CLIMATOLOGICAL TRENDS IN THE BLACK HILLS

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ABSTRACT

This paper represents parts of an M.S. thesis entitled "A Climatology of the Black Hills Region", written by the first author. The purpose of this study was to examine climatological trends for the Black Hills through much of the 20th century, and determine how elevation affects temperature, precipitation, and snowfall at locations in and around the Black Hills. A comparison between climatological results in this study was made with climatological results from the 1949 study by Harley Johnson. Trends over the 1910 to 1994 period indicated a slight increase of 0.4°F in temperature and an increase of 0.3 inches in annual precipitation in the Black Hills. Elevation was found to be a significant forcing factor for temperature and snowfall in the region. Comparisons were made with the 1949 study to see how the averages and extremes had changed over the intermediate 45-year time span. It was found that mean annual temperatures did not appear to have changed, but annual precipitation had increased up to 20% in some areas, while annual snowfall had generally increased in all areas from about 5% to over 100% over the last 50 years.

INTRODUCTION

Weather in the northern Great Plains is quite variable with rapid and extreme changes in temperature and calm-to-storm transition. The Black Hills rise prominently from the adjacent plains of western South Dakota and eastern Wyoming and add an extra element to the weather in this area. Temperature and precipitation totals are often quite different between the surrounding plains and higher elevations of the Black Hills. The orographic effects of the Black Hills allow for large differences in weather in small distances.

The Black Hills are dome shaped with the major axis oriented 340 degrees by 160 degrees (Thornbury, 1954). They rise from about 900 to 1200 meters above the surrounding plains. The area of the Black Hills is approximately 200 kilometers long from north to south and 80 kilometers wide from east to west.

The Black Hills region has its own micro-climate compared to the northern Great Plains region surrounding it. If not for the Black Hills, this area would be the ideal type of continental climate with high daytime temperatures, low nighttime temperatures, extreme alterations of hot and cold, and generally dry with a wet season in the spring and early summer. In the Black Hills, the continental type climate clashes with a mountain type climate, characterized by an increase in rainfall up to elevations of 1500 to 1800 meters, a rapid decrease of humidity with altitude, and wind movements altered (Johnson, 1949).

DATA SET

The instrumented sites which were chosen for this study were all Department of Commerce sites consisting of either National Weather Service sites or cooperative station sites, where people volunteer to take observations of maximum and minimum temperatures and/or precipitation readings on a daily basis (usually taken in the morning). Not every station was located in the center of town and their location from the center of town is designated after the town's name (see Appendix A). For example, the station Hermosa 3SSW was located about 3 miles south–southwest of the center of Hermosa.

The data for this study was taken from the National Climatic Data Centers' (NCDC) Summary of the Day CD-ROM, distributed by EarthInfo, Inc. (1996), which contains temperature, precipitation, snowfall, and where applicable, evaporation values for every NWS station and cooperative station going back to 1948, with a few going back even further.

The sites that were chosen for the study needed to fulfill two requirements in order to be used. One was that the site needed to be located in or within about 20 kilometers of either the South Dakota or Wyoming Black Hills. Belle Fourche and Newell are a little beyond the 20 km perimeter, but are considered important locations that can be used for comparisons to locations in the Black Hills in the analysis. The other consideration was that the sites needed to have at least 30 years of continuous records and include the years of 1965 through 1994.

There were 17 stations with temperature data and 21 sites with precipitation data that satisfied all criteria (see Appendix A). Figure 1 shows the locations of the stations presented in the study. All these sites had temperature, precipitation, and snowfall data, except Buffalo Gap, Buskala Ranch, Hermosa, and Hill City, at which just precipitation and snowfall data were available.

CLIMATOLOGICAL ANALYSIS

Temperature and Precipitation Trends in the Black Hills

When looking at temperature trends, there are different ways to develop them. One general way is a linear trend model (Figure 2), which develops a straight line trend of how temperature has changed over the preceding years. Non-linear trends are better treated by a quadratic trend model (Figure 3), which can show increasing or decreasing trends for the same period of record over shorter periods of time.

Trends of annual mean temperatures were evaluated using averaged values for four of the station sites: Hot Springs, Lead, Rapid City, and Spearfish. These sites give a good representation of the Black Hills, in general, over the 1910 - 1994 period. Annual mean temperatures ranged over 7°F (4°C) difference on a yearly basis (from ~43°F to 50°F). The linear trend indicated an increase of about 0.4°F (0.2°C) over the 1910 to 1994 period (Fig. 2). The quadratic trend (Fig. 3) shows an increase in annual mean temperature of 0.65°F (0.35°C) till the early 1960's and then a decrease through the rest of the period of about 0.25°F (0.14°C).

The linear R^2 value indicates a poor correlation to the yearly temperature values, as would be expected considering the wide variability of the yearly temperatures. The t-test significance of the linear trend slope coefficient showed a *t* value of 0.67, which is low. The significance of the slope was about $\alpha = 0.25$; thus no significant trend was found.

As with the temperature trends, precipitation trends were looked at using the linear trend model (Figure 4) and the quadratic trend model (Figure 5). The yearly mean values were based on mean annual precipitation using the same four stations (Hot Springs, Lead, Rapid City, and Spearfish). The annual precipitation at these four sites ranged from just over 10 inches (250 mm) in 1936 to over 33 inches (840 mm) in 1945. An increase of about 0.35 inches (8.8 mm) was shown over the 1910 - 1994 period. The quadratic model showed most of the increase taking place in the earlier half of the century and the trend leveling off at the end of the period. There is large variability in annual precipitation, even on a year to year basis.

In these plots, the correlation of the yearly precipitation values to the trend line was even poorer than for the temperature trends. The *t*-statistic value of the linear trend slope coefficient was only 0.21, which was significant at $\alpha = 0.42$; thus, no significant trend was found.

Overlapping the temperature and precipitation trend figures, it could be seen that dry years were typically associated with warmer than average temperatures, such as took place in the 1930's and the 1950's. However, the opposite was not necessarily true with wetter than average years, although it is often cooler than average or near average in those years. A scatter plot of temperature vs. precipitation is shown in Fig. 6. The best fit line had a correlation coefficient, *r*, of 0.38. This relationship suggested that lower than average annual temperature years were accompanied by higher than average annual precipitation years at an α of < 0.001.

Temperature, Precipitation, and Snowfall as a Function of Elevation

In Figure 7, the scatter plot of annual mean temperature as a function of elevation shows a rather uniform decrease in temperature with height. Each point and number represents a station listed in the legend to the right, and its corresponding annual mean temperature. The fitted linear regression equation, using the elevation and annual mean temperatures, were calculated using the Minitab version, a statistical software package.

The linear regression equation, above the graph, represents the expected precipitation values, based on elevation, from the values used to derive the equation. This line appears to be a good representation of the data. The average decrease of temperature with height was about 0.7∞F (0.4∞C) per 100 meters which was smaller than that expected.

Above the plot, the linear regression equation, along with the R^2 value, and a *t*-statistic value are given. In this temperature analysis, the observed *t*-statistic value for the slope coefficient was –4.07. The given value for $\alpha = 0.05$ is 1.75. The absolute value A^1–4.07A^1 was greater than 1.75; thus, elevation can be considered a significant variable at $\alpha = 0.001$.

The plot also suggested the possibility that the temperature decrease with elevation could be nonlinear at higher elevations. Deerfield's annual mean temperature was much lower than the fitted regression's expected value at that elevation. However, there were not enough high elevation stations to evaluate a trend.

The two stations that deviated the furthest from the fitted regression line were Mt. Rushmore (higher) and Deerfield (lower). Mt. Rushmore's temperature was higher than would be expected likely because of the location of its recording site. The National Weather Service office in Rapid City, responsible for the maintenance of the stations, reported that this site's location was near the rocky base of the monument mountain. The granite rocks release heat at night back into the atmosphere, keeping night-time temperatures 3∞F to 5∞F (1.5∞C to 3∞C) warmer than would be expected at that elevation. Deerfield's temperature was lower than would be expected at its elevation possibly because it is one of the highest locations in the Black Hills, where the lower water vapor content of the air absorbs less of the outgoing infrared radiation (IR) resulting in greater radiational cooling.

Figure 8 shows mean annual precipitation as a function of elevation for the Black Hills. Each point and number represents a station and its mean annual precipitation value. The middle solid line is the fitted linear regression line for the entire Black Hills. Closer examination of the scatter plot of the precipitation values reveals that many of the southern Black Hills locations are to the left of the Black Hills regression line and many of the northern Black Hills locations are to the right of the regression line. Therefore, it appeared appropriate to split the Black Hills into north and south sections and do a regression for each. The Black Hills data were thus split in half approximately perpendicular to the prevailing NNW winds of the region. In the figure, each station was designated as a southern Black Hills (S.H.) or northern Black Hills (N.H.) location in the legend. The fitted regression lines for the southern Black Hills (dashed line) and the northern Black Hills (dash-dot-dash line) are shown in Fig. 8.

The Black Hills regression line slope showed that precipitation increased approximately 0.71 in. (18 mm) per 100 m of increased elevation. The southern Black Hills had a smaller rate of increase, about 0.5 in. (13 mm) per 100 m, while the northern Black Hills had a slightly larger rate of increase of 0.75 in. (19 mm) per 100 m.

The snowfall as a function of elevation plot (Figure 9) shows a quite diverse distribution of mean annual snowfall with increase in elevation. Each point and number represent a station listed in the legend and its snowfall value. The same methods and regressions were performed with mean annual snowfall as with the mean annual precipitation.

The snowfall regressions show a much stronger correlation to the data than the precipitation regressions, especially when the stations are split into the northern and southern Black Hills. The significance tests at a = 0.05 show a strong correlation for locations in the southern Black Hills and even stronger in the northern Black Hills. All were significant to alpha values of less than 0.005. The regression equation for the entire Black Hills shows an average increase of 9.8 in. (25 cm) of snowfall per 100 meters rise in elevation, while the southern Black Hills shows an increase of only about 3 inches (7.5 cm) per 100 meters and the northern Black Hills shows an increase of over 12 inches (30 cm) per 100 meters.

Elevation was found to be significant in determining precipitation values when using the entire Black Hills data set. Elevation was not shown to be as strongly related to precipitation as it was to temperature and snowfall.

Comparison of this Climatological Study with the 1949 Study

The last detailed climatological study of the Black Hills region was completed by Harley N. Johnson of the then-United States Weather Bureau in 1949. This study compared means from the lead authors' thesis (Trimarchi, 1998) study, "A Climatology of the Black Hills Region", covering the 1965 - 1994 period for selected sites, to the analysis from Johnson's study completed almost 50 years earlier. An important note about Johnson's 1949 study was that the means in the following tables (Tables 1 - 3) were based on varying years of record, ranging from 20 to 61 years, and not all were continuous records.

Looking at the temperature comparisons between the two studies in Table 1, there appear to be no significant differences, except in a couple of northern locations, Belle Fourche and Sundance, WY. At these locations there has been an annual mean temperature increase of 1.2∞F (0.7˚C) at Belle Fourche and 2.7˚F (1.5˚C) at Sundance.

At Rapid City, there has been an increase in annual mean temperature of 1.0˚F (0.6˚C). This increase could be a small urban heat island effect due to growth in the city, which would have contributed to a small rise in temperature over the years. The temperature differences took place throughout the year and were not seasonal.

When comparing mean growing seasons (Table 1, last column), it was a little surprising to find that the mean growing season appears to be of shorter duration than those in the past. The difference ranges from a few days up to a couple of weeks.

Many people have thought that a general increase in annual precipitation has occurred in the Black Hills and surrounding region. The precipitation trend showed such an increase. Though there were periods of years, such as the 1920's and 1960's (Figure 4), when precipitation was often higher than average, there were other periods, such as the 1930's, 1950's, and 1980's (Figure 4), where it was lower than average.

Comparing modern with the historic precipitation data, Table 2, there did not appear to be a clear-cut trend. Some stations experienced an increase in mean annual precipitation, some a decrease, while others showed no change. Deadwood's precipitation was lower by 2.5 inches (64 mm) while Lead's increased by over 4 inches (100 mm). These could be due to changes in measuring techniques and/or gage location, and/or period of record. It was found that Deadwood did not record precipitation between 1923 and 1942.

Comparison of number of days with precipitation of 0.01" or more showed that all the stations in this study experienced a greater number of days with precipitation than the 1949 study. Some sites were slightly greater, while others were more so. Even at locations where current mean annual precipitation went down, the number of days with measurable precipitation was higher. The increased frequency of precipitation days could have been due to a difference in how the observations were taken by the observers in the first half of the century.

Mean annual snowfall amounts (Table 3) were greater in every location in this study as compared to the 1949 study. Most were small differences explained by low annual snowfall amounts in the 1920's and 1930's (Johnson, 1949) and annual snowfall increases in this part of the century, especially the last 10 years in the northern Black Hills. But a couple of sites, Lead and Deerfield, were much higher now than in the Johnson study. In the Johnson study period, Deadwood received more mean snowfall than Lead. These changes are hard to explain since the difference in annual snowfall in Deadwood is not any different than at the other station, percentage wise. The apparent increase in Lead's snowfall totals likely involves several factors, including measuring accuracy at the station, precipitation increases in the colder months, and possible changes in location of the observing site within the town over time. Small changes in location could result in significant differences in snowfall amounts on an annual basis.

In general, it appears temperatures were nearly constant, precipitation went up at some locations, down in others, and snowfall increased from the first half to the second half of the century. Overall, these two studies supported an increase in precipitation over the Black Hills in the wintertime in the second half of this century. The trend analysis also supported a small increase in precipitation over the same time period.

SUMMARY

The Black Hills region is a very diverse area weatherwise. Despite its small size, it plays a major role in the weather of the area. In the span of only a few miles, the weather can be dramatically different at any time of the year. Temperatures between observation stations differ by as much as 10˚F (6˚C) from one location to another, annual precipitation doubled from the surrounding plains to some higher northern Black Hills locations, and snowfall increased even more in those same locations. These wide variations spread to other climatic variables, such as heating and cooling degree days, length of growing season, and number of days with certain temperature thresholds.

The temperature and precipitation trends (Figures 2 - 5) both indicate small increases over the 1910 to 1994 period. Temperatures have increased by about 0.4°F (0.2°C) over that period and precipitation has increased by about 0.3 inches (8 mm). These trends have leveled off over recent years, however. In the Black Hills, temperature, precipitation, and snowfall appear to be strongly related to elevation. In particular, elevation is a very significant variable to temperature and snowfall in the region.

When comparing the results of this study to the earlier study done on the Black Hills in 1949, some differences do show up between the two time periods. While temperatures stayed fairly constant, precipitation increases in some areas, decreases in others. Snowfall generally increased everywhere since the earlier part of the century. These results generally support a wintertime increase in precipitation over the years of up to 20% in some locations.

Future topics of research related to this study could involve looking at possible microscale weather processes, which appear to be occurring in some areas, such as the very localized, heavy snowfall events in portions of the northern Black Hills, around the Lead area. Another possibility is to look in-depth at the synoptic and mesoscale weather patterns which affect the weather in the Black Hills region and what the specific effects are for different parts of the Black Hills. Another study could involve looking at the historic weather records in the Black Hills, and examining closely the differences between the past and present averages and why the differences are occurring.

ACKNOWLEDGMENTS

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APPENDIX A

List of stations used in the climatology, their location, and length of record.

South Dakota

Stat. ID	Station	Latitude (deg.)	Longitude (deg.)	Elevation (meters)	Temp. Yrs. (month/year)	Prec. and Snow Yrs. (month/year)
559	Belle Fourche	N 44.667	W 103.850	921	1/1908-12/1994	1/1908-12/1994
1124	Buffalo Gap	N 43.500	W 103.350	981	NONE	9/1951-12/1994
1246	Buskala Ranch	N 44.217	W 103.817	1862	NONE	1/1948-12/1994
2087	Custer	N 43.783	W 103.600	1670	10/1942-12/199	1/1926-12/1994
2207	Deadwood	N 44.383	W 103.733	1423	1/1909-12/1922	1/1909-12/1922
					1/1943-12/1994	1/1943-12/1994
2228	Deerfield 4NW	N 44.067	W 103.900	1896	12/1955-5/1980	12/1955-5/1980
2231	Deerfield 3SE	N 44.000	W 103.783	1847	7/1981-12/1994	7/1981-12/1994
3069	Fort Meade	N 44.400	W 103.467	1006	7/1949-12/1994	7/1949-12/1994
3775	Hermosa 3SSW	N 43.800	W 103.217	1045	NONE	1/1948-12/1994
3868	Hill City	N 43.933	W 103.567	1518	NONE	7/1955-12/1994
4007	Hot Springs	N 43.433	W 103.467	1085	1/1908-12/1994	1/1908-12/1994
4834	Lead	N 44.350	W 103.767	1631	1/1909-12/1994	1/1909-12/1994
5870	Mt. Rushmore Nat.	N 43.883	W 103.450	1576	2/1962-12/1994	2/1962-12/1994
6054	Newell	N 44.717	W 103.417	872	1/1908-12/1994	1/1908-12/1994
6427	Pactola Dam	N 44.067	W 103.483	1439	4/1955-12/1994	8/1951-12/1994
6937	Rapid City Airport	N 44.050	W 103.067	963	5/1948-12/1994	5/1948-12/1994
6947	Rapid City	N 44.117	W 103.283	1052	1/1888-12/1994	1/1888-12/1994
7882	Spearfish	N 44.500	W 103.867	1109	1/1889-12/1994	1/1889-12/1994
Wyoming						
200	Alva 5SE	N 44.650	W 104.350	1340	8/1948-9/1986	1/1948-9/1986
206	Alva	N 44.700	W 104.433	1218	2/1987-12/1994	2/1987-12/1994
2466	Devils Tower	N 44.583	W 104.700	1176	1/1959-12/1994	1/1959-12/1994
6660	Newcastle	N 43.850	W 104.217	1316	1/1918-12/1994	1/1918-12/1994
8705	Sundance	N 44.400	W 104.383	1447	5/1915-12/1994	5/1915-12/1994

Table 1. Comparison of this study with 1949 study of mean temperature.

	Annual Mean Temperature (°F)			Annual Mean Max. Temperature (°F)			Annual Mean Min. Temperature (°F)			Mean Annual Growing Season		
Station	1949 Study	1997 Study	Difference	1949 Study	1997 Study	Difference	1949 Study	1997 Study	Difference	1949 Study	1997 Study	Difference
Belle Fourche	45.8	47.0	1.2	60.0	61.3	1.3	31.0	32.7	1.7	134	136	2
Deadwood	43.7	43.7	0.0	56.4	56.0	-0.4	30.5	31.4	0.9	N/A	110	N/A
Hot Springs	48.1	48.1	0.0	62.6	63.0	0.4	33.5	33.1	-0.4	142	126	-16
Lead	44.2	44.2	0.0	55.1	54.9	-0.2	33.5	33.4	-0.1	129	119	-10
Rapid City Downtown	46.7	47.7	1.0	58.4	60.5	2.1	35.0	34.8	-0.2	154	140	-14
Spearfish	46.8	46.5	-0.3	58.6	58.6	0.0	34.8	34.4	-0.4	144	141	-3
Newcastle, WY	46.2	46.6	0.4	59.1	59.5	0.4	33.5	33.7	0.2	136	130	-6
Sundance, WY	41.3	44.0	2.7	N/A	56.2	N/A	N/A	31.7	N/A	119	115	-4

Table 2. Comparison of this study with 1949 study - precipitation results.

Station	Mean Annual Precipitation (in.) 1949 Study	1997 Study	Difference	Mean Annual Number of Days With Precipitation (0.01" or More) 1949 Study	1997 Study	Difference
Belle Fourche	13.92	16.87	2.95	65	108	43
Custer	18.47	19.13	0.66	83	110	27
Deadwood	30.15	27.62	-2.53	N/A	129	N/A
Deerfield	18.33	22.04	3.71	75	133	58
Hermosa	17.26	16.06	-1.20	69	87	18
Hot Springs	18.28	16.02	-2.26	65	102	37
Lead	24.20	28.62	4.42	113	150	37
Rapid City Downtown	17.49	17.78	0.29	96	111	15
Spearfish	21.37	21.30	-0.07	95	121	26
Newcastle, WY	15.61	15.08	-0.53	68	102	34
Sundance, WY	19.19	17.72	-1.47	76	127	51

Table 3. Comparison of this study with 1949 study - snowfall results.

Station	Mean Annual Snowfall (in.) 1949 Study	1997 Study	Difference
Belle Fourche	31.4	41.6	10.2
Custer	44.7	47.7	3.0
Deadwood	99.1	111.7	12.6
Deerfield	55.9	137.2	81.3
Hermosa	22.9	30.1	7.2
Hot Springs	30.5	34.5	4.0
Lead	87.7	175.8	88.1
Rapid City Downtown	32.5	36.1	3.6
Spearfish	61.5	69.6	8.1
Newcastle, WY	38.1	38.4	0.3
Sundance, WY	76.5	82.3	5.8

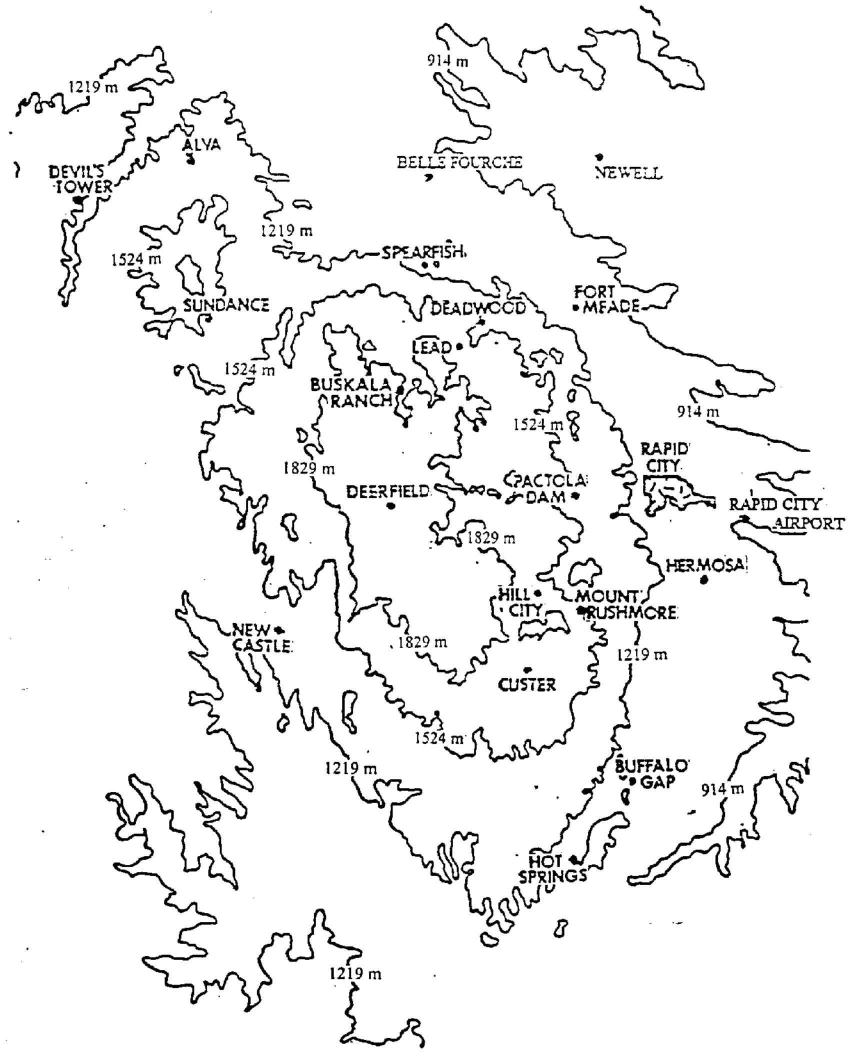

Figure 1: Map of station locations.

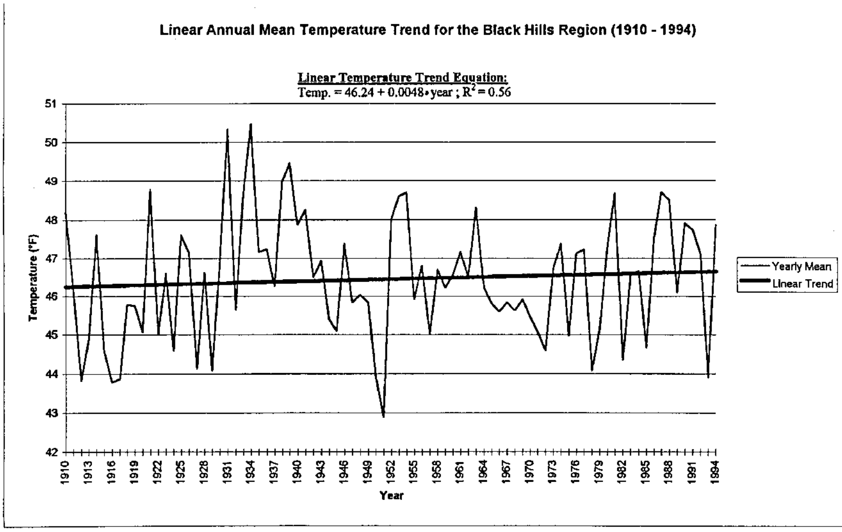

Figure 2. Linear annual mean temperature trend for the Black Hills region from 1910-1994. Based on annual mean temperatures at Hot Springs, Lead, Rapid City, and Spearfish.

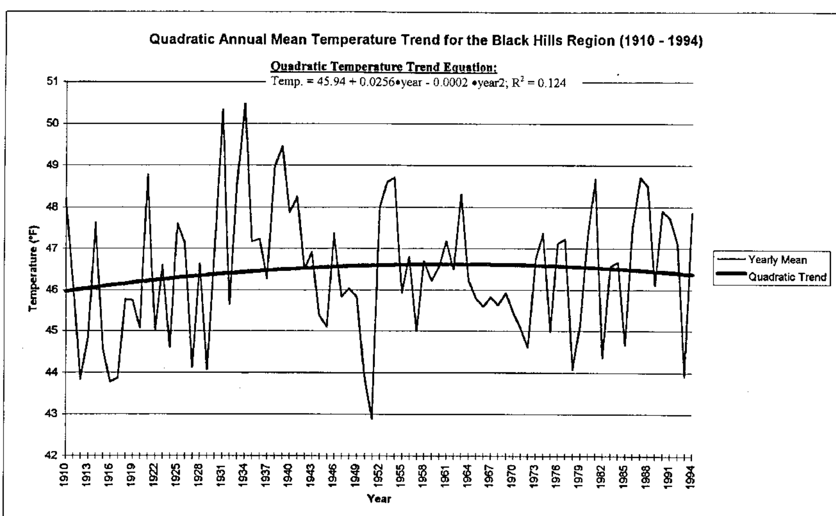

Figure 3. Quadratic annual mean temperature trend for the Black Hills region from 1910-1994. Based on annual mean temperatures at Hot Springs, Lead, Rapid City, and Spearfish.

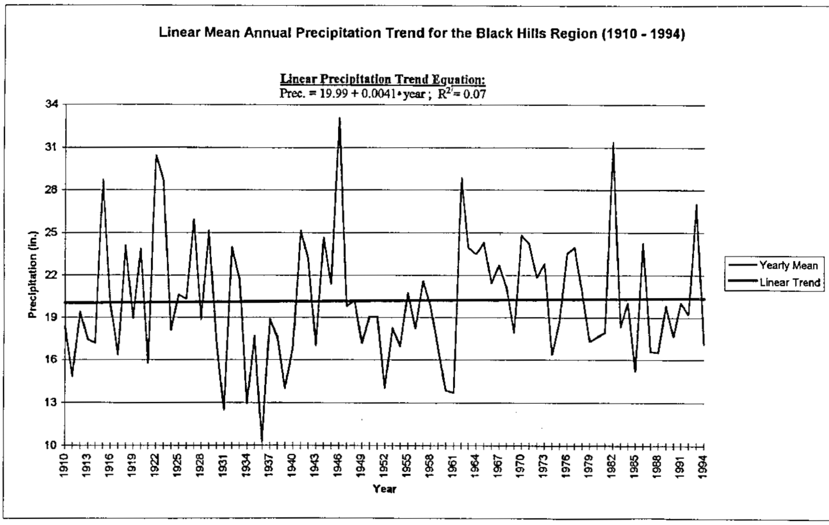

Figure 4. Linear mean annual precipitation trend for the Black Hills region from 1910-1994. Based on annual mean precipitation at Hot Springs, Lead, Rapid City, and Spearfish.

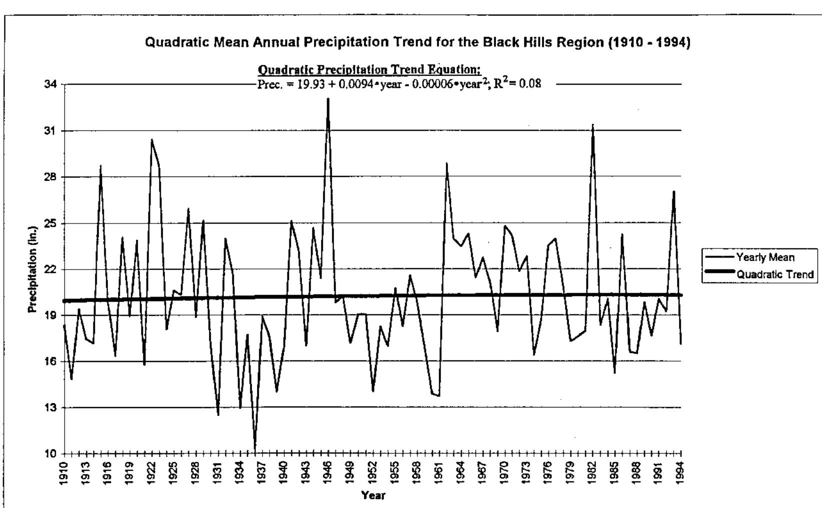

Figure 5. Quadratic mean annual precipitation trend for the Black Hills region from 1910-1994. Based on annual mean precipitation at Hot Springs, Lead, Rapid City, and Spearfish.

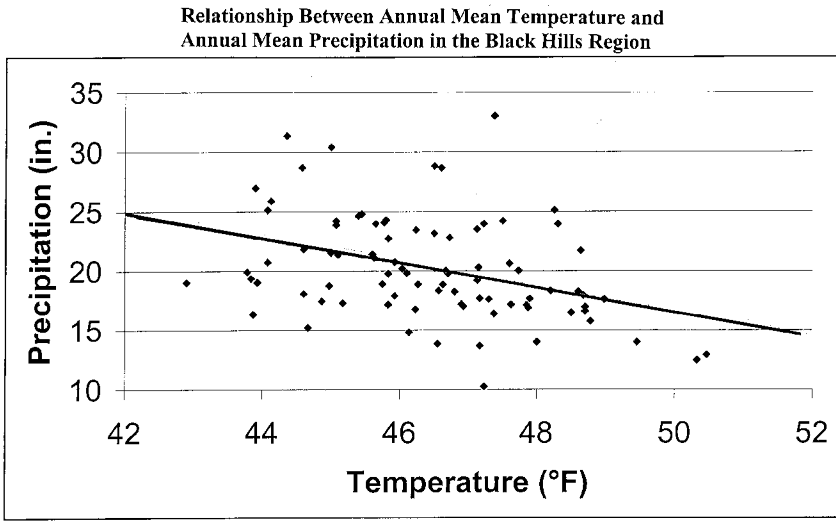

Figure 6. Figure shows relationship between annual mean temperature and annual mean precipitation and corresponding fitted regression line. It is based on an average of annual mean temperatures and annual precipitation values at Hot Springs, Lead, Rapid City, and Spearfish for each year from 1910 to 1994.

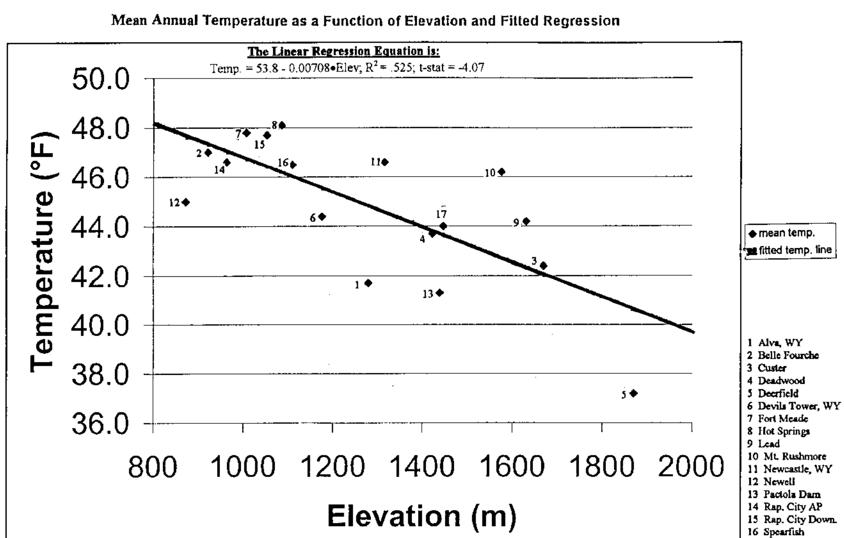

Figure 7. Scatter plot and linear regression of annual mean temperature as a function of elevation.

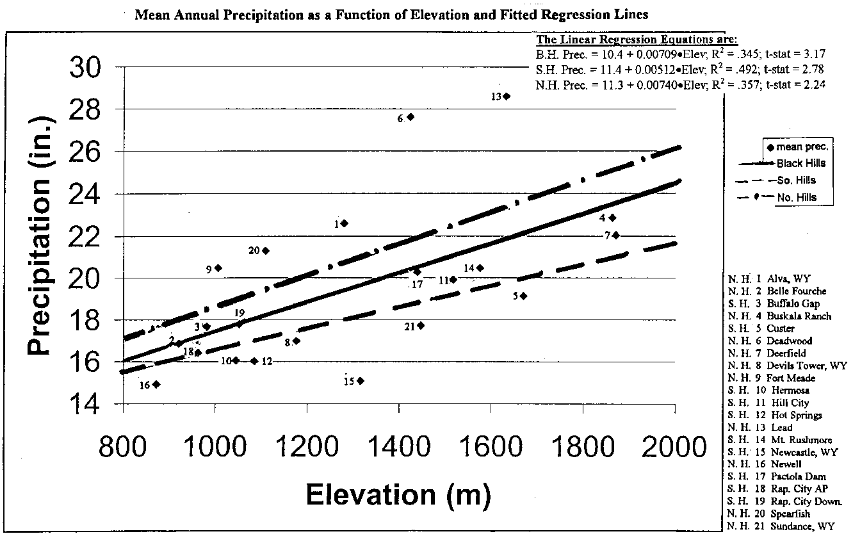

Figure 8. Scatter plot and linear regressions of mean annual precipitaiton as a function of elevation for the entire Black Hills (B.H.), the southern Black Hills (S.H.), and the northern Black Hills (N.H.).

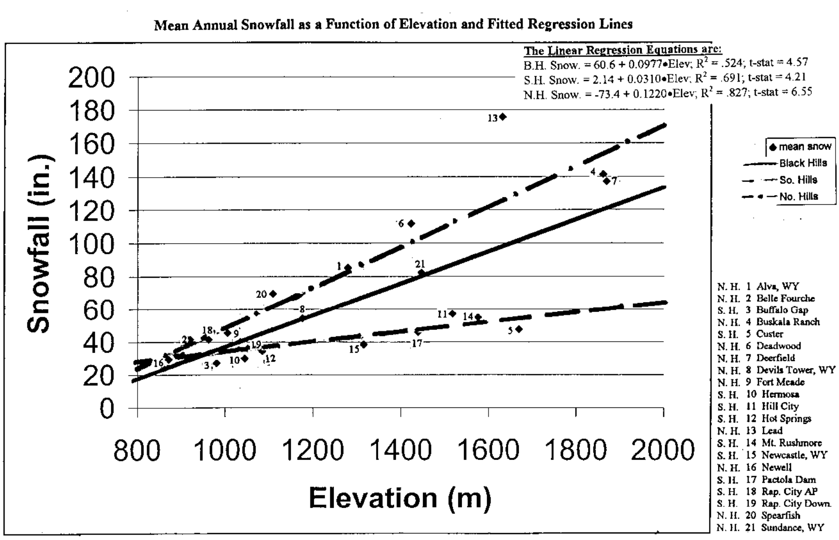

Figure 9. Scatter plot and linear regressions of mean annual snowfall as a function of elevation for the entire Black Hills (B.H.), the southern Black Hills (S.H.), and the northern Black Hills (N.H.).