The 2013 Boulder Flood: Can We Attribute Specific Extreme Weather Events to Climate Change?

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### Were the 2013 Boulder Floods Exacerbated by Climate Change-Induced Increased Precipitation?



***Figure 1.*** *A road washed out by an overflowing stream in the foothills of Boulder, September 2013 (Source: City of Boulder website).*

For decades, climate scientists have warned the public of the effects of historic and present anthropogenic greenhouse gas emissions on global climate patterns. Yet the scientific community continues to struggle to pinpoint with statistical certainty how climate change leads to an increase in regional natural disasters. Along with the politicized nature of climate science in America, the media in the United States has been quick to conflate or dismiss potential relationships between short-term weather-induced natural disasters with long-term global climatic patterns. The devastating September 2013 rainstorm and floods in Colorado became a prime example of such premature conclusions.

In one week in the middle of September 2013, news of heavy rain and flooding along the Front Range Corridor of Colorado dominated national headlines. The rainstorm hit the Rocky Mountain foothills of Boulder County particularly hard: in one week the area received one of the largest continuous volume of precipitation since meteorological records began. From the 9th to the 16th of September, Boulder received 17.15 inches of rain, accounting for 86% of the rain that would normally be distrubted over a year. (Brennan and Aguilar 2013; CCC 2013). Three days after the deluge began, the county received over 10 inches in just one day, the highest in recorded history (Brennan and Aguilar 2013; CCC 2013). Ensuing floods killed 4 people in the county, injured dozens and caused the evacuation of nearly 2,000 residents by road and helicopter (Brennan and Aguilar 2013). Overflowing waters in the region's waterways destroyed 345 homes and damaged 557 homes, and caused over a billion dollars in property and economic damage (Brennan and Aguilar 2013; 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.



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

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). The study developed a model to predict the likelihood of five-day flood event in the month of September. The authors fail to mention how their model can account for the change in flood probability throughout the whole year or other months of the year. 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 selected these two thirty-year periods.

Because of these issues, other local researchers on the September 2013 Boulder floods have disputed this initial study. In a field known as attribution science, climatologists and meteorologists attempt to pinpoint direct causal relationships between global and regional climate change with the probability of specific extreme weather events like the Boulder floods. What attribution science researchers focused on was the fact that much of the humid air causing the floods came from two concurrent hurricanes on Mexico's east and west coasts. In mid-September 2013, sea surface temperature around Mexico were the highest globally and likely exacerbated by anthropogenic climate change, fueling huge amounts of evaporation and condensation (Trenberth *et al.* 2015). This caused Hurricane Manuel on the Pacific and Hurricane Ingrid on the Gulf of Mexico to kill hundreds along the two Mexican coasts. Fast-moving humid air from the two hurricanes then moved north and clashed with a dry cold front above Colorado, creating the conditions for what the *Daily Camera* called a "1000-year rain and 100-year flood" (Brennan and Aguilar 2013; Brennan 2014). One later study concluded anthropogenic-induced sea surface warming had increased the historic rainfall up to 30% in 2013 when compared to regional climate models with anthropogenic variables removed (Pall *et al.* 2017; Brennan 2017). As seen in the 2013 Boulder floods, the attribution of climate change to any single extreme weather event continues to incite immense scientific discussion.

#### What are the aims and objectives of this study?

Using the 2013 Boulder floods as a case study, I wanted to test whether larger regional climate change in Colorado and climate change around the world could be measured by short-term conditions like daily temperatures and precipitation in the Boulder area. Because daily precipitation is highly variable, I use the daily summaries to create monthly averages for September instead. I hypothesized the six climate stations increase in daily max temperatures over time, and increase in monthly average precipitation over time. To test the plausibility of this alternative hypothesis, I test whether the null hypothesis (that daily max temperature and/or precipitation will not increase) can be rejected.

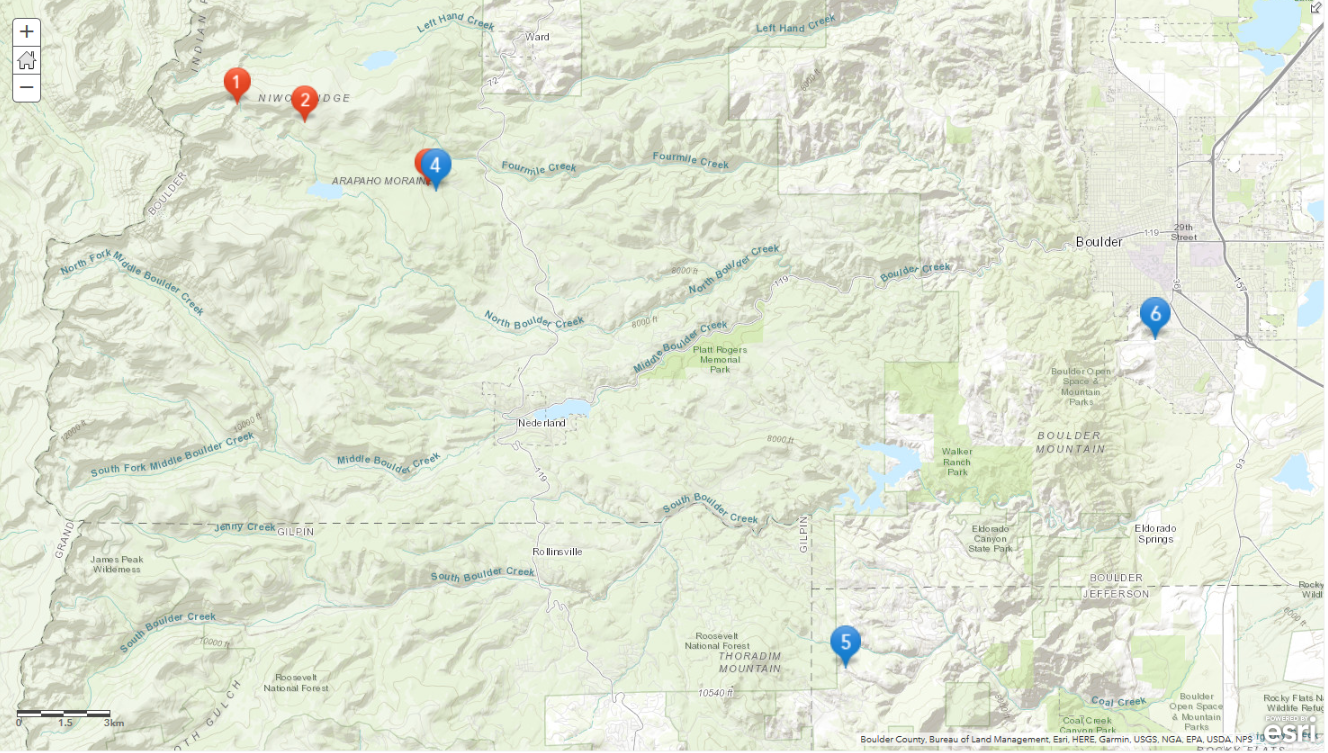
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### Methodology: How Did I Conduct My Study?

For this study, I chose six sites (Table 1; Figure 3) based on their location within the Boulder Creek watershed ("Boulder Area" 2013; USGS [date unknown]). I reviewed daily max temperature and precipitation summaries from three climate stations obtained from the National Oceanic and Atmospheric Administration's online database of daily summaries from the Global Historical Climate Network (NOAA GHCN). I also reviewed three climate stations from the site of the Niwot Ridge Long Term Ecological Research program (NWT LTER) 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 | Daily Max Temperature Start/End Date | Daily Precipitation Start/End Date | Altitude (m) | Agency/Program |
| 1. [D-1](http://niwot.colorado.edu/data/climate/d1-meteorological-data) | 1952-10-01 to 2017-12-31 | 1964-10-01 to 2017-12-31 | 3739 | NWT LTER |
| 2. [Saddle](http://niwot.colorado.edu/data/climate/saddle-meteorological-data) | 1981-07-09 to 2017-12-31 | 1981-07-31 to 2019-01-01 | 3528 | NWT LTER |
| 3. [C-1](http://niwot.colorado.edu/data/climate/c1-meteorological-data) | 1952-10-01 to 2017-12-31 | 1952-10-01 to 2017-12-31 | 3022 | NWT LTER |
| 4. [USW00094075 - Boulder 14 W](https://www.ncdc.noaa.gov/cdo-web/datasets/GHCND/stations/GHCND:USW00094075/detail) | 2003-09-28 to 2019-02-11 | 2003-09-28 to 2019-02-11 | 2996 | NOAA GHCN |
| 5. [USC00051681 - Coal Creek Canyon](https://www.ncdc.noaa.gov/cdo-web/datasets/GHCND/stations/GHCND:USC00051681/detail) | 1984-07-01 to 2018-12-31 | 1984-07-01 to 2018-12-31 | 2728 | NOAA GHCN |
| 6. [USC00050848 - Boulder](https://www.ncdc.noaa.gov/cdo-web/datasets/GHCND/stations/GHCND:USC00050848/detail) | 1893-10-01 to 2019-02-11 | 1893-10-01 to 2019-02-11 | 1672 | NOAA GHCN |



***Figure 3.*** *Topographic of climate station locations with corresponding numbers (#3 hidden behind #4). Map created via ArcGIS Online.*



***Figure 4.*** *North-facing side elevation of NWT climate station locations, or numbers 1-3 in Figure 3. (Source: NWT LTER website).*

On the statistical software R, I used a linear regression model for the daily max temperature and precipitation of each site to test whether the historical data has an increase or decrease, how much of the variability in the data can be explained by the model, and whether such results are statistically significant.

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### Is Daily Max Temperature and Monthly Precipitation Correlated?

Two of the three NWT stations, Saddle and C-1, and two of the three NOAA climate stations, Boulder 14 W and Boulder, had statistically significant increases in daily maximum temperature over time (Table 2). Four stations' daily max temperature increased 3.37°C to 8.72°C per 100 years (adjusted R^2 = 0.001 to 0.004; p-value = <0.001 to 0.002). In contrast, daily max temperatures at D-1 Canyon decreased -1.35°C per 100 years (adjusted R^2=0.001, p-value=<0.001).

***Table 2:*** *Linear regression model of daily maximum temperatures*

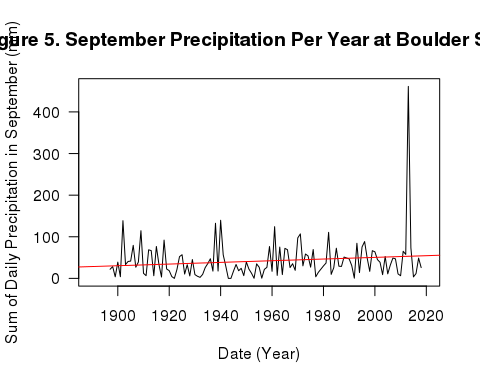
|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Climate Station | change in max temperature per 100 years (°C) | Adjusted R-squared | p-value | Statistical significance? |
| 1. D-1 | -1.35 | 0.001 | <0.001 | yes |
| 2. Saddle | +4.56 | 0.002 | <0.001 | yes |
| 3. C-1 | +3.37 | 0.004 | < 0.001 | yes |
| 4. Boulder 14 W | +8.72 | 0.001 | 0.002 | yes |
| 5. Coal Creek Canyon | +1.33 | 0.0001 | 0.124 | no |
| 6. Boulder | +1.73 | 0.004 | < 0.001 | yes |

Just one of the six stations, D-1, have a statistically significant increase in precipitation over time (Table 3). In five of the six stations' precipitation models, including the statistically significant model for D-1, the adjusted R^2 was less than zero (Table 2). This means these linear models are a worse predictor of the data's variation than the null hypothesis, regardless of the models' p-values. The adjusted R-squared for all sites' daily temperature and precipitation are below 0.02, meaning even the statistically significant linear models for temperature explained less than 2% of the variability in the data.

***Table 3:*** *Linear regression model of daily precipitation*

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Climate Station | precipitation change per 100 years (mm) | Adjusted R-squared | p-value | Statistical significance? |
| 1. D-1 | +7.64 | -0.018 | 0.016 | yes |
| 2. Saddle | +50.6 | -0.013 | 0.476 | no |
| 3. C-1 | -7.34 | -0.014 | 0.758 | no |
| 4. Boulder 14 W | +100. | -0.061 | 0.719 | no |
| 5. Coal Creek Canyon | +33.7 | -0.023 | 0.637 | no |
| 6. Boulder | +20.1 | +0.012 | 0.123 | no |

I provide the monthly sum precipitation graph I created for Boulder station below (Figure 5), showing the sums of daily precipitation each September from the start of records to the present and the corresponding linear regression model. The large variability in monthly precipitation by year makes it difficult to discern any pattern beyond the mean. The height of the 2013 floods is clearly visible as the tallest spike on the right side of Figure 5. I purposely omit the graphs of the other stations to prevent cluttering up the results section.



I found the six stations' varying results intriguing, since I chose all six based on their geographic proximity and location around the Boulder watershed. Rather than the expected consistent trend among all stations, each station's daily temperatures and precipitation seemed to trend in different directions.

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### Interpreting Flood Probability with Weather Station Data and Other Methods

One noteworthy comparison is between the C-1 weather station data from Niwot Ridge LTER and Boulder 14 W data from NOAA's GHCN database. The two stations are within 100 meters of each other (Figure 3), making me assume the max temperature and precipitation linear models would be very close. Both C-1 and Boulder 14 W have statistically significant increases in the model, but I find it surprising that there is a difference of 5.35°C per 100 years between the two (Table 2). These results highlight how wide variations in local, short-term collection of weather data are unreliable predictors of larger climate trends. Looking at only daily weather does not full encapsulate changes in seasons over years and decades, nor does it take into account atmospheric conditions such as changing global wind currents.

I ran into a couple 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. 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 may create models for a station's missing daily data based on the topography and distance of other nearby stations in Niwot Ridge that recorded data. They may also create models for obtaining proxy data from tree rings or local geomorphology. In future scenarios, combining monthly and yearly models obtained from the daily data with global wind and current patterns may more accurately attribute anthropegenic-influenced fluctuations of temperature and precipitation.

Local preparedness for future floods must take into account a variety of measurements on top of daily weather conditions (Ternberth *et al.* 2015; Pall 2017). Another way of addressing these issues could be modeling predicted future water flow of streams converging downstream into urbanized areas. After analyzing peak water flow in 15 streams affected by the 2013 Boulder floods, Yochum and Moore (2013) found flooding varied greatly depending on factors like stream depth, stream width, and surrounding stream bank topography. In Boulder County, multiple streams running down the Front Range mountain valleys and converge into the city of Boulder, concentrating flooding along areas closest to the waterways. Features of urbanization, such as impervious surfaces, waterway channeling, and damming, will also determine which areas will be most predisposed to future flood events.

Communities most affected by local and regional precipitation changes have first-hand knowledge on how climate-induced precipitation changes affect their lives (Gustafson, Cadena, Hartman 2018). Many Boulder residents have voiced concerns with funding cuts to FEMA and other public agenices. In 2018, a re-interpretation of FEMA rules threatened to remove up to $70 million in reimbursements for Boulder County's flood recovery projects, even as officials estimated up to $500 million would be needed to rebuild to the highest flood-resistant standards (Lounsberry 2018). Another way Boulder can prepare for future flooding in addition to reinstating government investment in flood prevention is combining existing weather and climate data to create predictive attributive models. Given our current trajectory for anthropogenic climate change, we must incorporate community voices into attribution science so we can best adapt for increasing "natural" disasters in the future.

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### Attributing Extreme Weather Events in the Future

Observing daily temperature and precipitation changes in the Boulder Creek watershed limited the scope and applicability of my study. Though four of the six climate stations saw a meaningful increase in daily max temperature, none saw a meaningful increase in monthly precipitation in September, the month the 2013 floods happened. However, I show how the range of data within a local area can vary considerably, despite close proximity. This narrow focus on daily weather can obscure the larger trends of regional climate over long periods of time. Arguments in the climate debate that rely exclusively on daily weather conditions should be taken with high caution due to its inability to accurately reflect larger trends. At the same time, local accounts of how long-term climate change affect short-term conditions in weather should be taken into account rather than dismissed.

The unusual September 2013 rainstorm across Colorado created once-in-a-lifetime floods across the highly populated foothills of Boulder County. As global anthropogenic climate change continues, scientists warn such unusual regional events may become increasingly common. Attribution science will play a prominent role finding relationships between long-term climate with short-term extreme weather. Establishing a relationship between global precipitation patterns and the future likelihood of floods like the disastrous Boulder floods will help us prepare for a more unpredictable future.

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