Land Surface Temperature retrieval and long-term pattern analysis for Gilpin County, Colorado between 2014 and 2018

This study retrieves Land Surface Temperature (LST) maps using a single-channel algorithm (Jiménez-Muñoz et al. 2009, 2014) on the thermal band (i.e., band 10) of Landsat 8 satellite images, then compares them to Landsat 8's available Analysis Ready Data (ARD8) in order to distinguish a LST trend over the five-year period (i.e., 2014-2018). Each of the datasets (mean, standard deviation, and other metrics for the retrieved and observed times series) resembles a "wave-like" curve, which is common when observing temperature graphs over an annual time-series.

Gilpin county lies on about 75.9% forest, located significantly west of the Denver metropolitan area, and encompasses the area just north of the I-70/ Hwy 119 exit until you reach the town of Nederland. Arapahoe National Forest occupies a majority of the county, separated by shrubland and a few urban developments of small mountain/ mining towns. With the combination of higher elevation and forest-vegetation land-cover in Gilpin county, the annual cycle of the solar zenith angle variation and the subsequent variation of solar shortwave down welling energy result in the "wave-like" LST curve for each of the metrics (minimum, maximum, median, mean and standard deviation) to be distributed amidst lower LST (Kelvin) values than those observed in the remaining 5 counties, with the exception of San Juan county. The minimum ARD8 LST average of Gilpin county is 276.14 degrees kelvin (˚K), which is the second lowest (following San Juan county) minimum ARD8 LST average of the 6 counties observed (e.g., average minimum LST between ARD8 and Retrieved is 263.99 ˚K for San Juan county (20% barren-land, with the rest forested)). For the maximum metric, LST averages are 301.47 ˚K for ARD8 and 301.4 ˚K for Retrieved data, again lower than maximum temperature of every county observed besides San Juan. Gilpin county's mean metric yielded averages at 287.73 ˚K for ARD8 LST and 287.42 ˚K for Retrieved LST. Remaining metrics also display this consistent trend with average median values of 287.4 ˚K for ARD8 and 287.41 ˚K for Retrieved LST. Plotted standard deviation values were 3.9 ˚K for ARD8 and 4.7 ˚K Retrieved LST, indicating that land surface temperature values are dispersed within moderate proximity of the mean, with account for a few drastic outliers.

Once acquired LST (°K) values for both ARD8 and Retrieved datasets were plotted, a standard sinusoidal model was used to best-fit the “wave-like” curve generated by the plots. The equation used for fitting each non-linear regression is as follows:

$$y = A\cos(B \cdot x + C) + D + E \cdot x$$

where ‘*y*’ is the optimized LST value (data point fit to each date-index), ‘*A*’ represents the amplitude (height from mean value), *‘B’* represents the period (frequency of the cycle; in this case days throughout an annual cycle) and ‘*x’* is the date-index from the starting date (of the five-year period). ‘*C*’ represents the phase- shift, ‘*D*’ is the displacement (vertical shift) and ‘*E*’ is the long-term slope of each metric over the five-year period.

In order to acquire parameters for the *A-E* values in the equation, the ‘Solver’ add-in tool of Excel Office 2016 was used to calculate optimized values. The optimizer asks for a set of parameters to base the optimization on. In this case, “Set objective: (desired cell)”, “To: (min objective cell value)” and “By changing variable cell: (cells containing initial estimations of *A-E* values) are the only parameters modified. Every ‘desired cell’ contained an objective function outputting the ‘Sum of Square Error” (*SSE*) of fitted y-values in comparison with the original y-values (here y refers to either ARD8 or retrieved LST). The initial *A-E* values were estimated using a-priori information and optimized via the default Excel “GRG non-linear” method that accommodates problems that are smoot non-linear.

For the non-linear regressions, R^2 values were calculated for every metric using the following equation:

$$R^2 = 1 - (SSE / SST)$$

where *SSE* (Sum of Square Error) is the ‘error variation’ (e.g., sum of the squared distances from the fitted to the original y-values) and *SST* (Total Sum of Squares) being the ‘total variation’ in the ‘y-value’. R^2 allows us to determine how close the model’s prediction is to the true values or how much of the total variation can be explained by the model (the closer to 1, the more accurate the model), which is essential in the validation process.

In addition, a linear regression was conducted and plotted for each metric as a second measure of the respective long-term increase and decrease patterns. This was done by plugging the calculated slope and y-intercept values (gathered using LINEST function built into Excel Office 2016) into the standard *Y* = *mx* + *B* equation, then plotting the start and end-date LST values for each counties' metrics. *Note: LINEST function uses "least squares" method to calculate a straight line to fit the data, as well as returning an array describing the regression statistics. The structure of the function is LINEST ([known_y's], [known_x's], [const], [stats]), where setting 'const' to 'True' allows a non-zero intercept, and 'stats' to 'True' returns additional regression statistics.

Gilpin County

Minimum LST

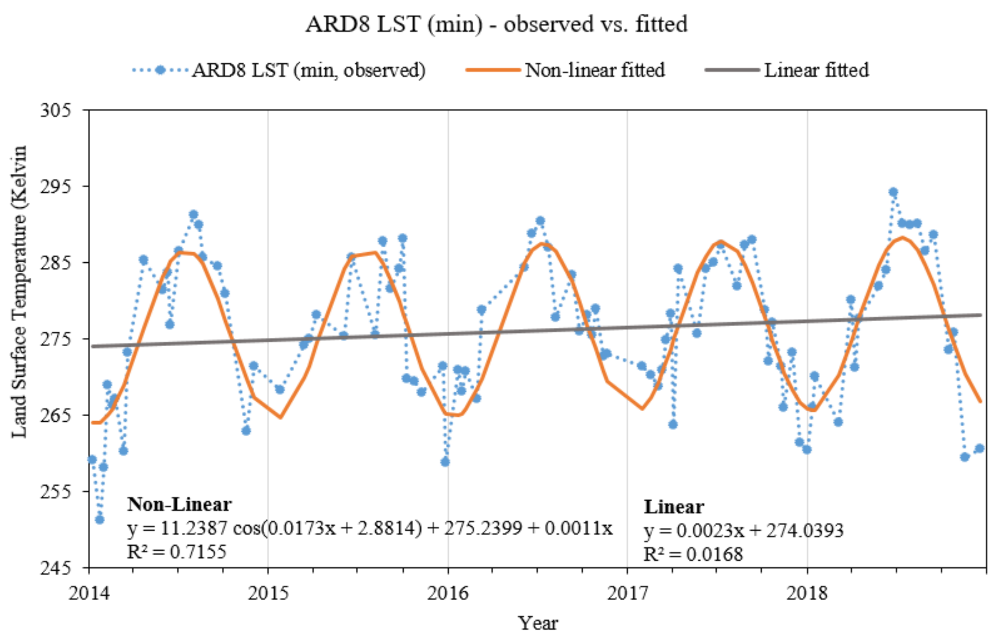

Figure 1. displays the minimum Land Surface Temperature of the Analysis Ready Data (Landsat 8) for Gilpin county 2014-2018.

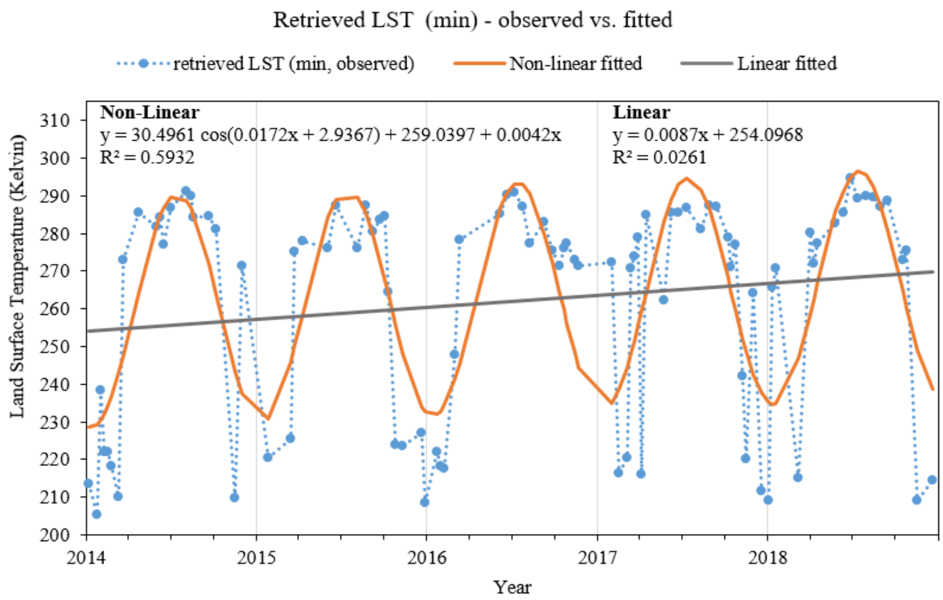

Figure 2. displays the minimum Land Surface Temperature of Gilpin county's Retrieved LST series from 2014- 2018.

Table 1. shows linear and non-linear R^2 values (minimum) from *Figures 1 & 2.*

Table 1. Gilpin County Minimum Regression Slopes and R^2 Values

	ARD 8 LST	Retrieved LST
Linear R^2	0.0168	0.0261
Non-linear R^2	0.7155	0.5932
Linear Slope	-0.0031	0.0087
Non-linear Slope	0.0011	0.0042

Calculations drawn from *Figures 1 & 2* of the 'minimum' metric for ARD LST and Retrieved LST yielded R^2 values that indicate a low linear correlation due to the annual wave-like pattern (non-linear). ARD8 LST showed an annual temperature change value of 0.4102 °K/year (minor increase in LST) while the Retrieved LST trend showed an annual change of 1.5197 °K/year (increase in LST). Non-linear R^2 values for both ARD8 and Retrieved LST were less than 0.5, indicating the model could use some adjustment for a better fit. R^2 values for non-linear regressions more accurately depict the ‘fit’ because the data points are not linearly changing with days.

Table 2. gives more statistical detail on the **linear** regressions from *Figures 1 & 2* the minimum temperature for both ARD 8 LST and retrieved LST.

Table 2. Gilpin County Minimum Linear Descriptive Statistics

	P-value *Slope*	P-value *Y-intercept*	Lower 95% *Slope*	Upper 95% *Slope*	Lower 95% *Y-intercept*	Upper 95% *Y-intercept*
ARD 8 LST	0.2133	2.61 E-68	-0.0013	0.0059	270.19	277.89
Retrieved LST	0.1197	1.25 E-62	-0.0023	0.0196	242.34	265.86

As shown in *Table 2*, the *p-value(slope)* yielded by the (minimum) ARD8 LST and Retrieved LST linear regression is greater than 0.1 ($P > 0.1$), meaning that there is consistency with the null hypothesis (no change over time). Both ARD8 and Retrieved LST *p-values(y-intercept)* show values that are less than 0.001 ($P < 0.001$), proving strong evidence against the null hypothesis, or in equivalent, there is significant evidence in favor of the alternative (minimum ARD8 LST changes over time). Since the slope terms are not significantly different from zero for both (minimum) ARD8 and retrieved LST, it can be inferred that the minimum LST values for Elbert county are from 270.19 °K to 277.89 °K for ARD8 and from 242.34 °K to 265.86 °K for Retrieved LST.

Maximum LST

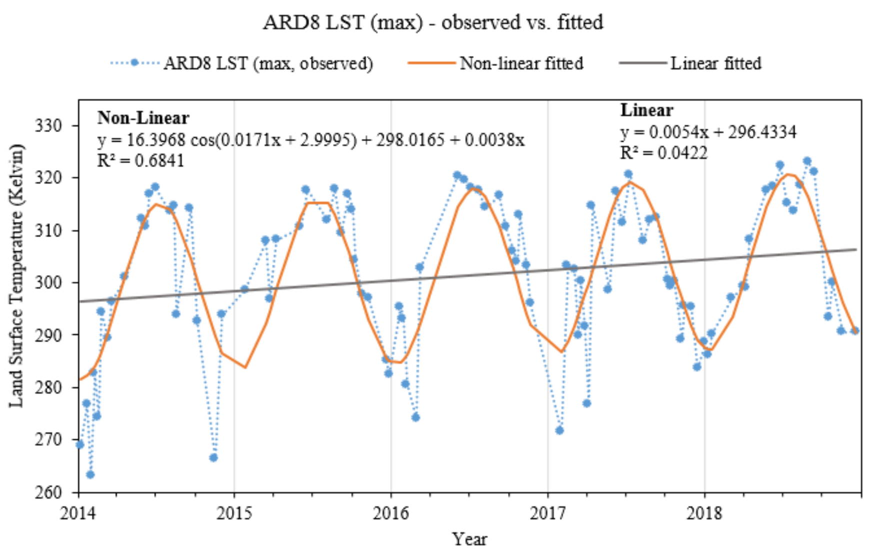

Figure 3. displays the maximum Land Surface Temperature of the Analysis Ready Data (Landsat 8) for Gilpin county 2014-2018.

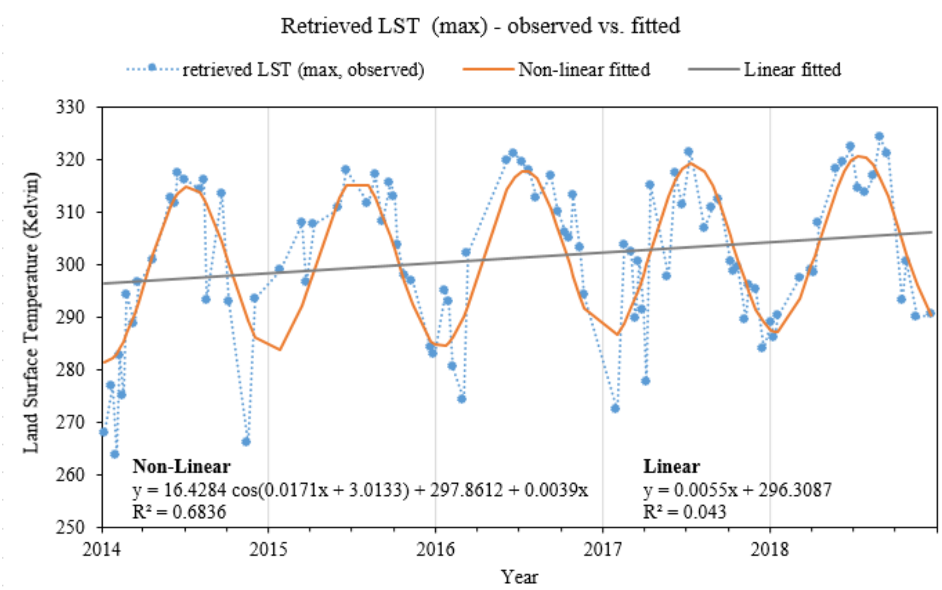

Figure 4. displays the maximum Land Surface Temperature of Gilpin county's Retrieved LST series from 2014- 2018.

Table 3. shows linear and non-linear R^2 values (maximum) from *Figures 3 & 4*.

Table 3. Gilpin County Maximum Regression Slopes and R^2 Values

	ARD 8 LST	Retrieved LST
Linear R^2	0.0422	0.043
Non-linear R^2	0.6841	0.6836
Linear Slope	0.0054	0.0055
Non-linear Slope	0.0038	0.0039

The 'maximum' metric calculations from *Figure 3 & 4* for ARD LST and Retrieved LST also yielded R^2 values that indicate a low linear correlation due to the annual wave-like pattern. ARD8 LST showed an annual temperature change value of 1.393 °K/year (slight increase in LST) while the Retrieved LST trend showed an annual change of 1.4293 °K/year (also slight increase in LST). Non-linear R^2 values for both ARD8 and Retrieved LST are at ~0.68, indicating the model is fit at least 68% accurate.

Table 4. gives more statistical detail on the **linear** regressions for the maximum temperature of ARD 8 LST and retrieved LST datasets.

Table 4. Gilpin County Maximum Linear Descriptive Statistics

	P-value *Slope*	P-value *Y-intercept*	Lower 95% *Slope*	Upper 95% *Slope*	Lower 95% *Y-intercept*	Upper 95% *Y-intercept*
ARD 8 LST	0.047	1.26 E-96	0.00007	0.0108	290.69	302.18
Retrieved LST	0.045	1.5 E-96	0.00012	0.0109	290.56	302.06

The *p-values(slope)* yielded by both (maximum) ARD8 LST and Retrieved LST data plots lie between 0.01 and 0.05, which demonstrates moderate evidence against the null hypothesis (no change), in favor of LST change for the maximum metric. Both ARD 8 and

Retrieved LST *p-values(y-intercept)* show values that are less than 0.001 (P < 0.001), proving strong evidence against the null hypothesis, in favor of a non-zero maximum LST. Because the slope terms were not significantly different from zero for both (maximum) ARD8 and retrieved LST, a suggestion that the maximum LST values for Gilpin county lie from 290.69 °K to 302.18 °K for ARD8 and from 290.56 °K to 302.06 °K for Retrieved LST.

Median LST

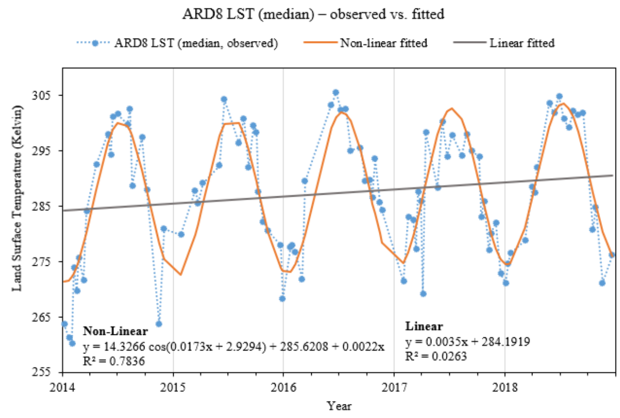

Figure 5. displays the median Land Surface Temperature of the Analysis Ready Data (Landsat 8) for Gilpin county 2014-2018.

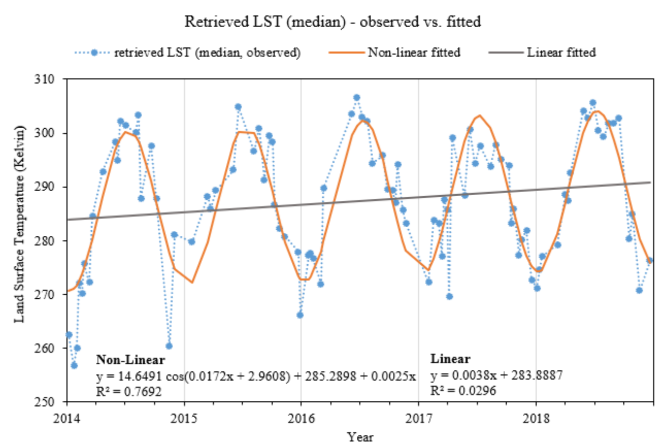

Figure 6. displays the median Land Surface Temperature of Gilpin county's Retrieved LST series from 2014- 2018.

Table 5. table shows linear and non-linear R^2 values (median) from *Figures 5 & 6.*

Table 5. Elbert County Median Regression Slopes and R² Values

	ARD 8 LST	Retrieved LST
Linear R^2	0.0256	0.031
Non-linear R^2	0.7553	0.7402
Linear Slope	0.0048	0.0047
Non-linear Slope	0.0023	0.0023

Again, *Figure 5 & 6* displaying the 'median' metric for ARD LST and Retrieved LST yielded R^2 values that indicate a low linear correlation due to the annual wave-like pattern (non-linear). ARD8 LST showed an annual temperature change value of 0.8293 °K/year (increase in LST) and similarly, the Retrieved LST trend showed an annual change of 0.8217 °K/year. Non-linear R^2 values for both ARD8 and Retrieved LST were at about ~0.75, indicating the model is fit relatively well. One thing to note is that R^2 values for non-linear regressions more accurately depict the 'fit' because the data points are not linearly changing with days.

Table 6 gives more statistical detail on the **linear** regressions for the median temperature of ARD 8 LST and retrieved LST datasets.

Table 6. Gilpin County Median Linear Descriptive Statistics

	P-value *Slope*	P-value *Y-intercept*	Lower 95% *Slope*	Upper 95% *Slope*	Lower 95% *Y-intercept*	Upper 95% *Y-intercept*
ARD 8 LST	0.1183	4.33 E-103	-0.0009	0.0078	279.51	288.87
Retrieved LST	0.097	7.58 E-102	-0.0007	0.0083	279.07	288.71

The *p-values(slope)* results for both(median) ARD8 LST and Retrieved LST data plots are right around 0.1, demonstrating weak evidence against the null hypothesis (no change). Both ARD8 and Retrieved LST *p-values(y-intercept)* show values that are less than 0.001 ($P < 0.001$), proving strong evidence against the null hypothesis, in favor of a non-zero median LST. As a result of the slope terms not showing significant difference from zero for both (median) ARD8 and retrieved LST, one can infer that the median LST values for Gilpin county range from 279.51 °K to 288.87 °K for ARD8 and from 279.07 °K to 288.71 °K for Retrieved LST.

Mean LST

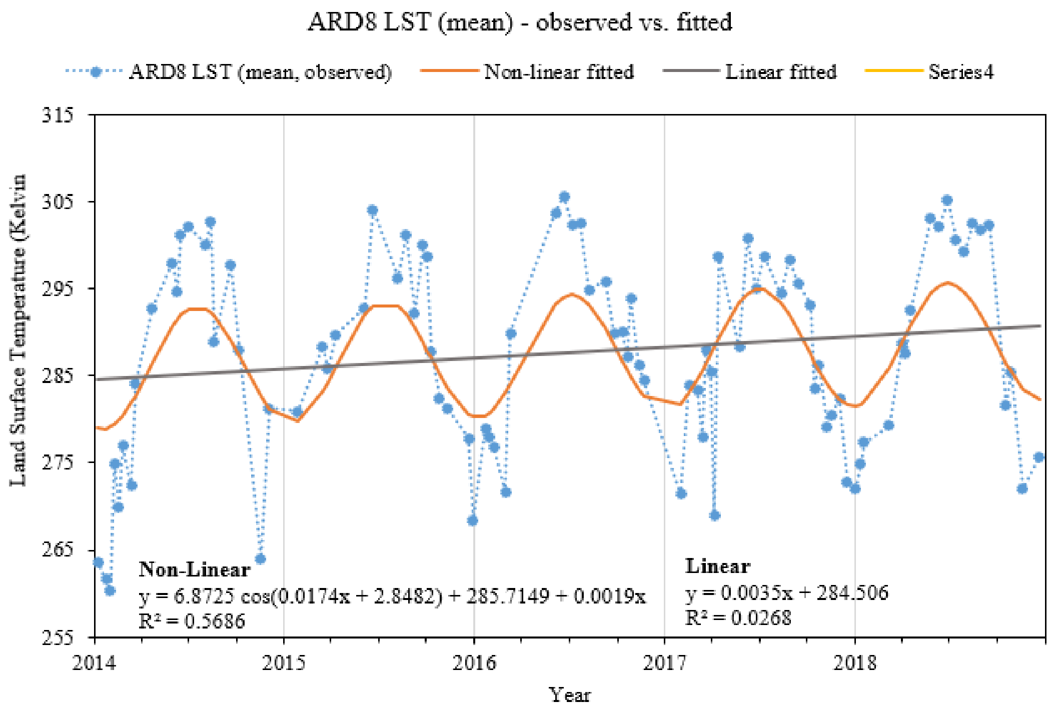

Figure 7. displays the mean Land Surface Temperature of the Analysis Ready Data (Landsat 8) for Gilpin county 2014-2018.

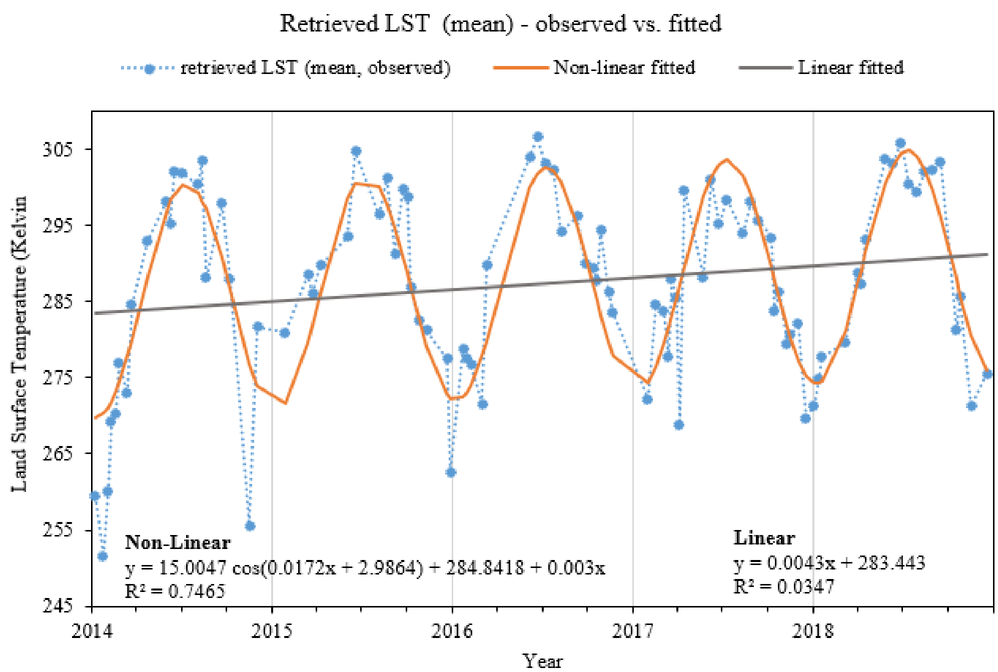

Figure 8. displays the mean Land Surface Temperature of Gilpin county's Retrieved LST series from 2014- 2018.

Table 7. shows linear and non-linear R^2 values (mean) from *Figure 7 & 8* (ARD 8 & retrieved LST).

Table 7. Gilpin County Mean Regression Slopes and R^2 Values

	ARD 8 LST	Retrieved LST
Linear R^2	0.0268	0.0347
Non-linear R^2	0.5686	0.7465
Linear Slope	0.0035	0.0043
Non-linear Slope	0.0019	0.003

Just as previous metrics, the 'mean' in *Figures 7 & 8* for ARD LST and Retrieved LST yielded R^2 values that indicate a low linear correlation due to the annual wave-like pattern (non-linear). ARD8 LST showed an annual temperature change value of 0.6798 °K/year (slight increase in LST) while the Retrieved LST trend showed an annual change of 1.0942 °K/year (significant increase, greater than 1). The non-linear R^2 value for ARD8 LST was substantially weaker than what has been commonly observed in the study (0.5686), likely due to the large number of outliers that made it difficult for the model to account for. Retrieved LST yielded a bit stronger of an R^2 with 0.7465, indicating the model fit to data in that figure is ~75% accurate. As previously mentioned, the R^2 values for non-linear regressions more accurately depict the 'fit' because the data points are not linearly changing with days.

Table 8. gives more statistical information on the **linear** regressions for the mean temperature of ARD 8 LST and retrieved LST plots.

Table 8. Gilpin County Mean Linear Descriptive Statistics

	P-value *Slope*	P-value *Y-intercept*	Lower 95% *Slope*	Upper 95% *Slope*	Lower 95% *Y-intercept*	Upper 95% *Y-intercept*
ARD 8 LST	0.1151	2.15 E-103	-0.0009	0.0078	279.86	289.16
Retrieved LST	0.0721	3.03 E-100	-0.0004	0.009	278.43	288.46

The *p-values(slope)* yielded by both (mean) ARD8 LST and Retrieved LST data plots are in close proximity to 0.1, which demonstrates weak evidence against the null hypothesis (no change). Both ARD8 and Retrieved LST *p-values(y-intercept)* show values that are less than 0.001 ($P < 0.001$), again proving strong evidence against the null hypothesis, in favor of a non-zero mean LST. Once again since the slope terms do not show significant difference from zero for both (mean) ARD8 and retrieved LST, one can infer that the mean LST values for Elbert county range from 279.86 to 289.16 °K for ARD8 and from 278.43 to 288.46 °K for Retrieved LST.

Standard Deviation

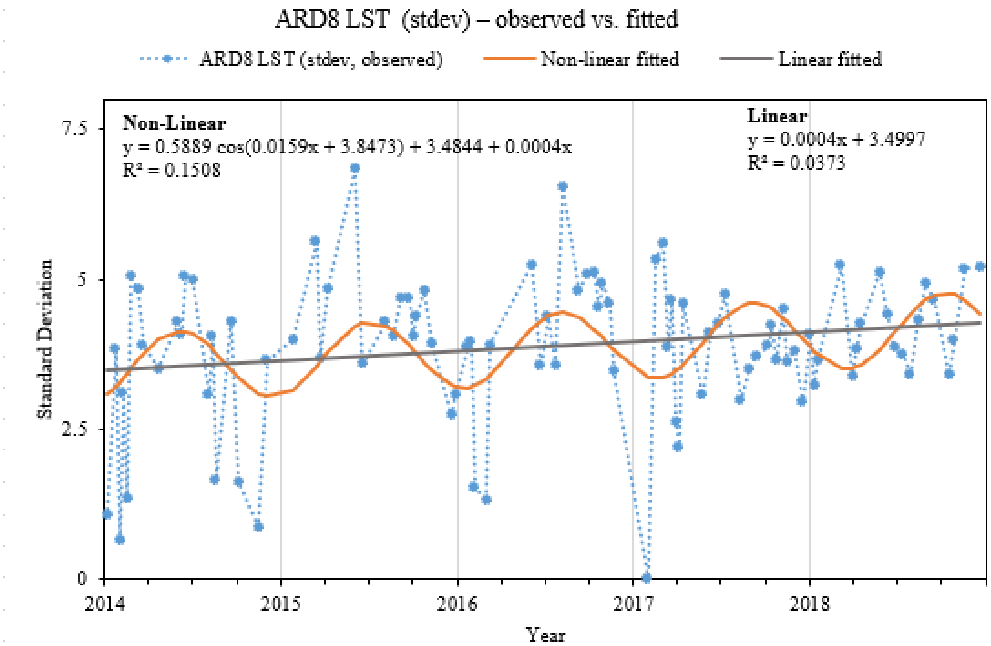

Figure 9. displays the standard deviation of Land Surface Temperature for the Analysis Ready Data (Landsat 8) in Gilpin county 2014-2018.

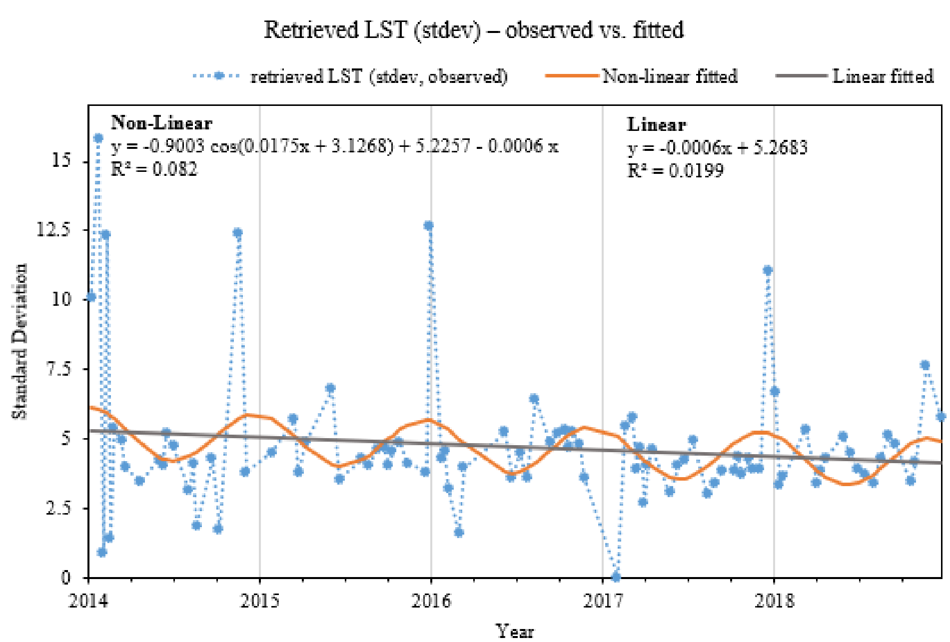

Figure 10. displays the standard deviation of Land Surface Temperature for Gilpin county's Retrieved LST series from 2014- 2018.

Table 9. shows linear and non-linear *R^2* values (standard deviation) of regressions in *Figures 9 & 10* (ARD 8 & retrieved LST).

Table 9. Gilpin County Standard Deviation Regression Slopes and R^2 Values

	ARD 8 LST	Retrieved LST
Linear R^2	0.0373	0.0199
Non-linear R^2	0.1508	0.082
Linear Slope	0.0004	-0.0006
Non-linear Slope	0.0004	-0.0006

The standard deviation for ARD LST and Retrieved LST also yielded R^2 values that indicate a low linear correlation due to the annual wave-like pattern. ARD8 LST showed an annual temperature change value of 0.1471 °K/year resembling a slight increase in total variation from the mean LST. The Retrieved LST trend showed an annual change of -0.2278 °K/year (minor decrease). Non-linear R^2 values for both ARD8 and Retrieved LST were below 0.5, indicating the model is fit is weak-moderate for the standard deviation metric.

Table 10. gives more statistical background on the **linear** regressions for the standard deviation of temperature for ARD 8 LST and retrieved LST datasets.

Table 10. Gilpin County Standard Deviation Linear Descriptive Statistics

	P-value *Slope*	P-value *Y-intercept*	Lower 95% *Slope*	Upper 95% *Slope*	Lower 95% *Y-intercept*	Upper 95% *Y-intercept*
ARD 8 LST	0.0624	3.84 E-25	-0.00002	0.0009	3.01	3.99
Retrieved LST	0.1753	3.23 E-18	-0.0015	0.0003	4.31	6.23

The *p-values(slope)* yielded by both (standard deviation) ARD8 LST and Retrieved LST lie between 0.05 and slightly over 0.1 which demonstrates weak-moderate evidence against the null hypothesis (no change in total variation from mean LST). Both ARD8 and Retrieved LST *p-values(y-intercept)* show values that are less than 0.001 ($P < 0.001$), again proving strong evidence against the null hypothesis, in favor of a non-zero standard deviation LST. Once again since the slope terms do not show significant difference from zero for both ARD8 and retrieved LST, is safe to say that the variation from the mean for LST values for Gilpin county is between 3.01 and 3.99 °K for ARD8 or from 4.31 to 6.23 °K for Retrieved LST.

Conclusion for Gilpin County

After running these analyses on land surface temperature data for both ARD 8 and Retrieved images, there are a few conclusions that can be drawn as this research moves forward. The average R^2 value yielded for all non-linear regression metrics is 0.5749 for ARD 8 LST, and 0.5691 for Retrieved LST. The quality of these R^2 values desire a much better yield in order to give the model more significance in how the data were fit. It is still noticeable that the "fit" is more accurate at winter and summer peaks on the curve, but for this county, even the transitional periods resemble a poor adjustment to outliers which entails model uncertainty.

The outliers were more apparent in metrics of this county than the previous observed. This could be due to possible inaccuracy in the way snow cover (which is far more prominent in the intermountain region of Colorado) and emissivity were interpreted on certain days of image retrieval.

Linear trends were in close enough proximity for both non-linear and linear regressions to be able to say they show a similar pattern (or some change over time). Whether that pattern demonstrates enough significance is a different story. The average non-linear slope for all metrics is 0.0038 for ARD8 LST and 0.0026 for Retrieved LST. This shows a minor positive trend (increase in land surface temperature over the five-year range). The average linear slope for all metrics is 0.0022 for ARD8 LST and 0.0045 for Retrieved LST, also showing a very minimal positive trend (increase in land surface temperature over the five-year range).

Generally speaking, there is a slight trend in favor of increasing land surface temperature over time, but more statistically significant results are still desired to solidify there is in fact a change is LST over specified time series. Applying certain changes to the model as previously mentioned, as well as exceeding the annual date-range to be at least two or three times greater could create a foreseeable trend that will carry much more value in this research.

References

Jiménez-Muñoz, J. C., Cristóbal, J., Sobrino, J. A., Sòria, G., Ninyerola, M., & Pons, X. (2008). Revision of the single-channel algorithm for land surface temperature retrieval from Landsat thermal-infrared data. *IEEE Transactions on geoscience and remote sensing*, *47*(1), 339-349.

Jiménez-Muñoz, J. C., Sobrino, J. A., Skoković, D., Mattar, C., & Cristóbal, J. (2014). Land surface temperature retrieval methods from Landsat-8 thermal infrared sensor data. *IEEE Geoscience and remote sensing letters*, *11*(10), 1840-1843.