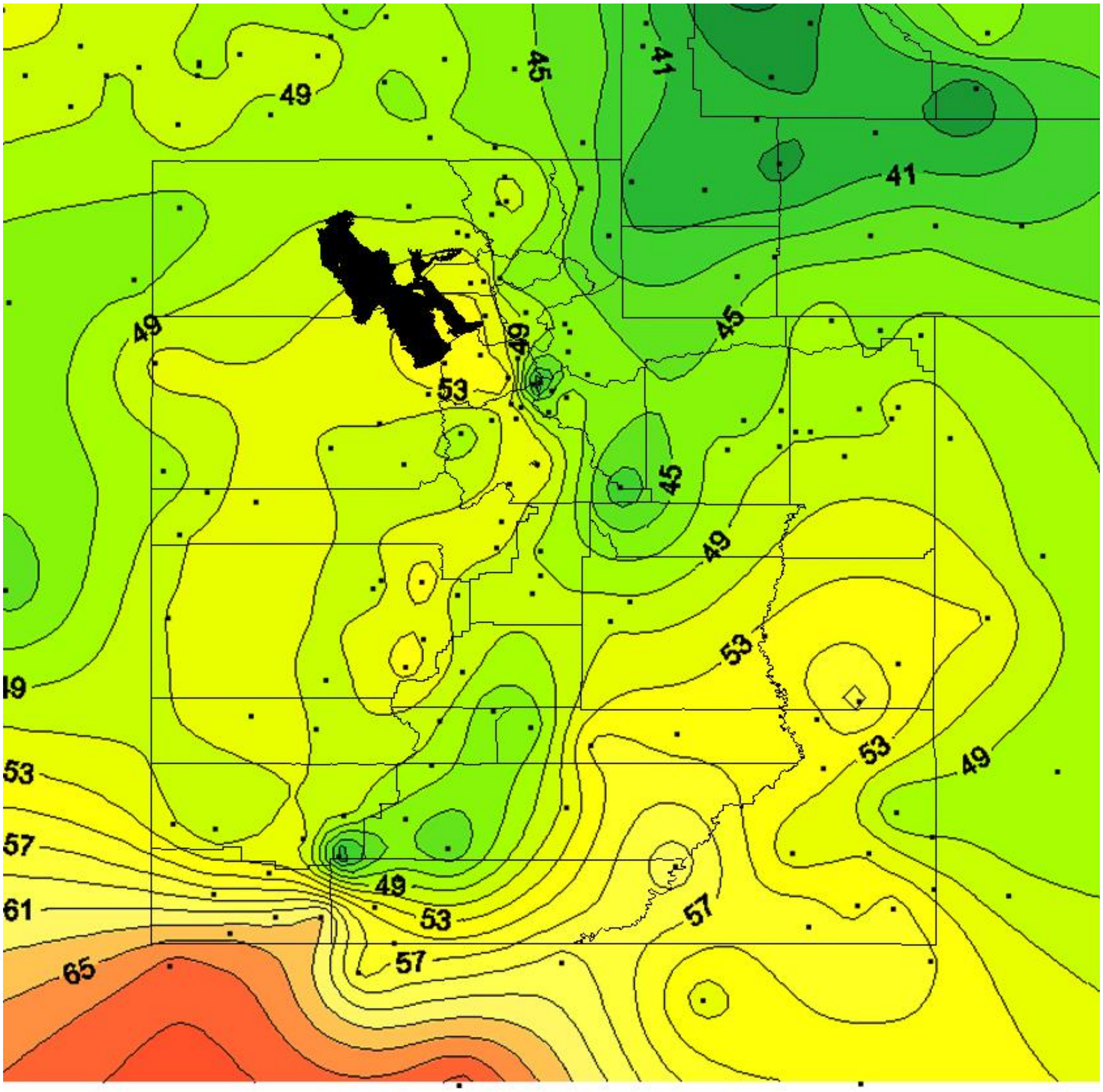

Figure A20. October temperature contours for Questar Gas service area.

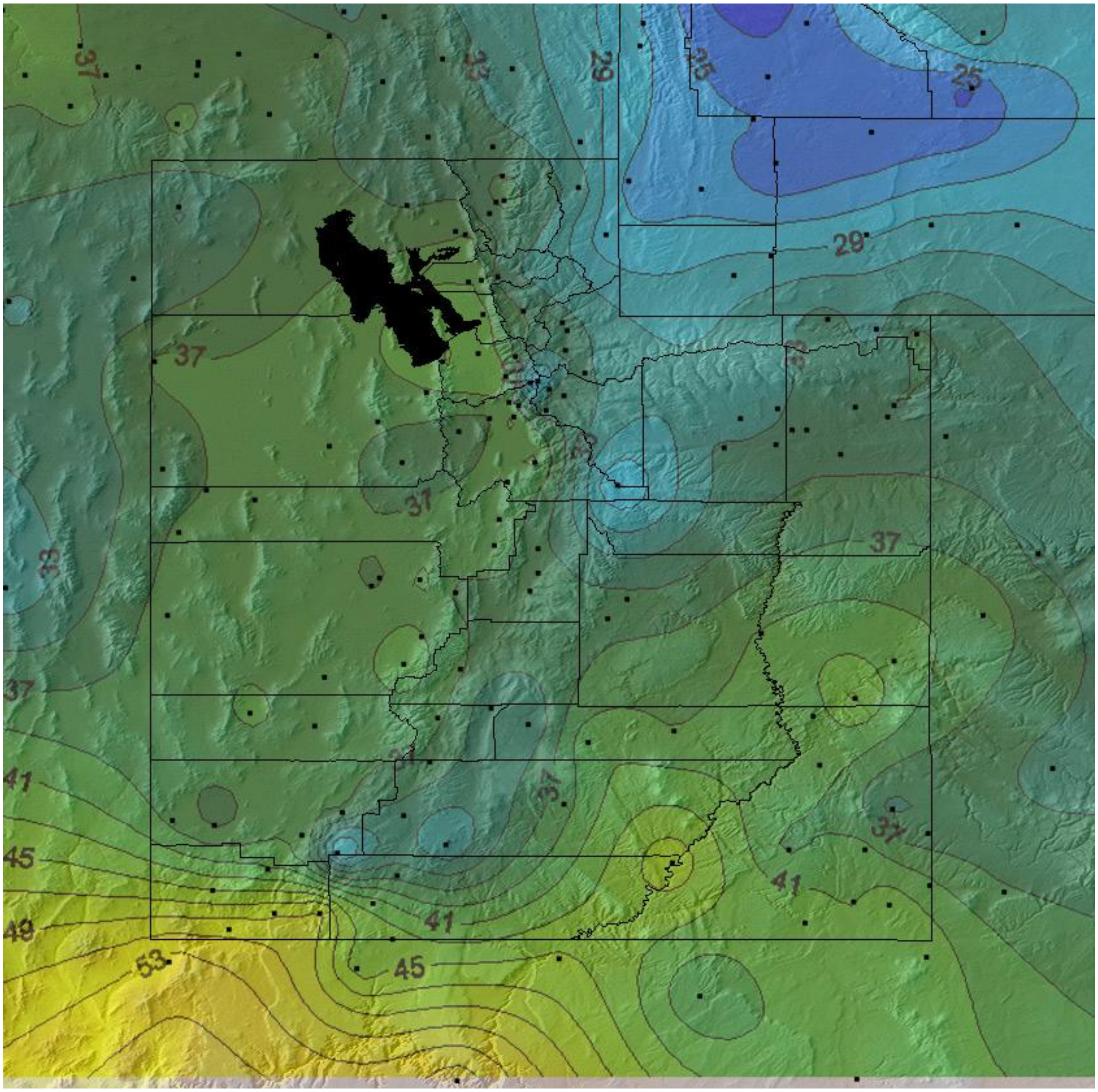

Figure A21. November temperature contours and topography for Questar Gas service area.

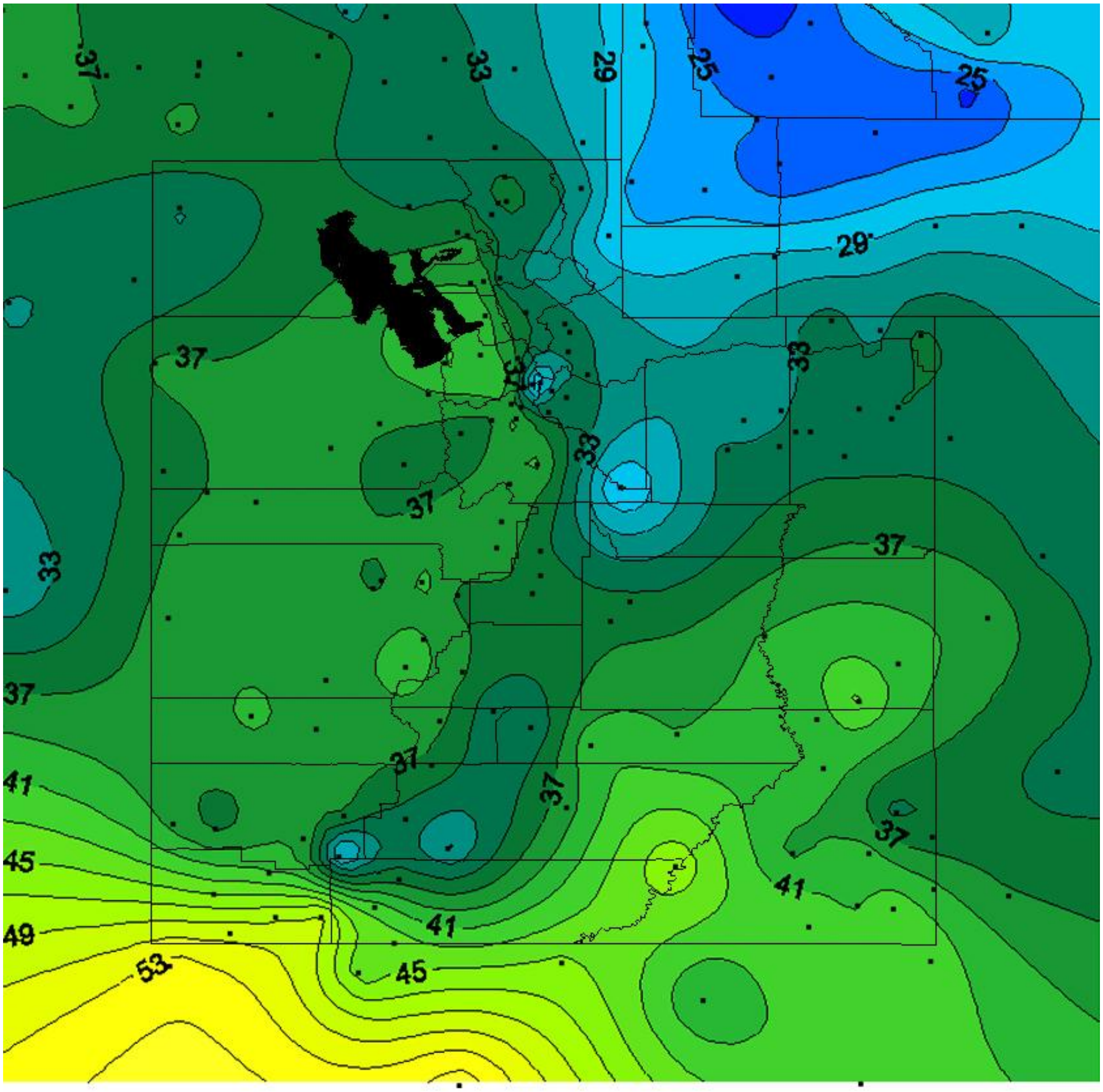

Figure A22. November temperature contours for Questar Gas service area.

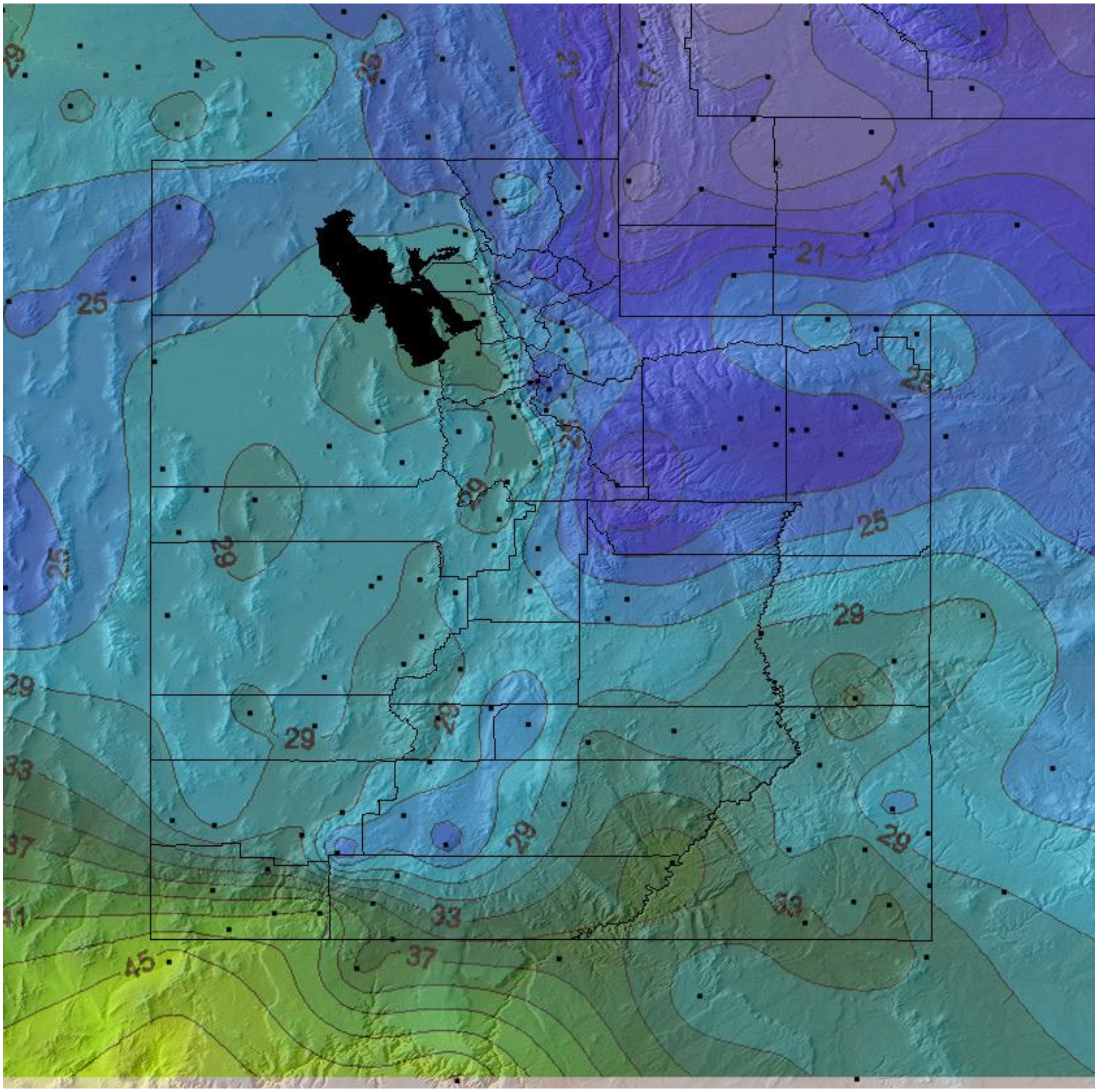

Figure A23. December temperature contours and topography for Questar Gas service area.

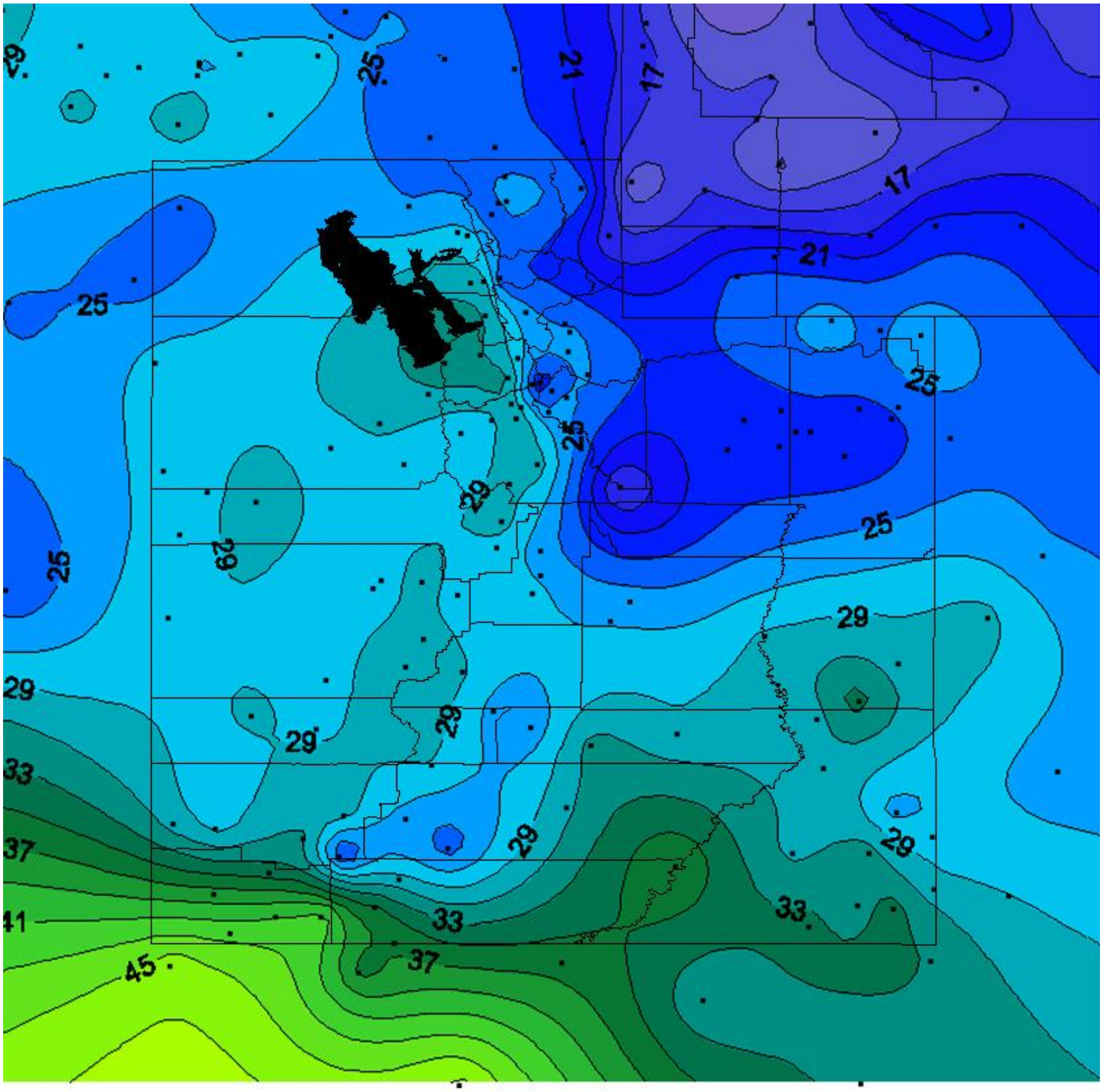

Figure A24. December temperature contours for Questar Gas service area.

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APPENDIX B

TEMPERATURE DELTAS FOR 14 PROPOSED TEMPERATURE ZONES

Table B. Temperature Deltas for 14 Proposed Temperature Zones

Zone 1 Northern Wasatch Front

Station Code	Station	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0928	Brigham City	26.3	31.7	41.4	49.0	57.4	66.4	73.7	71.9	63.0	50.8	37.6	28.4
	Max Temp	26.3	31.7	41.4	49.0	57.4	66.4	73.7	71.9	63.0	50.8	37.6	28.4
	Min Temp	26.3	31.7	41.4	49.0	57.4	66.4	73.7	71.9	63.0	50.8	37.6	28.4
	Delta Temp	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Zone 2 Ogden Valley

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
6869	Pineview	19.2	23.0	32.8	43.4	51.9	60.5	68.4	66.7	57.5	46.3	33.2	23.0
	Max Temp	19.2	23.0	32.8	43.4	51.9	60.5	68.4	66.7	57.5	46.3	33.2	23.0
	Min Temp	19.2	23.0	32.8	43.4	51.9	60.5	68.4	66.7	57.5	46.3	33.2	23.0
	Delta Temp	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Zone 3 East Wasatch Front

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
3809	Heber	23.1	27.5	37.3	45.4	53.3	61.5	68.4	67.2	59.1	48.1	35.0	25.4
4467	Kamas	24.3	27.4	34.8	42.5	50.7	58.9	66.5	65.5	56.9	46.2	33.3	25.2
1588	Coalville	24.2	28.5	37.6	44.7	52.4	60.3	66.9	65.3	57.2	46.4	34.2	25.8
5826	Morgan	24.4	28.9	38.4	46.4	54.3	63.0	70.4	68.5	59.6	48.3	34.9	25.8
5194	SW Logan	21.6	26.4	37.2	45.8	53.4	62.2	69.8	68.1	58.5	46.9	34.0	23.4
5182	W Logan	21.7	26.2	37.6	46.3	54.6	63.4	71.4	69.9	60.3	48.4	34.7	24.4
5186	E Logan	24.5	28.9	38.7	47.2	55.3	64.8	73.4	72.1	62.1	50.4	36.0	26.3
7346	Preston	21.7	26.2	37.5	45.5	54.1	62.3	69.8	68.8	59.1	47.0	33.6	23.5
	Max Temp	24.5	28.9	38.7	47.2	55.3	64.8	73.4	72.1	62.1	50.4	36.0	26.3
	Min Temp	21.6	26.2	34.8	42.5	50.7	58.9	66.5	65.3	56.9	46.2	33.3	23.4
	Delta Temp	2.9	2.7	3.8	4.7	4.6	5.9	6.9	6.8	5.2	4.2	2.8	2.9

Temps Sorted by Station Min Temp to Max Temp	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	5194	7346	4467	4467	4467	4467	4467	1588	4467	4467	4467	5194
	5182	5182	5194	1588	1588	1588	1588	4467	1588	1588	7346	7346
	7346	5194	3809	3809	3809	3809	3809	3809	5194	5194	5194	5182
	3809	4467	7346	7346	5194	5194	5194	5194	3809	7346	1588	4467
	1588	3809	5182	5194	7346	7346	7346	5826	7346	3809	5182	3809
	4467	1588	1588	5182	5826	5826	5826	7346	5826	5826	5826	1588
	5826	5826	5826	5826	5182	5182	5182	5182	5182	5182	3809	5826
	5186	5186	5186	5186	5186	5186	5186	5186	5186	5186	5186	5186

Zone 4 Wyoming North

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
9595	Woodruff	15.8	19.0	30.5	39.8	48.1	56.5	63.1	61.3	52.5	41.6	27.8	17.6
5105	Kemmerer	16.6	18.1	27.0	37.0	46.9	55.1	62.0	60.5	51.3	40.0	26.4	17.2
5252	Labarge	13.5	17.2	29.2	39.5	48.3	56.6	63.8	61.4	52.3	40.8	25.3	15.1
0695	Big Piney	13.4	16.4	26.1	35.8	45.7	54.0	60.3	58.2	49.5	38.7	23.7	15.2
	Max Temp	16.6	19.0	30.5	39.8	48.3	56.6	63.8	61.4	52.5	41.6	27.8	17.6
	Min Temp	13.4	16.4	26.1	35.8	45.7	54.0	60.3	58.2	49.5	38.7	23.7	15.1
	Delta Temp	3.2	2.6	4.5	4.0	2.6	2.7	3.5	3.2	3.0	2.9	4.1	2.5

Temps Sorted by Station	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Min Temp to Max Temp	0695	0695	0695	0695	0695	0695	0695	0695	0695	0695	0695	5252
	5252	5252	5105	5105	5105	5105	5105	5105	5105	5105	5252	0695
	9595	5105	5252	5252	9595	9595	9595	9595	5252	5252	5105	5105
	5105	9595	9595	9595	5252	5252	5252	5252	9595	9595	9595	9595

Zone 5 Wyoming South

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
7845	Rock Springs	20.9	24.2	33.1	41.9	50.7	60.7	68.4	66.0	56.4	44.4	29.8	21.8
4065	Green River	17.6	22.8	34.1	42.7	51.2	60.1	67.1	64.9	55.6	44.2	28.8	19.1
6555	Mt. View	22.5	24.2	32.7	40.6	49.1	57.9	64.3	62.8	54.8	44.2	30.2	23.3
2864	Dutch John	23.2	26.5	35.0	42.9	51.8	60.6	67.9	66.0	57.4	45.9	32.3	24.4
	Max Temp	23.2	26.5	35.0	42.9	51.8	60.7	68.4	66.0	57.4	45.9	32.3	24.4
	Min Temp	17.6	22.8	32.7	40.6	49.1	57.9	64.3	62.8	54.8	44.2	28.8	19.1
	Delta Temp	5.6	3.6	2.3	2.4	2.6	2.7	4.1	3.2	2.6	1.7	3.5	5.4

Temps Sorted by Station	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Min Temp to Max Temp	4065	4065	6555	6555	6555	6555	6555	6555	6555	6555	4065	4065
	7845	6555	7845	7845	7845	4065	4065	4065	4065	4065	7845	7845
	6555	7845	4065	4065	4065	2864	2864	7845	7845	7845	6555	6555
	2864	2864	2864	2864	2864	7845	7845	2864	2864	2864	2864	2864

Zone 6 Wasatch Front

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
8973	Utah Lake	25.9	30.9	39.0	47.9	56.2	65.9	73.4	71.3	61.6	49.6	36.3	28.1
1759	Cottonwood	30.5	35.5	43.9	51.5	60.1	70.5	78.6	77.1	67.3	54.9	40.4	31.7
7686	Santaquin	28.1	32.5	40.9	48.2	57.2	67.0	75.5	73.6	63.5	51.4	37.6	29.3
8119	Spanish Fork	28.9	33.8	43.0	51.0	59.4	68.7	76.1	74.2	65.3	53.4	39.5	30.4
6919	Pleasant Grove	29.7	34.5	43.0	50.4	58.5	67.9	75.2	73.5	64.8	52.8	39.9	31.4
61	Alpine	28.7	32.8	41.3	48.8	56.8	65.9	73.4	71.8	62.8	51.0	38.4	30.4
7598	SLC Airport	29.7	34.5	43.6	50.8	59.6	69.7	78.3	76.5	66.3	53.4	40.0	31.1
2726	Kaysville	29.6	34.3	43.0	50.9	59.0	68.8	76.5	74.8	65.3	53.0	39.8	31.1
6414	W. Ogden	27.8	33.3	42.6	50.6	59.0	68.8	76.4	74.4	64.8	52.4	38.7	29.9
6404	E Ogden	29.0	33.8	43.0	51.1	59.2	69.0	77.1	75.3	65.6	53.5	39.6	30.8
	Max Temp	30.5	35.5	43.9	51.5	60.1	70.5	78.6	77.1	67.3	54.9	40.4	31.7
	Min Temp	25.9	30.9	39.0	47.9	56.2	65.9	73.4	71.3	61.6	49.6	36.3	28.1
	Delta Temp	4.6	4.6	4.9	3.6	3.9	4.6	5.3	5.8	5.8	5.3	4.0	3.6

Temps Sorted by Station	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Min Temp to Max Temp	8973	8973	8973	8973	8973	8973	61	8973	8973	8973	8973	8973
	6414	7686	7686	7686	61	61	8973	61	61	61	7686	7686
	7686	61	61	61	7686	7686	6919	6919	7686	7686	61	6414
	61	6414	6414	6919	6919	6919	7686	7686	6919	6414	6414	8119
	8119	6404	6404	6414	6414	8119	8119	8119	6414	6919	8119	61
	6404	8119	8119	7598	2726	6414	6414	6414	8119	2726	6404	6404
	2726	2726	2726	2726	6404	2726	2726	2726	2726	8119	2726	7598
	7598	7598	6919	8119	8119	6404	6404	6404	6404	7598	6919	2726
	6919	6919	7598	6404	7598	7598	7598	7598	7598	6404	7598	6919
	1759	1759	1759	1759	1759	1759	1759	1759	1759	1759	1759	1759

Zone 7 Western Utah

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1267	Cedar City	30.9	34.9	41.5	48.2	56.9	67.1	74.2	72.3	63.8	51.5	38.8	31.2
2828	Fillmore	29.4	34.6	43.1	50.1	58.6	68.2	75.2	73.4	65.0	52.9	39.1	30.3
2090	Delta	26.4	32.4	41.5	48.7	57.4	67.0	74.7	72.9	63.2	50.6	36.6	27.4
5654	Milford	27.7	33.2	41.0	48.3	56.5	66.5	74.0	72.0	62.9	50.8	37.7	28.7
8771	Tooele	29.4	33.9	42.1	49.8	58.6	68.6	76.7	75.0	65.0	52.5	38.7	30.5
7714	Scipio	25.8	31.2	39.8	46.9	55.3	64.9	73.2	70.7	61.3	49.5	36.4	27.0
6686	Parowan	28.4	32.6	38.9	46.0	54.5	64.8	71.2	69.5	61.5	49.9	37.0	29.9
	Max Temp	30.9	34.9	43.1	50.1	58.6	68.6	76.7	75.0	65.0	52.9	39.1	31.2
	Min Temp	25.8	31.2	38.9	46.0	54.5	64.8	71.2	69.5	61.3	49.5	36.4	27.0
	Delta Temp	5.1	3.7	4.1	4.1	4.1	3.7	5.4	5.4	3.8	3.4	2.7	4.2

Temps Sorted by Station	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Min Temp to Max Temp	7714	7714	6686	6686	6686	6686	6686	6686	7714	7714	7714	7714
	2090	2090	7714	7714	7714	7714	7714	7714	6686	6686	2090	2090
	5654	6686	5654	1267	5654	5654	5654	5654	5654	2090	6686	5654
	6686	5654	1267	5654	1267	2090	1267	1267	2090	5654	5654	6686
	8771	8771	2090	2090	2090	1267	2090	2090	1267	1267	8771	2828
	2828	2828	8771	8771	2828	2828	2828	2828	2828	8771	1267	8771
	1267	1267	2828	2828	8771	8771	8771	8771	8771	2828	2828	1267

Zone 8 Sanpete Valley

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
7260	Richfield	28.5	33.8	41.3	47.9	55.7	64.6	70.9	69.1	61.2	49.9	37.3	29.2
2578	Ephraim	25.2	30.5	39.2	46.5	54.9	64.8	72.1	70.2	61.2	49.5	36.6	26.8
5837	Moroni	24.3	29.5	38.2	45.6	53.5	62.6	69.4	67.9	59.9	48.5	35.4	25.8
5402	Manti	26.4	30.9	38.9	46.2	54.2	63.5	70.5	68.7	60.7	49.5	36.6	27.7
6601	Panguitch	25.6	30.1	36.7	43.6	51.9	60.6	66.7	64.6	57.1	46.0	34.3	26.2
1432	Circleville	28.0	32.7	38.7	45.6	54.2	63.8	70.1	68.0	60.0	48.3	36.6	29.1
	Max Temp	28.5	33.8	41.3	47.9	55.7	64.8	72.1	70.2	61.2	49.9	37.3	29.2
	Min Temp	24.3	29.5	36.7	43.6	51.9	60.6	66.7	64.6	57.1	46.0	34.3	25.8
	Delta Temp	4.3	4.3	4.6	4.3	3.8	4.2	5.4	5.6	4.1	3.9	2.9	3.4

Temps Sorted by Station		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Min Temp to Max Temp		5837	5837	6601	6601	6601	6601	6601	6601	6601	6601	6601	5837
		2578	6601	5837	1432	5837	5837	5837	5837	5837	1432	5837	6601
		6601	2578	1432	5837	1432	5402	1432	1432	1432	5837	2578	2578
		5402	5402	5402	5402	5402	1432	5402	5402	5402	5402	5402	5402
		1432	1432	2578	2578	2578	7260	7260	7260	7260	2578	1432	1432
		7260	7260	7260	7260	7260	2578	2578	2578	2578	7260	7260	7260

Zone 9 Southeast Utah

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1214	Castle Dale	23.1	29.7	39.6	47.1	55.9	65.1	71.2	69.1	61.0	49.2	35.6	26.1
2798	Ferron	24.7	30.7	40.2	48.1	57.2	67.0	73.2	71.0	62.6	50.8	36.4	26.8
5805	Monticello	24.5	29.0	36.7	44.6	53.1	62.5	68.6	66.7	58.9	47.3	34.4	26.3
	Max Temp	24.7	30.7	40.2	48.1	57.2	67.0	73.2	71.0	62.6	50.8	36.4	26.8
	Min Temp	23.1	29.0	36.7	44.6	53.1	62.5	68.6	66.7	58.9	47.3	34.4	26.1
	Delta Temp	1.7	1.6	3.5	3.5	4.1	4.4	4.6	4.3	3.7	3.4	2.0	0.8

Temps Sorted by Station		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Min Temp to Max Temp		1214	5805	5805	5805	5805	5805	5805	5805	5805	5805	5805	1214
		5805	1214	1214	1214	1214	1214	1214	1214	1214	1214	1214	5805
		2798	2798	2798	2798	2798	2798	2798	2798	2798	2798	2798	2798

Zone 10 Uinta Basin

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
2253	Duchesne	20.1	25.6	38.2	47.3	55.7	64.7	70.9	68.8	60.5	48.2	33.5	22.8
7395	Roosevelt	17.6	24.5	38.5	48.4	57.5	66.4	72.6	70.7	61.6	48.9	33.5	21.5
9111	Vernal	19.4	25.7	38.3	47.6	56.2	65.3	71.7	69.6	60.5	47.9	33.3	22.2
0074	Altamont	19.6	23.8	34.5	43.0	51.6	60.7	67.8	66.0	57.5	45.8	31.7	21.5
5969	Myton	18.3	24.5	38.4	48.0	56.5	65.6	72.3	70.1	61.3	48.7	33.7	21.6
	Max Temp	20.1	25.7	38.5	48.4	57.5	66.4	72.6	70.7	61.6	48.9	33.7	22.8
	Min Temp	17.6	23.8	34.5	43.0	51.6	60.7	67.8	66.0	57.5	45.8	31.7	21.5
	Delta Temp	2.5	1.8	4.0	5.4	5.8	5.7	4.8	4.7	4.0	3.1	2.0	1.3

Temps Sorted by Station		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Min Temp to Max Temp		7395	0074	0074	0074	0074	0074	0074	0074	0074	0074	0074	7395
		5969	7395	2253	2253	2253	2253	2253	2253	2253	9111	9111	0074
		9111	5969	9111	9111	9111	9111	9111	9111	9111	2253	7395	5969
		0074	2253	5969	5969	5969	5969	5969	5969	5969	5969	2253	9111
		2253	9111	7395	7395	7395	7395	7395	7395	7395	7395	5969	2253

Zone 11 Moab

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
5733	Moab	32.3	39.5	49.5	57.7	66.7	76.3	82.3	80.4	71.1	58.0	43.4	34.0
	Max Temp	32.3	39.5	49.5	57.7	66.7	76.3	82.3	80.4	71.1	58.0	43.4	34.0
	Min Temp	32.3	39.5	49.5	57.7	66.7	76.3	82.3	80.4	71.1	58.0	43.4	34.0
	Delta Temp	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Zone 12 Washington Co. North

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
9136	Veyo	37.3	40.6	45.8	52.6	61.2	70.8	76.6	74.8	68.2	57.4	44.5	37.6
	Max Temp	37.3	40.6	45.8	52.6	61.2	70.8	76.6	74.8	68.2	57.4	44.5	37.6
	Min Temp	37.3	40.6	45.8	52.6	61.2	70.8	76.6	74.8	68.2	57.4	44.5	37.6
	Delta Temp	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Zone 13 Southern Utah

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
7516	St George	42.4	47.1	54.3	62.0	71.6	80.8	86.8	84.9	76.8	64.2	50.1	42.0
4968	La Verkin	41.2	46.1	52.6	59.5	67.8	77.1	82.6	81.1	73.7	61.9	48.4	41.0
	Max Temp	42.4	47.1	54.3	62.0	71.6	80.8	86.8	84.9	76.8	64.2	50.1	42.0
	Min Temp	41.2	46.1	52.6	59.5	67.8	77.1	82.6	81.1	73.7	61.9	48.4	41.0
	Delta Temp	1.2	1.0	1.7	2.5	3.8	3.7	4.2	3.8	3.1	2.3	1.7	0.9

Temps Sorted by Station	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Min Temp to Max Temp	4968	4968	4968	4968	4968	4968	4968	4968	4968	4968	4968	4968
	7516	7516	7516	7516	7516	7516	7516	7516	7516	7516	7516	7516

Zone 14 High Altitude

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0757	Cedar Breaks	21.5	21.6	24.4	30.6	38.7	49.8	56.2	54.4	47.9	38.2	27.4	22.4
0072	Alta	22.1	23.1	26.9	33.4	42.3	52.3	60.5	59.3	51.1	39.9	27.7	22.9
	Max Temp	22.1	23.1	26.9	33.4	42.3	52.3	60.5	59.3	51.1	39.9	27.7	22.9
	Min Temp	21.5	21.6	24.4	30.6	38.7	49.8	56.2	54.4	47.9	38.2	27.4	22.4
	Delta Temp	0.7	1.5	2.5	2.8	3.6	2.5	4.3	4.8	3.2	1.7	0.3	0.5

Temps Sorted by Station	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Min Temp to Max Temp	0757	0757	0757	0757	0757	0757	0757	0757	0757	0757	0757	0757
	0072	0072	0072	0072	0072	0072	0072	0072	0072	0072	0072	0072

APPENDIX C

PHOTOS OF FIELD TEST SITES

Figure C1 – Station 1

Figure C2 – Station 1 Location View

Figure C3 – Station 2

Figure C4 – Station 3

Figure C5 – Station 4

Figure C6 – Station 5

FigureC7 – Station 6

Figure C8 – Station 6 Location View

Figure C9 – Station 7

Figure C10 – Station 7 Location View

Figure C11 – Station 8

Figure C12 – Station 9

Figure C13 – Station 9 Location View

Figure C14 – Station 10

Figure C15 – Station 11

Figure C16 – Station 11 Location View

Figure C17 – Station 12

Figure C18 – Station 13

Figure C19 – Station 14

Figure C20 – Station 15

Figure C21 – Station 16

APPENDIX D

DATA PLOTS

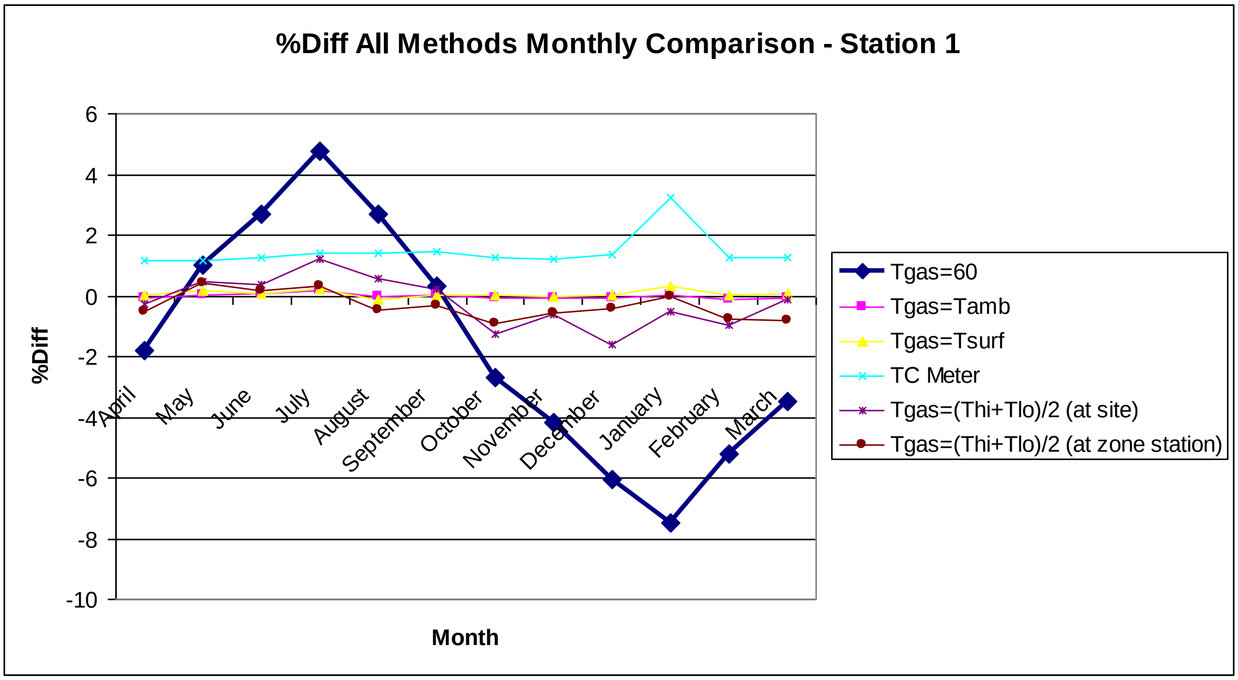

Figure D1. % Diff All Methods Monthly Comparison – Station 1

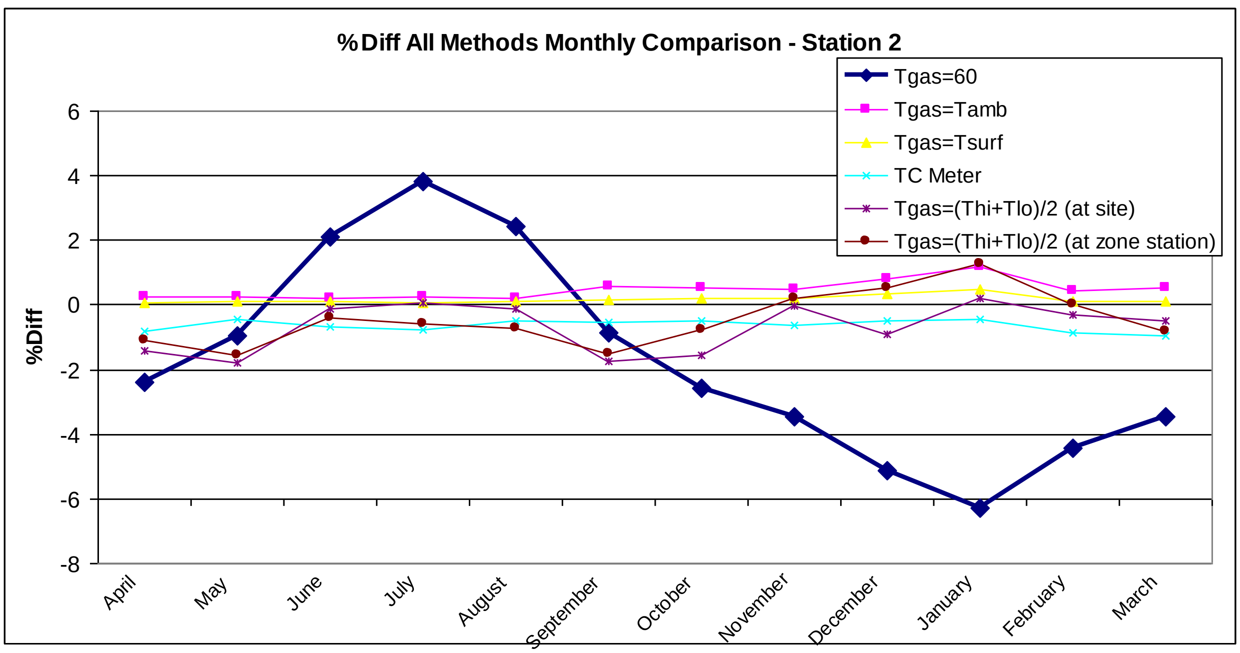

Figure D2. %Diff All Methods Monthly Comparison – Station 2

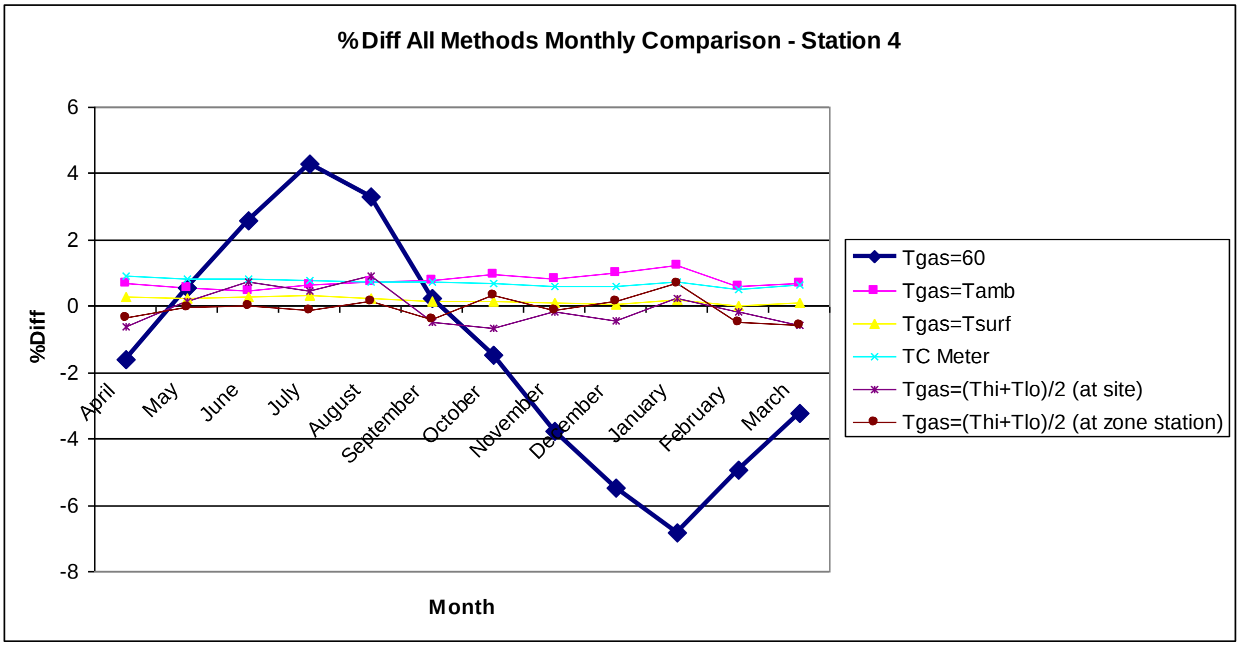

Figure D3. %Diff All Methods Monthly Comparison – Station 4

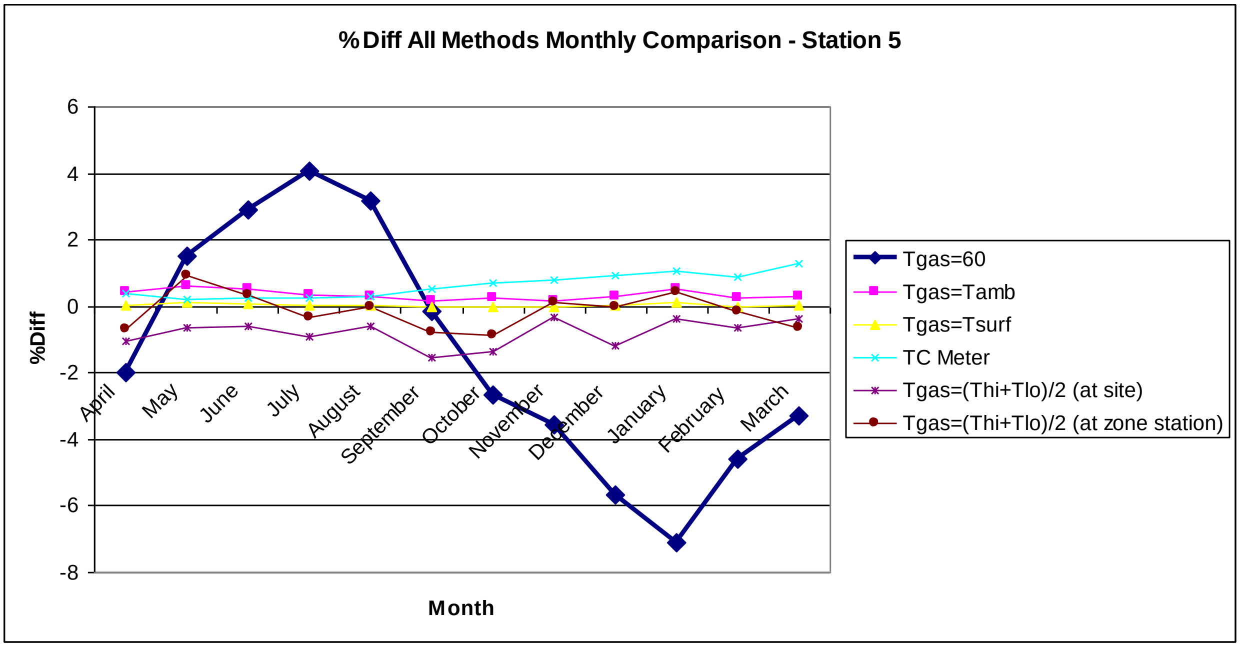

Figure D4. %Diff All Methods Monthly Comparison – Station 5

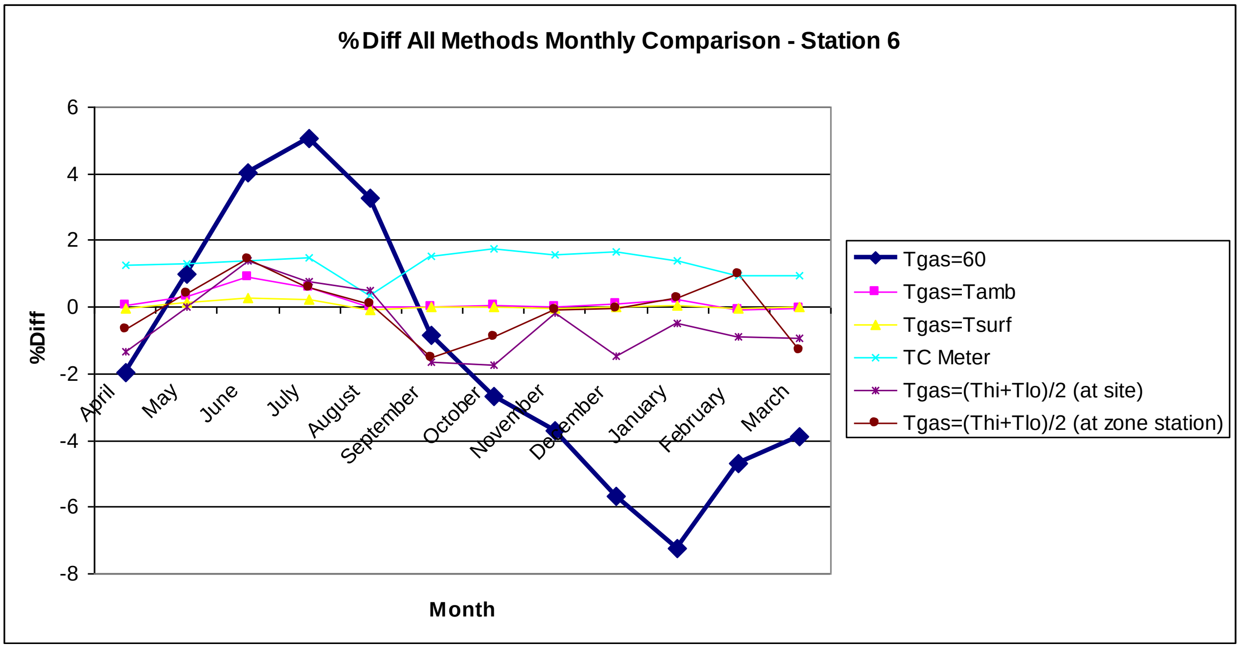

Figure D5. %Diff All Methods Monthly Comparison – Station 6

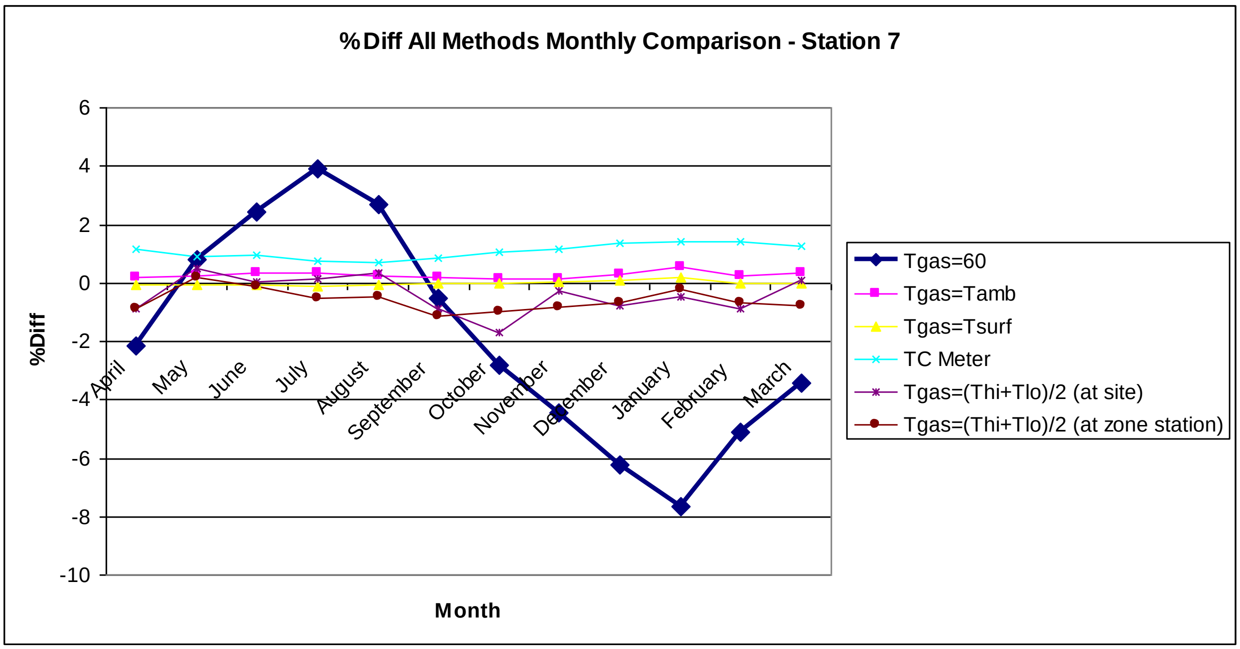

Figure D6. %Diff All Methods Monthly Comparison – Station 7

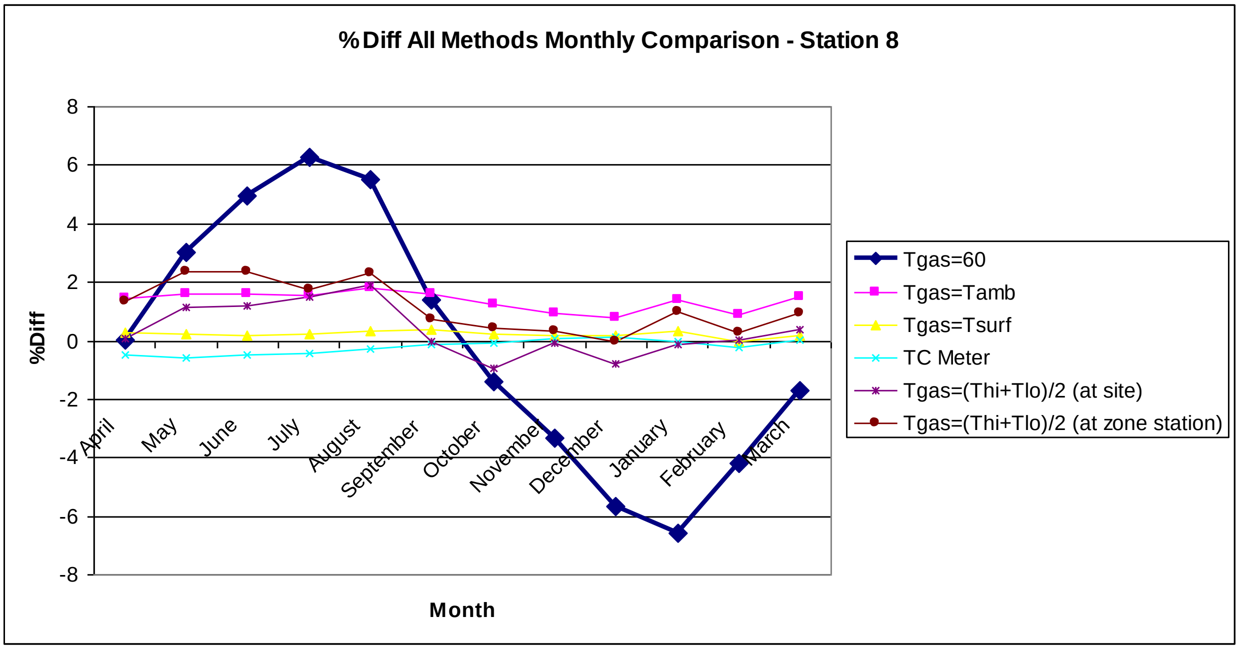

Figure D7. %Diff All Methods Monthly Comparison – Station 8

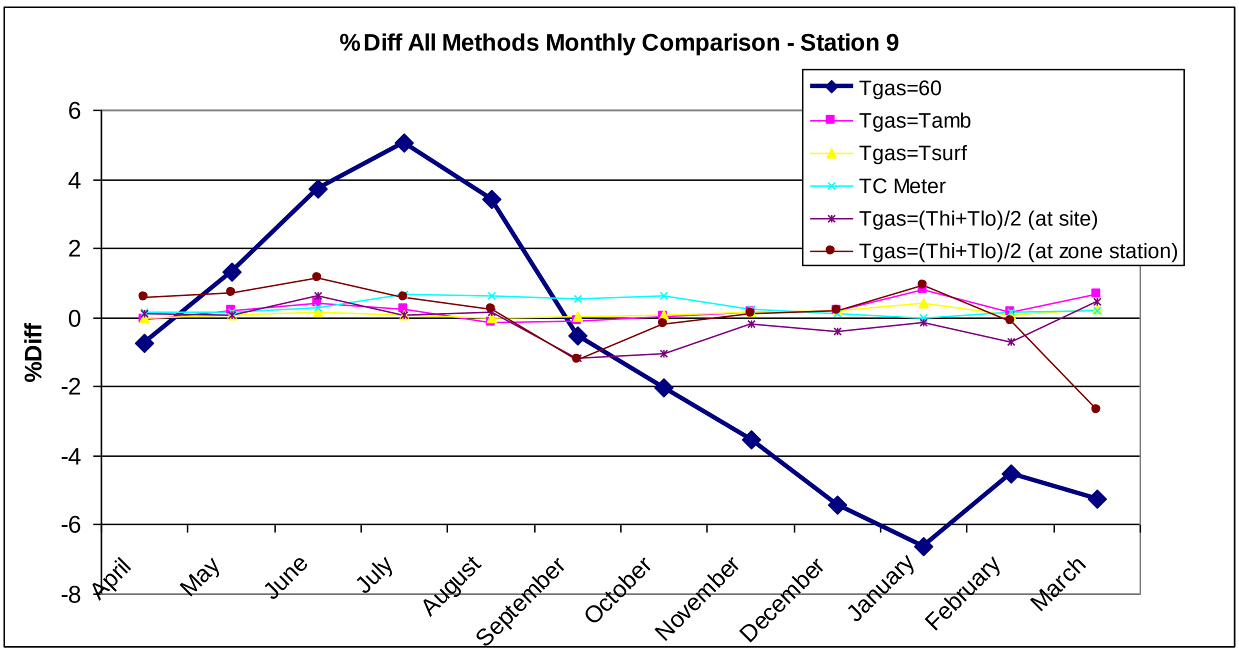

Figure D8. %Diff All Methods Monthly Comparison – Station 9

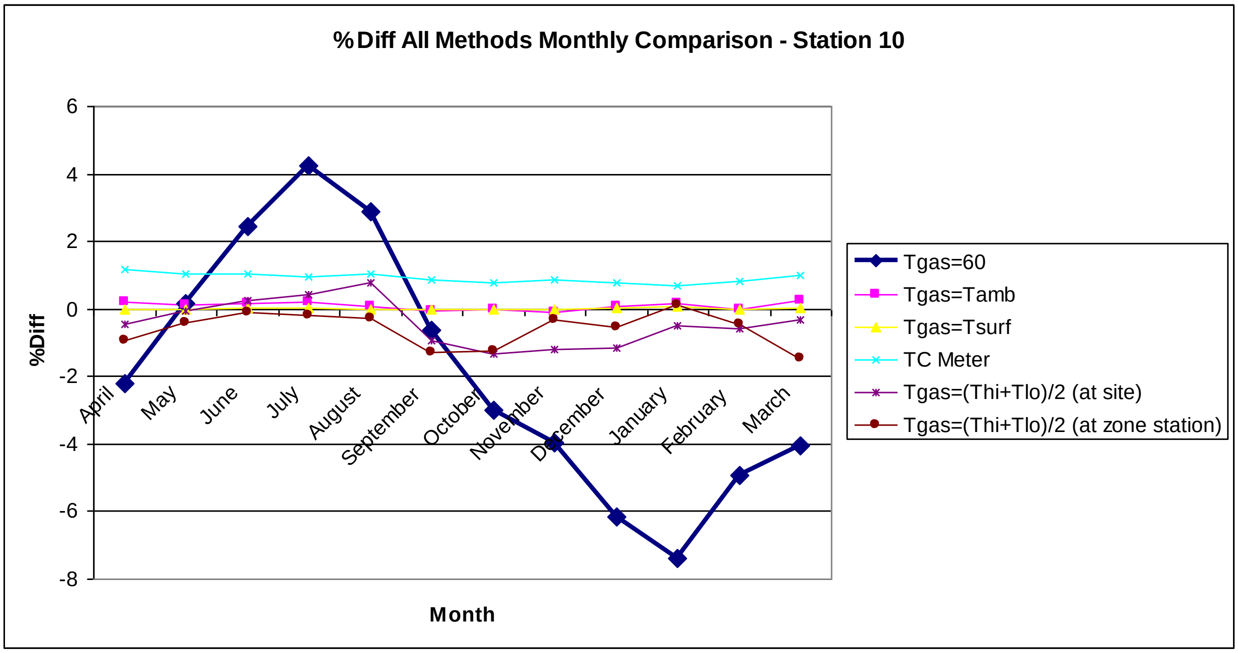

Figure D9. %Diff All Methods Monthly Comparison – Station 10

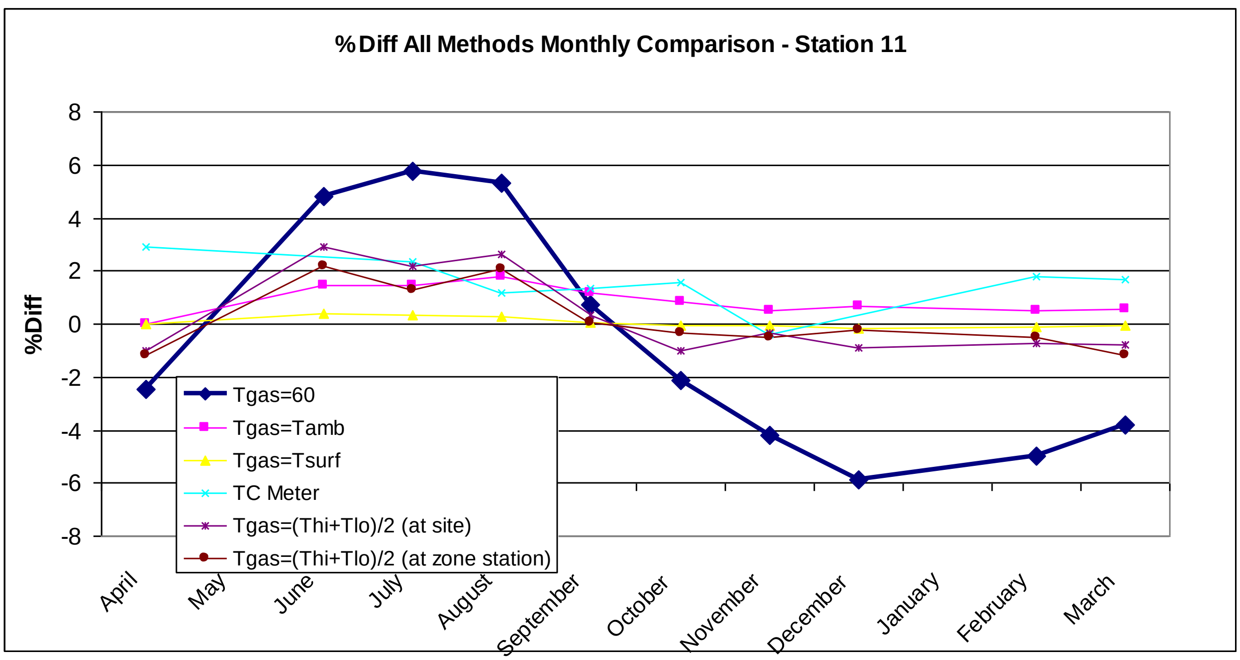

Figure D10. %Diff All Methods Monthly Comparison – Station 11

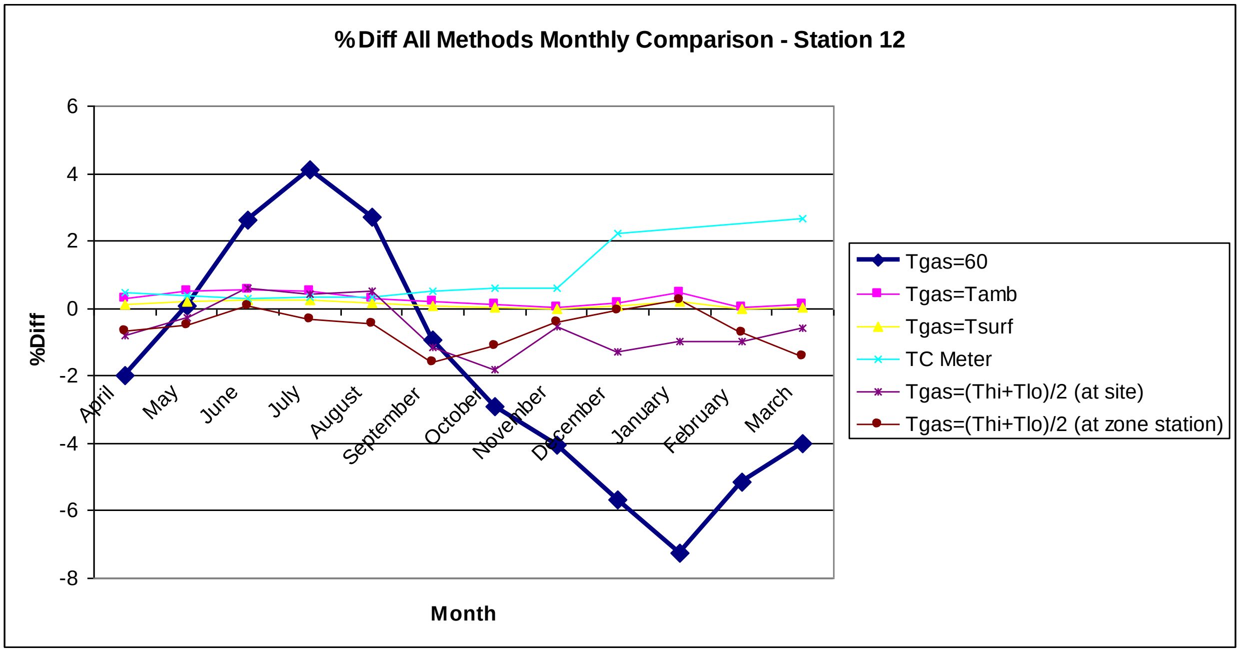

Figure D11. %Diff All Methods Monthly Comparison – Station 12

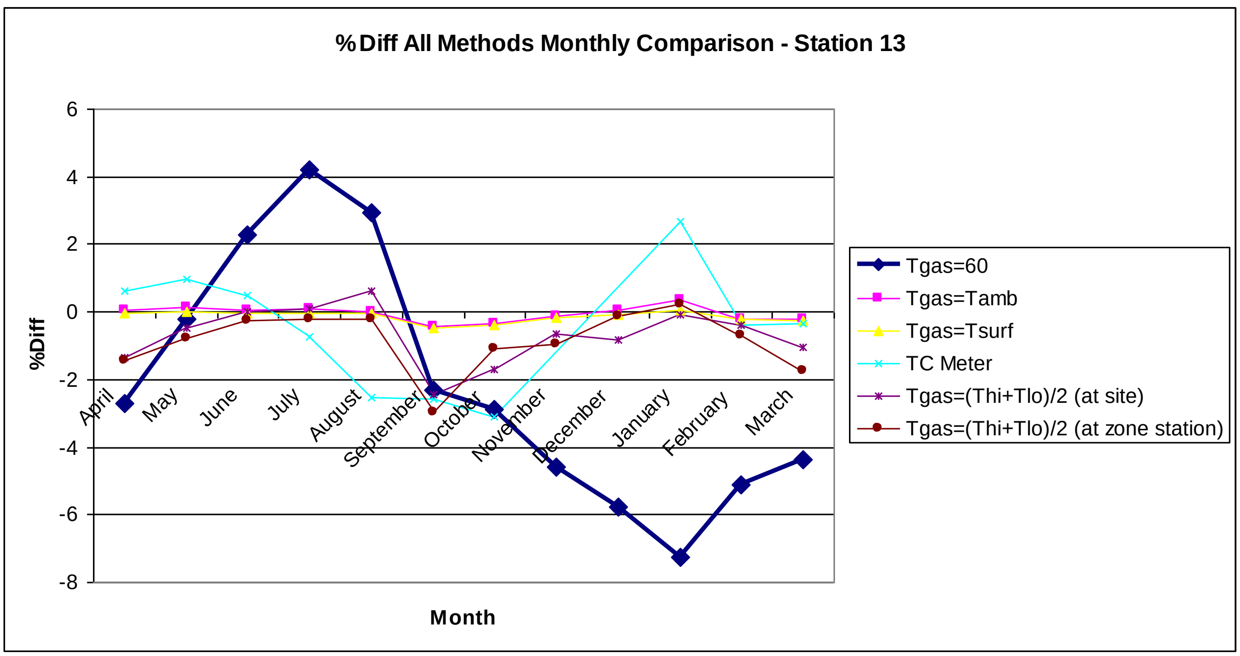

Figure D12. %Diff All Methods Monthly Comparison – Station 13

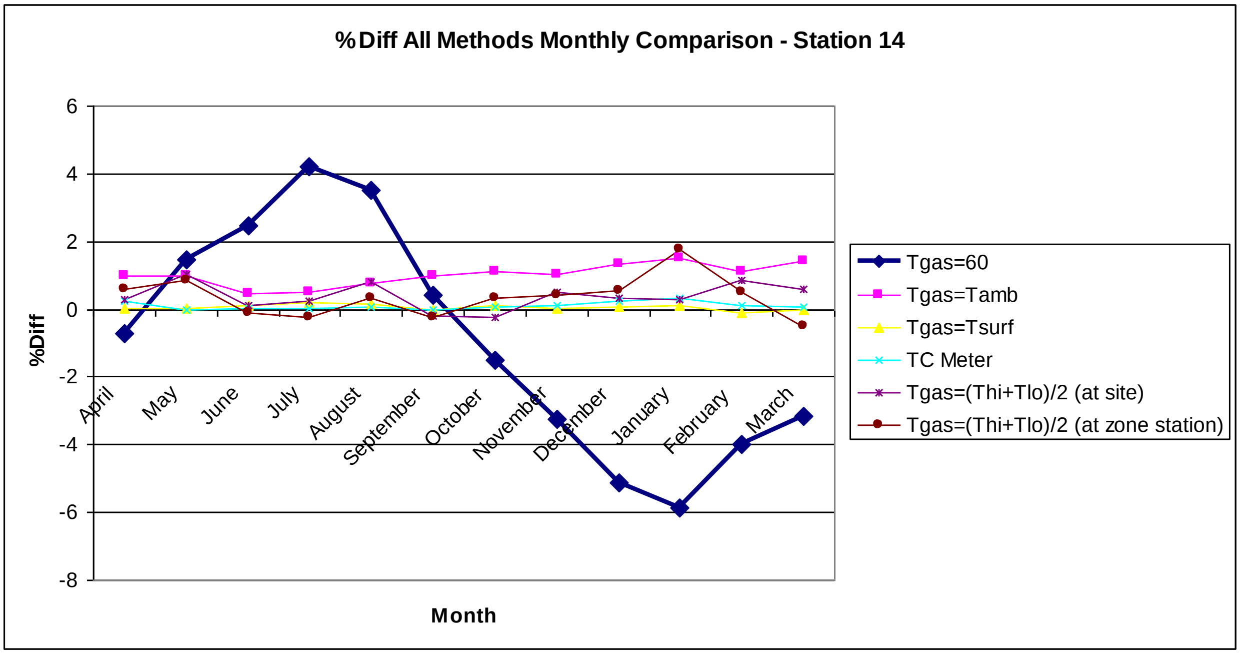

Figure D13. %Diff All Methods Monthly Comparison – Station 14

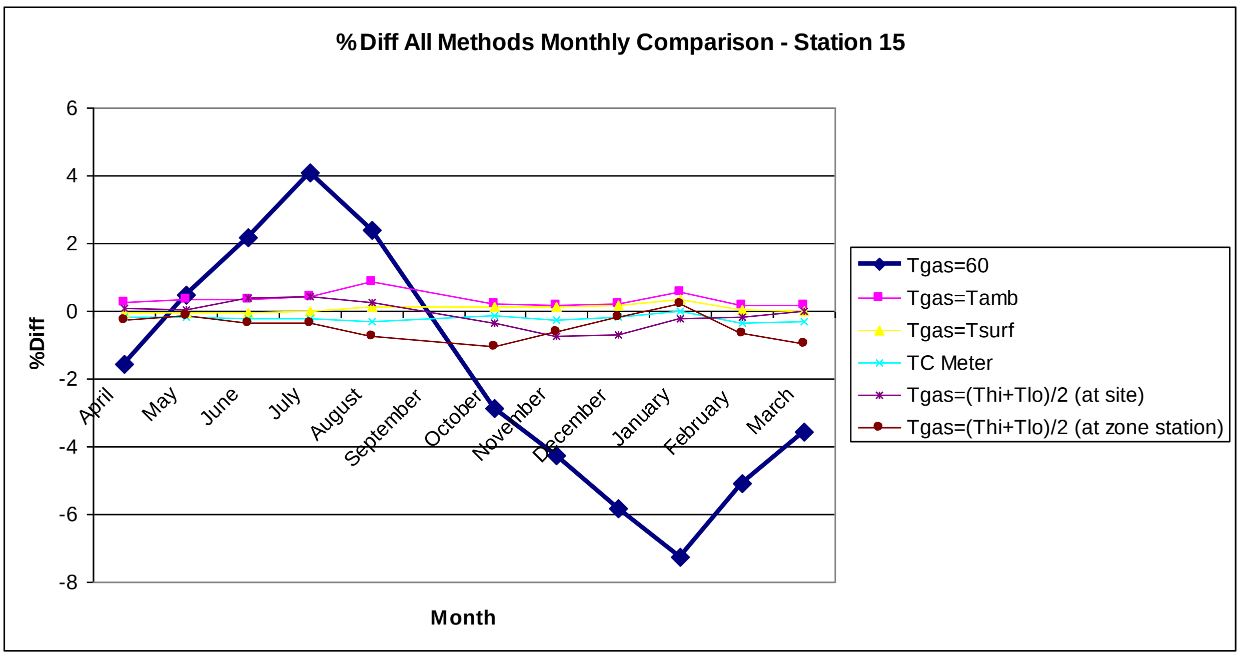

Figure D14. %Diff All Methods Monthly Comparison – Station 15

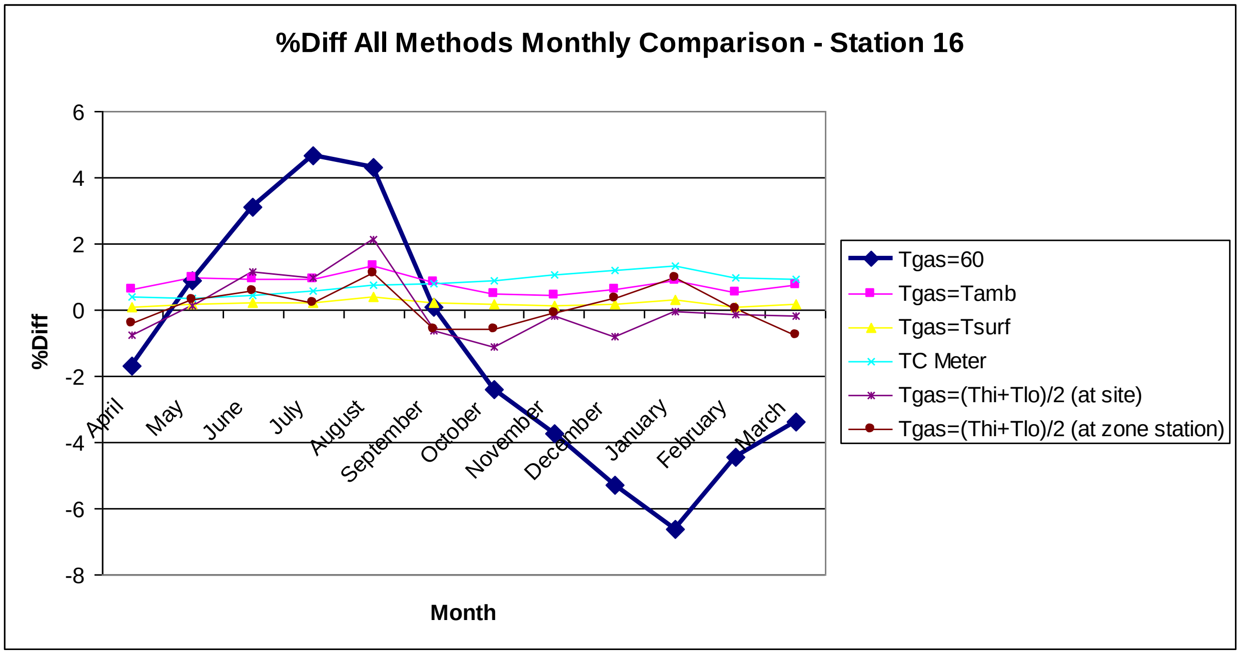

Figure D15. %Diff All Methods Monthly Comparison – Station 16

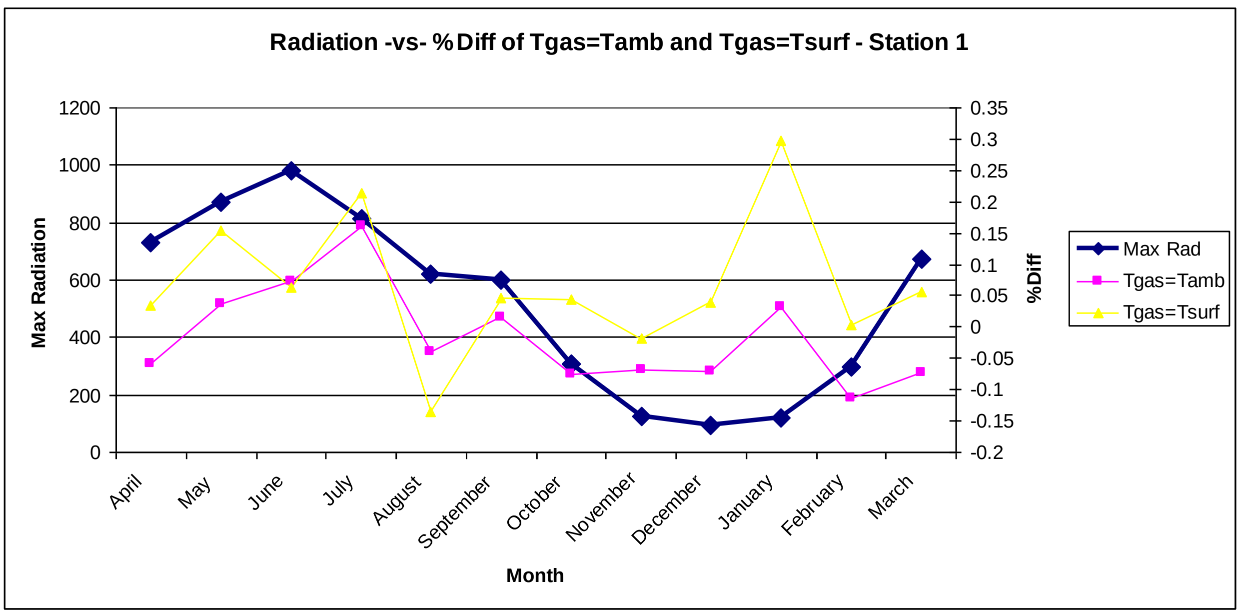

Figure D16. Radiation vs. %Diff of Tgas=Tamb and Tgas=Tsurf - Station 1

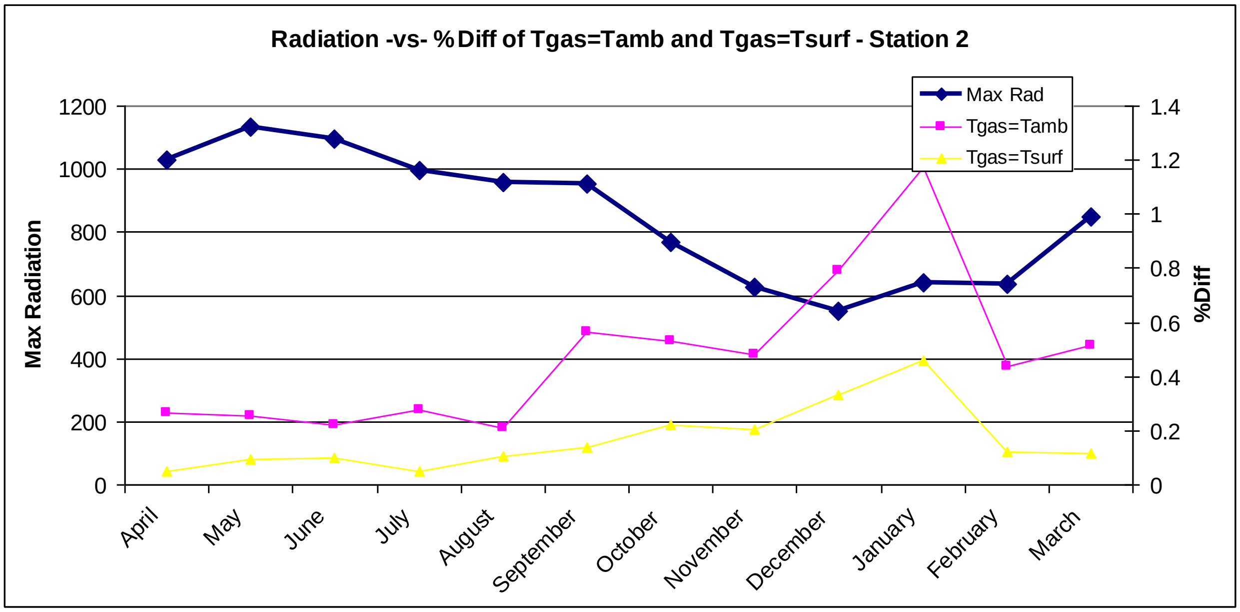

Figure D17. Radiation vs. %Diff of Tgas=Tamb and Tgas=Tsurf - Station 2

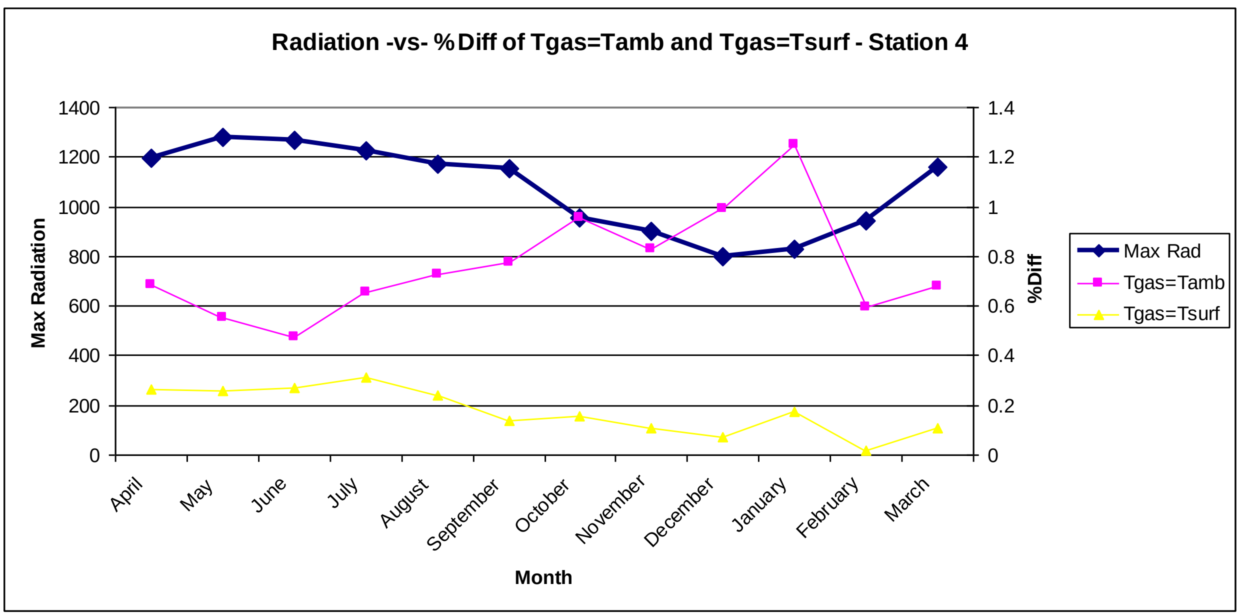

Figure D18. Radiation vs. %Diff of Tgas=Tamb and Tgas=Tsurf - Station 4

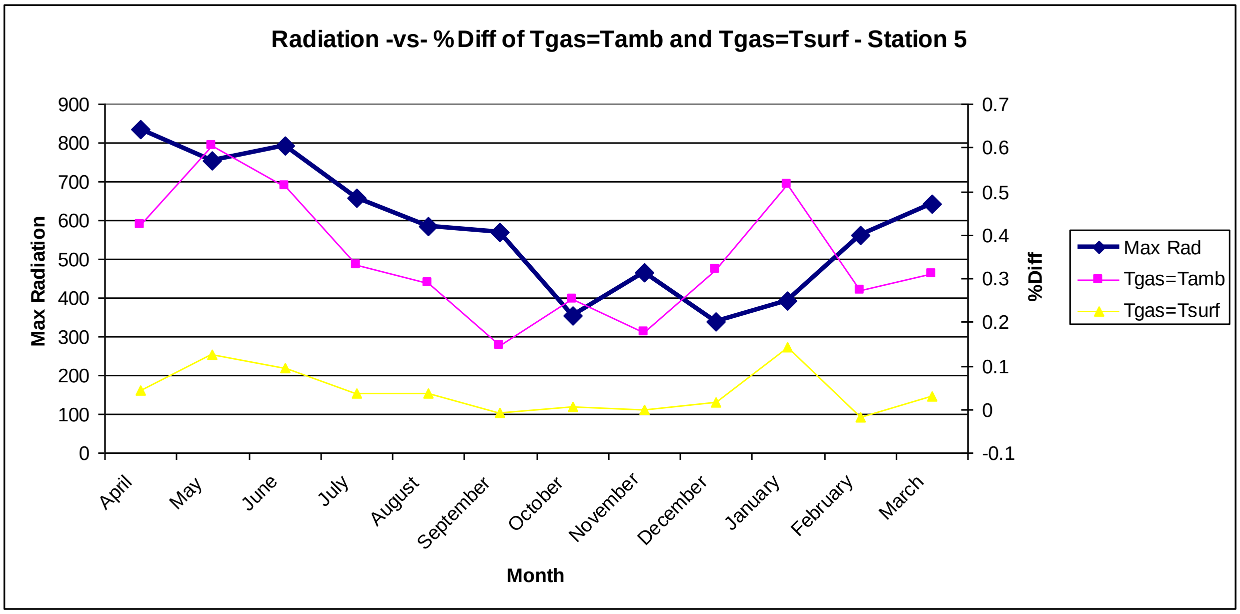

Figure D19. Radiation vs. %Diff of Tgas=Tamb and Tgas=Tsurf - Station 5

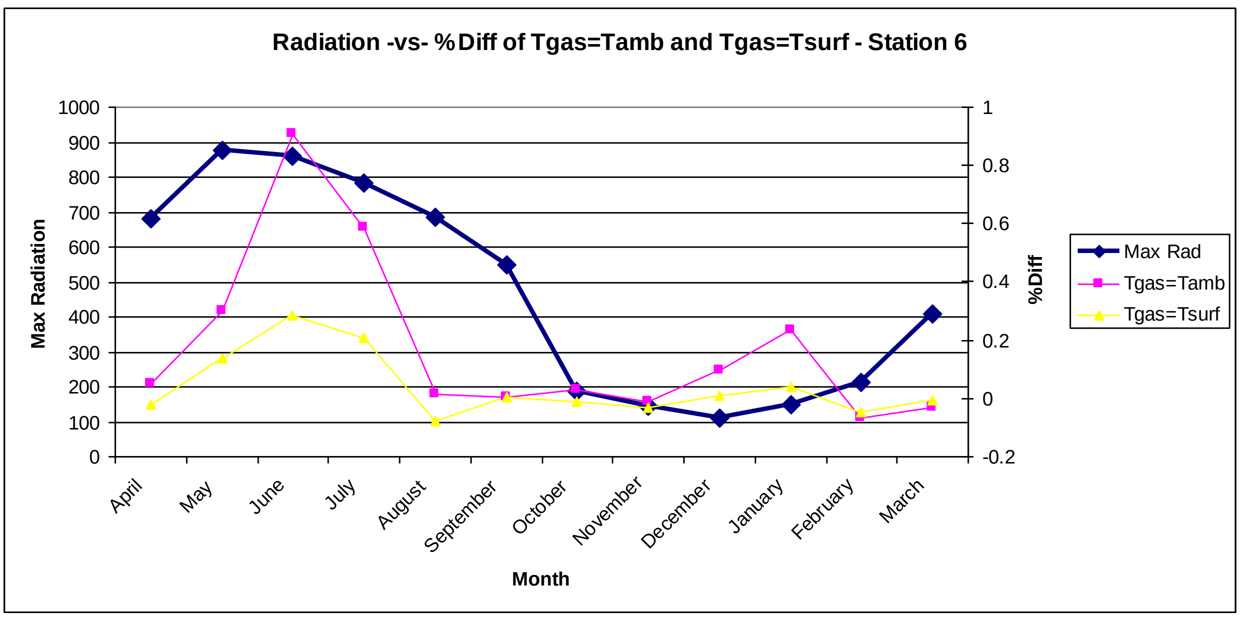

Figure D20. Radiation vs. %Diff of Tgas=Tamb and Tgas=Tsurf - Station 6

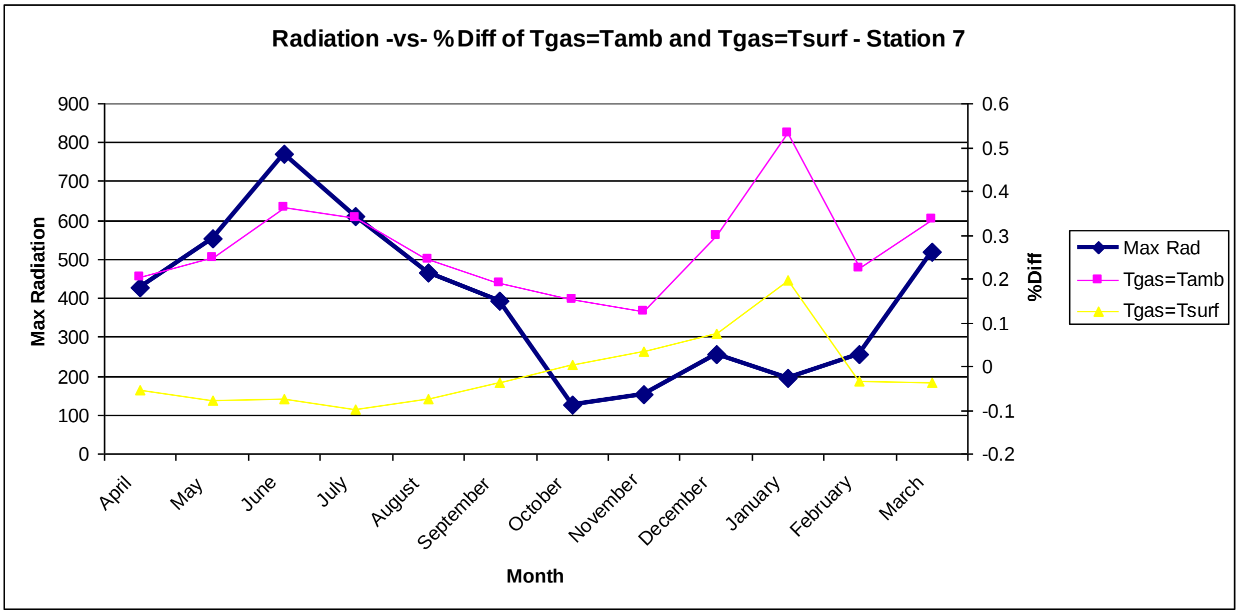

Figure D21. Radiation vs. %Diff of Tgas=Tamb and Tgas=Tsurf - Station 7

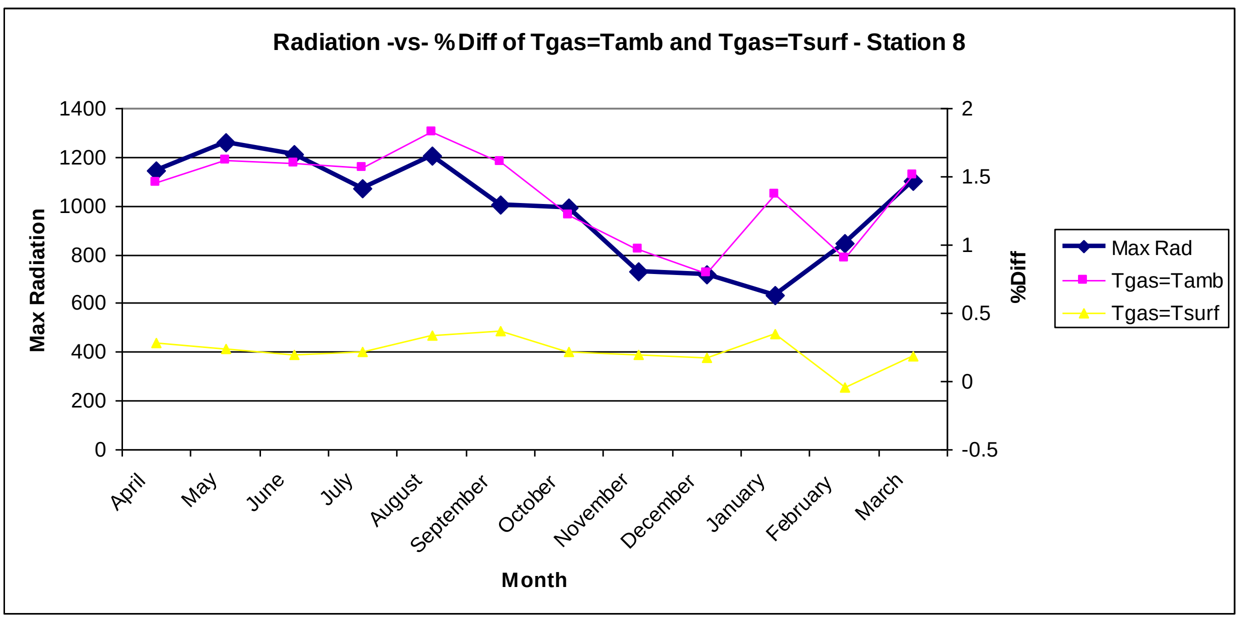

Figure D22. Radiation vs. %Diff of Tgas=Tamb and Tgas=Tsurf - Station 8

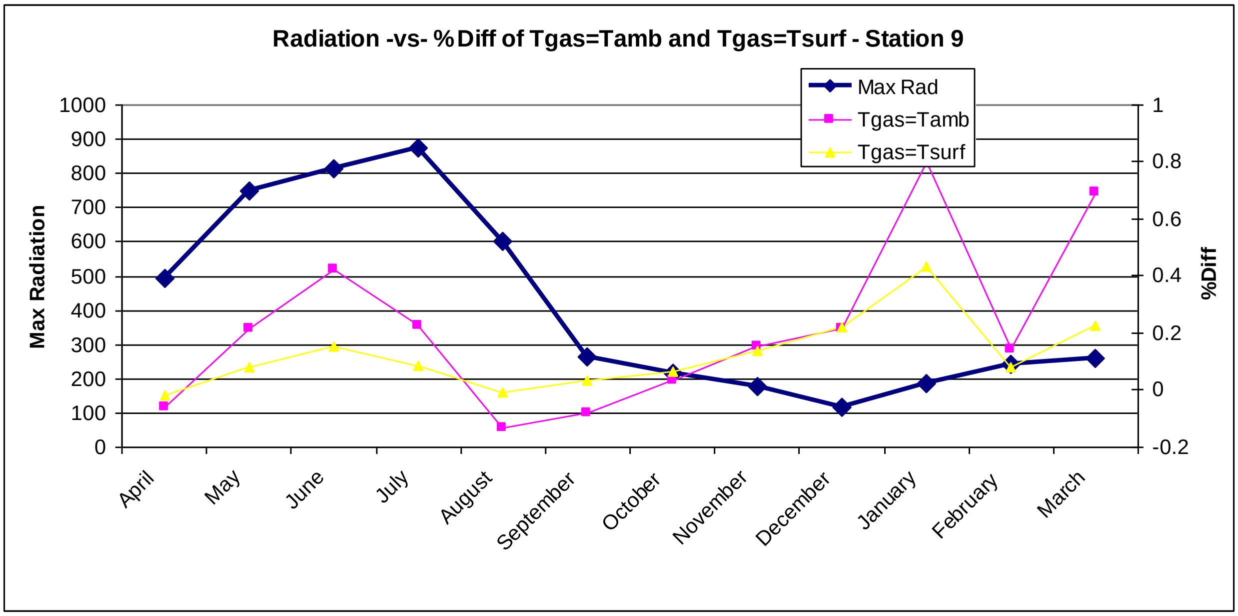

Figure D23. Radiation vs. %Diff of Tgas=Tamb and Tgas=Tsurf - Station 9

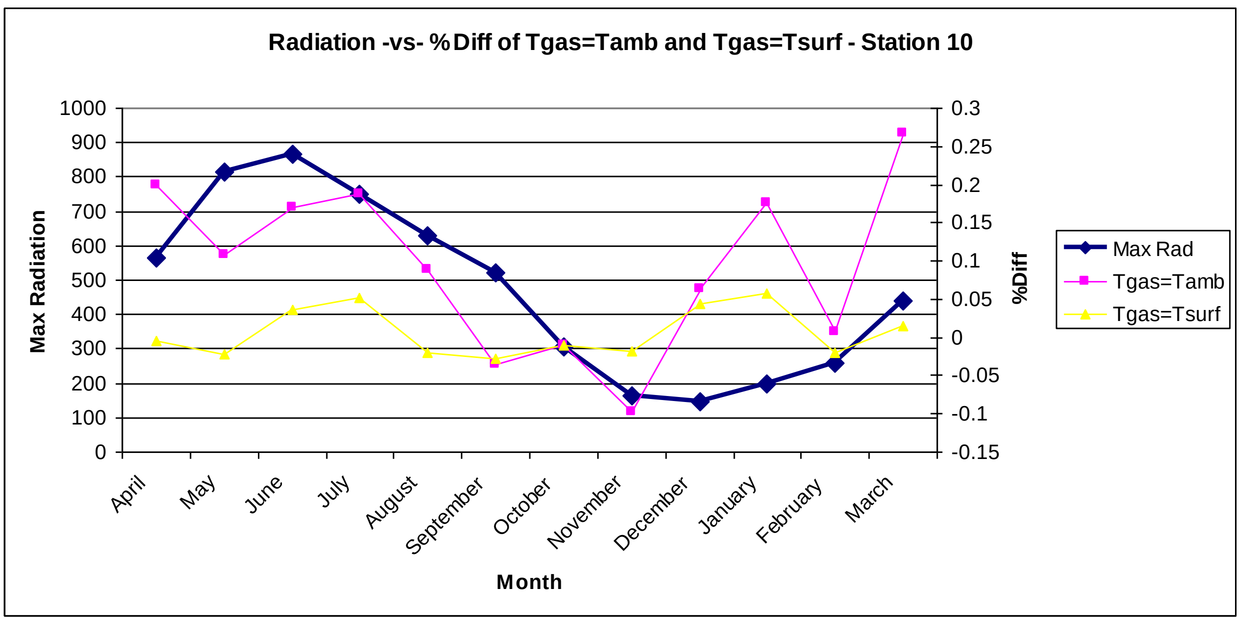

Figure D24. Radiation vs. %Diff of Tgas=Tamb and Tgas=Tsurf - Station 10

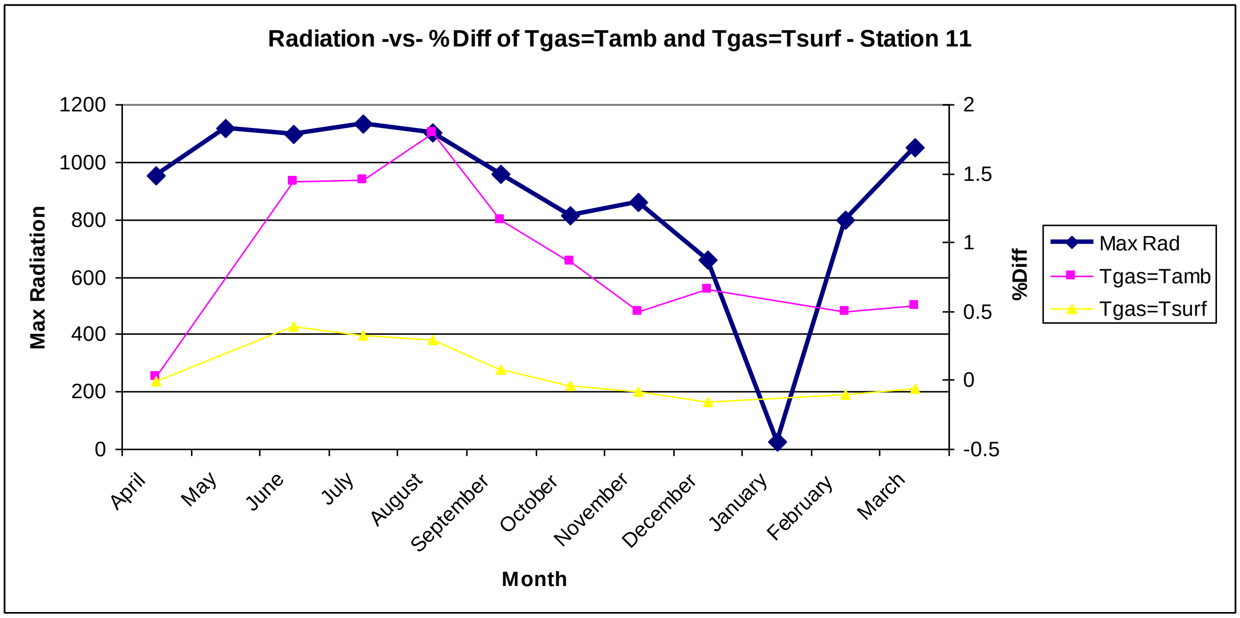

Figure D25. Radiation vs. %Diff of Tgas=Tamb and Tgas=Tsurf - Station 11

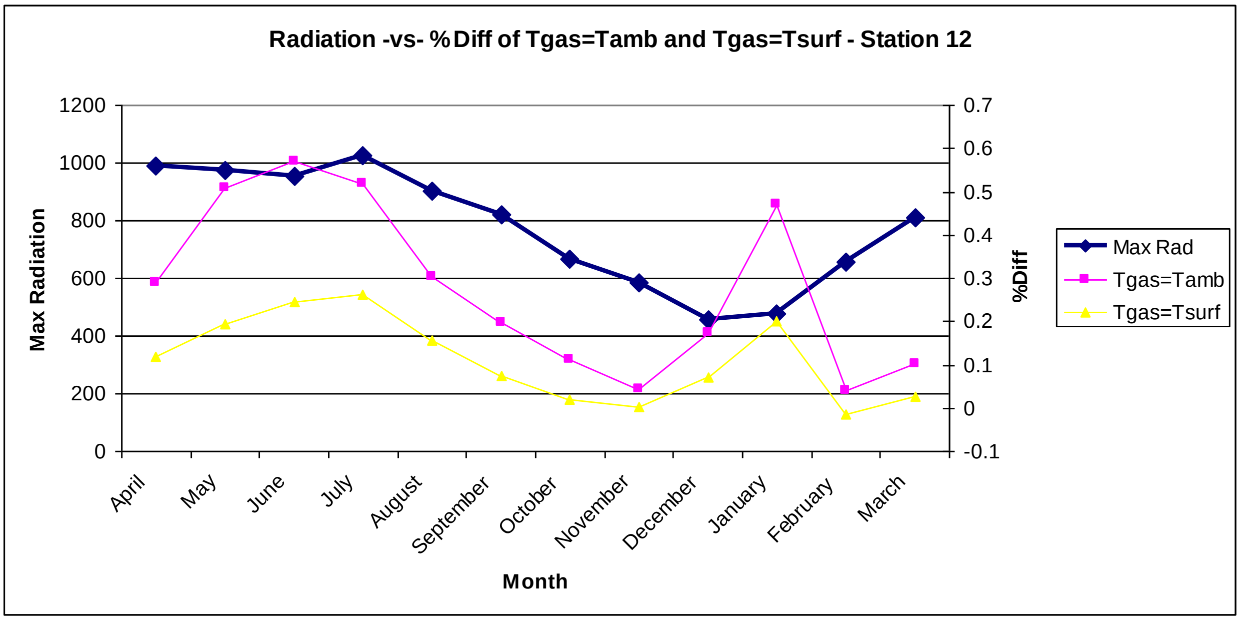

Figure D26. Radiation vs. %Diff of Tgas=Tamb and Tgas=Tsurf - Station 12

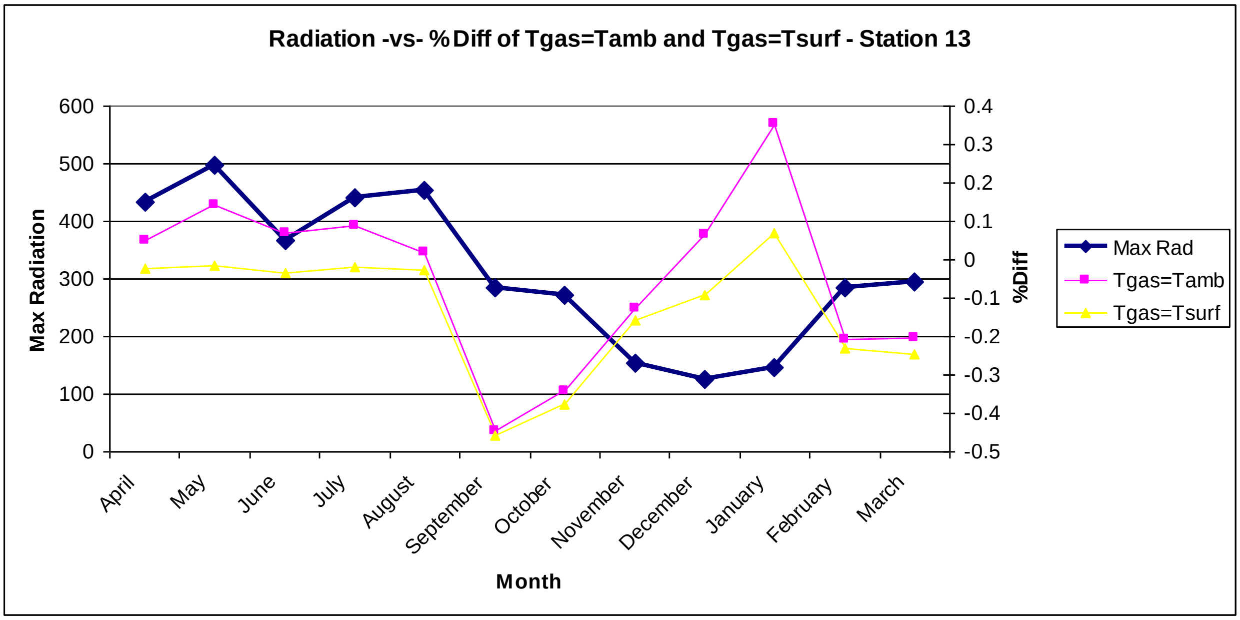

Figure D27. Radiation vs. %Diff of Tgas=Tamb and Tgas=Tsurf - Station 13

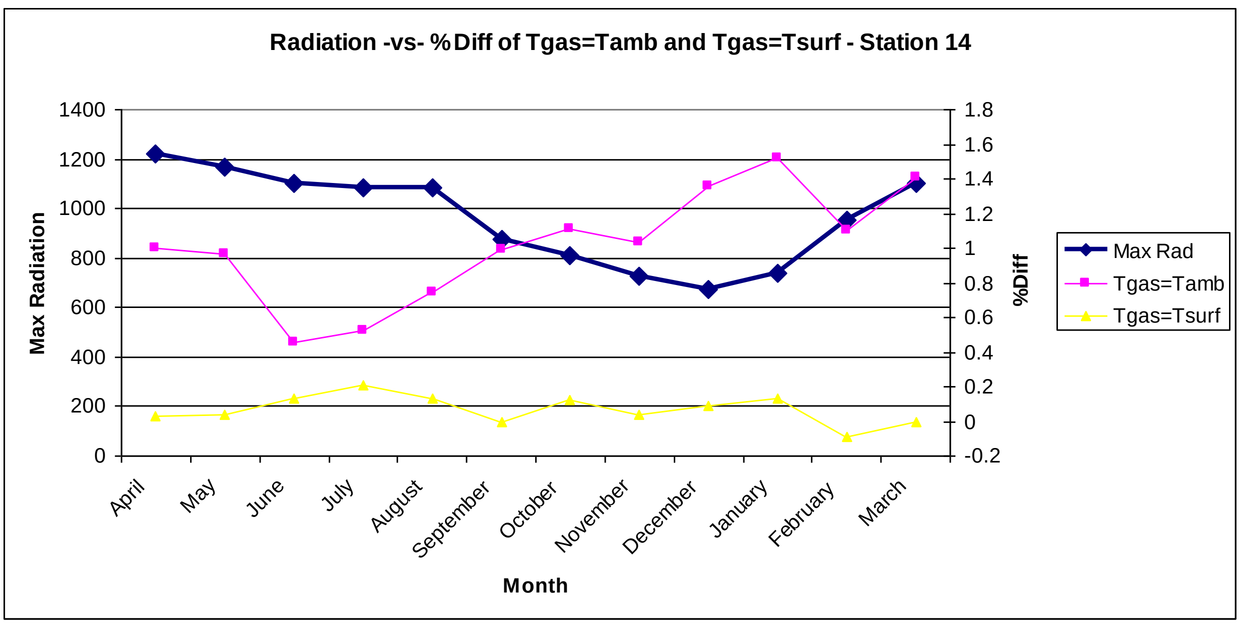

Figure D28. Radiation vs. %Diff of Tgas=Tamb and Tgas=Tsurf - Station 14

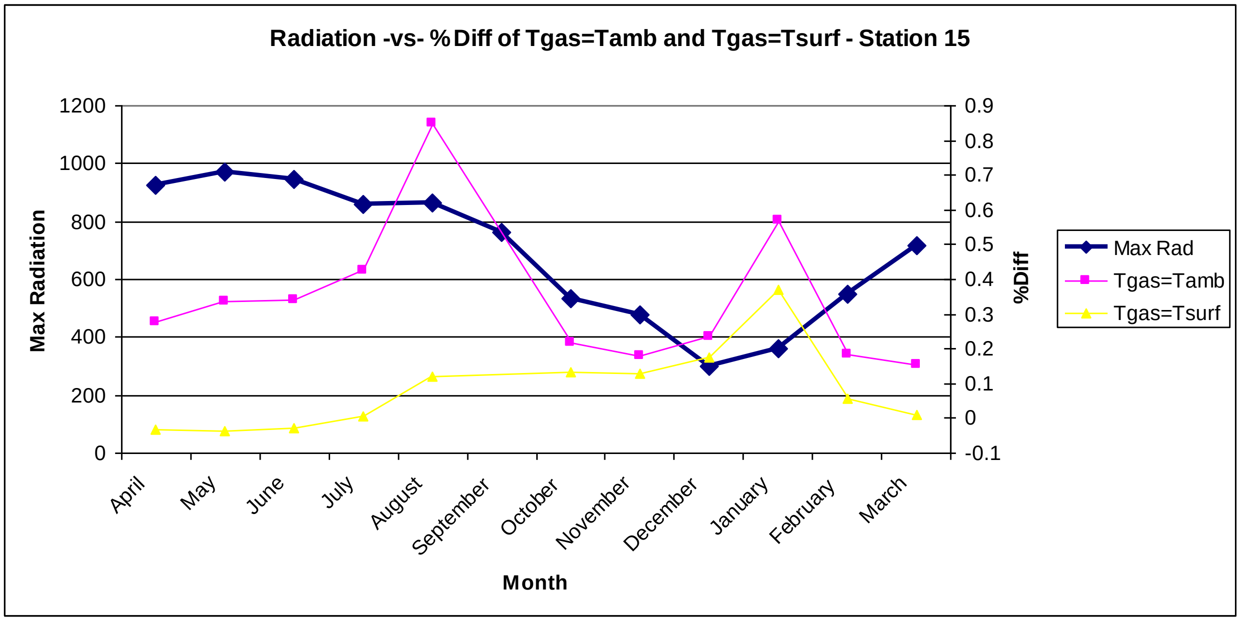

Figure D29. Radiation vs. %Diff of Tgas=Tamb and Tgas=Tsurf - Station 15

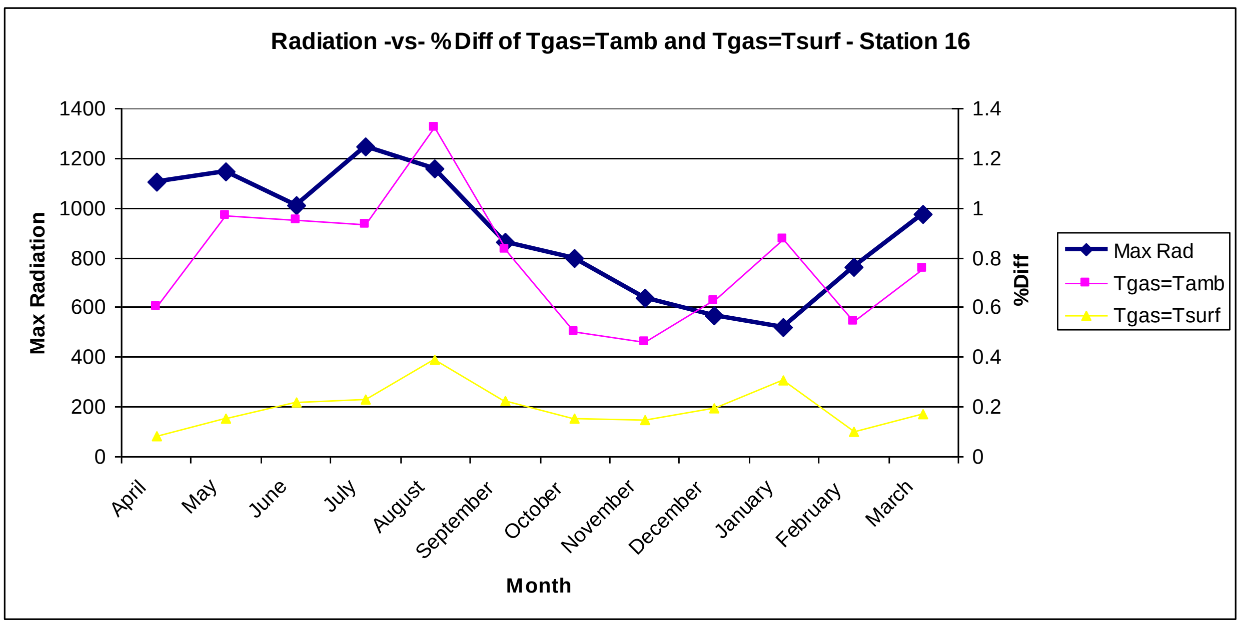

Figure D30. Radiation vs. %Diff of Tgas=Tamb and Tgas=Tsurf - Station 16

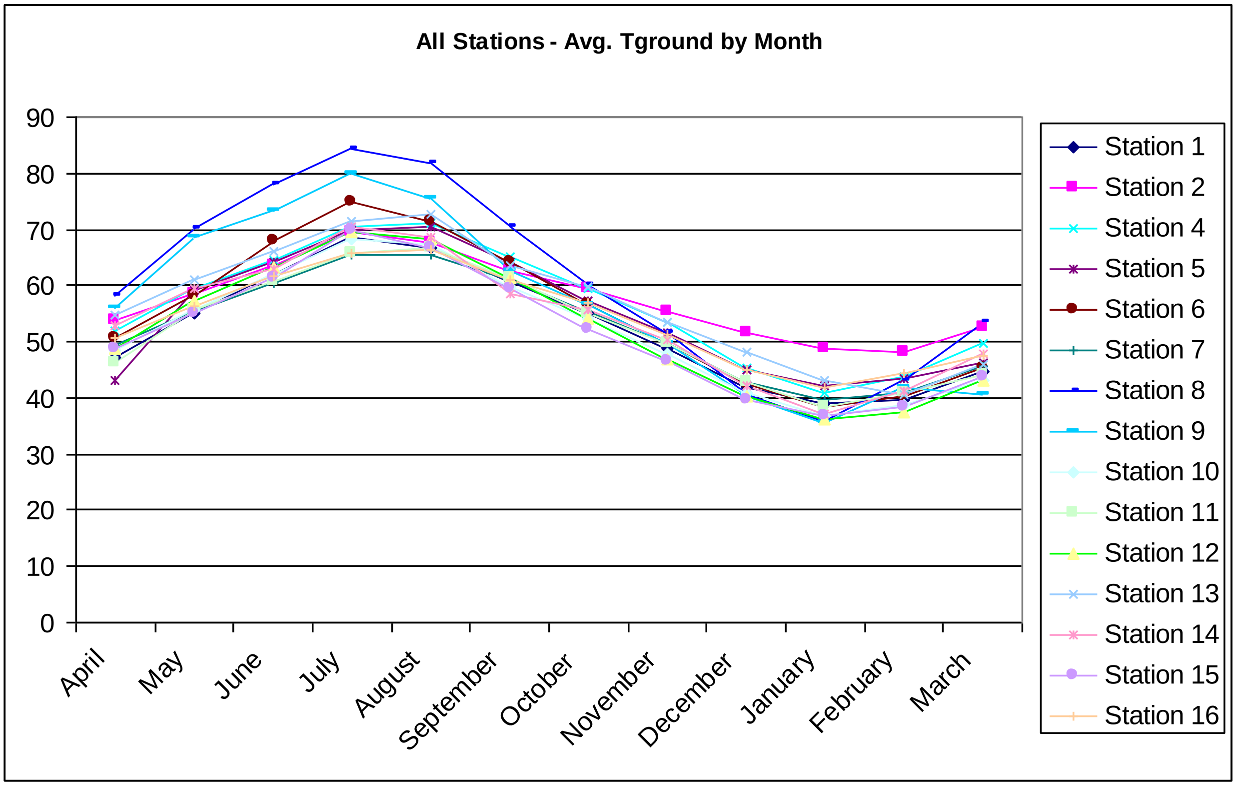

Figure D31. Ground temperature for all stations and all months.