Boulder, Colorado Local Climate Change Effects DRAFT (TITLE needs to be a question!)

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Introduction

Figure 1: ***Figure 1.*** *A road washed out by an overflowing stream in the foothills of Boulder, September 2013. Image obtained from City of Boulder website.*

Background

Climate science has become increasingly poignant in warning the public about the effects of historic and present anthropogenic greenhouse gas emissions on global climate patterns, yet scientists continue to struggle pinpointing with statistical certainty the effects of climate change on regional natural disasters. Due to this uncertainty along with the politicized nature of climate science, local media in the United States has been quick to conflate or dismiss any relationships between short-term weather-induced natural disasters with long-term global climatic patterns.

This jump to conclusions was seen in the devastating September 2013 rainstorm and floods in Colorado. The rainstorm hit Boulder County particularly hard. In the span of one week in September 2013, Boulder received one of the largest sustained precipitation levels in a one-week period since the start of historic records. In an eight-day period from Monday 09 September to Monday 16 September, Boulder received 17.15 inches of rain, just shy of the 20 inches of precipitation the county receives on average annually (Brennan and Aguilar 2013). The county received over 10 inches in just 12 September alone. The ensuing floods killed 4 people in the county, injured dozens and caused the evacuation of nearly 2,000 residents by road and helicopter (ibid.). Overflowing waters in the region's waterways also destroyed 345 homes and damaged 557 homes, and caused over a billion dollars in property and economic damage (ibid., Figures 1 & 2). In the aftermath, FEMA declared the entire county a disaster zone, and public and private reconstruction efforts around the county continued for years.

A year after the floods, local newspaper Daily Camera declared "2013's flood-triggering rains not caused by climate change" (Brennan 2014). This bold claim was based on a local study modeling the probability of increased precipitation in Northeast Colorado as a result of anthropogenic-induced warming (Hoerling et al. 2014). However, even the article noted other scientists' criticism of the paper's suspect methodology. For example, Hoerling et al. (2014) developed a model to predict the likelihood of five-day flood event in just the month of September, rather than five-day and different-day intervals in all months of the year. The authors

Figure 2: ***Figure 2.*** *A bridge collapse in Lafayette, CO causes three cars to fall into a creek on 13 September 2013. Image obtained from Cliff Grassmick of Daily Camera.*

fail to mention how their model can account for the change in flood probability through different times of the year by just looking at the month of September, or why five-day flood events were specifically chosen. The study also focuses on two thirty-year periods, the years 1871-1900 and 1984-2013, presumably to model before and after worldwide anthropogenic emissions increased exponentially in the 20th century. The authors do not explain why they decided to pick two thirty-year periods specifically. Therefore, looking at one month in two 30-year periods prevents the model used in Hoerling et al. (2014) from making general conclusions on how climate change has affected the overall likelihood of floods across Northeast Colorado in the past century.

Unsurprisingly, a multitude of other local and national researchers on the September 2013 Boulder floods have disputed this initial study. Some climatologists and meteorologists attempt to pinpoint direct causal relationships between and the probability of specific extreme weather events, a field of study known as attribution science. Much of the humid air causing the floods came from the convergence of two concurrent hurricanes on Mexico's east and west coasts. In mid-September 2013, Hurricane Manuel on the Pacific and Hurricane Ingrid on the Gulf of Mexico killed hundreds along the Mexican coast, fuelled by the highest sea surface temperatures globally at the time (Trenberth *et al.* 2015). As the two storms' combined warm monsoonal air met up and headed north into the United States, huge amounts of moisture built up above the Southwest (*ibid.*). Meteorologists at the time noted a front of cold, dry air had also stalled along the Front Range Urban Corridor (Brennan and Aguilar, 2013), Northeast Colorado's relatively flat and heavily populated area just east of the Rocky Mountains. This combination of exceptionally warm, humid air and cold, dry air created the conditions for what the *Daily Camera* called a "1000-year rain and 100-year flood" (Brennan and Aguilar 2013, Brennan 2014). Years later, *Daily Camera* also followed up on the initial study with new studies claiming the opposite of Hoerling *et al.* (2013). The model in Hoerling *et al.* (2013) did not take into account the abnormal conditions south of Colorado causing the hurricanes that led to massive rainstorms. One later attribution study created models combining global climate change with local trends, taking the hurricanes' abnormally warm conditions into account (Pall *et al.*, 2017). Their results showed anthropogenic climate change had increase rainfall up to 30% in the 2013 storms compared to regional climate models with anthropogenic variables removed (Pall *et al.* 2017, Brennan 2017).

Based on this case study, I wanted to test whether larger regional and global climate change could be hidden by highly variable, short-term conditions like daily temperatures and precipitation obtained by local weather stations.

Methodology

I chose six sites based on their location within the Boulder Creek watershed (Table 1, Figure 3). I look at three climate stations around Boulder obtained from the National Oceanic and Atmospheric Administration's online database of daily summaries from the Global Historical Climate Network (NOAA GHCN). One is located in the city of Boulder, and two are located in the Rocky Mountains just west of Boulder (Figure 3). I also look at three climate stations from the site of the Niwot Ridge Long Term Ecological Research program (NWT LTER), up in the Rocky Mountains to the west of Boulder and close to the headwaters of the Boulder Creek watershed (Table 1, Figures 3 and 4).

Table 1: *Climate stations analyzed for daily maximum temperatures and daily precipitation*

Climate Station	Latitude	Longitude	Altitude (m)	Agency/Program

1. D-1 | 40.059793 | -105.6165 | 3739 | NWT LTER
2. Saddle | 40.0547 | -105.5892 | 3528 | NWT LTER
3. C-1 | 40.03616 | -105.5440 | 3022 | NWT LTER
4. USW00094075 - Boulder 14 W | 40.0354 | -105.5409 | 2995.6 | NOAA GHCN
5. USC00051681 - Coal Creek Canyon | 39.8958 | -105.3847 | 2728 | NOAA GHCN
6. USC00050848 - Boulder | 39.9919 | -105.2667 | 1671.5 | NOAA GHCN

On the statistical software R, I used a linear regression model for the daily max temperature and precipitation

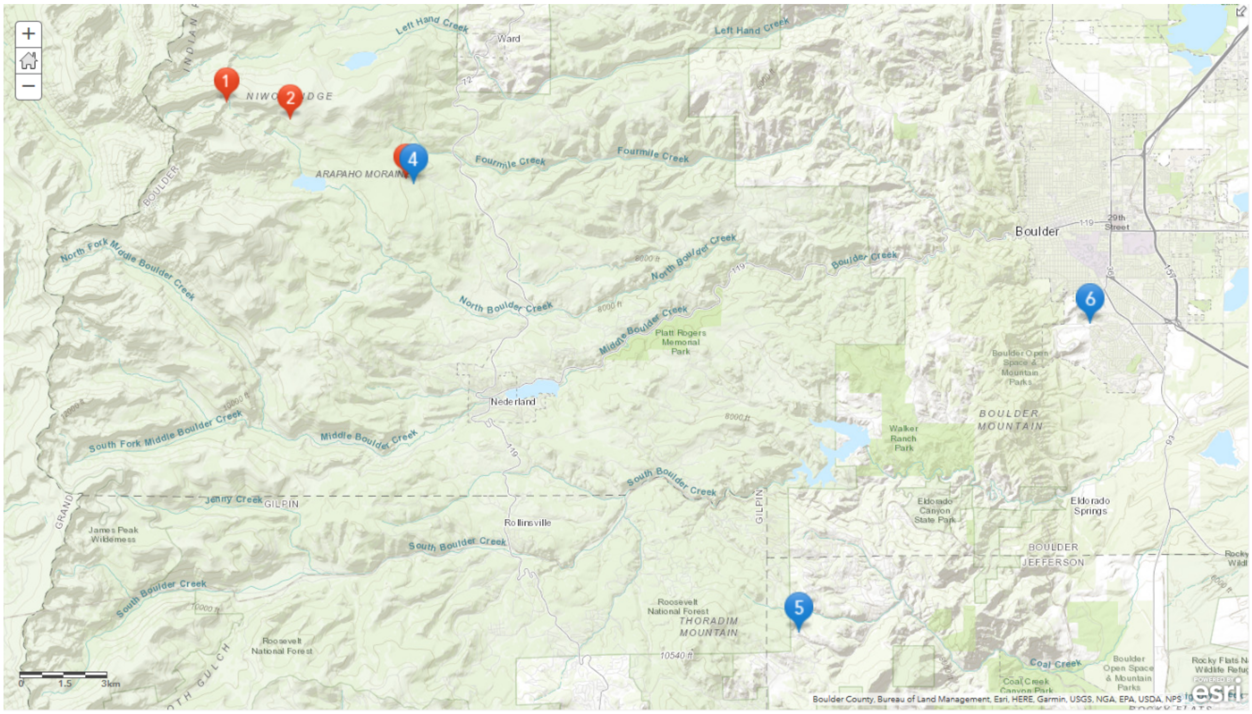


Figure 3: ***Figure 3.*** *Topographic of climate station locations with corresponding numbers*

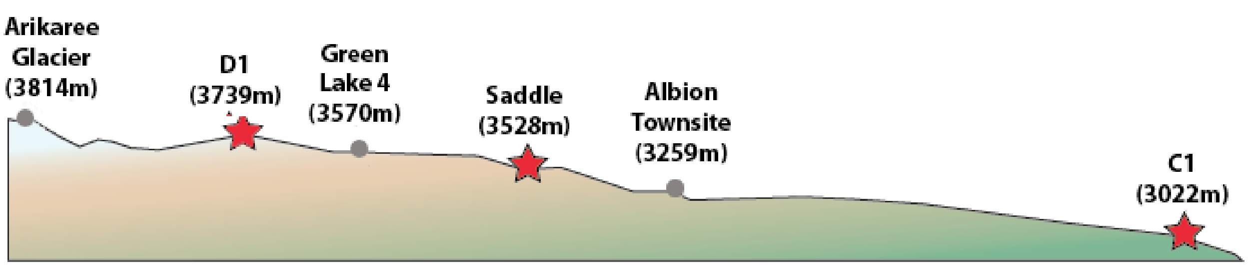


Figure 4: ***Figure 4.*** *Side elevation of NWT climate station locations (Numbers 1-3 in Figure 3). Image obtained from NWT LTER website. (not sure which direction this is facing???)*

of each site to test whether the historical data had a statistically significant.

Hypothesis

I hypothesize the six climate stations have a statistically significant increase in daily max temperatures over time, and a statistically significant increase in daily precipitation over time.

Results

Two of the three NWT stations and two of the three NOAA climate stations had statistically significant increases in daily maximum temperature over time (Table 2). For these stations, we can reject the null hypothesis.

Table 2: *Linear regression of daily maximum temperatures*

Climate Station	slope	Adjusted R-squared	p-value	Statistical significance?
1. D-1	-3.69e-05	0.000630	7.08e-05	yes
2. Saddle	+1.25e-04	0.00248	1.15e-08	yes
3. C-1	+9.23e-05	0.00438	< 2e-16	yes
4. Boulder 14 W	+2.39e-04	0.00146	0.00247	yes
5. Coal Creek Canyon	+3.65e-05	0.000109	0.124	no
6. Boulder	+4.74e-05	0.00366	< 2e-16	yes

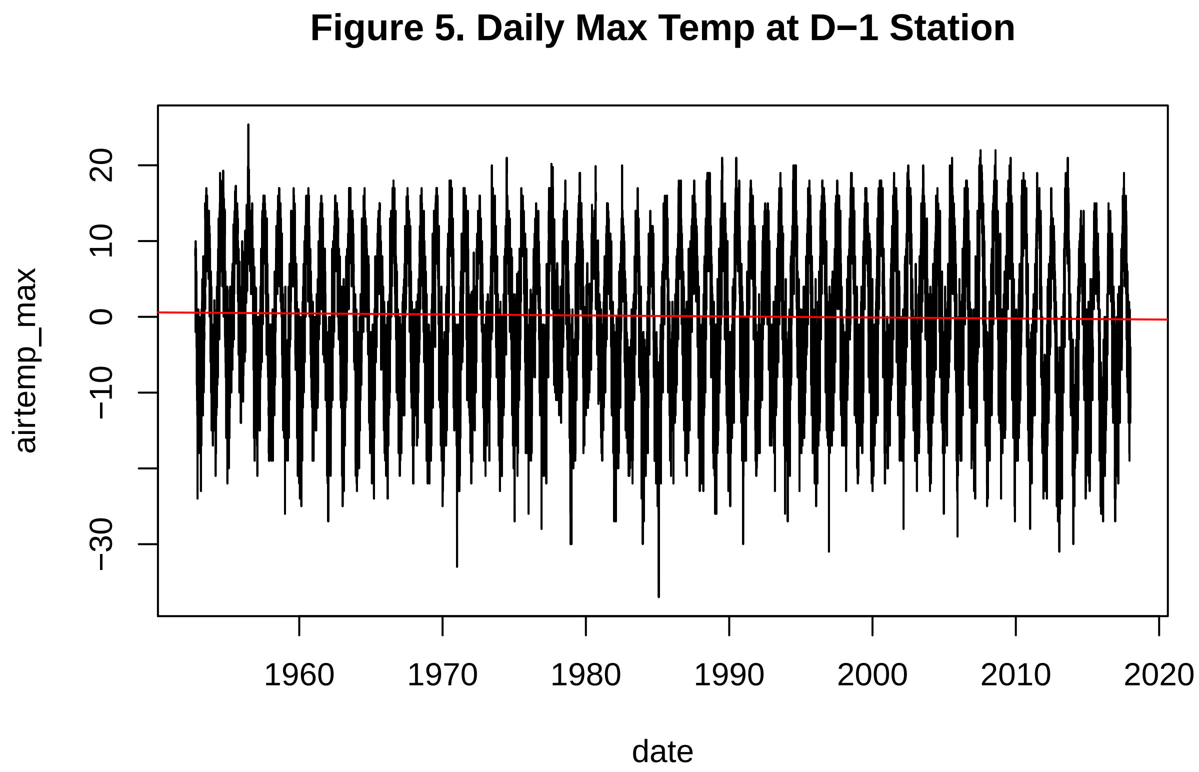
Only one of the six stations, Saddle, had a statistically significant increase in daily precipitation over time (Table 3). One station, C-1, had a statistically significant decrease in precipitation over time.

Table 3: *Linear regression of daily precipitation*

Climate Station	slope	Adjusted R-squared	p-value	Statistical significance?
1. D-1	+2.243e-05	0.000262	0.0164	no
2. Saddle	+2.57e-04	0.00725	<2e-16	yes
3. C-1	-8.744e-05	0.00954	<2e-16	yes
4. Boulder 14 W	+8.30e-05	0.000492	0.0531	no
5. Coal Creek Canyon	+5.15e-06	-6.66e-05	0.688	no
6. Boulder	+1.62e-06	-5.28e-06	0.379	no

An example of D-1 station's linear regression for daily maximum temperature over time (Figure 5) and daily precipitaion over time (Figure 6) is also shown below.

```
plot(airtemp_max~date, D1_daily_temp, main="Figure 5. Daily Max Temp at D-1 Station", ty='l') & abline(
```

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## logical(0)
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```
plot(pppt_tot~date, main="Figure 6. Daily Precipitation at D-1 Station", D1_daily_precip, ty='l') & abl
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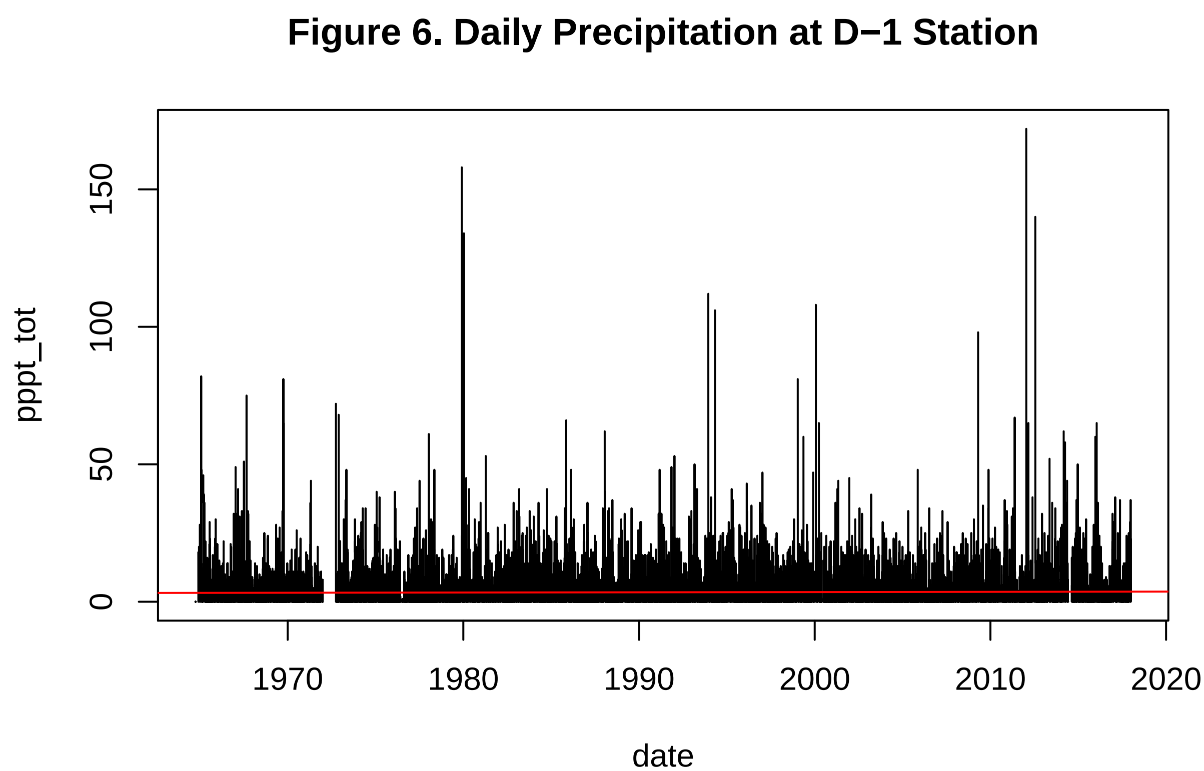


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## logical(0)
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Discussion

The adjusted R-squared is relatively small for all sites' temperature and precipitation linear regression, with all of them below 0.01. For example, D-1's increasing linear model for temperature is statistically significant but shows a high amount of variation or "noise" (Figure 5), as reflected in the adjusted R-squared value of 0.000630 (Table 2). Although this study cannot conclude that temperature and precipitation are correlated or are increasing in the Boulder Creek watershed, it does highlight how wide variations in local, short-term weather data can obscure studies showing larger global trends of warming climate and increased precipitation.

I ran into a few limitations when creating this study. The time range of available data from GHCN on NOAA's website vary widely. For example, daily summaries from Boulder (USC00050848) began October 1893, whereas daily summaries from Coal Creek Canyon (USC00051681) began July 1984. Because of such huge variances in time records, I cannot draw concrete direct comparisons between the daily data of each station. the In the Niwot Ridge LTER data, "various circumstances" required the data compilers to estimate daily summaries for missing values stretching many consecutive days in each station's daily summaries. Researchers should focus on maintaining accurate data to avoid estimating daily summaries. In the future monthly summaries may be more appropriate in looking at seasonal fluctuations of temperature and precipitation over time.

Future studies could model predicted future water flow of the streams converging downstream into urbanized areas. For example, Yochum and Moore (2013) estimated peak water flow in 15 streams affected by the 2013 Boulder floods instead of focusing on long-term precipitation or air temperature data. Local geographic conditions also greatly affect the likelihood of flooding and should be accounted for. Multiple streams running down the Front Range mountain valleys converge into Boulder Creek, heading east into the city of Boulder and concentrating flooding along areas closest to the waterways. Features of urbanization, such as impervious surfaces, waterway channelling, and damming, will have an impact on which areas will be predisposed to flood events.

Conclusion

The unusual September 2013 rainstorm across Colorado created once-in-a-lifetime floods across the highly populated Rocky Mountain foothills of Boulder County. However, with global anthropogenic climate change scientists warn such unusual regional events may become increasingly common.

The results show that two of the three NOAA climate stations has a statistically significant change in TMAX, but none of the NOAA stations had a statistically significant change in PRCP. **not sure how to interpret the climate station data**

Attribution science will continue to play a prominent role in attempting to find relationships between long-term climate change models with short-term extreme weather events. Establishing a relationship between global precipitation patterns and the future likelihood of floods like the one afflicting Colorado in September 2013 will help us predict and prepare for potential future disasters.

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