EVALUATION OF YSI TEMPERATURE CORRECTION EQUATIONS FOR BIAS-REDUCING SNOTEL NETWORK TEMPERATURE DATA

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ABSTRACT

A bias was discovered in Snow Telemetry (SNOTEL) network temperature data that uses the YSI Extended Range thermistor (YSI) causing a shift in data starting in the late 1990s. In 2016, the Snow Survey formed a working group to evaluate debiasing the YSI data. The working group tested 30 field deployed YSIs in a temperature chamber ranging from -40° to 50° C to produce a fifth order polynomial (SNOW5). Separately, the National Oceanic and Atmospheric Administration (NOAA) develop a 5th (NOAA5) and 9th order polynomial (NOAA9) fitted to data produced by four YSIs tested in a temperature chamber, ranging from -60° to 60° C. Comparing all three equations to both the Snow Survey 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, the working group concludes that using the NOAA9 will produce the best results when bias reducing YSI temperature data between -55° and 60° C. (KEYWORDS: SNOTEL, temperature correction, instrumentation changes, temperature sensor, thermistor)

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BACKGROUND

YSI Extended range has a known bias that has been shown to produce temperature errors greater than 1° C in some instances (Julander and Beard, 2007; Harms, et al., 2016). Due to SNOTEL temperature data now being used in more research-grade applications, the Snow Survey has decided to debias the temperature data to provide a better historical record across the SNOTEL network. Historically, the Snow Survey has relied on two linear equations to convert voltage ratios, measured from the YSI, to temperature. These equations were applied in a variety of ways. For older data loggers and telemetry systems the temperature was calculated from telemetered voltages on the database side. Newer dataloggers calculate temperature internally and telemeter temperature in engineering units.

Origins of CONUS and Alaska YSI Temperature Equations

The SNOTEL network in the contiguous 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 (YSI, 2001). 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 in in the 44311A resistor network due to the configuration of the resistors and thermistors.

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 R_1 and the resistors in the circuit (see Figure 1). Both the CONUS and AK equation relate the voltage change across R_1 divided by the excitation voltage, called the fractional voltage, to temperature. To develop a resistance to fractional voltage relationship, Ohms law is applied to relate the voltage change across $R_1$to current and resistance:

Equation 1: $V_1 = R_1 * I_1$

Where V_1 is the voltage change across R_1 and is obtained by multiplying the resistance R_1 by the current across the resistor, I_1. Next, using Kirchhoff's Current Law, a relationship with the current can be found through Node 1:

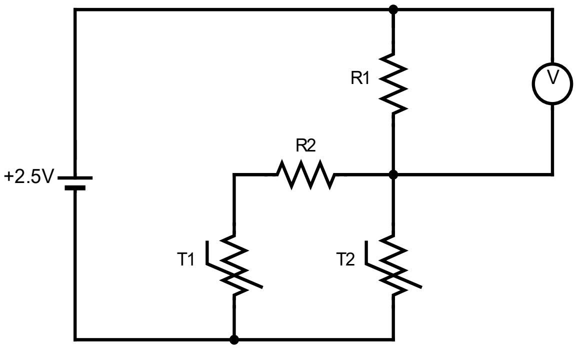


Figure 1: The YSI Extended Range thermistor circuit diagram where the V parameter is the measurement made across R_1 to calculate temperature. T_1 and T_2 is the 44019A thermistor network whereas R_1 and R_2 is the 44311A is the resistor network.

Equation 2: $I_1 - I_2 - I_3 = 0$

where I_1 is the current entering Node 1 and I_2 and I_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: $V_1 + V_{T2} = E$ and $V_1 + V_2 + V_{T1} = E$

Where V_1 and V_2 are the voltages across resistor 1 and resistor 2 and V_{T1} and V_{T2} are the voltages across thermistor one and two. The excitation voltage of the circuit is represented by E. Applying Ohm's Law to Equation 3 results in:

Equation 4: $R_1 * I_1 + R_{T2} * I_3 = E$ and $R_1 * I_1 + R_2 * I_2 + R_{T1} * I_2 = E$

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

$$\begin{bmatrix} 1 & -1 & -1 \\ R_1 & 0 & R_{T2} \\ R_1 & R_2 + R_{T1} & 0 \end{bmatrix} * \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} 0 \\ E \\ E \end{bmatrix}$$

The solution for I_1 is as follows:

Equation 5: $$I_1 = \frac{E(R_2+R_{T1}+R_{T2})}{R_1(R_2+R_{T1}+R_{T2})+R_{T2}(R_2+R_{T1})}$$

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

Equation 6: $$\left(\frac{E(R_2+R_{T1}+R_{T2})}{R_1(R_2+R_{T1}+R_{T2})+R_{T2}(R_2+R_{T1})}\right) * \frac{R_1}{E} = \frac{V_1}{E}$$

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 R_1 and R_2 which are 3550 and 6025 ohms, respectively. Both the CONUS and Alaska equations are derived directly from fitting linear functions to the data in Figure 2. Fitting methods may have deviated which explains some of the differences between the CONUS and Alaska equations. The CONUS equation is as follows:

Equation 7 (CONUS): $$194.45 * \frac{V_1}{E} - 65.929 = T_c$$

Alaska uses a different linear equation to convert a single ended voltage measurement to temperature in Fahrenheit. The original equations used in Alaska SNOTEL stations is as follows:

Equation 8: $$0.14204 * V_1 - 69.1335 = T_f$$

where V_1 is the single ended voltage measured across resistor 1 and T_f is the temperature in Fahrenheit. The conversion of the original Alaskan equation is necessary to be comparable to the output of the other equations used in these studies. Converting Equation 8 to use Celsius and to use a voltage fraction the equation becomes:

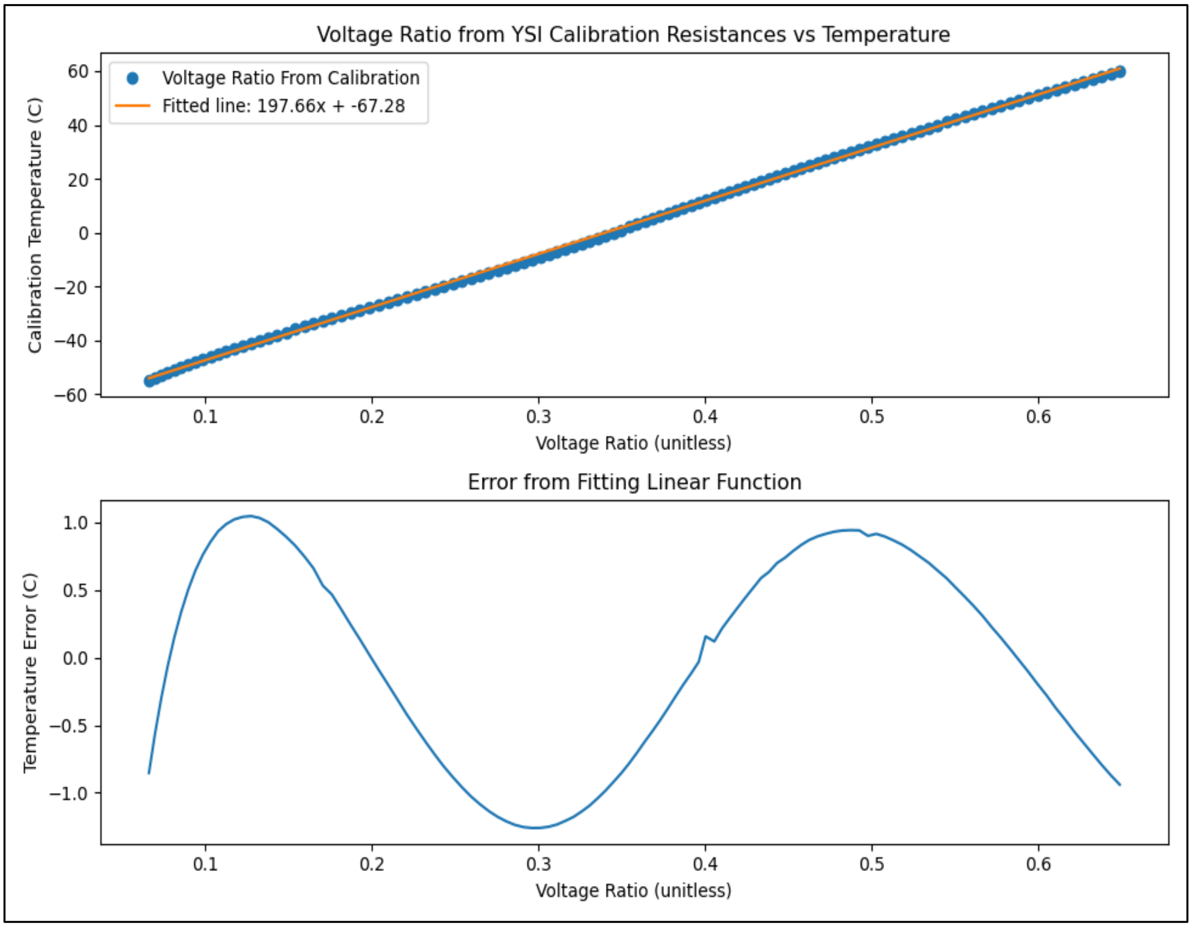
Equation 9 (AK): $$197.278 * \frac{V_1}{E} - 67.296 = T_c$$

Snow Survey Temperature Chamber Study to Evaluate YSI Bias

The Snow Surveys electronics maintenance facility (EMF) tested 30 YSI sensors in a temperature chamber from -40° to 60° degrees to quantify the bias that results from using the linear CONUS and AK 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 (Brown, et al., 2019). The study concluded that error resulting from the use of the linear equations can be on the order of 1.5 degrees. EMF also generated a 5th order polynomial to replace the linear equations that convert voltages to temperature, shown below:

Equation 10 (SNOW5):

$$4766.05146484375 * \left(\frac{V_1}{E}\right)^5 - 9280.2580859375 * \left(\frac{V_1}{E}\right)^4 + 6612.560359375 * \left(\frac{V_1}{E}\right)^3 - 2089.41573125 * \left(\frac{V_1}{E}\right)^2 + 476.8520699999999 * \left(\frac{V_1}{E}\right) - 79.098511 = T_c$$


Voltage Ratio from YSI Calibration Resistances vs Temperature

Error from Fitting Linear Function

Figure 2: An example of error produced when fitting a linear equation to voltage ratio vs temperature calibration data. The voltage ratios are calculated using Equation 6 and the calibration resistances provided by YSI. A least square fitting method results in a function approximately equal to the operational equation used in Alaska.

NOAA Group Produces Equation to Bias Reduce NPS YSI Data

A team from 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 YSI sensors never deployed in the field (Hill, et al. 2016). The fifth and ninth order polynomial are as follows:

Equations 11 (NOAA5):

$$4823.128484 \ast \left(\frac{V_1}{E}\right)^5 - 9429.534608 \ast \left(\frac{V_1}{E}\right)^4 + 6744.164264 \ast \left(\frac{V_1}{E}\right)^3 - 2139.119324 \ast \left(\frac{V_1}{E}\right)^2 + 484.7566852 \ast \left(\frac{V_1}{E}\right) - 79.57962269 = T_c$$

Equations 12 (NOAA9):

$$610558.226380138 \ast \left(\frac{V_1}{E}\right)^9 - 2056177.65461394 \ast \left(\frac{V_1}{E}\right)^8 + 2937046.42906361 \ast \left(\frac{V_1}{E}\right)^7 - 2319657.12916417 \ast \left(\frac{V_1}{E}\right)^6 + 1111854.33825836 \ast \left(\frac{V_1}{E}\right)^5 - 337069.883250001 \ast \left(\frac{V_1}{E}\right)^4 + 66105.7015922199 \ast \left(\frac{V_1}{E}\right)^3 - 8386.78320604513 \ast \left(\frac{V_1}{E}\right)^2 + 824.818021779729 \ast \left(\frac{V_1}{E}\right) - 86.7321006757439 = T_c$$

ANALYSIS

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 various lengths of time and 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.

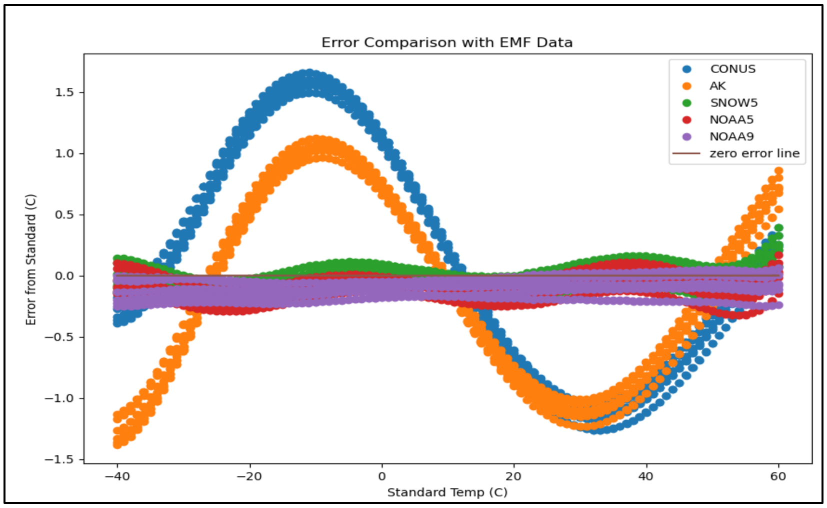


Figure 3: Error from the reference thermistor when applying the five temperature conversion equations to the EMF temperature chamber data.

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 3 and 4. The two NOAA equations show some bias where much of the error is less than the reference temperature. Because the NOAA equations were fit to YSIs never deployed in the field, 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.

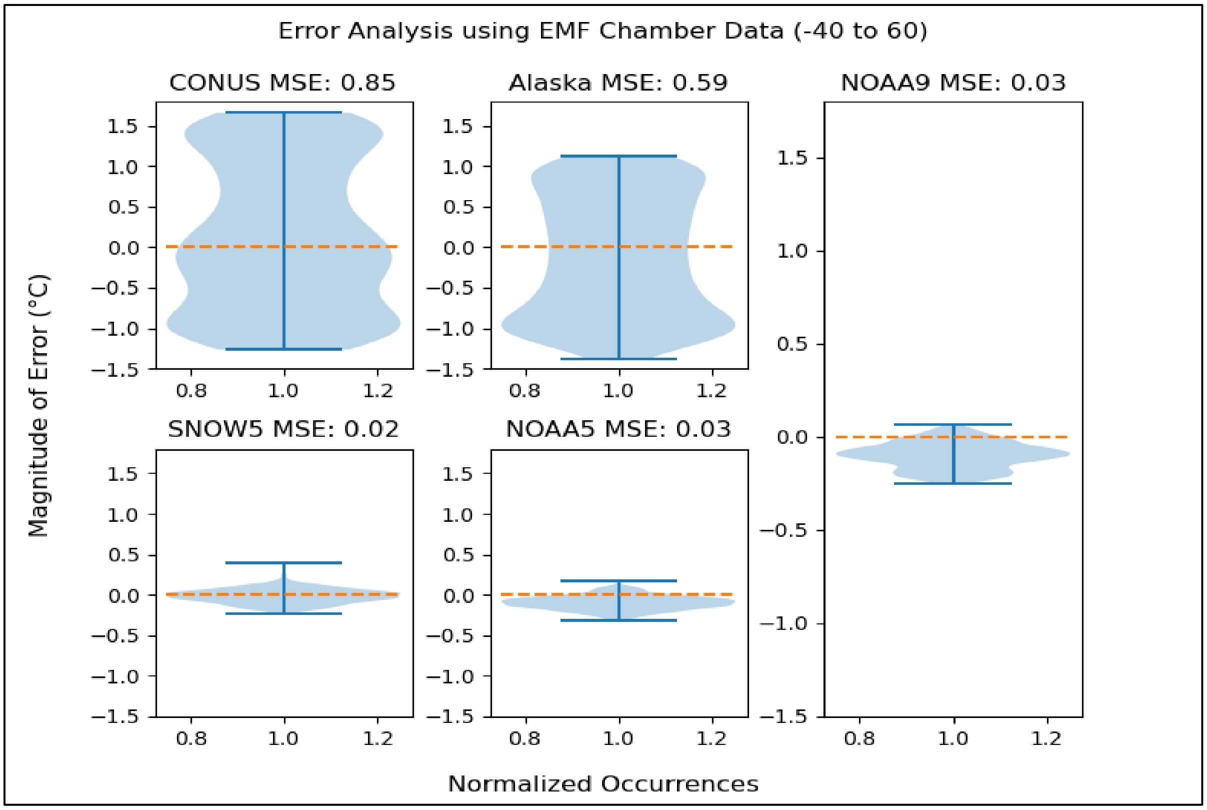


Figure 4: Violin plots of error when using different correction equations on EMF temperature chamber data.

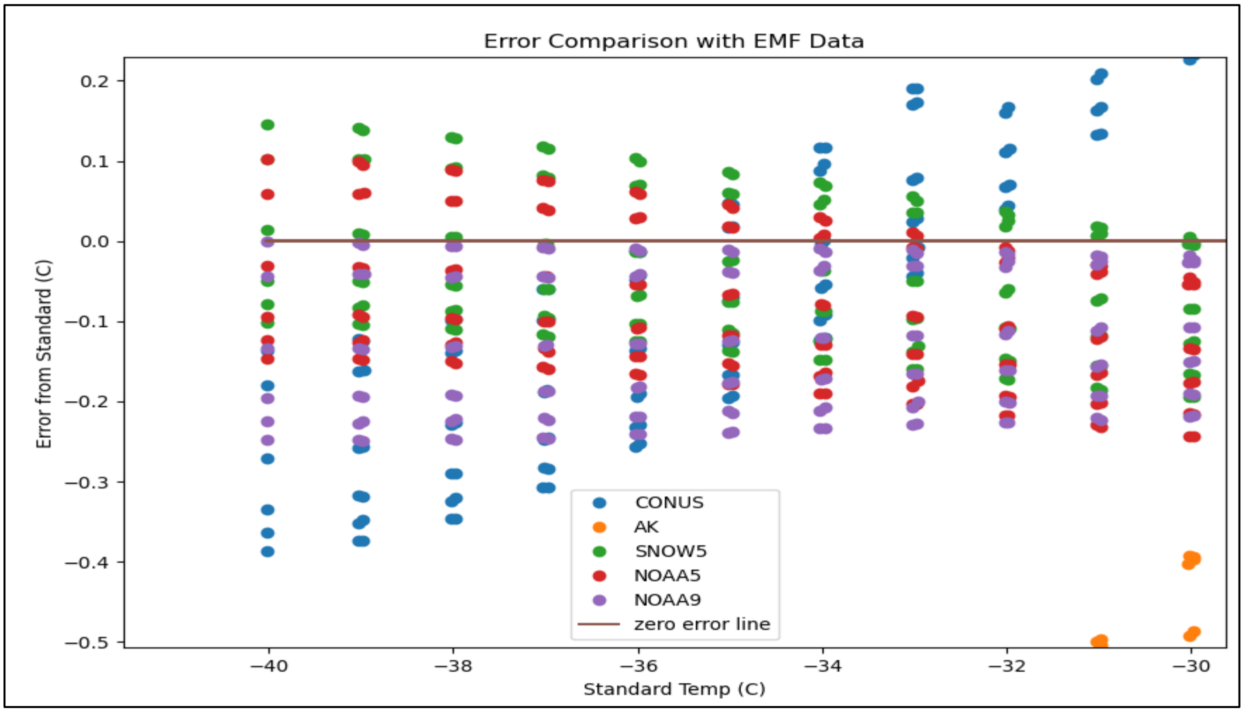


Figure 5: A comparison of the five temperature equations at the cold end of the EMF temperature chamber data. These results show that the SNOW5, NOAA5 and NOAA9 produce similar results.

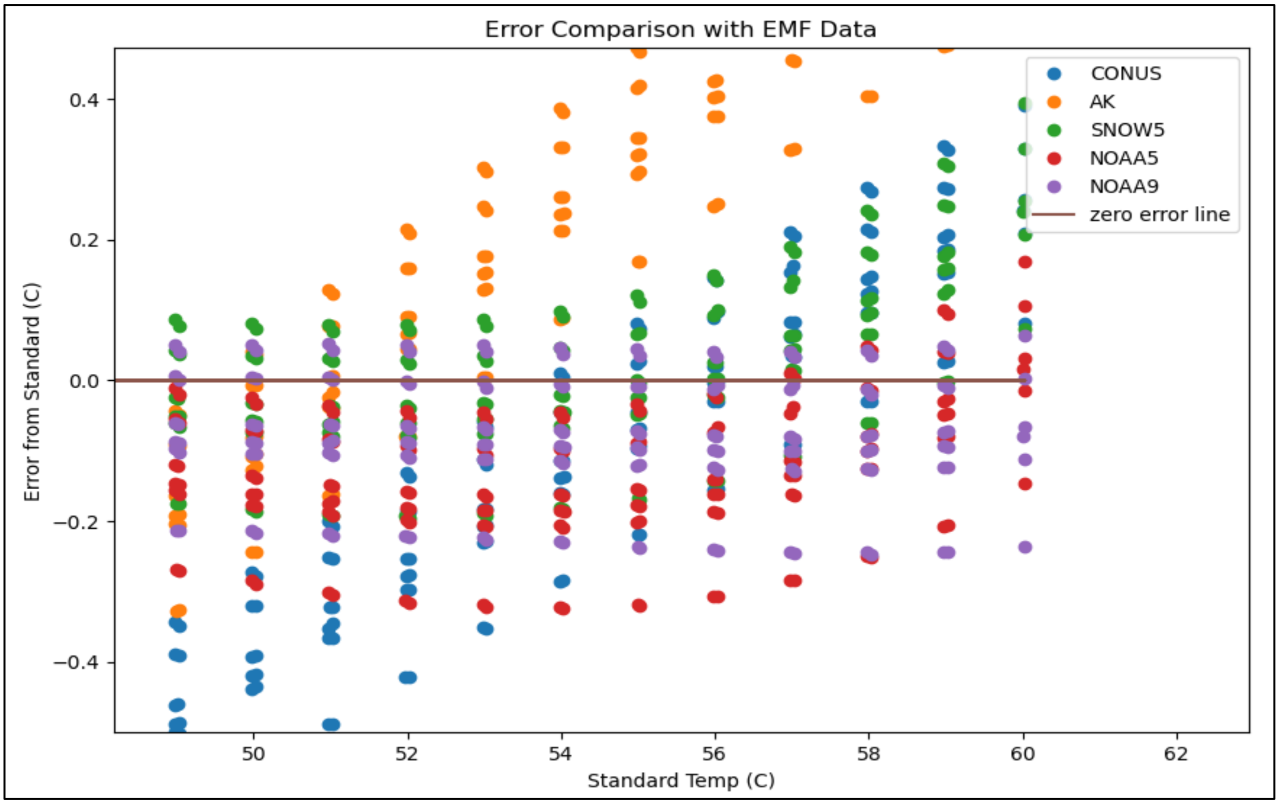


Figure 6: A comparison of the five temperature equations at the warm end of the EMF temperature chamber data. Despite less overall bias, SNOW5 does display more bias at extreme temperatures then the NOAA5 and NOAA9 equations.

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 7 through 10. As with the EMF chamber data, the SNOW5, NOAA5 and NOAA9 equations all produce a similar correction. Bias can be seen in Figure 8 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.

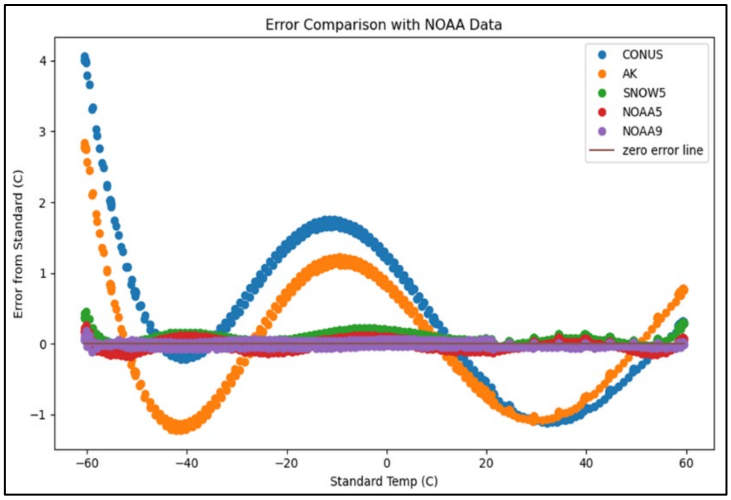


Figure 7: Error from the reference thermistor when applying the five temperature conversion equations to the NOAA temperature chamber data.

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.

A risk when dealing with higher-order polynomials is the risk of overfitting the data. Taking the derivative and calculating critical points we can prove the equation does not overfit and have predictable behavior between the intervals desired. Figure 11 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 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.

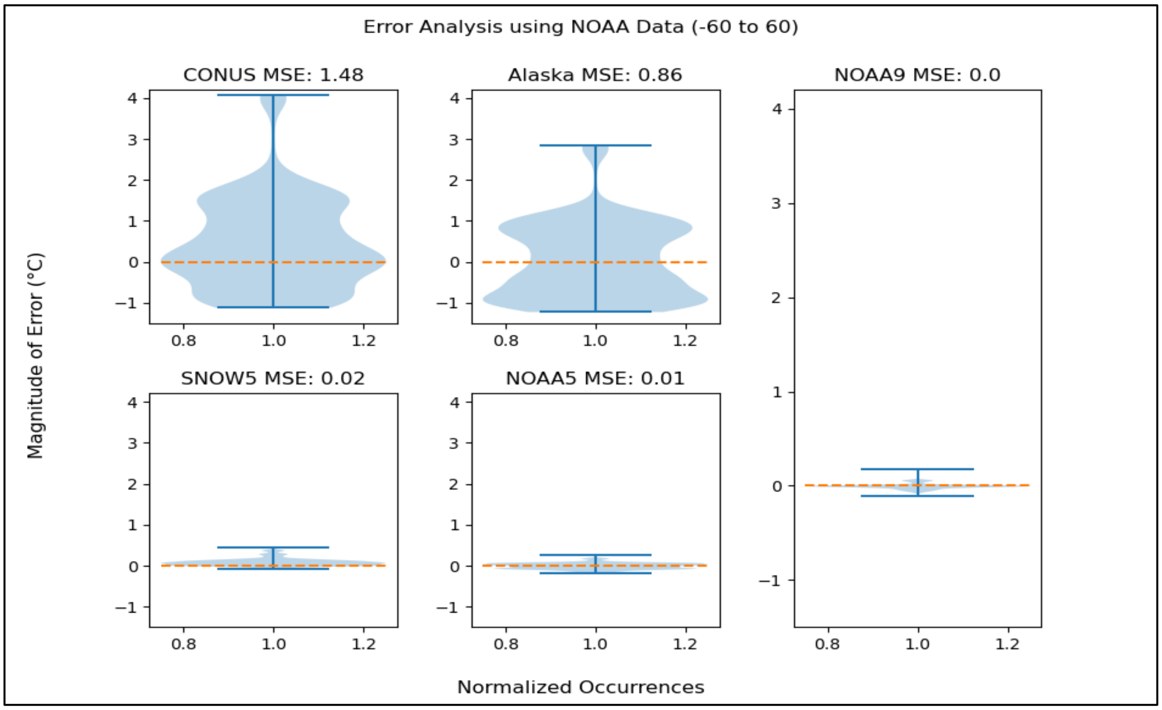


Figure 8: Violin plots of error when using different correction equations on NOAA temperature chamber data.

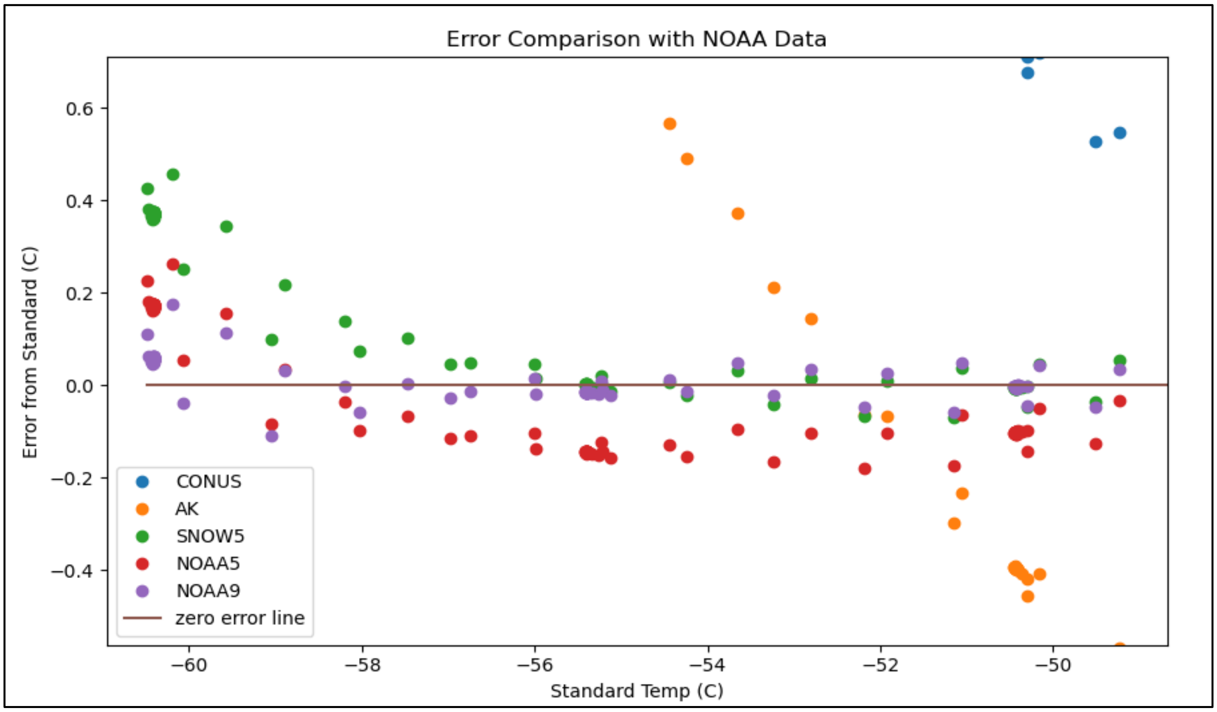


Figure 9: A comparison of the five temperature equations at the cold end of the NOAA temperature chamber data. The SNOW5, NOAA5 and NOAA9 produce similar results except when the sensors exceed their design limit.

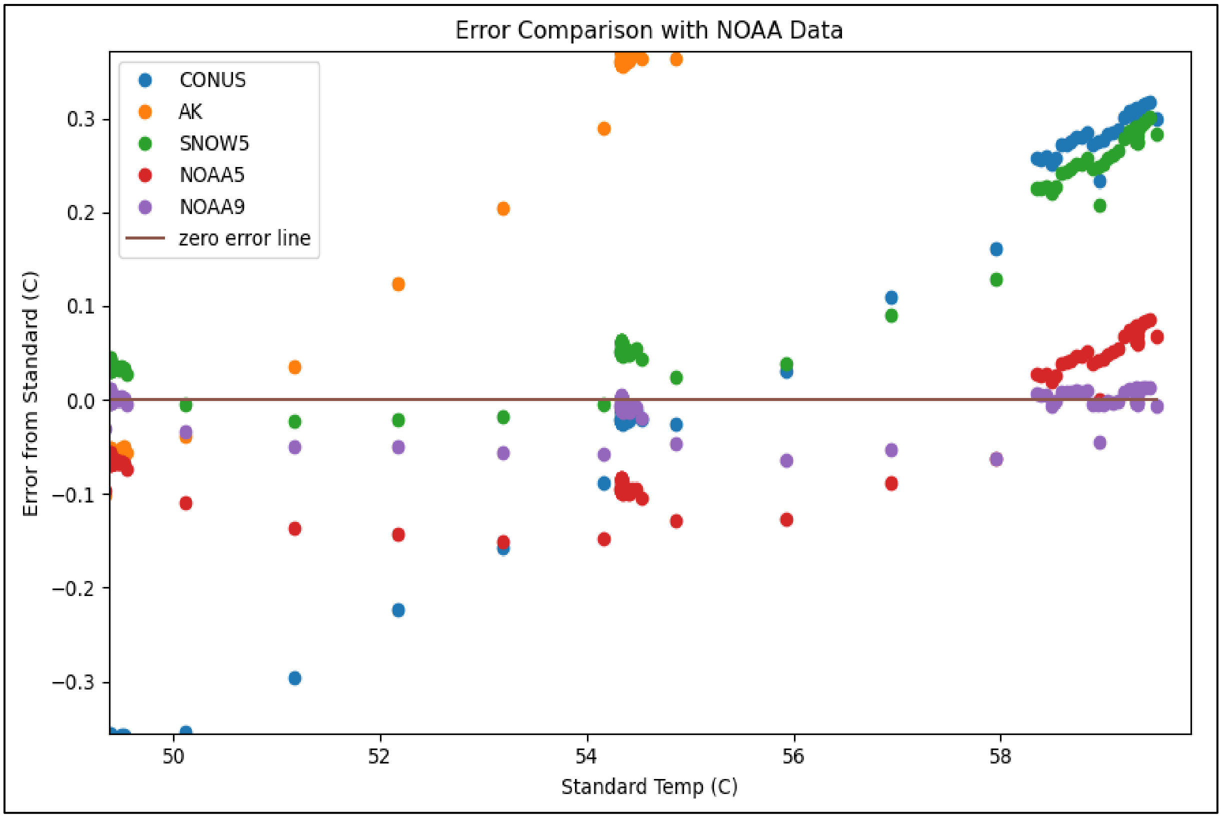


Figure 10: A comparison of the five temperature equations at the warm end of the NOAA temperature chamber data. Both NOAA5 and SNOW5 show bias; SNOW5 higher than 55 C and NOAA5 between 48 C and 58 C.

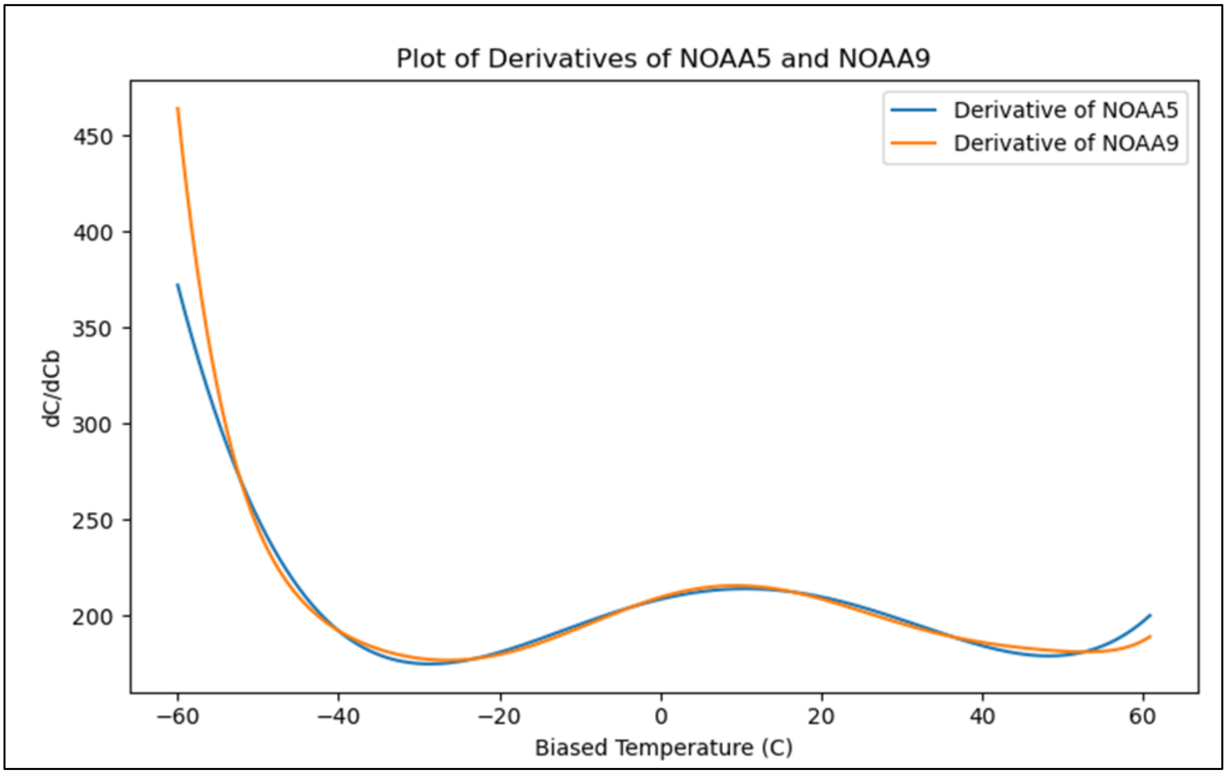


Figure 11: Plot showing the derivatives of NOAA5 and NOAA9 equations.

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 sensor 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 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 13 Correction equation using NOAA9 CONUS:

$$\begin{aligned}
610558.226380138 * \left(\frac{(T_{bias-c} + 65.929)}{194.45}\right)^{9} - 2056177.65461394 * \left(\frac{(T_{bias-c} + 65.929)}{194.45}\right)^{8} \\
+ 2937046.42906361 * \left(\frac{(T_{bias-c} + 65.929)}{194.45}\right)^{7} - 2319657.12916417 \\
* \left(\frac{(T_{bias-c} + 65.929)}{194.45}\right)^{6} + 1111854.33825836 * \left(\frac{(T_{bias-c} + 65.929)}{194.45}\right)^{5} \\
- 337069.883250001 * \left(\frac{(T_{bias-c} + 65.929)}{194.45}\right)^{4} + 66105.7015922199 \\
* \left(\frac{(T_{bias-c} + 65.929)}{194.45}\right)^{3} - 8386.78320604513 * \left(\frac{(T_{bias-c} + 65.929)}{194.45}\right)^{2} \\
+ 824.818021779729 * \left(\frac{(T_{bias-c} + 65.929)}{194.45}\right) - 86.7321006757439 = T_c
\end{aligned}$$

Equations 14 Correction equation using NOAA9 AK:

$$\begin{aligned}
610558.226380138 * \left(\frac{(T_{bias-c} + 67.296)}{197.278}\right)^{9} - 2056177.65461394 * \left(\frac{(T_{bias-c} + 67.296)}{197.278}\right)^{8} \\
+ 2937046.42906361 * \left(\frac{(T_{bias-c} + 67.296)}{197.278}\right)^{7} - 2319657.12916417 \\
* \left(\frac{(T_{bias-c} + 67.296)}{197.278}\right)^{6} + 1111854.33825836 * \left(\frac{(T_{bias-c} + 67.296)}{197.278}\right)^{5} \\
- 337069.883250001 * \left(\frac{(T_{bias-c} + 67.296)}{197.278}\right)^{4} + 66105.7015922199 \\
* \left(\frac{(T_{bias-c} + 67.296)}{197.278}\right)^{3} - 8386.78320604513 * \left(\frac{(T_{bias-c} + 67.296)}{197.278}\right)^{2} \\
+ 824.818021779729 * \left(\frac{(T_{bias-c} + 67.296)}{197.278}\right) - 86.7321006757439 = T_c
\end{aligned}$$

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