Evaluation of NOAA vs SNOW YSI Temperature Correction Equations

Joel Atwood, NRCS Snow Survey and Water Supply Forecasting Program, Denver CO
Paper presented at the Western Snow Conference, 2023

Abstract

A bias was discovered in SNOTEL temperature data that uses the YSI Extended Range thermistor (YSI) due to use of a linear equation to convert voltages to temperature. To create a debiasing equation, the Snow Survey tested 30 field deployed YSIs in a temperature chamber from -40° to 50° C to produce a fifth order polynomial (SNOW5). Separately, the National Oceanic and Atmospheric Administration (NOAA) develop a 5^{th} (NOAA5) and 9^{th} order polynomial (NOAA9) fitted to data produced by four new YSIs tested in a temperature chamber, ranging from -60° to 60° C. Comparing all three equations to both the Snow Survey dataset and the NOAA dataset produced similar results. Using the Snow Survey dataset, the NOAA5 and NOAA9 equations produced a mean squared error (MSE) of 0.3, where-as the SNOW5 equation produced a MSE of 0.2. The SNOW5 equation did reasonably well on the NOAA dataset with a MSE of 0.2 compared to a MSE of 0.1 and 0.0 for NOAA5 and NOAA9. On inspection SNOW5 performance degraded towards the more extreme temperature ranges. Due to the limited temperature range used to create the SNOW5 equation and the NOAA equations equitable performance on the Snow Survey data, this study concludes that using the NOAA9 will produce the best results when bias reducing temperature data between -55° and 60° C.

Background

YSI Extended range has a known bias that has been shown to produce temperature errors greater than 1° C in some instances. Due to SNOTEL temperature data now being used in more research-grade applications, the Snow Survey has decided to debias these data to provide a better historical record of temperature data across the western high country. Historically, the Snow Survey has relied on two linear equations to convert voltages, measured from the YSI Extended Range thermistor, to temperature.

Origins of CONUS YSI Temperature Equation:

The SNOTEL network in the Continental United States (CONUS) has used a linear equation to convert fractional voltage to temperature derived from the manufacturer-provided resistance measurements for the two thermistors contained in the 44211A sensor. The YSI Extended Range sensor measures temperature by combining a 44311A resistor network and a 44019A thermistor network (see Figure 1 for details). The resistance of the two resistors in the 44211A resistor network help the network produce a more linear response when combined with the thermistor network. The manual provides the known resistances of the resistors in the 44211A resistor network and calibration data for the thermistors as resistance measurements versus temperature. The claim is a near-linear voltage response is produced across resistor one (RR_1 shown in Figure 1) due to the configuration of the resistors and thermistors. After a 2500 mV excitation voltage is applied to the circuit, the voltage measurement is taken across RR_1 and is shown in Figure 1 by “Eout Positive Slope”.

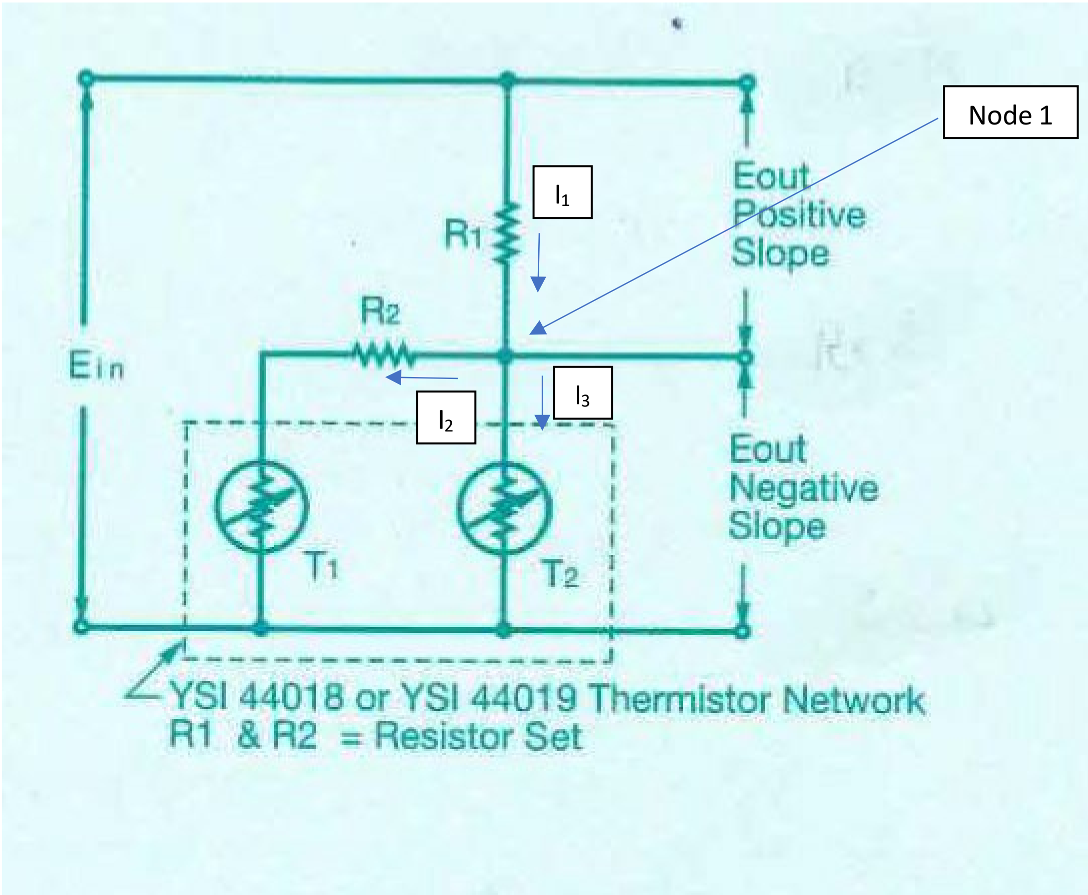

Figure 1: Circuit diagram of YSI Extended Range

To create a linear function that relates temperature to voltage using the thermistor resistances provided in the manual, a relationship must be developed between the voltages across RR_1 and the resistors in the circuit. The CONUS equation relates the voltage change across RR_1 divided by the excitation voltage, called the fractional voltage, to temperature. To develop this resistance to fractional voltage relationship, Ohms law is applied to relate the voltage change across $RR_1$to current and resistance:

Equation 1: $$VV_1 = RR_1 * II_1$$

Where VV_1 is the voltage change across RR_1 and is obtained by multiplying the resistance RR_1 by the current across the resistor, II_1. Next, using Kirchhoff's Current Law, a relationship with the current can be found through Node 1:

Equation 2: $$II_1 - II_2 - II_3 = 0$$

where II_1 is the current entering Node 1 and II_2 and II_3 is the current leaving the node. Two more equations are obtained by applying voltage continuity across a closed-circuit loop. There are two loops in the circuit which produce the following equations:

Equation 3: $$VV_1 + VV_{TT2} = EE \quad \text{and} \quad VV_1 + VV_2 + VV_{TT1} = EE$$

Where VV_1 and VV_2 are the voltages across resistor 1 and resistor 2 and VV_{TT1} and VV_{TT2} are the voltages across thermistor one and two. The excitation voltage of the circuit is represented by EE. Applying Ohm's Law to Equation 3 results in:

Equation 4: $RR_1 * II_1 + RR_{TT2} * II_3 = EE$ and $RR_1 * II_1 + RR_2 * II_2 + RR_{TT1} * II_2 = EE$

With three equations and three unknowns we can solve the system of linear equations for current:

$$\begin{bmatrix} 1 & -1 & -1 \\ RR_1 & 0 & RR_{TT2} \\ RR_1 & RR_2 + RR_{TT1} & 0 \end{bmatrix} * \begin{bmatrix} II_1 \\ II_2 \\ II_3 \end{bmatrix} = \begin{bmatrix} 0 \\ EE \\ EE \end{bmatrix}$$

The solution for II_1 is as follows:

Equation 5: $$II_1 = \frac{EE(RR_2 + RR_{TT1} + RR_{TT2})}{RR_1(RR_2 + RR_{TT1} + RR_{TT2}) + RR_{TT2}(RR_2 + RR_{TT1})}$$

Plugging that solution back into Equation 1 and dividing by the excitation voltage, we can obtain the voltage fraction:

Equation 6: $$\left(\frac{EE(RR_2 + RR_{TT1} + RR_{TT2})}{RR_1(RR_2 + RR_{TT1} + RR_{TT2}) + RR_{TT2}(RR_2 + RR_{TT1})}\right) * \frac{RR_1}{EE} = \frac{VV_1}{EE}$$

Equation 6 can be used to convert the resistance measurements of the thermistors, measured at specific temperatures which are provided in the manual, to fractional voltages. The manual provides the values for the RR_1 and RR_2 which are 3550 and 6025 ohms, respectively. Plotting the fractional voltages vs temperature are shown in Figure 2. The CONUS equation, used in the contiguous United States, converts voltage ratios to temperature in Celsius, and is derived directly from fitting a linear function to the data in Figure 2. The CONUS equation is as follows:

Equation 7 (CONUS): $$194.45 * \frac{VV_1}{EE} - 65.929 = TT_{cc}$$

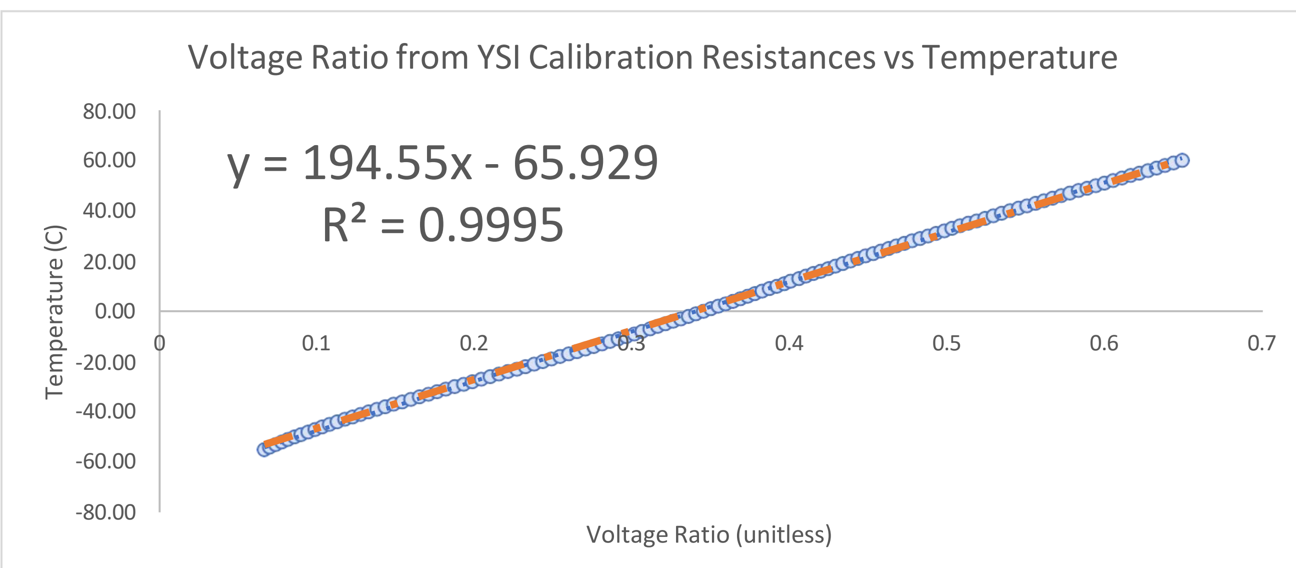

Figure 2: Calibration equation resulting from voltage ratio vs temperature. The voltage ratio is calculated via the calibration thermistor resistors provided by the company. The CONUS calibration equation is derived directly from those calibration factors.

Origins of Alaska Correction Equation:

Alaska uses a different linear correction equation to convert a single ended voltage measurement to temperature in Fahrenheit. The origin of this equation is not specifically known but likely was created via experimentally fitting YSI single ended voltage measurements to a standard thermistor. The equation is as follows:

Equation 6: $$0.14204 * VV_1 - 69.1335 = TT_{ff}$$

where VV_1 is the single ended voltage measured across resistor 1 and TT_{ff} is the temperature in Fahrenheit. Converting this equation to use Celsius and to use a voltage fraction the equation becomes:

Equation 7 (AK): $$197.278 * \frac{VV_1}{EE} - 67.296 = TT_{cc}$$

The conversion of the original Alaskan equation was performed to be comparable to the output of the other equations used in these studies.

SNOW Survey Temperature Chamber Study to evaluate YSI Bias:

Using 30 YSI sensors, the Snow Survey tested the sensors in a temperature chamber from -40° to 60° degrees to quantify the bias that results from using the above-mentioned linear equations and to create a correction equation that could then be used to bias reduce the temperature data produced using the linear CONAS and AK equations. The bias resulting from the EMF experiment is shown in Figure 3. The study concluded that error resulting from the use of the linear equations can be on the order of 1.5 degrees. The Snow Survey then created a 5th order polynomial to better convert voltage fractions to temperature, shown below:

Equation 8 (SNOW5):

$$4766.05146484375 * \left(\frac{W_1}{EE}\right)^5 - 9280.2580859375 * \left(\frac{W_1}{EE}\right)^4 + 6612.560359375 * \left(\frac{W_1}{EE}\right)^3 - 2089.41573125 * \left(\frac{W_1}{EE}\right)^2 + 476.8520699999999 * \left(\frac{VV_1}{EE}\right) - 79.098511 = TT_{cc}$$

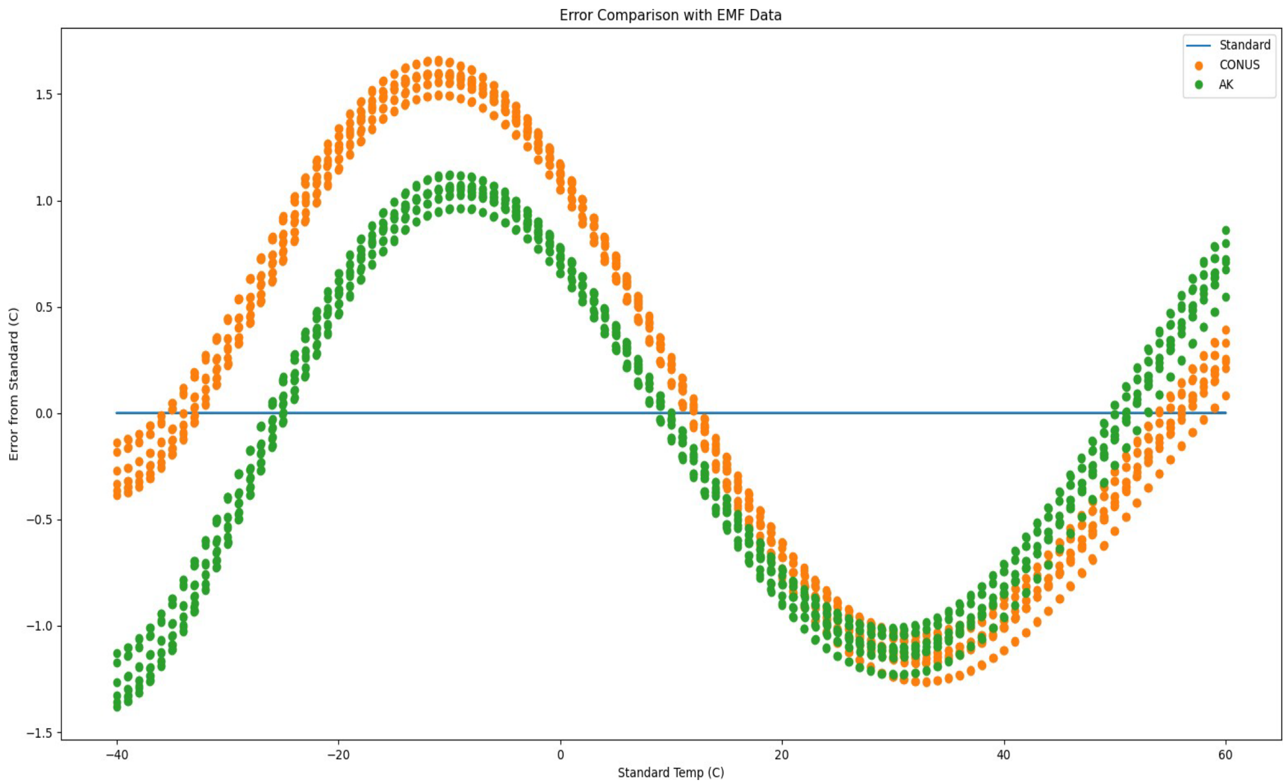

Figure 3: Bias produced from using a linear mapping from fractional voltage to temperature for the YSI Extended Range.

NOAA Group Produces Equation to Bias Reduce NPS YSI Data

NOAA also ran temperature chamber experiments on the YSI Extended range in 2015 to develop a debiasing equation for the National Park Service's ARCN and CAKN Stations. They produced a fifth order and ninth order polynomial from four new and freshly calibrated YSI sensors. The fifth and ninth order polynomial are as follows:

Equations 9 (NOAA5):

$$4823.128484 * \left(\frac{W_1}{EE}\right)^5 - 9429.534608 * \left(\frac{W_1}{EE}\right)^4 + 6744.164264 * \left(\frac{W_1}{EE}\right)^3 - 2139.119324 * \left(\frac{W_1}{EE}\right)^2 + 484.7566852 * \left(\frac{W_1}{EE}\right) - 79.57962269 = TT_{cc}$$

Equations 10 (NOAA9):

$$610558.226380138 * \left(\frac{W_1}{EE}\right)^9 - 2056177.65461394 * \left(\frac{W_1}{EE}\right)^8 + 2937046.42906361 * \left(\frac{W_1}{EE}\right)^7 - 2319657.12916417 * \left(\frac{W_1}{EE}\right)^6 + 1111854.33825836 * \left(\frac{W_1}{EE}\right)^5 - 337069.883250001 * \left(\frac{W_1}{EE}\right)^4 + 66105.7015922199 * \left(\frac{W_1}{EE}\right)^3 - 8386.78320604513 * \left(\frac{W_1}{EE}\right)^2 + 824.818021779729 * \left(\frac{W_1}{EE}\right) - 86.7321006757439 = TT_{cc}$$

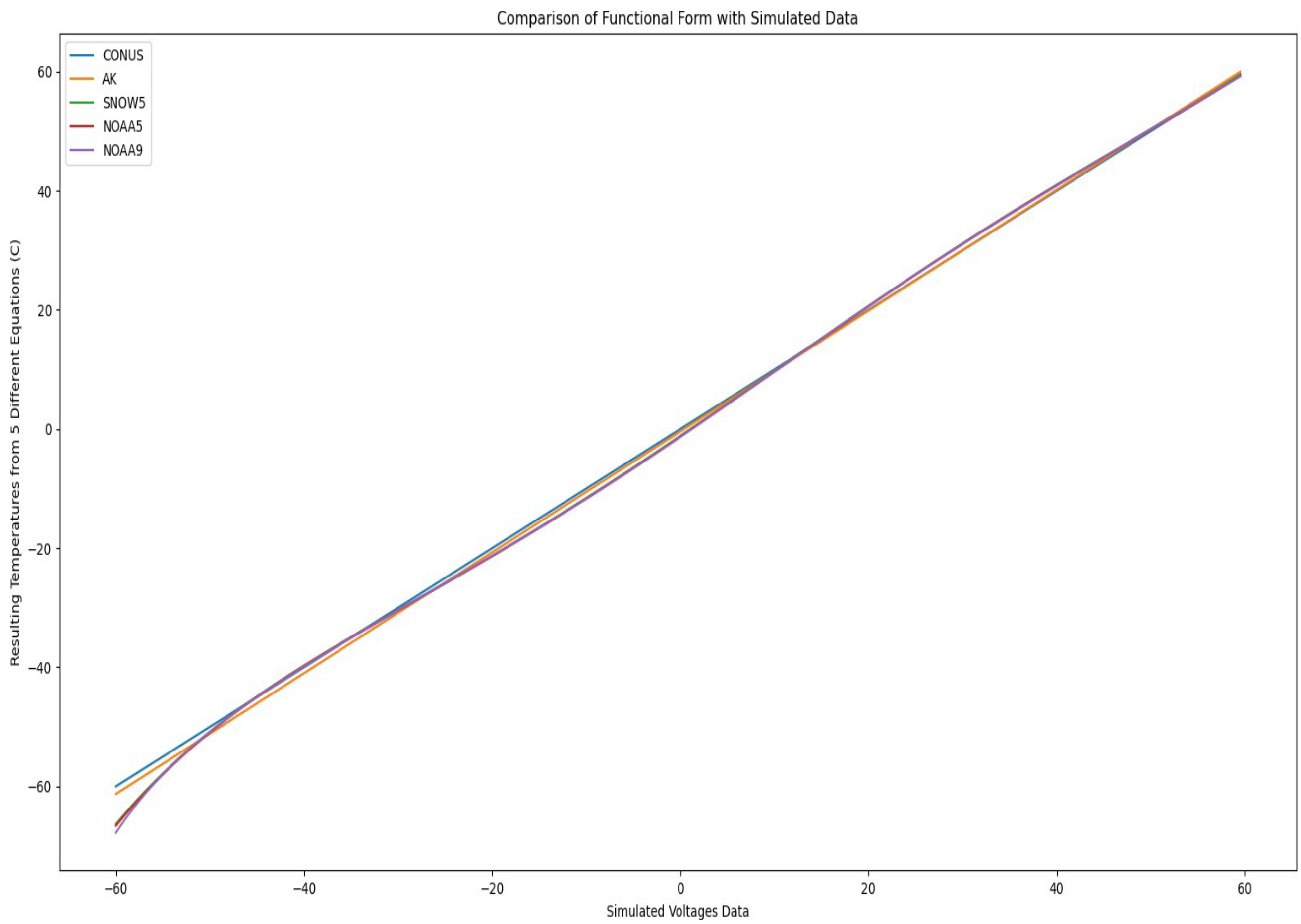

Figure 4: Plot of the functional form of each equation with simulated data.

Comparison of 5 functions using EMF voltage data

As stated above, the Snow Survey EMF ran 30 YSI sensors that had been deployed in the field for a variety length of time. The YSI voltages were compared to a reference thermistor. By applying the five correction equations described in detail above, we can glean some understanding of how each equation will affect real world uncalibrated, field deployed YSI thermistors.

Much of the YSI thermistors in the SNOTEL network have been out in the field for longer than 15 years with no testing to make sure the sensors haven't drifted over time. Also, many stations' data loggers have never been recalibrated adding another element of uncertainty to the measurements. The temperature chamber experimentation removes the variability likely imposed by old data loggers out of calibration, but evidence of drift can be observed in Figure 6. The two NOAA equations show some bias where much of the error is less than the standard temperature. Because the NOAA equations were fit to new freshly calibrated YSIs, the drift is likely due to changes in the resistivity of the field deployed thermistors over time. Despite the slight bias the NOAA equation produce very similar results to the fitted SNOW5 equation.

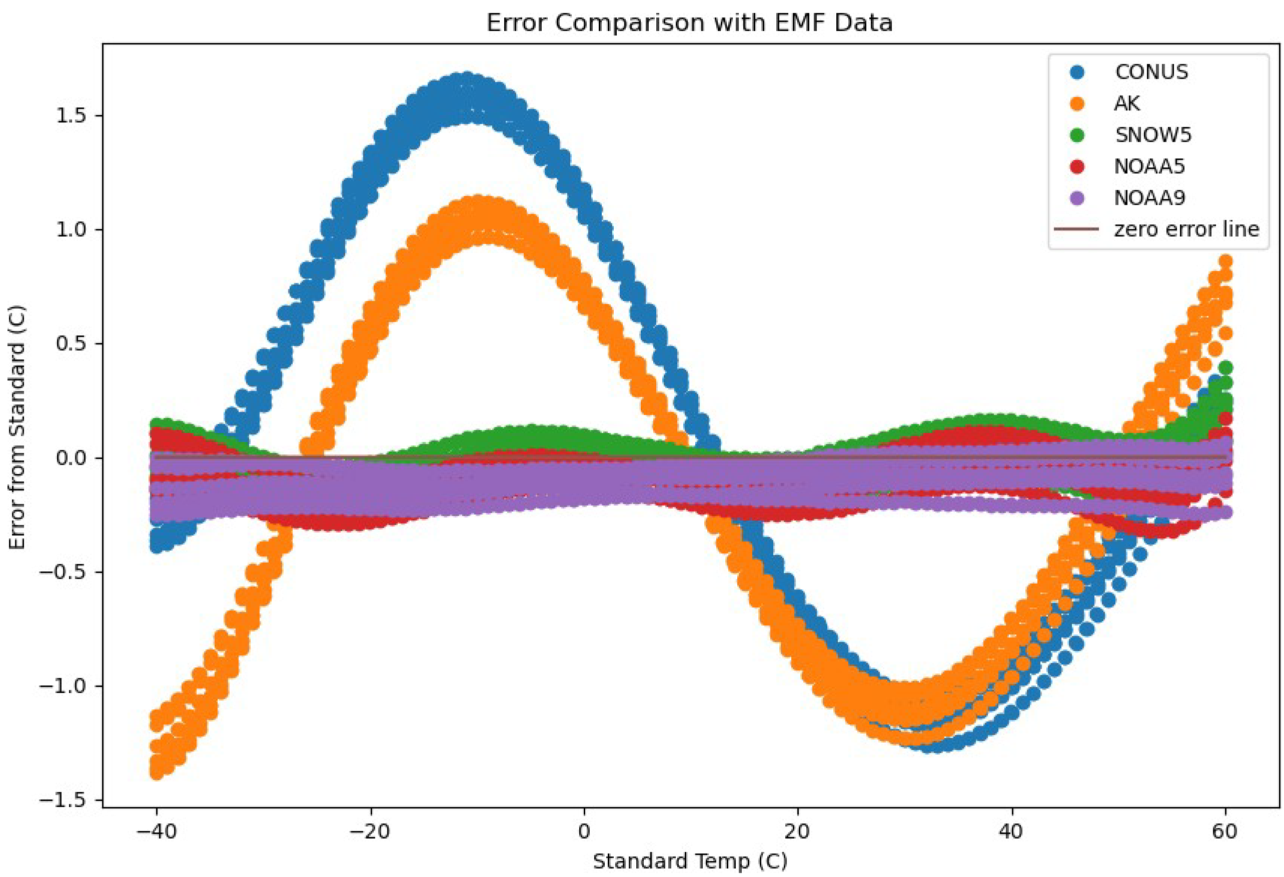

Figure 5: Error from standard when applying a given conversion equation to the EMF YSI data.

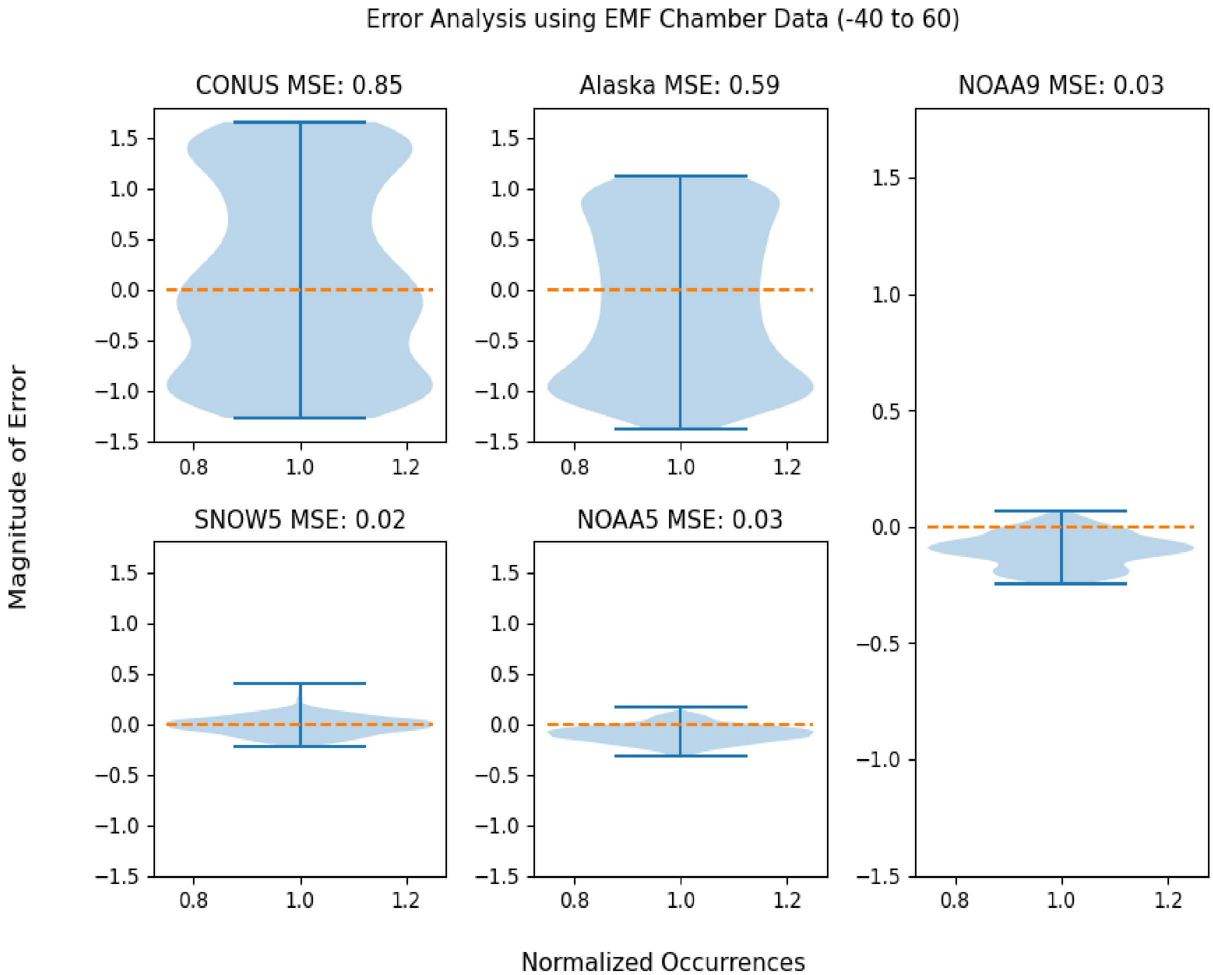

Figure 6: Violin plots of error when different correction equations are used.

Edge Case Comparison Graphs:

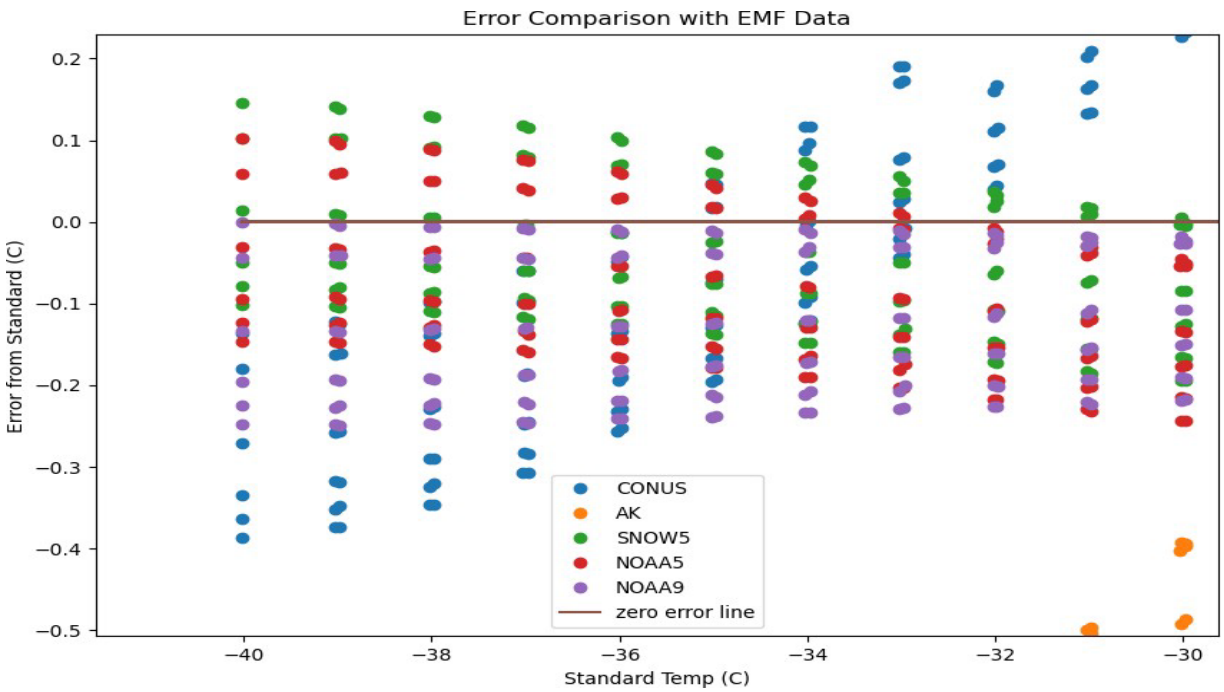

Figure 7: Zoomed in comparison of the five correction equations at the cold end of the EMF YSI data. These results show that the SNOW5, NOAA5 and NOAA9 produce similar results.

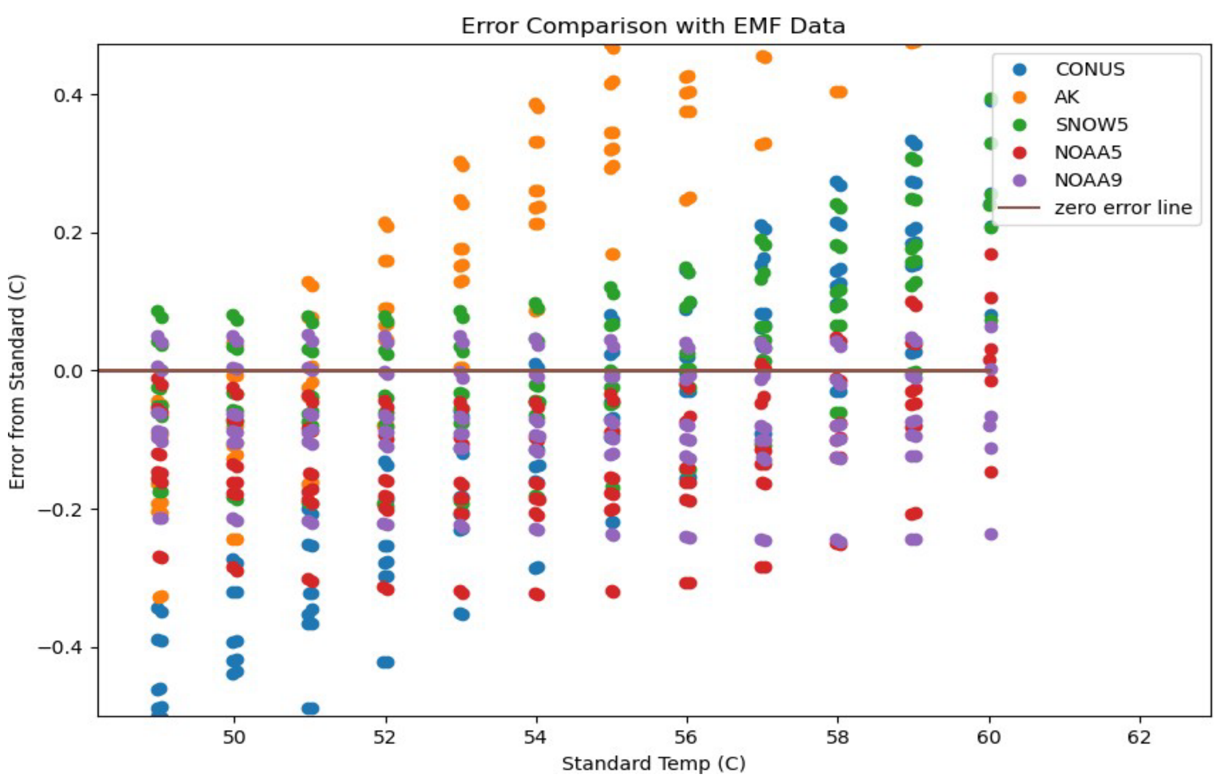

Figure 8: Zoomed in comparison of the five correction equations at the warm end of the EMF YSI data. SNOW5 shows despite less overall bias does display more bias at extreme temperatures then the NOAA5 and NOAA9 equations.

Comparison of 5 functions using NOAA calibrated YSI data

The results of applying the five equations to NOAAs temperature chamber experiment data are shown in Figure 9 and 10. As with the EMF chamber data, the SNOW5, NOAA5 and NOAA9 equations all produce a similar correction. Bias can be seen in Figure 10 with the SNOW5 equation which is because SNOW5 was fit on the field deployed sensors data. Overall, SNOW5, NOAA5 and NOAA9 produce very similar results where much of the differences are observed in the extreme ends of the temperature spectrum.

The NOAA temperature chamber data tested the four YSI sensors at a greater range then the EMF data. At the extreme cold end, below around -55° C, the thermistors begin to display a very non-linear response. This is likely due to those temperatures exceeding the temperature rating of the sensor that has a manufacturer-stated range of -55° to 85°. Despite the SNOW5 equation not being fit on data below -40°, it still does reasonably well up to -55°. Even the NOAA9 seems to have issues capturing the non-linear response below -55° accurately.

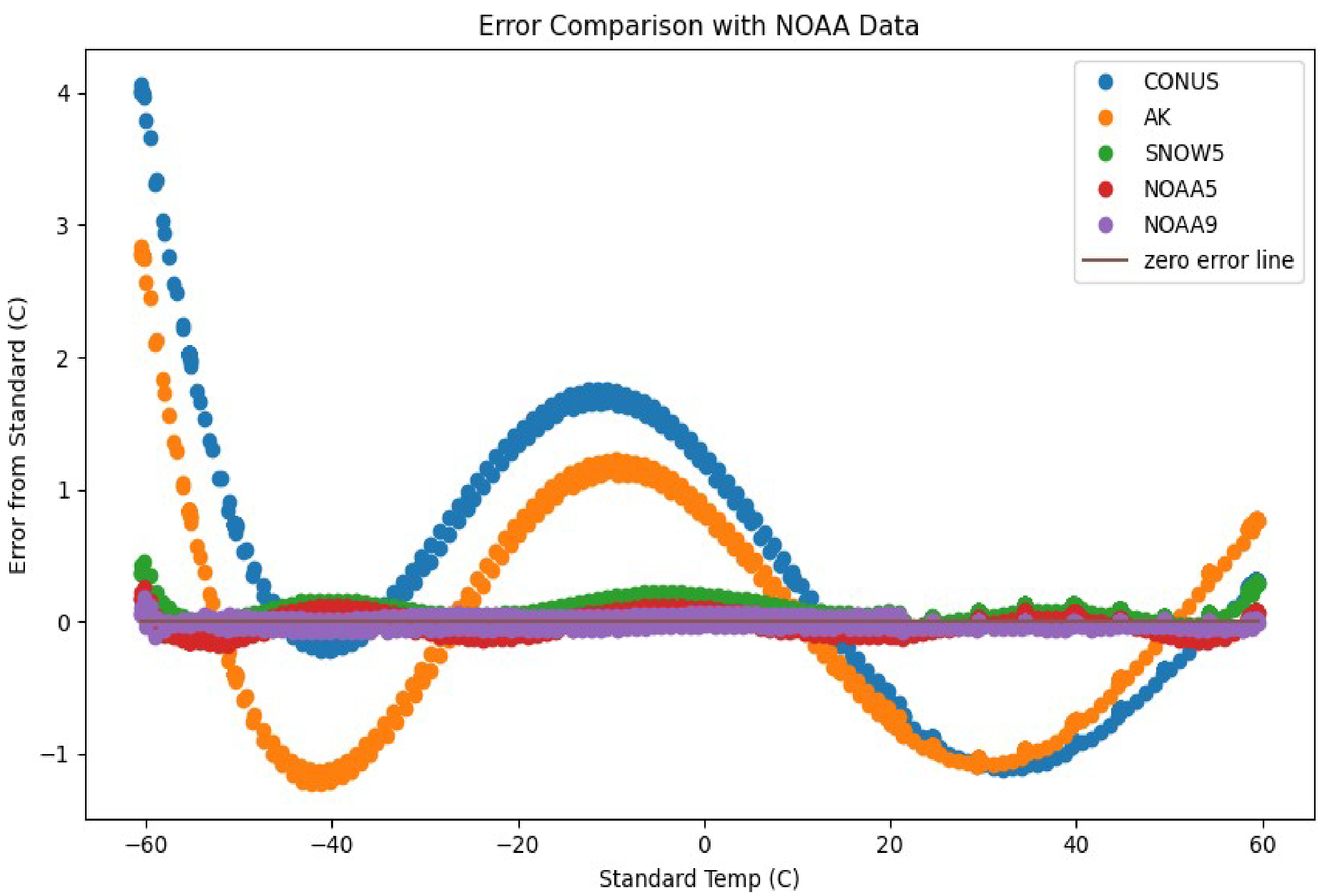

Figure 9: Error from standard when applying a given conversion equation to NOAA YSI data.

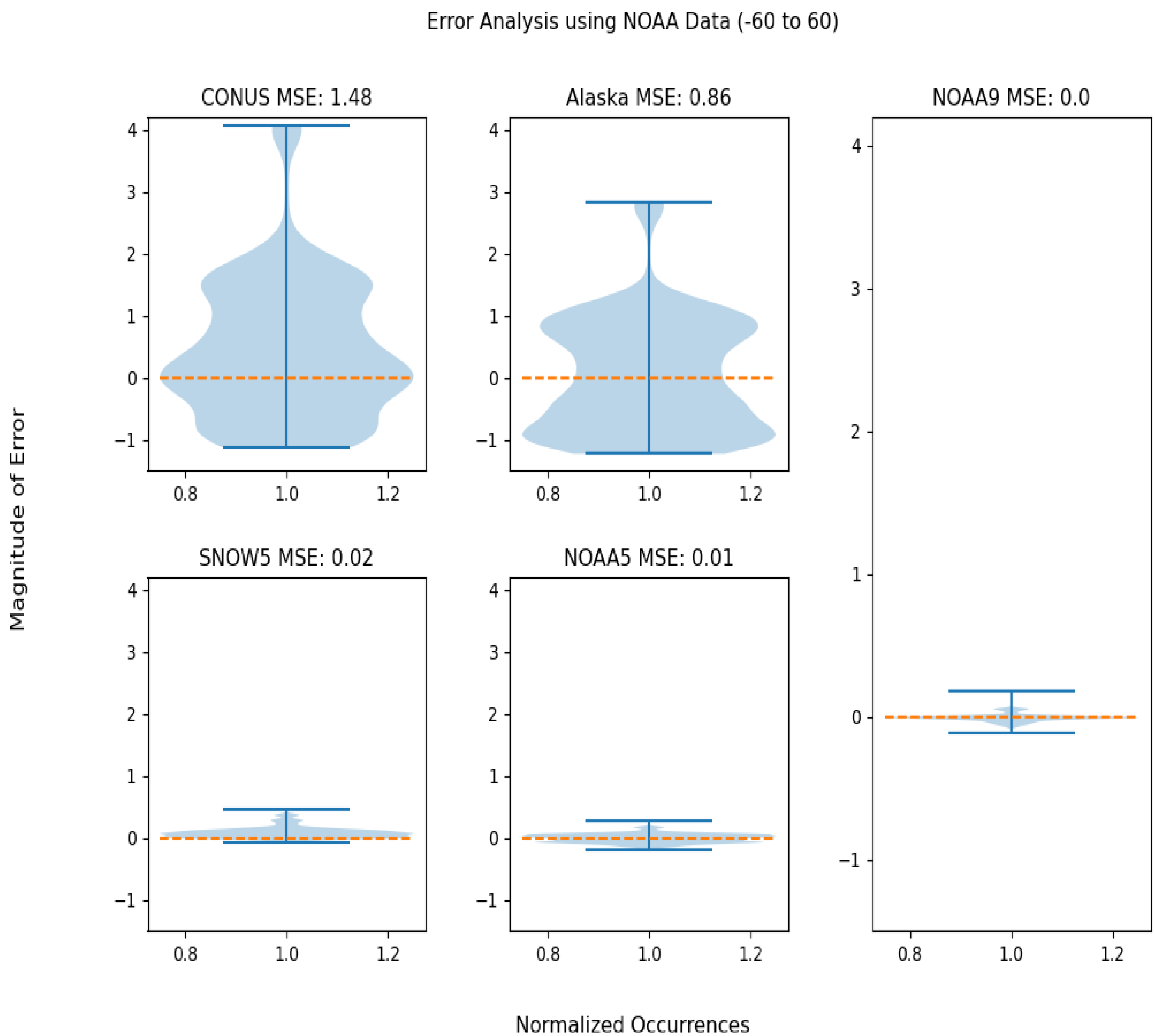

Figure 10: Violin plots of error when different correction equations are used with NOAA temperature chamber data.

Edge Case Comparison:

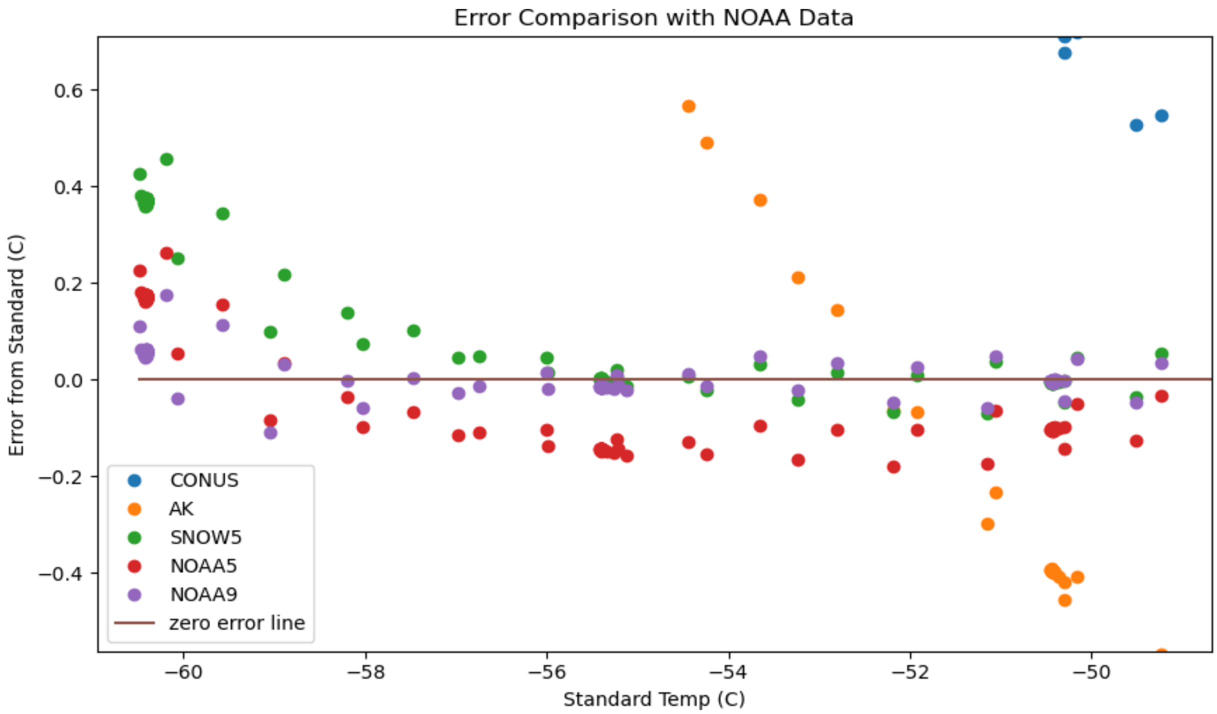

Figure 12: Zoomed in comparison of the five correction equations at the cold end of the NOAA YSI data. These results show that the SNOW5, NOAA5 and NOAA9 produce similar results except for when the sensor exceeds its design limits at -55 C.

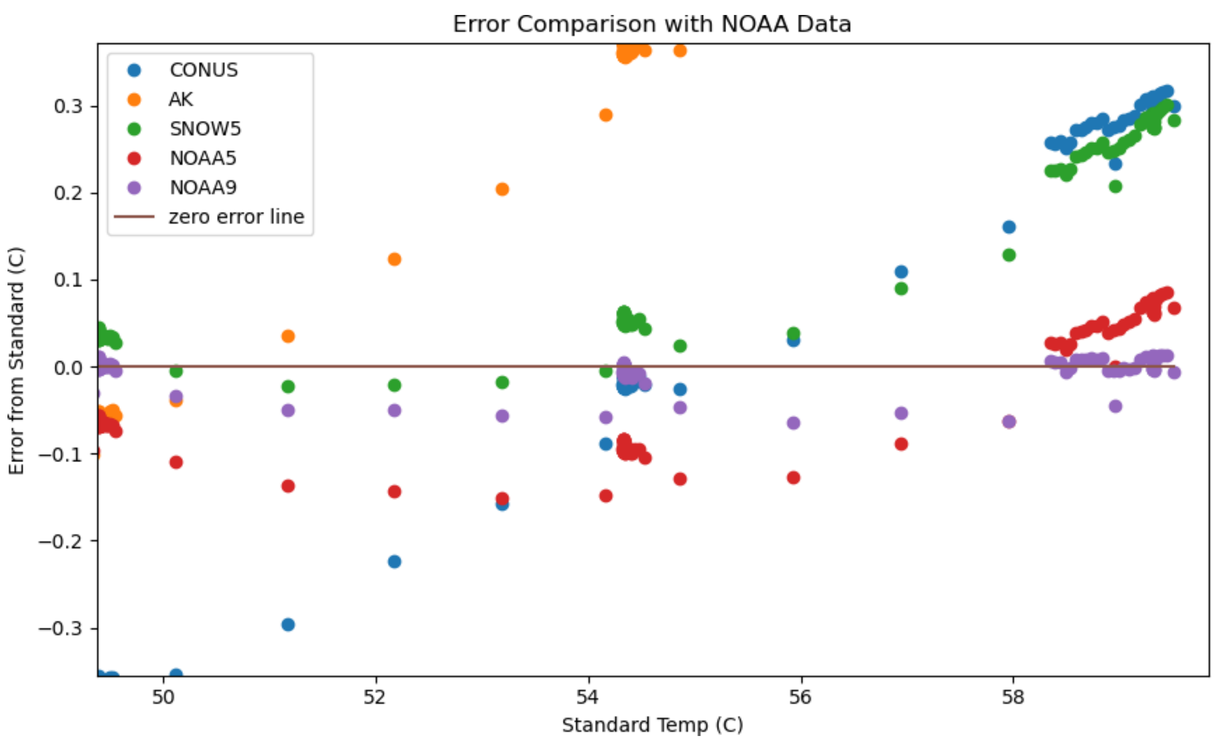

Figure 13: Zoomed in comparison of the five correction equations at the warm end of the NOAA YSI data. Bot NOAA5 and SNOW5 show bias; SNOW5 higher than 55 C and NOAA5 between 48 C and 58 C.

Conclusion:

The NOAA5 and NOAA9 equation both perform reasonably considering the inherent uncertainties in the YSI measurements. Both NOAA5 and NOAA9 perform better for extreme values, with the NOAA9 polynomial performing the best at very cold temperatures. SNOW5 performance is still reasonable despite not being fit to data below -40° C. SNOW5 is likely within the margin of error of the true value, considering all the uncertainties introduced by other factors effecting the YSI sensors measurements at SNOTEL Sites. The National Park Service concluded that NOAA9 produced the most accurate temperatures and used it to correct their YSI thermistors deployed in the field. Considering NOAA5 and NOAA9 passes basic sanity checks for higher order polynomials within the range of interest (see Appendix 2) and performs reasonably well on field deployed YSI data, using one of the NOAA equations is a sensible path considering the better fit at more extrema values. With the NPS using the NOAA9 equation, we recommend that the Snow Survey also uses NOAA9 polynomial to bias reduce SNOTEL YSI data. Due to the magnitude of the non-linear response of the YSI Extended Range thermistor below -55 C, we recommend only bias reducing temperatures that fall, after correction, between -55° and 60° C.

Final de-biasing Correction Equations:

Equations 11 Correction equation using NOAA5 CONUS:

$$4823.128484 * \left(\frac{(TT_{bbbbbbb-cc} + 65.929)}{194.45}\right)^5 - 9429.534608 * \left(\frac{(TT_{bbbbbbb-cc} + 65.929)}{194.45}\right)^4 + 6744.164264 * \left(\frac{(TT_{bbbbbbb-cc} + 65.929)}{194.45}\right)^3 - 2139.119324 * \left(\frac{(TT_{bbbbbbb-cc} + 65.929)}{194.45}\right)^2 + 484.7566852 * \left(\frac{(TT_{bbbbbbb-cc} + 65.929)}{194.45}\right) - 79.57962269 = TT_{cc}$$

Equations 12 Correction equation using NOAA9 CONUS:

$$610558.226380138 * \left(\frac{(TT_{bbbbbbb-cc} + 65.929)}{194.45}\right)^9 - 2056177.65461394 * \left(\frac{(TT_{bbbbbbb-cc} + 65.929)}{194.45}\right)^8 + 2937046.42906361 * \left(\frac{(TT_{bbbbbbb-cc} + 65.929)}{194.45}\right)^7 - 2319657.12916417 * \left(\frac{(TT_{bbbbbbb-cc} + 65.929)}{194.45}\right)^6 + 1111854.33825836 * \left(\frac{(TT_{bbbbbbb-cc} + 65.929)}{194.45}\right)^5 - 337069.883250001 * \left(\frac{(TT_{bbbbbbb-cc} + 65.929)}{194.45}\right)^4 + 66105.7015922199 * \left(\frac{(TT_{bbbbbbb-cc} + 65.929)}{194.45}\right)^3 - 8386.78320604513 * \left(\frac{(TT_{bbbbbbb-cc} + 65.929)}{194.45}\right)^2 + 824.818021779729 * \left(\frac{(TT_{bbbbbbb-cc} + 65.929)}{194.45}\right) - 86.7321006757439 = TT_{cc}$$

Equations 13 Correction equation using NOAA5 AK:

$$4823.128484 * \left(\frac{(TT_{bbbbbbb-cc} + 67.296)}{197.278}\right)^{5} - 9429.534608 * \left(\frac{(TT_{bbbbbbb-cc} + 67.296)}{197.278}\right)^{4} + 6744.164264 * \left(\frac{(TT_{bbbbbbb-cc} + 67.296)}{197.278}\right)^{3} - 2139.119324 * \left(\frac{(TT_{bbbbbbb-cc} + 67.296)}{197.278}\right)^{2} + 484.7566852 * \left(\frac{(TT_{bbbbbbb-cc} + 67.296)}{197.278}\right) - 79.57962269 = TT_{cc}$$

Equations 14 Correction equation using NOAA9 AK:

$$610558.226380138 * \left(\frac{(TT_{bbbbbbb-cc} + 67.296)}{197.278}\right)^{9} - 2056177.65461394 * \left(\frac{(TT_{bbbbbbb-cc} + 67.296)}{197.278}\right)^{8} + 2937046.42906361 * \left(\frac{(TT_{bbbbbbb-cc} + 67.296)}{197.278}\right)^{7} - 2319657.12916417 * \left(\frac{(TT_{bbbbbbb-cc} + 67.296)}{197.278}\right)^{6} + 1111854.33825836 * \left(\frac{(TT_{bbbbbbb-cc} + 67.296)}{197.278}\right)^{5} - 337069.883250001 * \left(\frac{(TT_{bbbbbbb-cc} + 67.296)}{197.278}\right)^{4} + 66105.7015922199 * \left(\frac{(TT_{bbbbbbb-cc} + 67.296)}{197.278}\right)^{3} - 8386.78320604513 * \left(\frac{(TT_{bbbbbbb-cc} + 67.296)}{197.278}\right)^{2} + 824.818021779729 * \left(\frac{(TT_{bbbbbbb-cc} + 67.296)}{197.278}\right) - 86.7321006757439 = TT_{cc}$$

Appendix 1: Logger Measurement History

The logger configuration to measure the YSI has been done is several different ways depending on logger type, telemetry system used, and logger function used. Many modern loggers in SNOTEL network use the half-bridge function by Campbell available in all loggers that utilize the CRbasic programming language (See Figure 14). The half-bridge function applies an excitation voltage, then a settling time, and then takes a single ended measurement and divides it by the excitation voltage. A multiplier and offset can also be applied to convert the voltage fraction to engineering units via the CONUS or AK equations.

```
Sub Temp_measurement
  Dim tmp
  #If UpperCase(Temp_Type) = UpperCase("YSI") Then
    BrHalf (tmp,1,AutoRange,3,Vx1,1,2500,False,50000,250,194.45,- 65.929) 'takes measurement from YSI on SE3 nad VX.
```

Figure 14: Example form Colorado Data Collection Office standard cr1000x program using Campbell's CRbasic half bridge function which outputs a fractional voltage. The CONUS equation is applied directly to the voltage fraction in the function through the offset and multiplier parameters.

Older cr10x dataloggers applied an excitation voltage, applied a settling time, then took a single ended measurement across R_1 in several lines of instructions (See Figure 15). Several scaling factors are applied for historic telemetry reasons. First the single ended measurement was multiplied by (4095/2500) to rescale the measurement as a fractional voltage between 0 and 4095 mv. The scaling is required for historic telemetry systems which used an 8-bit digital to analog converter. On the database side the value is then scaled again by a scaling factor (5/4095) which results in a voltage fraction multiplied by 5. To apply the CONUS equation to this value, the 194.45 scaling factor is divided by 5.

```
;*****************************TEMPERATURE**************************************
;Measures YSI Air Temperature Thermistor.
;Thermistor is excited with 2.5V from excitation channel 1 for .05 sec before
;  reading the sensor
;The value to be transmitted to SNOTEL is read first and then converted to
;  degrees Celcius amd Fahrenheit

     11:  Excite-Delay (SE) (P4)
      1: 1         Reps
      2: 5         2500 mV Slow Range
      3: 3         SE Channel
      4: 1         Excite all reps w/Exchan 1
      5: 5         Delay (units 0.01 sec)
      6: 2500      mV Excitation
      7: 110       Loc [ txtemp    ] ;This is the value to be transmitted to SNOTEL
      8: 1.638     Mult ;SNOTEL wants a 0-4095 #, we have a 0-2500 #, to convert it
      9: 0.0       Offset ;we multiply by 4095/2500=1.638
```

Figure 15: cr10x code from Austin2016 Montana program. The instruction applies in 2500 mV excitation (line 2) with a 0.05 second delay (line 5) then reads a single ended measurement across resistor 1 in millivolts.

With Alaska's use of different telemetry systems, both Alaska's CR10x and CR1000/1000x logger programs telemetered in engineering units and therefore data was never rescaled to 0 and 4045 like for many systems in the CONUS network. Instead, the Alaska function is used directly in the CR10x code (Figure 16) and in the CR1000 code (Figure 7) to produce a temperature in Fahrenheit.

```
#Snotel and NPS CR10X Instruction for ThermX Sensor
49:P4
1:1
2:5
3:5
4:1
5:20
6:X``
7:16
8:0.14204
9:-89.1335
```

Figure 16: Alaska CR10x YSI Extended Range instruction set. The offset and multiplier are used to convert the single ended measurement to temperature in Fahrenheit.

```
'YSI Air Temp probe
If hasYSI > 0 Then 'measure YSI thermister
  ExciteV(1,2500,0)
  Delay(0,20,mSec)
  VoltSe(airTemp,1,mv2500,4,0,0,250,0.14204,-89.1335)
  ExciteV(1.0.0)
```

Figure 17: Alaska CR1000 YSI measurement instruction. The sensor is excited by the ExcitV instruction then a single ended measurement is taken. The measurement is scaled by the same multiplier and offset used in Alaska's CR10x instruction to produce a to temperature in Fahrenheit.

Appendix 2: NOAA Equation Sanity Checks

Taking the derivative and calculating critical points we can prove the equation does not overfit and has sane behavior between the intervals desired. Figure one plots the derivatives of Equation NOAA5 and NOAA9. No real-valued critical points are found between the interval -60° or 60° C which proves that there are no positive or negative spiking (local minimum or maximum) that takes place between -60° and 60° C. Therefore, we can conclude that the equations do not overfit and behave predictably between the interval of interest.

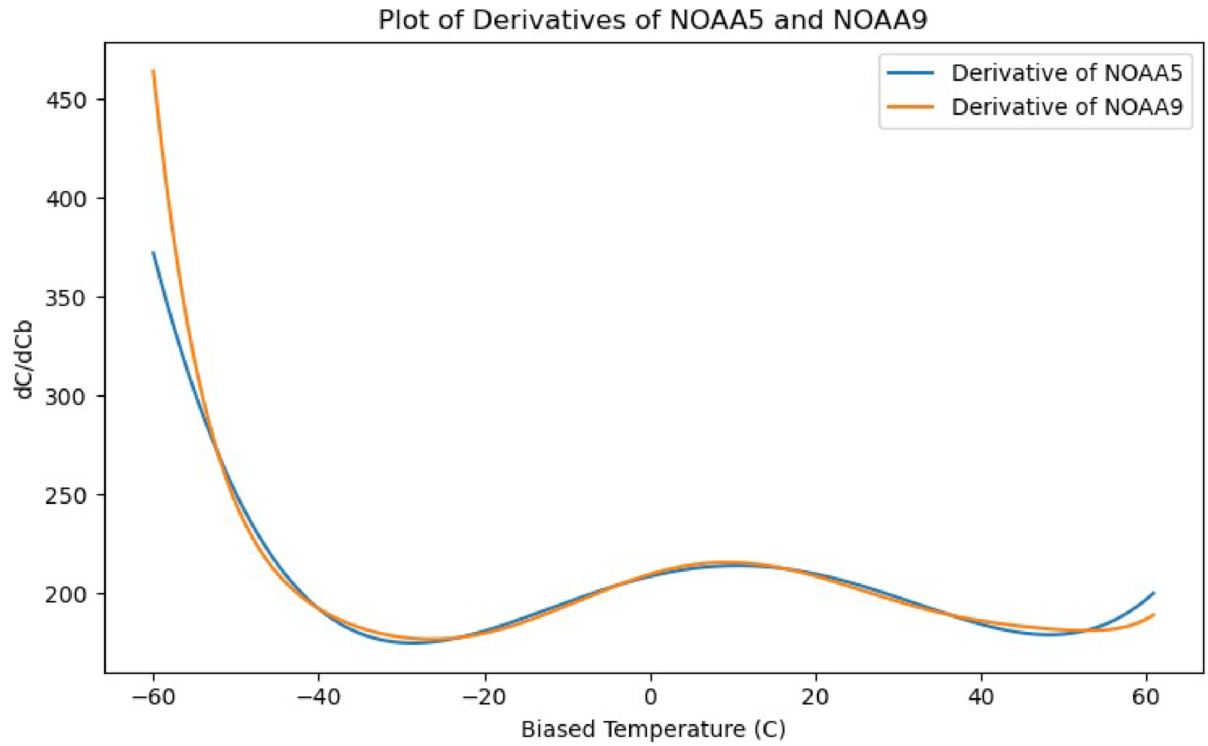

Figure 18: Plot showing the derivatives of NOAA5 and NOAA9 equations.