Land Surface Temperature retrieval and long-term pattern analysis for Moffat 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.

Moffat county lies on about 77.9% shrubland, with the remaining land-uses allocated to agriculture, mineral mining/ exploration, and electrical power generation/ transmission. Though Moffat county is less developed than both Denver and Elbert county, it still contains industrialized areas that are continually being developed. The western front range of Colorado tends to have hot summer days and moderate-temperature, high-precipitation winters. Temperatures tend to fluctuate a bit more throughout the days (higher highs, and lower lows), which agrees with Moffat county's climate summaries (U.S. climate-data). 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 similarly to LST (Kelvin) values observed for Gilpin and Elbert counties, aside from a few variations in average temperature that should be noted. The minimum ARD8 LST average of Moffat county is 276.03 degrees kelvin (°K), which happens to be about the same for Gilpin county, and only warmer than San Juan county's ARD8 LST average when compared to the 6 counties observed (e.g., average minimum LST ARD8 for Gilpin county is 276.14 °K and 272.34 °K for San Juan county). For the maximum metric, LST averages are 310.65 °K for ARD8 and 309.75 °K for Retrieved data, again higher than maximum temperature values of 5 of the 6 counties (Denver county being highest with its metropolitan area contributing to a "heat-island" effect). Moffat county's mean metric yielded averages at 297.11 °K for ARD8 LST and 295.85 °K for Retrieved LST, being warmer than Gilpin and San Juan counties only. Remaining metrics also display this consistent trend with average median values of 299.45 °K for ARD8 and 296.64 °K for Retrieved LST.

Plotted standard deviation values were 4.15 °K for ARD8 and 4.55 °K Retrieved LST, indicating that land surface temperature values are dispersed a bit higher from the mean, likely due to larger daily temperature fluctuations.

Once acquired LST (°K) values for both ARD8 and Retrieved datasets were plotted, and 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.

Moffat County

Minimum LST

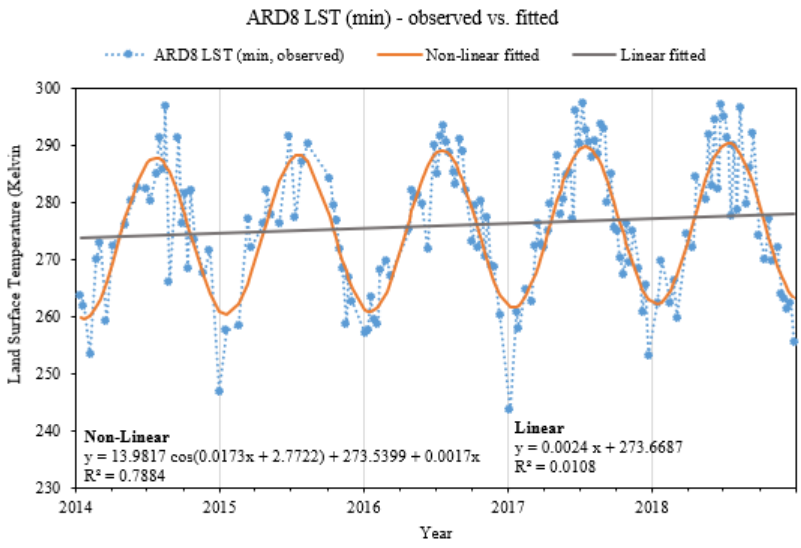

Figure 1. displays the minimum Land Surface Temperature of the Analysis Ready Data (Landsat 8) for Moffat county 2014-2018.

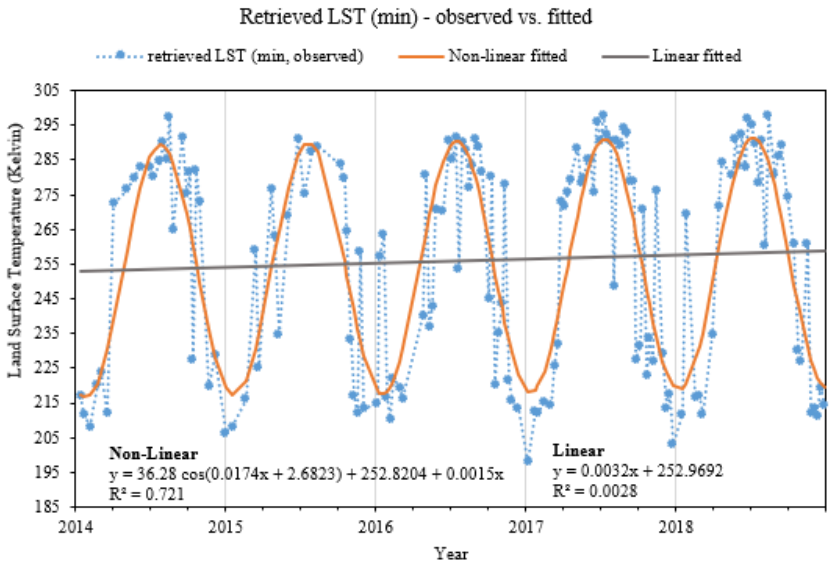

Figure 2. displays the minimum Land Surface Temperature of Moffat county's Retrieved LST series from 2014- 2018.

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

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

	ARD 8 LST	Retrieved LST
Linear R^2	0.0108	0.0028
Non-linear R^2	0.7884	0.721
Linear Slope	0.0024	0.0032
Non-linear Slope	0.0017	0.0015

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 0.6315 °K/year (slight increase in LST) while the Retrieved LST trend showed an annual change of 0.5445 °K/year (minor increase in LST). Non-linear R^2 values for both ARD8 and Retrieved LST were greater than 0.7, indicating the model is fit moderately well. 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. Moffat 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	0.2003	2.47 E-158	-0.0013	0.006	269.60	277.74
Retrieved LST	0.5133	6.17 E-90	-0.0065	0.013	241.96	263.98

As shown in *Table 2*, the *p-value(slope)* yielded by both (minimum) ARD8 LST and Retrieved LST linear regression is greater that 0.1 ($P > 0.1$), meaning that there is strong evidence in favor of the null hypothesis, which is no (minimum) ARD8 LST change over the five-year period. Both ARD8 and Retrieved LST *p-values(y-intercept)* show values that are less than 0.001 ($P < 0.001$), indicating strong evidence against the null hypothesis, in favor of a non-zero minimum LST. 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 Moffat county are from 269.60 °K to 277.74 °K for ARD8 and from 241.96 °K to 263.98 °K for Retrieved LST.

Maximum LST

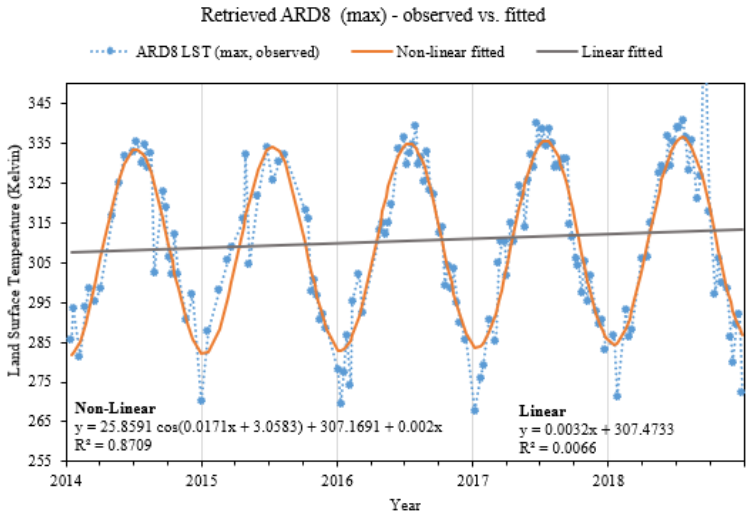

Figure 3. displays the maximum Land Surface Temperature of the Analysis Ready Data (Landsat 8) for Moffat county 2014-2018.

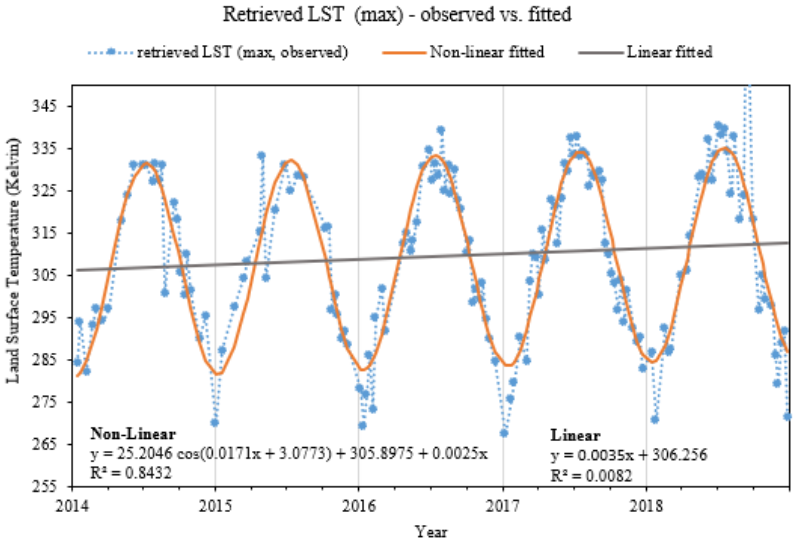

Figure 4. displays the maximum Land Surface Temperature of Moffat county's Retrieved LST series from 2014- 2018.

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

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

	ARD 8 LST	Retrieved LST
Linear R^2	0.0066	0.0082
Non-linear R^2	0.8709	0.8432
Linear Slope	0.0032	0.0035
Non-linear Slope	0.002	0.0025

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 0.7415 °K/year (slight increase in LST) while the Retrieved LST trend showed an annual change of 0.9015 °K/year (slight increase in LST). Non-linear R^2 values for both ARD8 and Retrieved LST were greater than 0.80, indicating the model is fit at least 80% accuracy.

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

Table 4. Moffat 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	0.3176	1.49 E-130	-0.0031	0.0094	300.45	314.5
Retrieved LST	0.266	5.36 E-131	-0.0027	0.0096	299.31	313.2

The *p-values(slope)* yielded by both (maximum) ARD8 LST and Retrieved LST data plots are greater than 0.1 ($P > 0.1$), which demonstrates consistency with the null hypothesis (no change). 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 Moffat county lie from 300.45 °K to 314.5 °K for ARD8 and from 299.31 °K to 313.2 °K for Retrieved LST.

Median LST

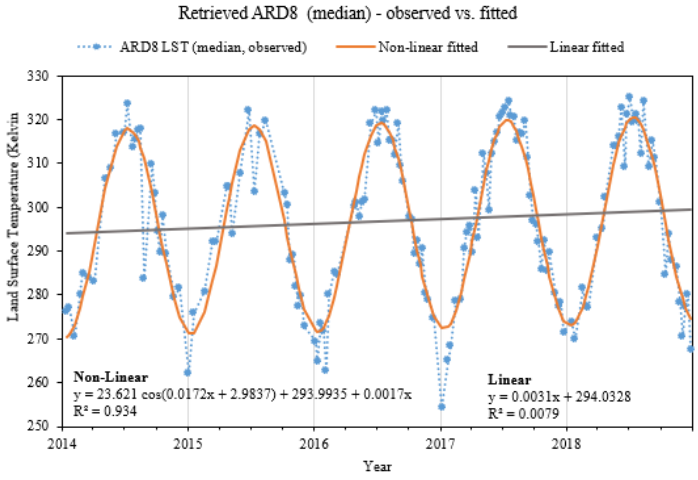

Figure 5. displays the median Land Surface Temperature of the Analysis Ready Data (Landsat 8) for Moffat county 2014-2018.

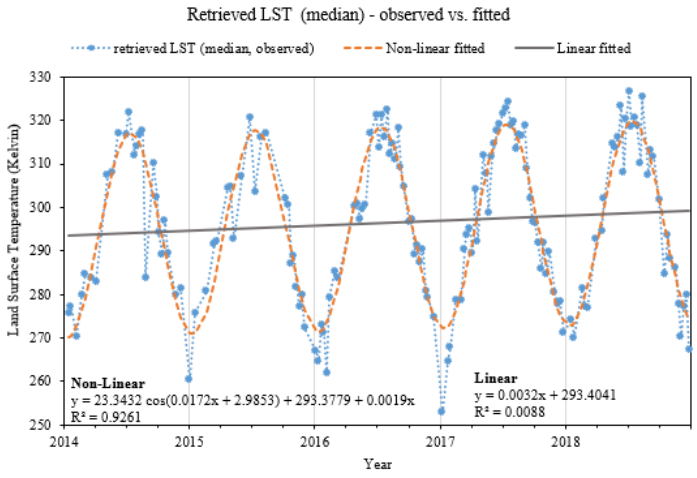

Figure 6. displays the median Land Surface Temperature of Moffat county's Retrieved LST series from 2014- 2018.

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

Table 5. Moffat County Median Regression Slopes and R^2 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 0.6366 °K/year (increase in LST) and similarly, the Retrieved LST trend showed an annual change of 0.693 °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. Moffat 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	0.2747	2.44 E-135	-0.0025	0.0086	287.8	300.27
Retrieved LST	0.2479	1.1 E-135	-0.0023	0.0087	287.22	299.59

The *p-values(slope)* results for both (median) ARD8 LST and Retrieved LST data plots are greater than 0.1 (P > 0.1), indicating strong consistency with 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 Moffat county range from 287.8 °K to 300.27 °K for ARD8 and from 287.22 °K to 299.59 °K for Retrieved LST.

Mean LST

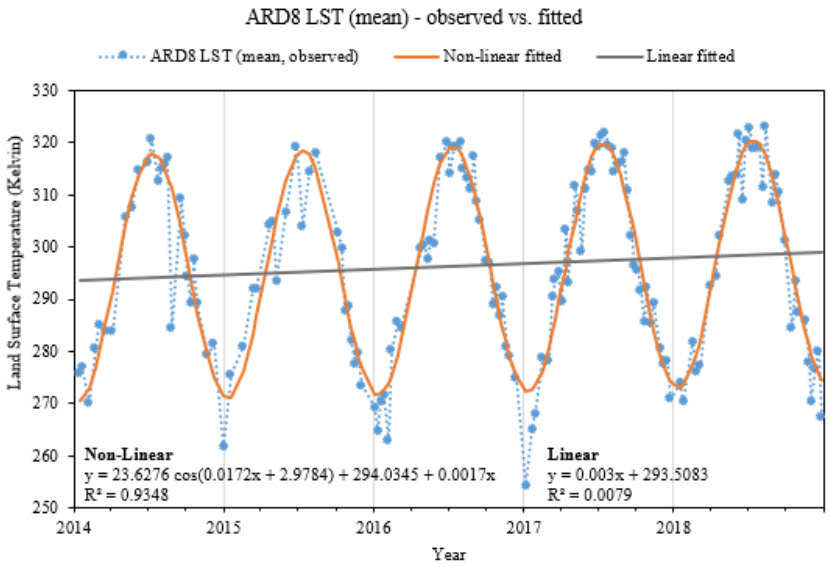

Figure 7. displays the mean Land Surface Temperature of the Analysis Ready Data (Landsat 8) for Moffat county 2014-2018.

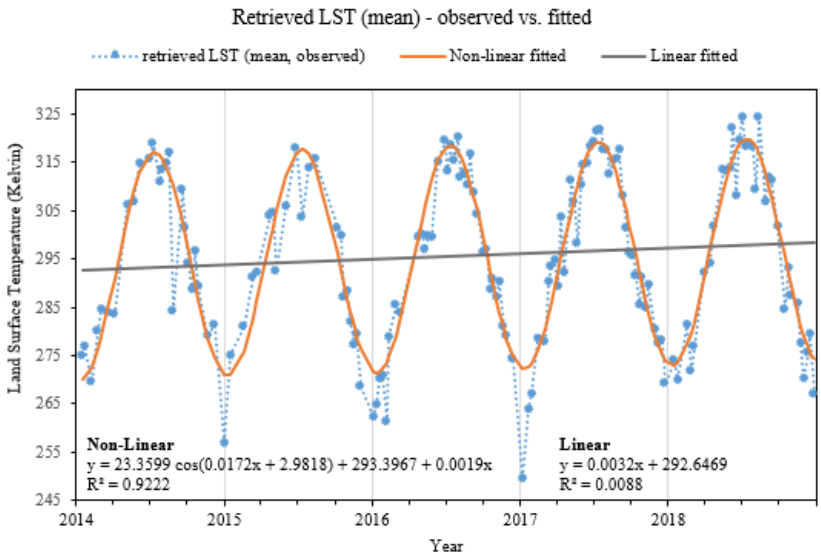

Figure 8. displays the mean Land Surface Temperature of Moffat county's Retrieved LST series from 2014- 2018.

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

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

	ARD 8 LST	Retrieved LST
Linear R^2	0.0079	0.0088
Non-linear R^2	0.9348	0.9222
Linear Slope	0.003	0.0032
Non-linear Slope	0.0017	0.0019

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 0.6159 °K/year (slight increase in LST) and the Retrieved LST trend showed a similar annual change of 0.6849 °K/year. Non-linear R^2 values for both ARD8 and Retrieved LST are greater than 0.90, indicating the model is fit exceptionally well to this metric. As previously mentioned, there is a common R^2

value pattern 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. Moffat 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	0.2748	5.55 E-137	-0.0024	0.0084	287.44	299.58
Retrieved LST	0.2477	3.82 E-136	-0.0022	0.0086	286.52	298.78

The *p-values(slope)* yielded by both (mean) ARD8 LST and Retrieved LST data plots are greater than 0.1 ($P < 0.1$), again demonstrating strong compliancy with 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 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 Moffat county range from 287.44 to 299.58 °K for ARD8 and from 286.52 to 298.78 °K for Retrieved LST.

Standard Deviation

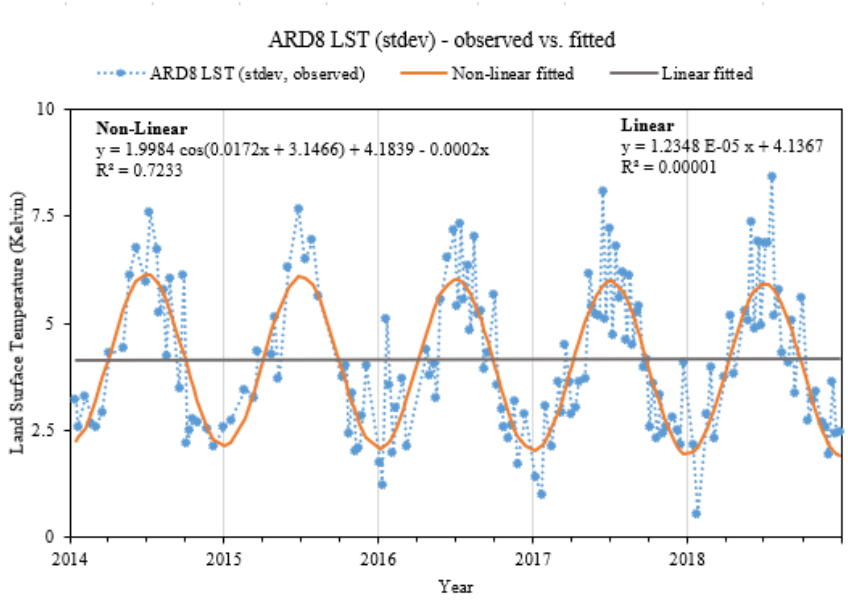

Figure 9. displays the standard deviation of Land Surface Temperature for the Analysis Ready Data (Landsat 8) in Moffat county 2014-2018.

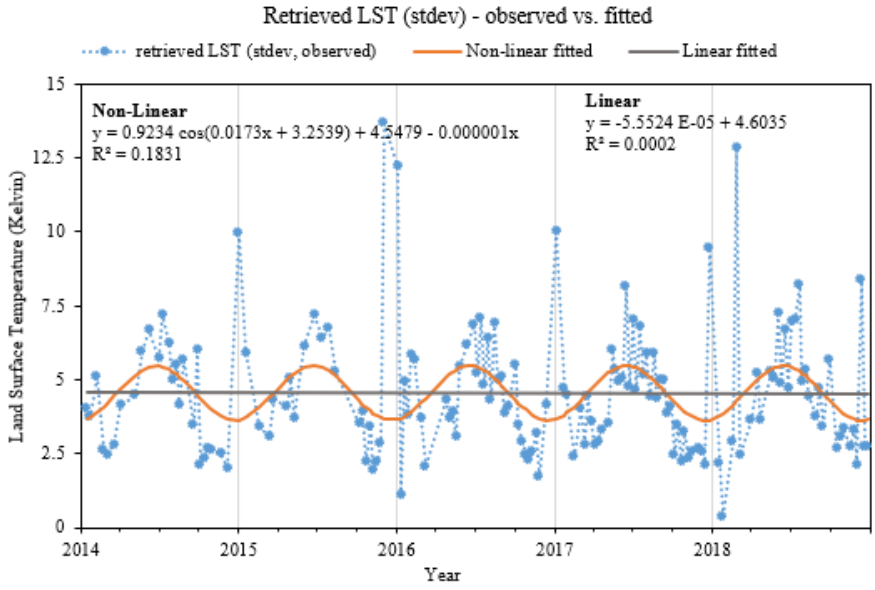

Figure 10. displays the standard deviation of Land Surface Temperature for Moffat county's Retrieved LST series from 2014- 2018.

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

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

	ARD 8 LST	Retrieved LST
Linear R^2	0.00001	0.0002
Non-linear R^2	0.7233	0.1831
Linear Slope	1.24 E-05	-5.55 E-05
Non-linear Slope	0.0002	- 0.000001

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 -0.1835 °K/year which is a minor decrease in total variation from the mean LST. The Retrieved LST trend showed an annual change of -0.0439 °K/year (again, a 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. Moffat 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	0.0985	3.18 E-23	-0.0009	7.68 E-05	2.84	3.95
Retrieved LST	0.05	1.68 E-24	-0.001	1.88 E-08	2.92	4.01

The *p-values(slope)* yielded by both (standard deviation) ARD8 LST and Retrieved LST lie between 0.05 and 0.1 which demonstrates moderate evidence against the null hypothesis, favoring change in total variation from the mean over the five-year period. 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 Moffat county is between 2.84 and 3.95 °K for ARD8 or from 2.92 to 4.01 °K for Retrieved LST.

Conclusion for Moffat County

After running several analyses on land surface temperature data for both ARD 8 and Retrieved images, somethings can surely be noted as this research moves forward. The average R^2 value yielded for all non-linear regression metrics is 0.8503 for ARD 8 LST, and 0.7191 for Retrieved LST. These values demonstrate a fair amount of strength in terms of how the model was fit, indicating that fitted regressions are on average at least 70% accurate. With that in mind, there is still a desire to yield values closer to 1. It is still noticeable that the "fit" is much more accurate at winter and summer peaks on the curve, while the transitional periods appear to show larger model uncertainty.

The outliers were most apparent in the standard deviation metric for this county, and moderately apparent in the remaining metrics. These variations inevitably contribute to the skewing of the non-linear model and general trend represented. This could be due to possible inaccuracy in the way snow cover 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. Whether that pattern demonstrates enough significance is a different story. The average non-linear slope for all metrics is 0.0014 for ARD8 LST and 0.0015 for Retrieved LST. This shows a very minor increase in land surface temperature over the five-year range (positive trend). The average linear slope for all metrics is

0.0023 for ARD8 LST and 0.0026 for Retrieved LST, also a very slight positive trend in increasing land surface temperature over the five-year period.

Generally speaking, there a minor agreement with the hypothesis being in favor of increasing land surface temperature over time, but more statistically significant results are very much desired. 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

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