Detecting Climate Change through Means and Extremes

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This study investigates how the climate is changing at individual weather stations around the world by measuring means and extremes. Extensive python code was written to read in the daily data from thousands of stations and compute average yearly temperature, precipitation, and extremes such as heat waves, cold spells, very wet and dry periods. A best-fit line and goodness-of-fit statistic were computed for each statistic at each station. All these linear trends were collected into histograms and geographic distribution plots. It was found that the earth is undergoing significant changes: 97% of all stations are increasing in temperature since 1950, averaging 4° F per century. All measures of extreme heat are increasing, and all measures of extreme cold are decreasing. Almost all stations are recording significant increases in the number of warm days (days above a reference 90th percentile) and heat waves (three consecutive warm days) and the warmest day of the year is getting hotter. There are fewer cold nights and cold spells. The number of frost nights is significantly decreasing, averaging 25 fewer frost nights per year over a century. Changes in precipitation vary by geography: some regions are drier while others are wetter. For example, precipitation changes are strongly varied in both the U.S. and Australia. This study confirms that the earth's climate is rapidly changing in both means and extremes. To help the public better understand climate change, this data is presented in an online map for interactive exploration at http://lillianpetersen.github.io.

INTRODUCTION

There are often events on the news reporting extreme weather events such as droughts, floods, and heat waves. People remember these extreme events and they want to know how climate change is affecting them. Whenever there is a massive heat wave, people think, "that must be caused by climate change!", but when there are snowstorms people wonder, "maybe our climate isn't changing after all." This paper presents answers to how the extreme events are changing.

Climate change is hotly debated by politicians and in the media, even though leading scientists have reached a consensus (IPCC 2013). The goal of this project is to test whether climate change can be documented using the simplest data set and methods possible.

The global annual average of land-surface air temperature has warmed about 1.5 °C (2.7° F) since 1850 (figure 1 and figure 2). Note that there is natural variability from year to year, but there is a definite upward trend. Since 1970 the trend has significantly increased. The earth is also getting either wetter or drier based on geographic location (figure 3).

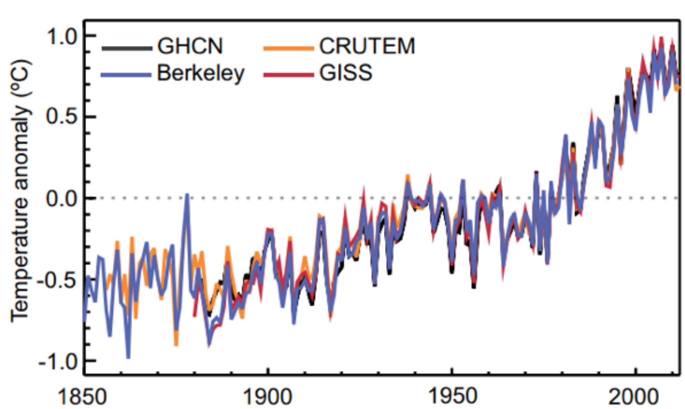

Figure 1. The global annual average of land-surface air temperature anomaly from 1850 to 2015. (Hartmann et al. 2013, ch. 2 pg. 29 fig. 2.14)

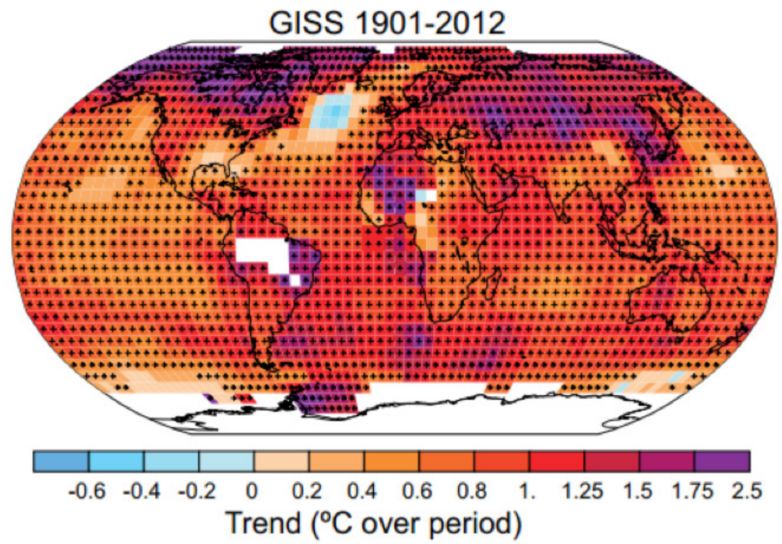

Figure 2. Global trends in surface temperature. The plus sign indicates a significant trend (i.e., a trend of zero lies outside the 90% confidence level). White areas mean that data in those places is missing. These trends were created with a combination of observed temperatures and a model to fill in the gaps. (Hartmann et al. 2013, ch. 2 pg. 193 fig. 2.21)

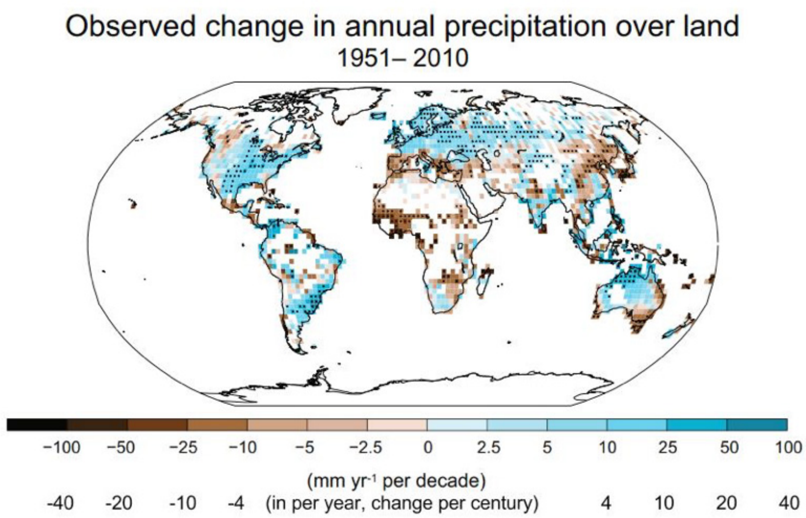

Figure 3. (IPCC 2013, pg. 6 fig. SPM.2)

METHODS

Python code was written to read in data, find averages and extremes, and plot the results. First, daily data from the Daily Global Historical Climatology Network (Menne et al. 2012a, 2012b) was read in. Four thousand cities around the world had records with daily data going back before 1950. The daily data included the maximum and minimum daily temperature, and daily precipitation (table 1).

Cities with too much bad data had to be removed. Some cities had many -9999 values, meaning the data was not recorded that day. Other cities were missing longer chunks of data. For example Podor, Senegal, had a few years of data starting in 1857, then skipped about 8 decades and started recording again in 1945. Several steps were used to sort through all of this bad data. First, single bad data days were not included in the monthly average. If at least one day in all 12 months was good, the year was kept. If even one month in the year was completely bad, the whole year was thrown out. Finally,

```
station year month variable

RQC00664702190101TMAX  294  0  294  0  294  0  294  0  300  0  300  0  294  0  283  0
289  0  278  0  300  0  283  0  289  0  289  0  289  0  294  0  300  0  306  0  306  0
300  0  283  0  283  0  294  0  300  0  294  0  289  0  272  0  294  0  294  0  289  0
RQC00664702190101TMIN  206  0  206  0  206  0  200  0  194  0  194  0  189  0  178  0
206  0  194  0  189  0  189  0  189  0  189  0  183  0  178  0  183  0  189  0  189  0
189  0  183  0  194  0  189  0  189  0  189  0  189  0  161  0  183  0  183  0  189  0
RQC00664702190101PRCP    0  0    0  0    0  0    0  0    0  0    0  0   64  0   13  0
0  0    0  0   25  0    0  0    0  0    0  0    0  0    0  0    0  0    0  0    0  0
660  0    0  0    0  0  132  0    0  0    0  0    0  0    0  0    0  0    0  0    0
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RQC00664702190102TMIN  189  0  189  0  189  0  194  0  194  0  206  0  211  0  206  0
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289  0  289  0  294  0  294  0  300  0  300  0  300  0  311  0  317  0  294  0  300  0
```

Table 1. The raw data. Downloaded from Daily Global Historical Climatology Network (Menne et al. 2012b).

cities were thrown out completely if 15% or more of the years were bad.

This project consists of two parts: finding climate change through means and through extremes (Table 2). Means include yearly averages of daily highs and lows and yearly sums of precipitation (figure 4).

Many of the extremes (figures 5-7) were calculated using percentiles. Percentiles were found by putting the daily data from 1961 to 1990 in order. Once the 90th and 10th percentiles for temperature and the 95th percentile for precipitation was found for every city, extremes could be computed.

RESULTS

Results are presented for a single weather station (Atlantic City, NJ, figures 4-7) as explanation and then for all stations with data since 1950 (figures 8-19).

The plots for Atlantic City, NJ were made for every mean and extreme. Atlantic City was chosen as an example because it has the longest record of good data in the U.S. A best fit line was fitted to the each plot. R2 was then computed. R2 shows how much of the variance can be explained by the linear trend.

In Atlantic City, the mean temperature of daily highs (figure 4a) has warmed by 2.6 °F in the past century. The R2 value for that plot is 0.46, so 46 percent of the variance can be explained by the best fit line. On the yearly average of daily lows (figure 4b), the R2 value is higher at 0.62, because the data has a tighter fit to the line.

For Atlantic City, the slopes of the best fit lines of the heat extremes (figure 5) are increasing and all of the slopes of the cold extremes (figure 6) are decreasing. Precipitation is not changing uniformly in either the means (figure 4c) or extremes (figure 7).

The slope and R2 value was recorded in a text data file for every mean and extreme, for every weather station with data since 1950. This included 1243 stations for temperature and 4534 for precipitation. Another python code read in these numbers and made plots of the aggregated data. It made a histogram of the slopes of the best fit lines for every mean and extreme. Then it plotted the location of the stations on a world map and colored the points based on how much each station is warming.

The average over all stations of the mean temperatures is warming by about 4oF per century (figures 8, 9). Of the 1,500 cities going back before 1950, about 97% of the stations are showing an increase in temperature and only 3% are cooling. Although almost everywhere is warming, the most intense warming varies by geography. Europe and Asia are warming more than the U.S (figures 8b, 17, 18). Extremes give even more insight on how our

MEANS

Descriptive name	Definition	Units	Figures
Yearly Average of Daily High Temperature	Average of all the daily maximum temperatures each year	°F	4a 8
Yearly Average of Daily Low Temperature	Average of all the daily minimum temperatures each year	°F	4b 9
Total Yearly Precipitation	Sum of all the precipitation in a year	inches	4c 14

TEMPERATURE EXTREMES

Descriptive name	Definition	Units	Figures
WARM DAYS	Number of days with daily high temperature >90th percentile	days per year	5a 10a 11a
HEAT WAVES	Frequency of 3 days in a row >90th percentile	number per year	5b 10b 11b
WARMEST DAY	Annual maximum value of daily high temperature	°F	5c 10c 11c
COLD NIGHTS	Number of days with daily low temperature <10th percentile	days per year	6a 12a 13a
COLD SPELLS	Frequency of 3 days in a row <10th percentile	number per year	6b 12b 13b
FROST NIGHTS	Number of days with daily low temperature <32 °F (0 °C)	days per year	6c 12c 13c

PRECIPITATION EXTREMES

Descriptive name	Definition	Units	Figures
WETTEST DAYS	Amount of precipitation from days with precipitation >95th percentile	inches	7a 15a 16a
WET SPELLS	Maximum of consecutive 5-day precipitation	inches	7b 15b 16b
DRY SPELLS	Number of days with precipitation <1mm	days per year	7c 15c 16c

EXTREMES COMPUTED BUT NOT SHOWN due to space & time restrictions

Descriptive name	Definition	Units
COLDEST DAY	Annual minimum value of daily temperature, computed for highs and lows	°F
TROPICAL NIGHTS	Number of days with daily low temperature >68oF (20oC)	days per year
WETTEST DAY	Maximum one-day precipitation	inches
WARMEST NIGHT	Annual maximum value of daily low temperature	°F
COLD DAYS	Number of days with daily high temperature <10th percentile	days per year
WARM NIGHTS	Number of days with daily low temperature >90th percentile	days per year

Table 2. Definitions of means and extremes. These are standard definitions from the Intergovernmental Panel on Climate Change (IPCC). (Hartmann et al. 2013, Box 2.4 pg. 221)

climate is changing. All measures of extreme heat are increasing (figures 10, 11), and all measures of extreme cold are decreasing (figures 12, 13). This confirms that climate change strongly affects average temperatures and has a pronounced influence on extreme temperatures.

The R2 value can be used to tell how significant a trend is. On the geographic distribution plots of R2 (figures 8c, 9c), all points that are red means that there is less than one-in-one thousand chance that the increase in slope happened by a random process. All points that are blue means that there is less than one-in-one million chance that the increase in slope happened by a random process. This was computed using a significance of correlation coefficient calculator (Lowry 2015) with number of samples N=65 years and correlation coefficient, *R*, where *R2* is the R2 value.

More heat extremes and fewer cold extremes affect agriculture and are bad for crops. In extreme heat, many seeds cannot germinate so plants cannot reproduce. Fruits have more trouble maturing and in many cases fall off the tree before they are ripe. Many plants die as they are more susceptible to diseases and pest infestations. While fewer frost nights make for a longer growing season thus making it possible to grow plants further north, it will also increase pests and bring on more severe heat stress that will kill of crops.

Precipitation results are more varied (figures 14-16). While most places are changing, how they change varies by geography. There is high spatial correlation amongst stations that are getting wetter and those that are getting drier. For example, the eastern and western coasts of Australia are significantly drying, by about 17 inches per year over a century. Just inland is about neutral, and northern Australia is getting wetter (figure 19).

Because this project uses raw data straight from stations, places that didn't record data are underrepresented. For example, there are only a few stations in South America, Africa, and the southern half of Asia. Because of this, the data is biased towards the places that are most strongly represented. However, where there are stations in these places, those stations are warming too.

CONCLUSIONS

This project investigates changes in climate using data from individual weather stations. The history of means and extremes in both temperature and precipitation are evaluated. The world is getting warmer, there are more heat extremes, fewer cold extremes, and the change in precipitation varies by geography. The results clearly show that climate change is real because it can be seen at almost every single station around the world. It also shows that extremes are changing along with the means. In conclusion, this project proved that climate change is evident using the simplest data set and mathematical methods possible: conclusive evidence was found by using daily weather records, yearly averages, percentiles, and the slope of a best fit line.

One of the biggest challenges in working in the climate change field is helping the public better understand the risks of climate change. To accomplish this goal, an interactive map of the world was created that shows how each individual station is changing in the means and the extremes. It is more convincing when people can see how their home town is changing. The author is currently working with museum specialists to put this educational tool in an interactive exhibit that will travel to museums around the country (see http://lillianpetersen.github.io).

ACKNOWLEDGMENTS

Thanks goes out to Mark Petersen, Phillip Wolfram, and Francesca Samsel. Mark Petersen taught me how to write python code and pointed me to weather data sets and references. Phillip Wolfram of Los Alamos National Laboratory and Francesca Samsel of the University of Texas at Austin listened to my talk before I presented it and gave me ideas on how to improve it. Ms. Samsel develops museum exhibits and has advised me on how to display my data in an interactive map.

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Lowry, Richard. 2015. *Significance of a Correlation Coefficient*. http://vassarstats.net/rsig.html

DATA

Continues on the following pages.

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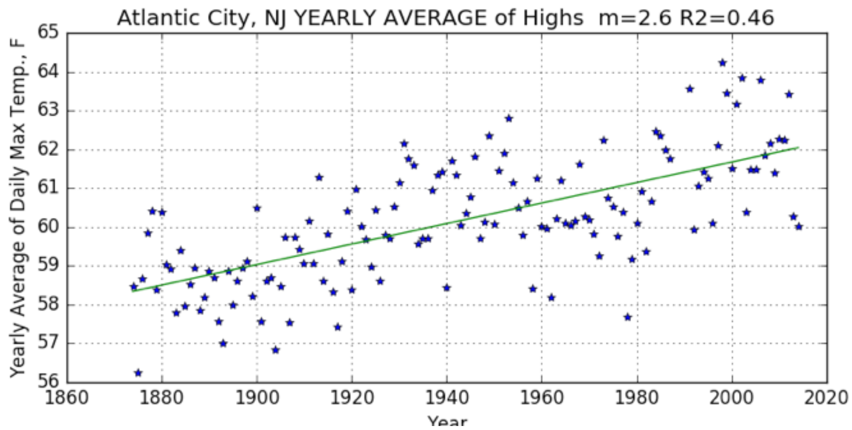
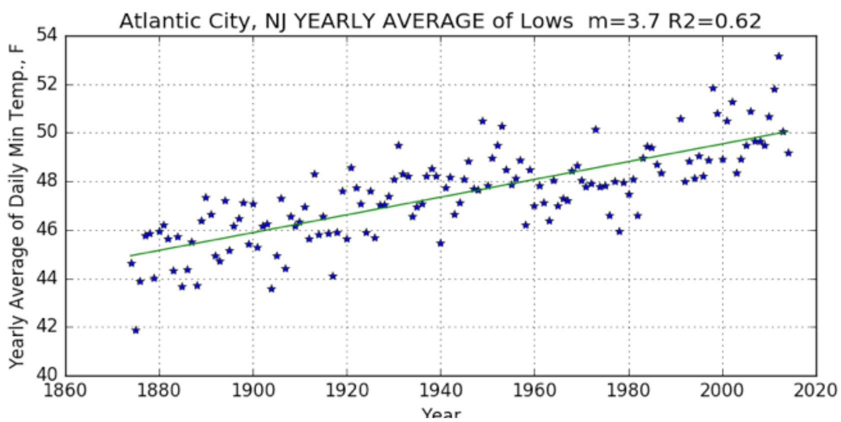
MEANS

a.) Daily Highs



b.) Daily Lows



c.) Precipitation

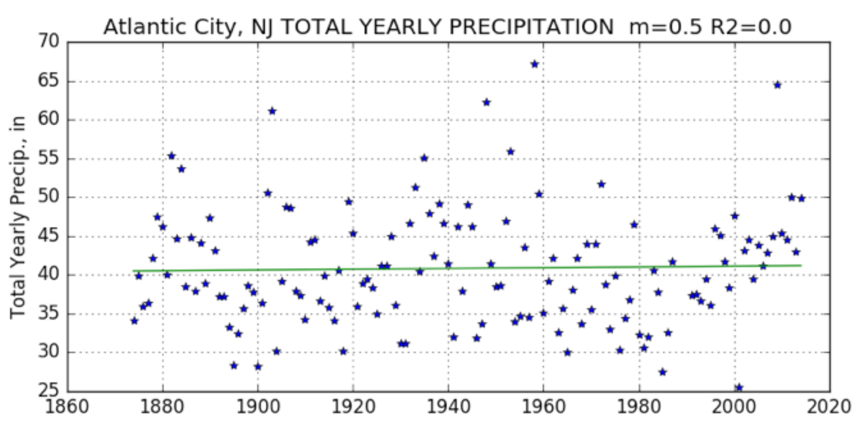
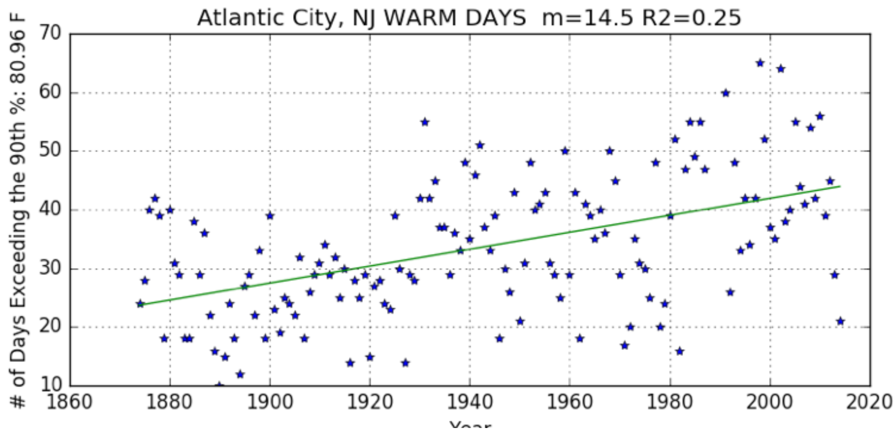


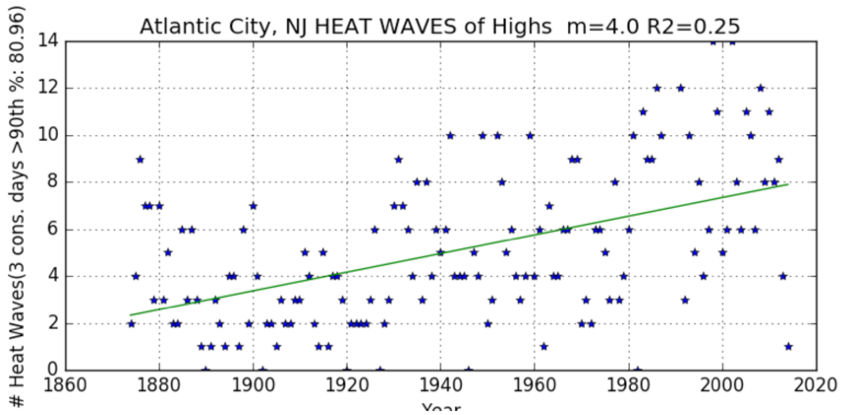
Figure 4. Data from Daily Global Historical Climatology Network (Menne et al. 2012). Each point represents the yearly average of daily highs (a), yearly average of daily lows (b), and yearly sum of precipitation (c). The green line is the best fit line and has a slope, m in title, of change per century. R2 (in title) is goodness of fit. All plots created by author.

HEAT EXTREMES: ATLANTIC CITY, NJ

a.) Warm Days: More



b.) Heat Waves: More



c.) Warmest Day: Warmer

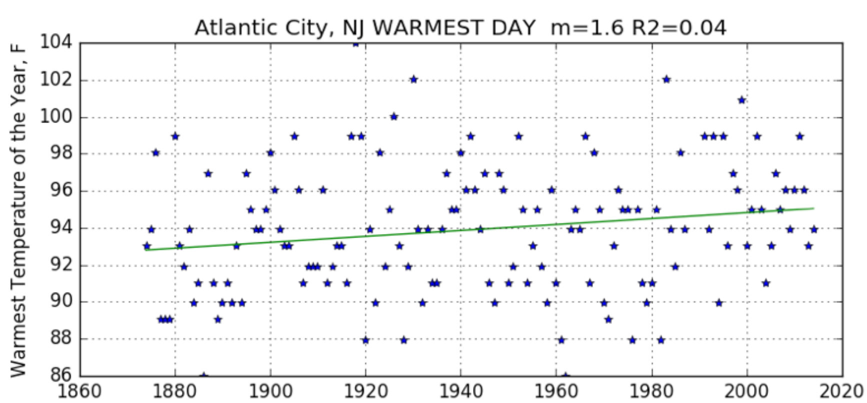
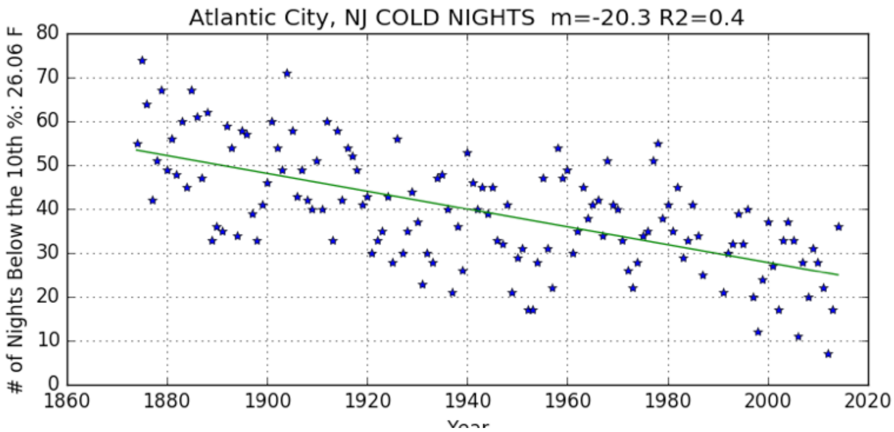


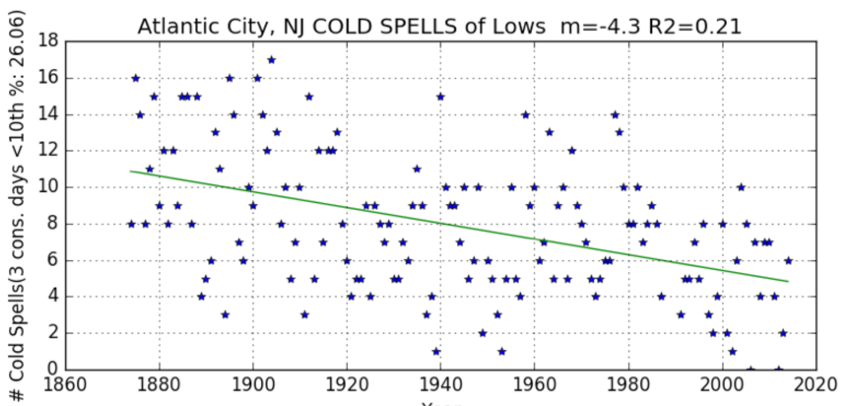
Figure 5. Same as figure 4, but for heat extremes.

COLD EXTREMES: ATLANTIC CITY, NJ

a.) Cold Nights: Fewer



b.) Cold Spells: Fewer



c.) Frost Nights: Fewer

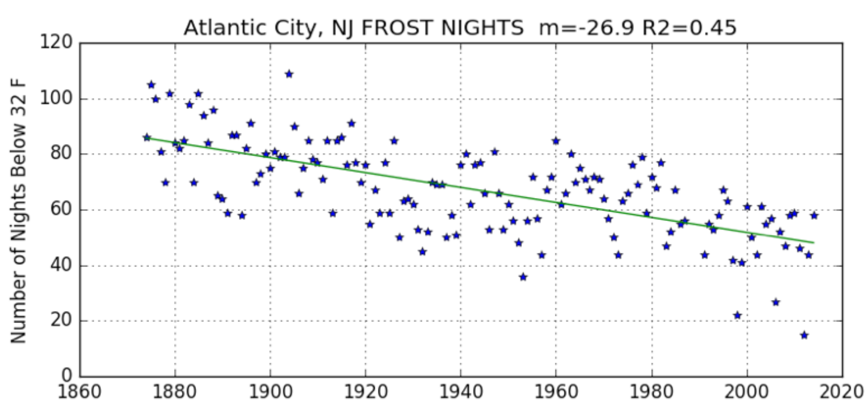
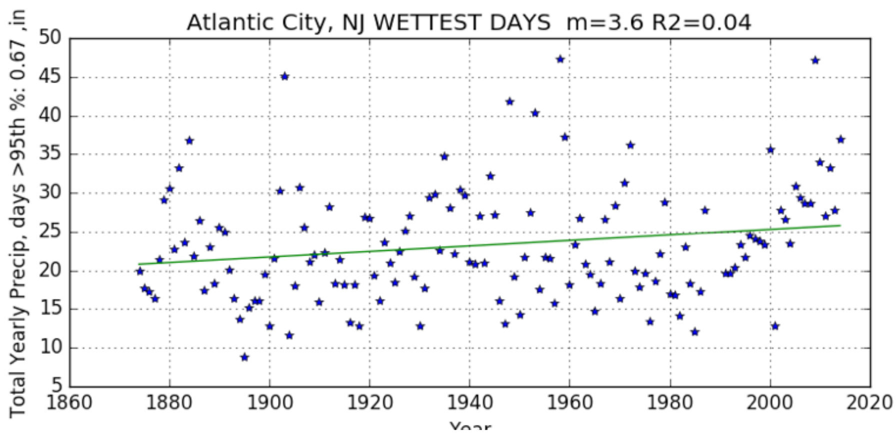


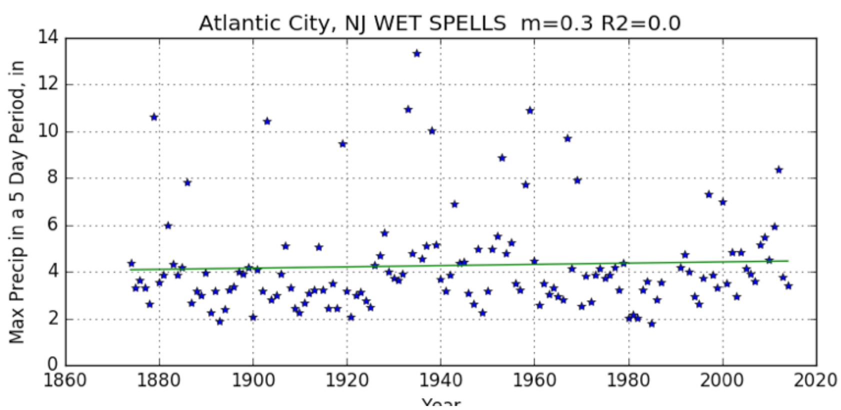
Figure 6. Same as figure 4, but for cold extremes.

PRECIPITATION EXTREMES: ATLANTIC CITY, NJ

a.) Wettest Days



b.) Wet Spells



c.) Dry Spells

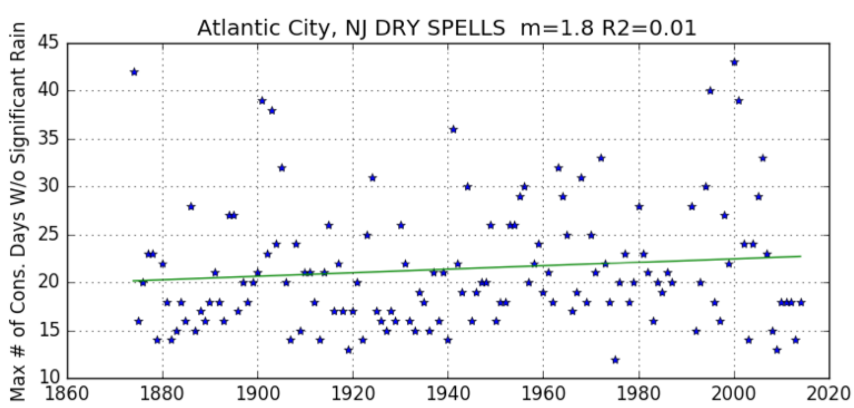
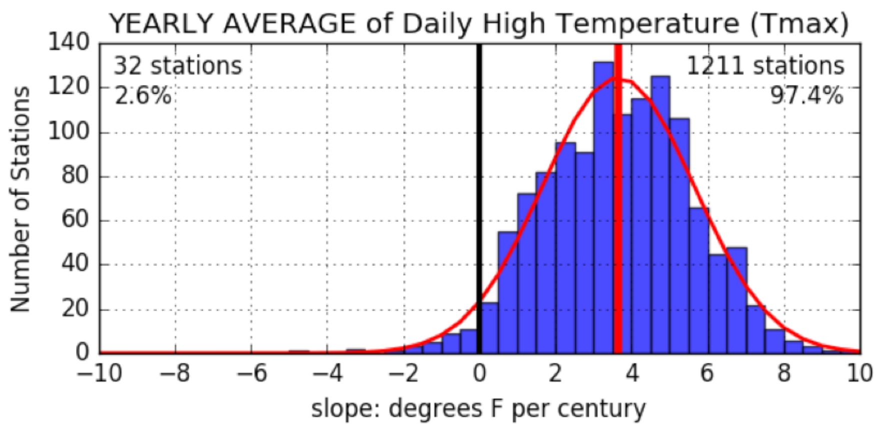


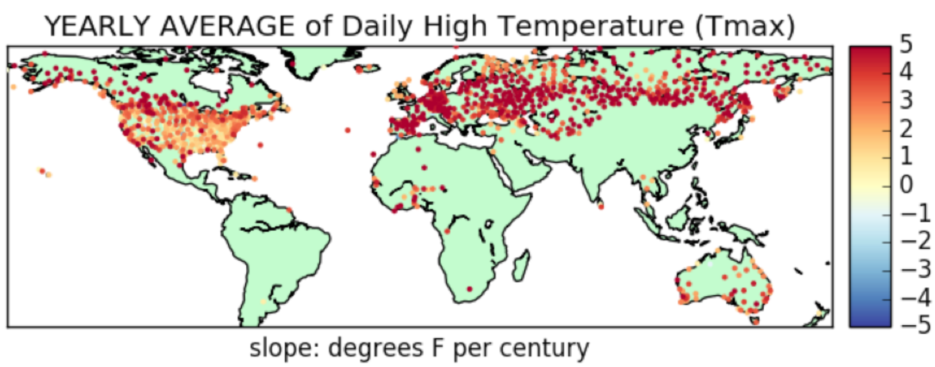
Figure 7. Same as figure 4, but for precipitation extremes.

MEANS OF DAILY HIGH TEMPERATURE

a.) Yearly Average of Daily High Temperature (Tmax)



b.) Yearly Average of Daily High Temperature (Tmax)



c.) R2 of Yearly Average of Daily High Temperature

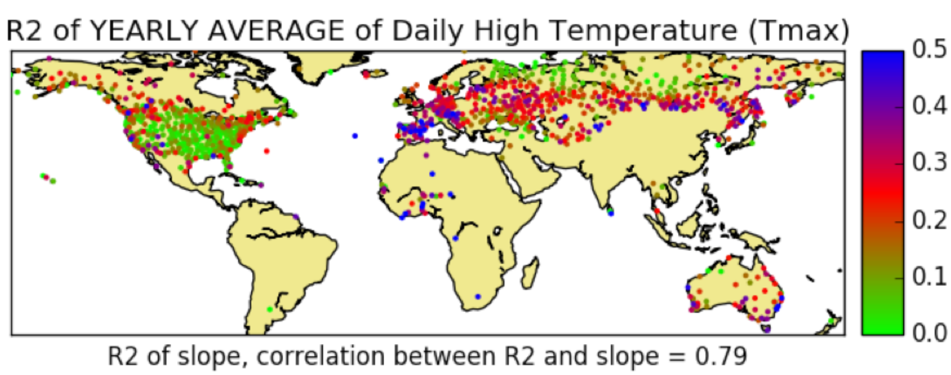
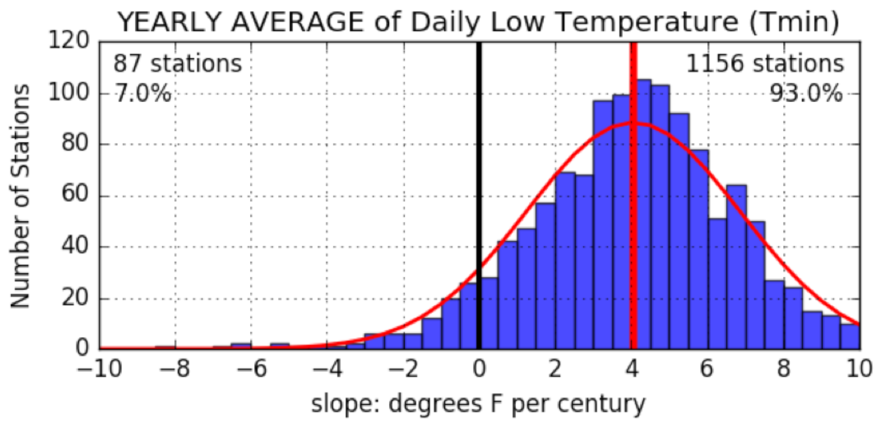


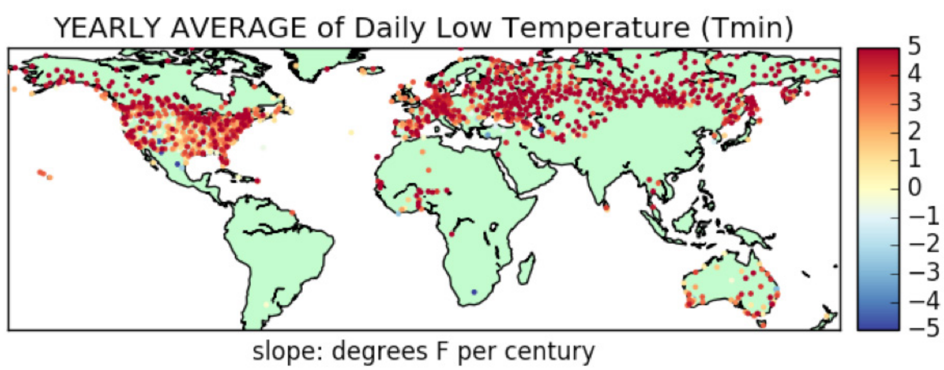
Figure 8. The histogram (a) and geographic distribution plot (b) of the slopes of the best fit lines and the geographic distribution plot of R2 (c) for all cities with data since 1950. On the histogram, the straight red line is the average, the curved red line is the best fit normal distribution, and the black line is zero. All plots by author.

MEANS OF DAILY LOW TEMPERATURE

a.) Yearly Average of Daily Low Temperature (Tmax)



b.) Yearly Average of Daily Low Temperature (Tmax)



c.) R2 of Yearly Average of Daily Low Temperature

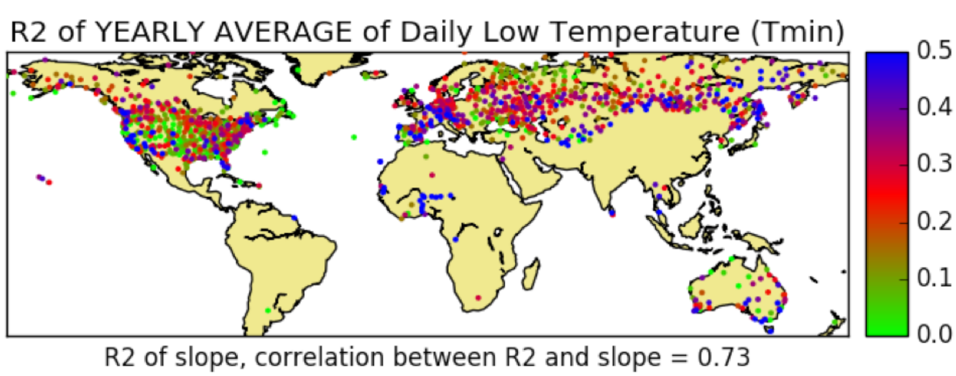
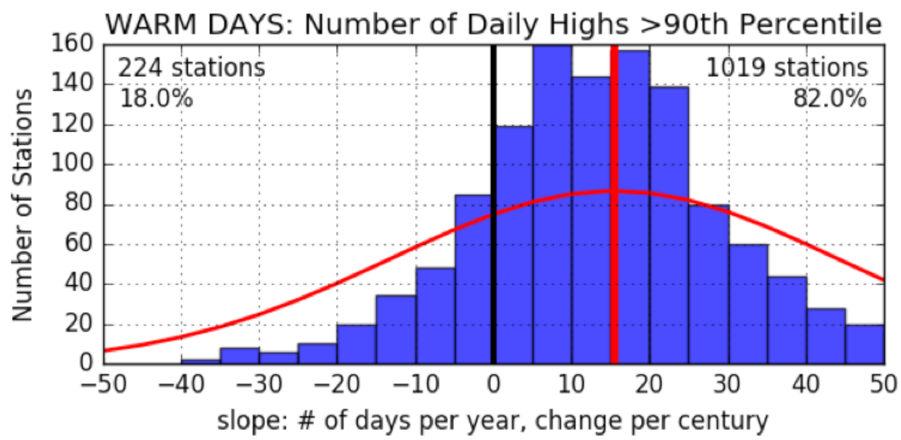


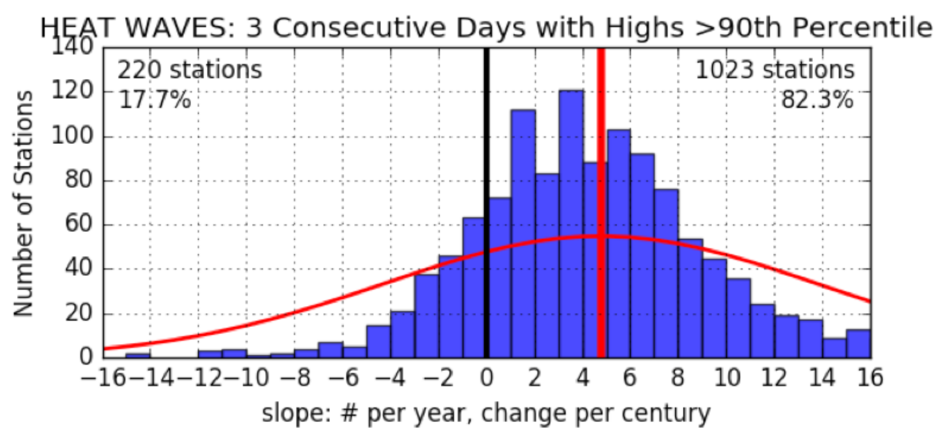
Figure 9. See previous figure for description.

HEAT EXTREMES: HISTOGRAMS

a.) Warm Days: More



b.) Heat Waves: More



c.) Warmest Day: Warmer

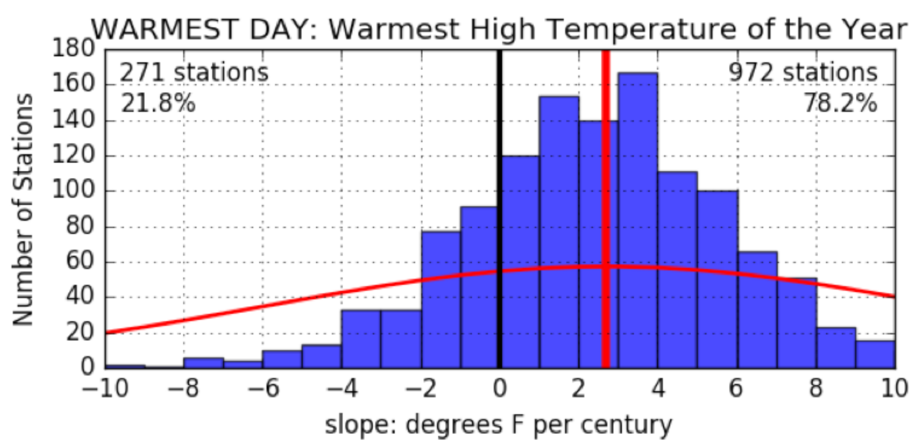
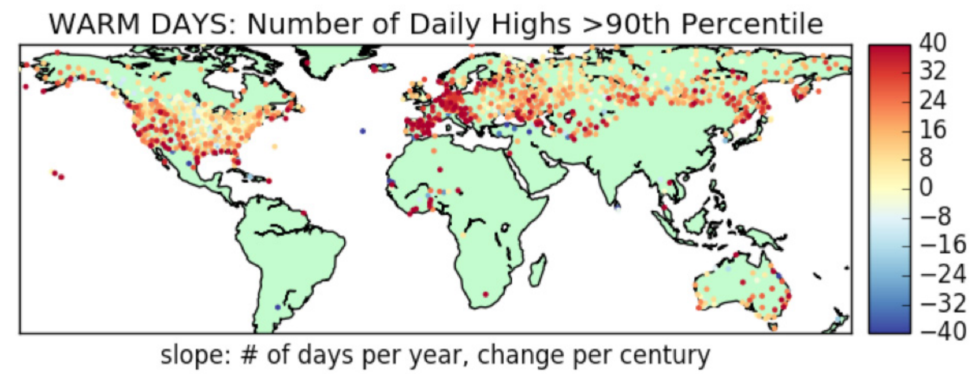


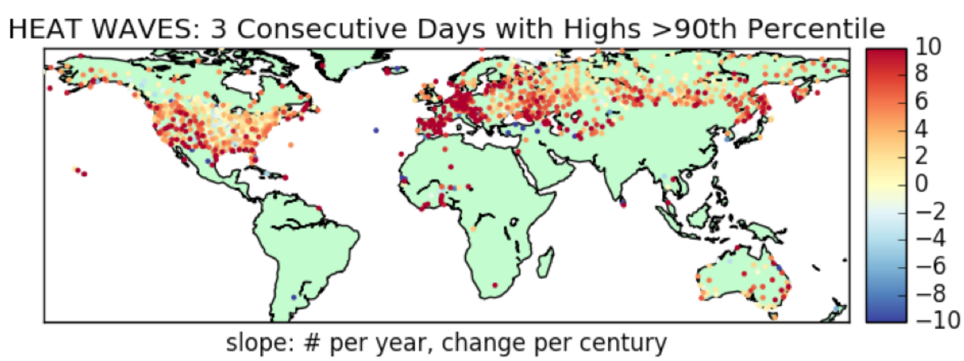
Figure 10. Histograms, slopes of best fit line of all stations, 1950-2015. Vertical red line is mean. All plots by author.

COLD EXTREMES: MAPS

a.) Warm Days: More



b.) Heat Waves: More



c.) Warmest Day: Warmer

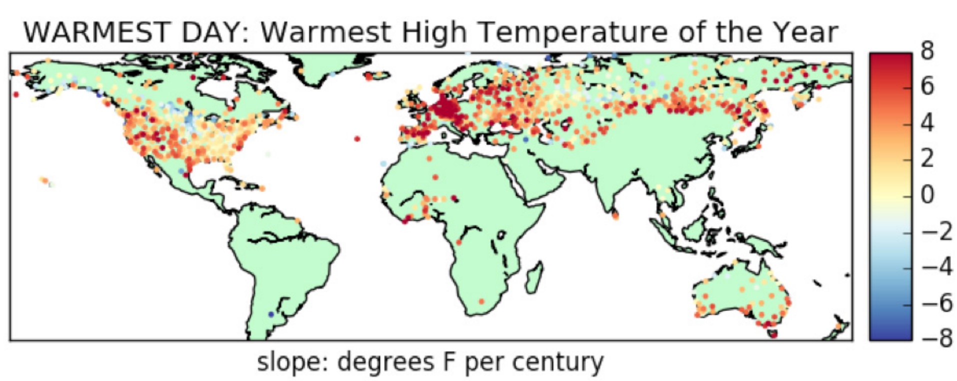
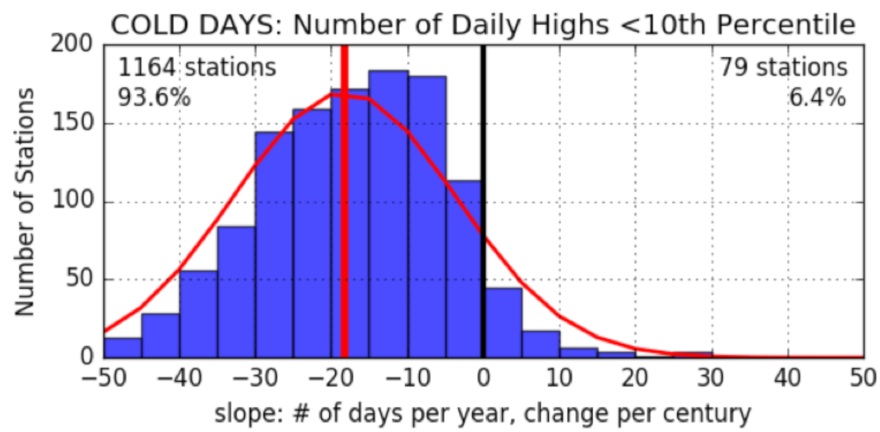


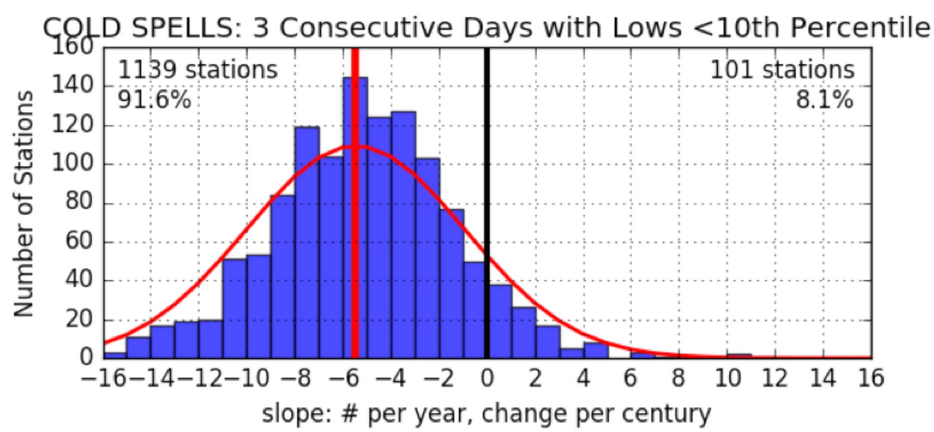
Figure 11. The change in different heat extremes by geographic location. All plots by author.

COLD EXTREMES: HISTOGRAMS

a.) Cold Days: Fewer



b.) Cold Spells: Fewer



c.) Frost Nights: Fewer

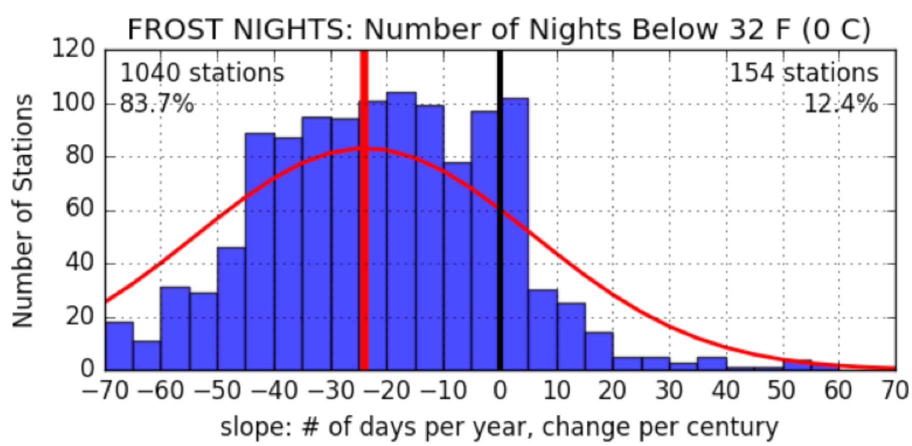
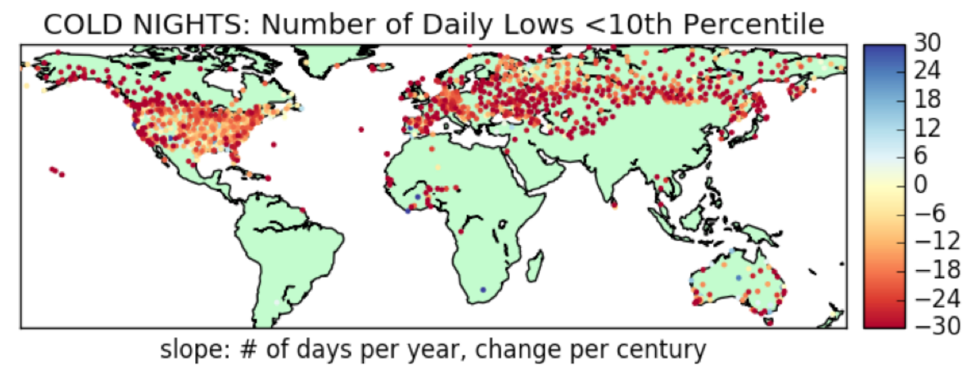


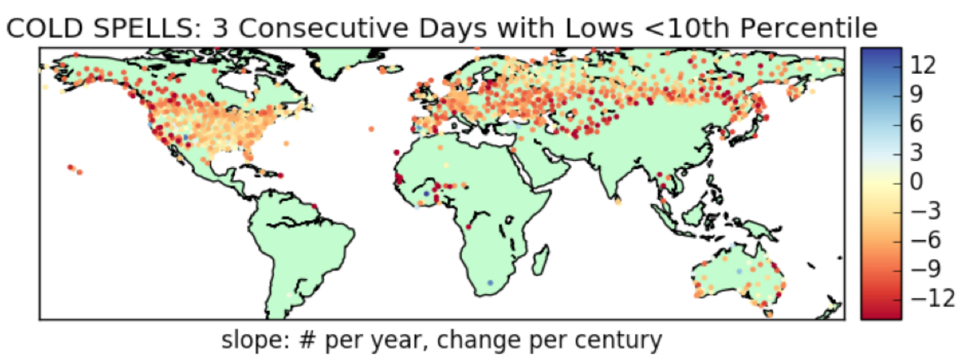
Figure 12. Same as figure 10 but for cold extremes.

COLD EXTREMES: MAPS

a.) Warm Days: More



b.) Heat Waves: More



c.) Warmest Day: Warmer

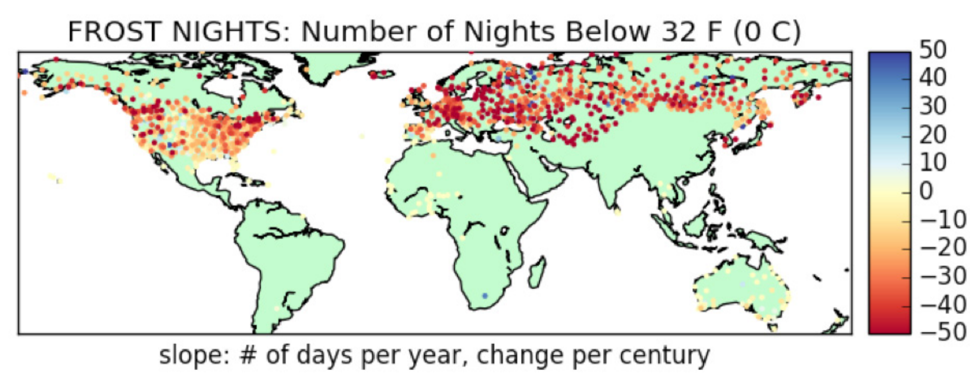
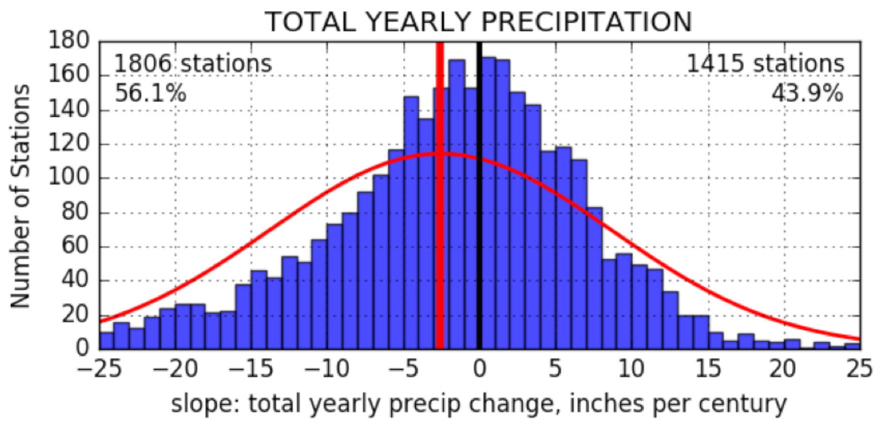


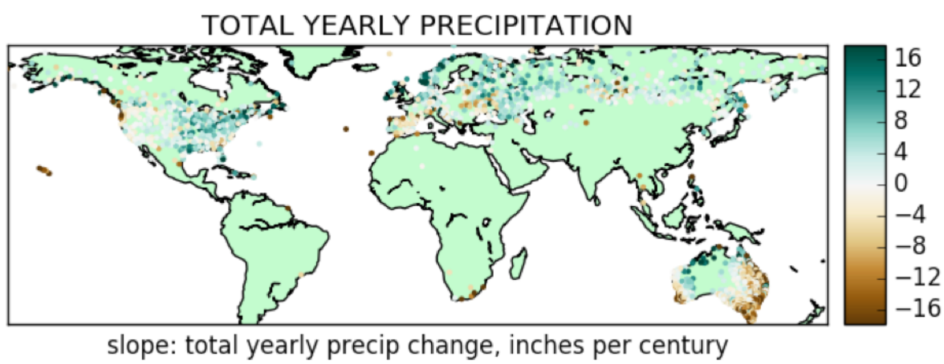
Figure 13. Same as figure 11 but for cold extremes.

PRECIPITATION MEANS

a.) Total Yearly Precipitation



b.) Total Yearly Precipitation



c.) R2 of Total Yearly Precipitation

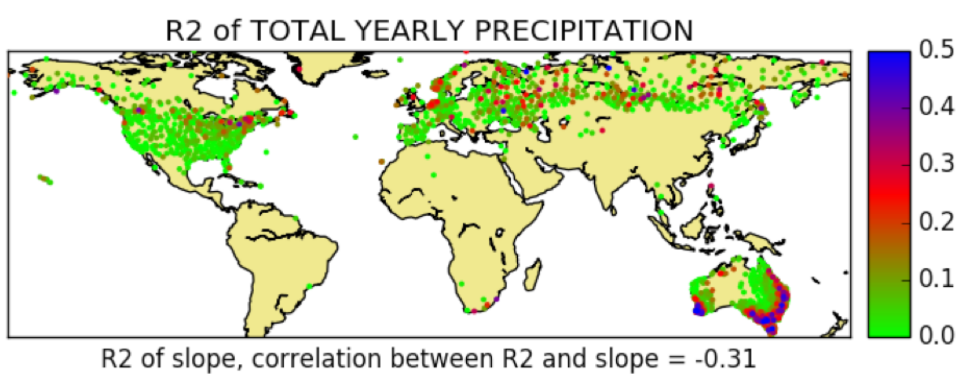
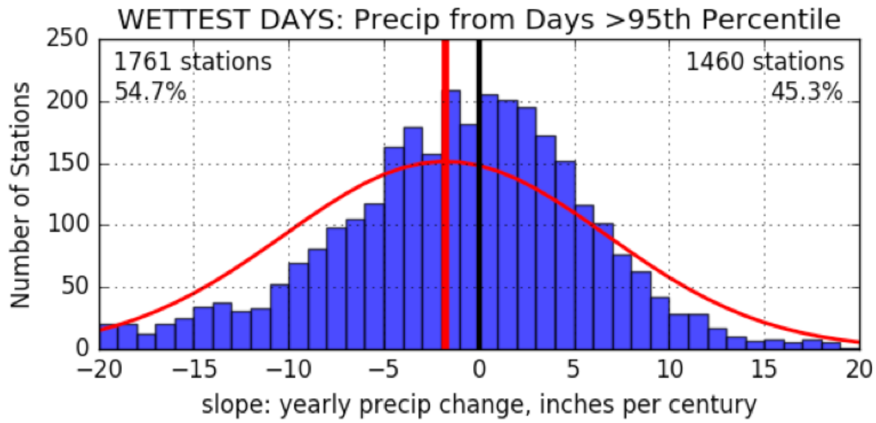


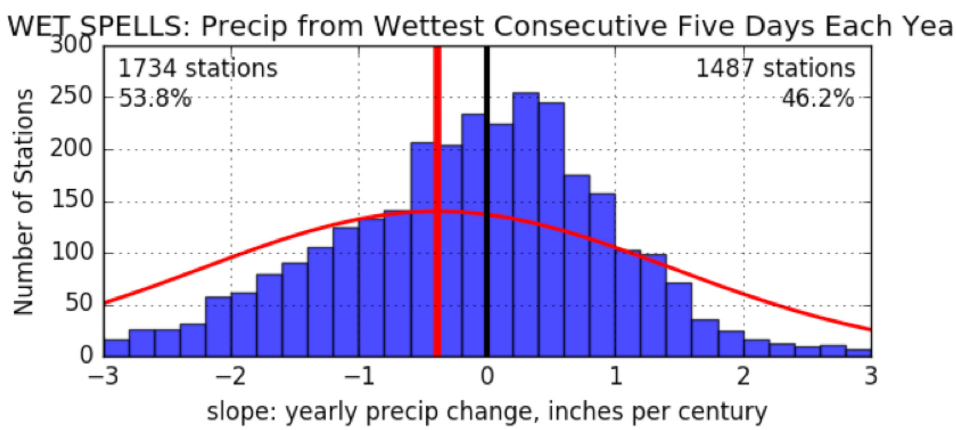
Figure 14. Same as figure 8 but for precipitation.

PRECIPITATION EXTREMES: HISTOGRAMS

a.) Wettest Days: Varied



b.) Wettest Spells: Varied



c.) Dry Spells: Varied

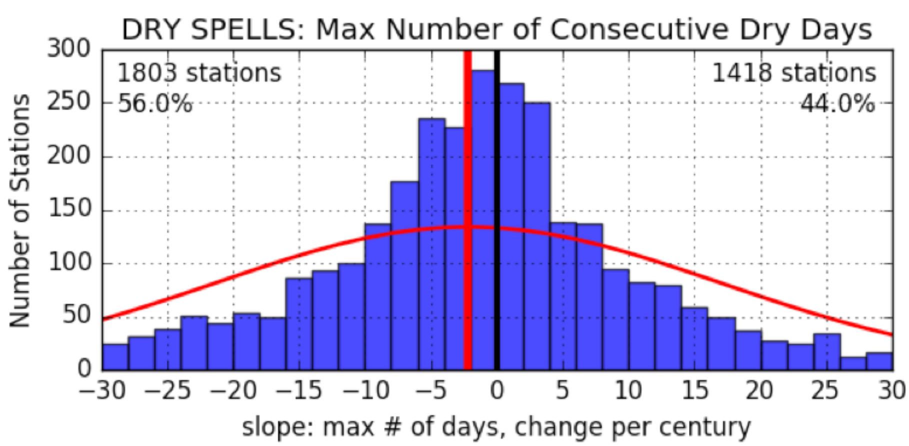
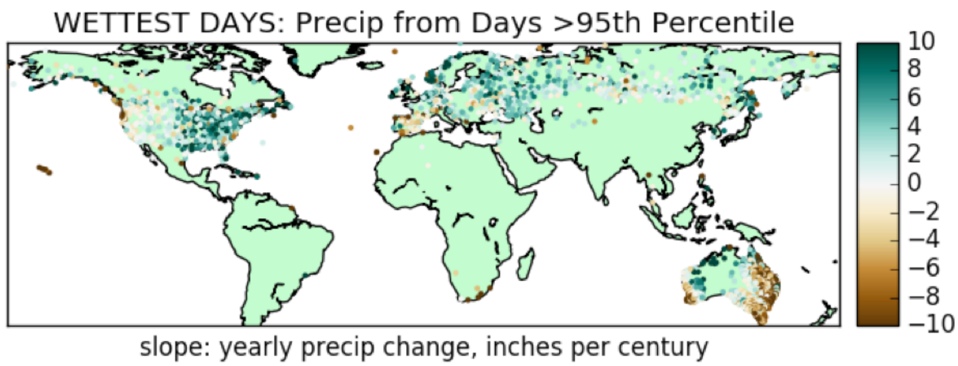


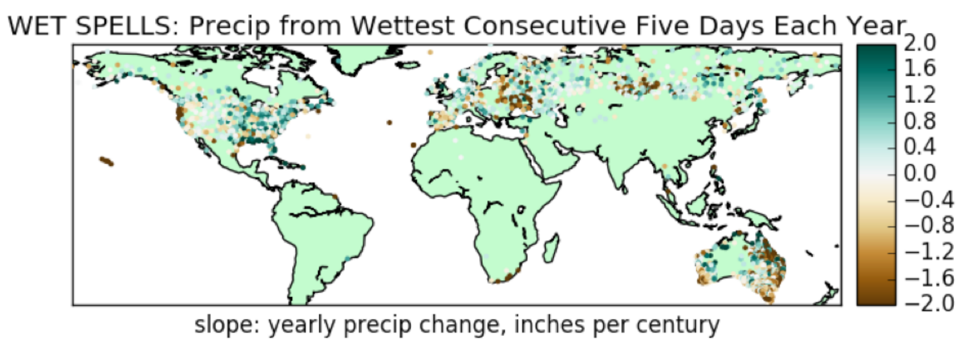
Figure 15. Same as figure 10 but for precipitation extremes.

PRECIPITATION EXTREMES: MAPS

a.) Wettest Days: Varied



b.) Wettest Spells: Varied



c.) Dry Spells: Varied

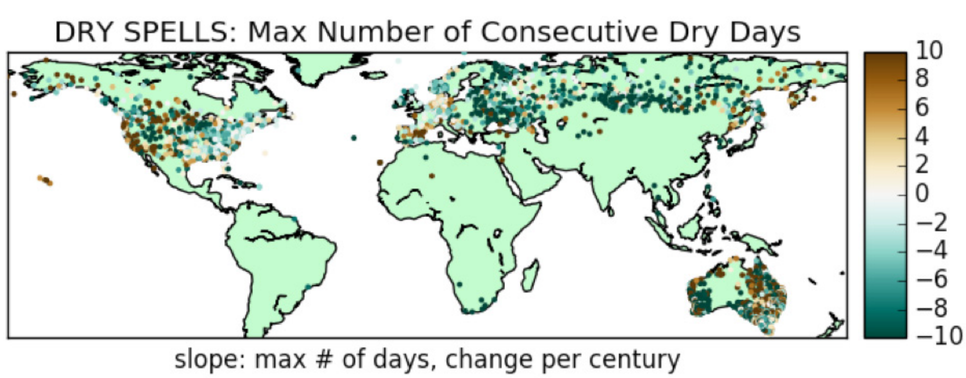


Figure 16. Same as figure 11 but for precipitation extremes.

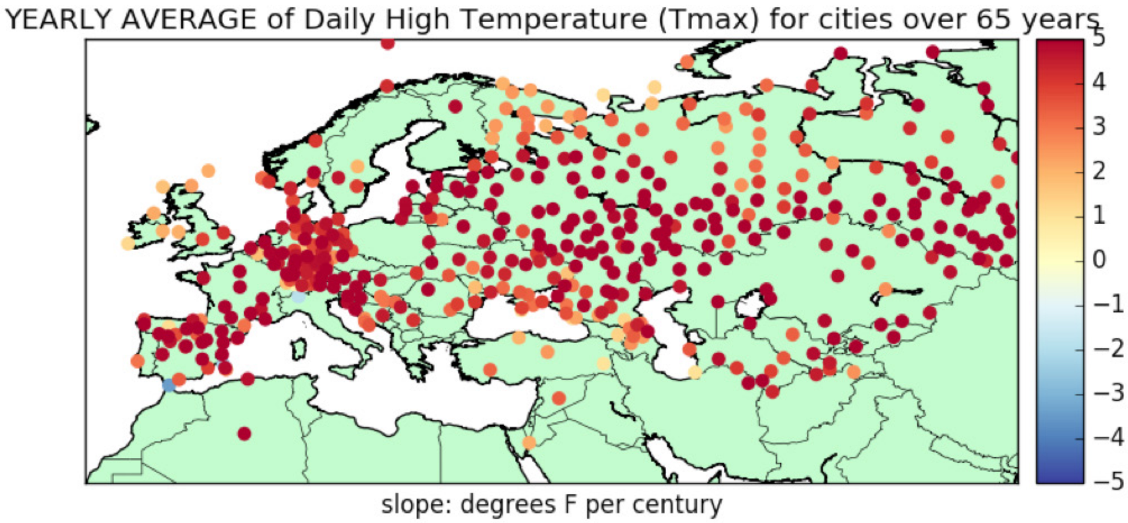


Figure 17. The change in yearly high temperature in Europe

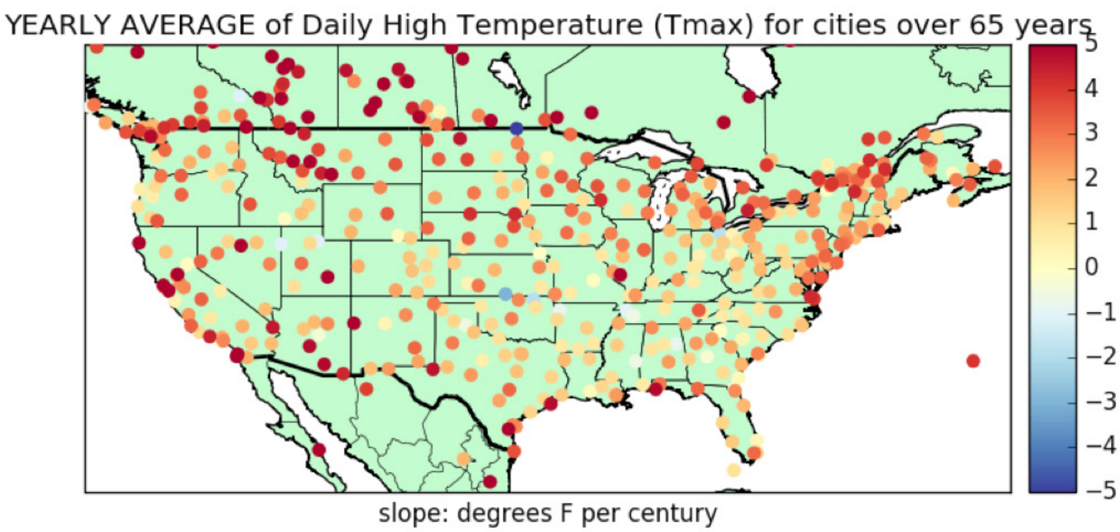


Figure 18. The change in yearly high temperature in the U.S.

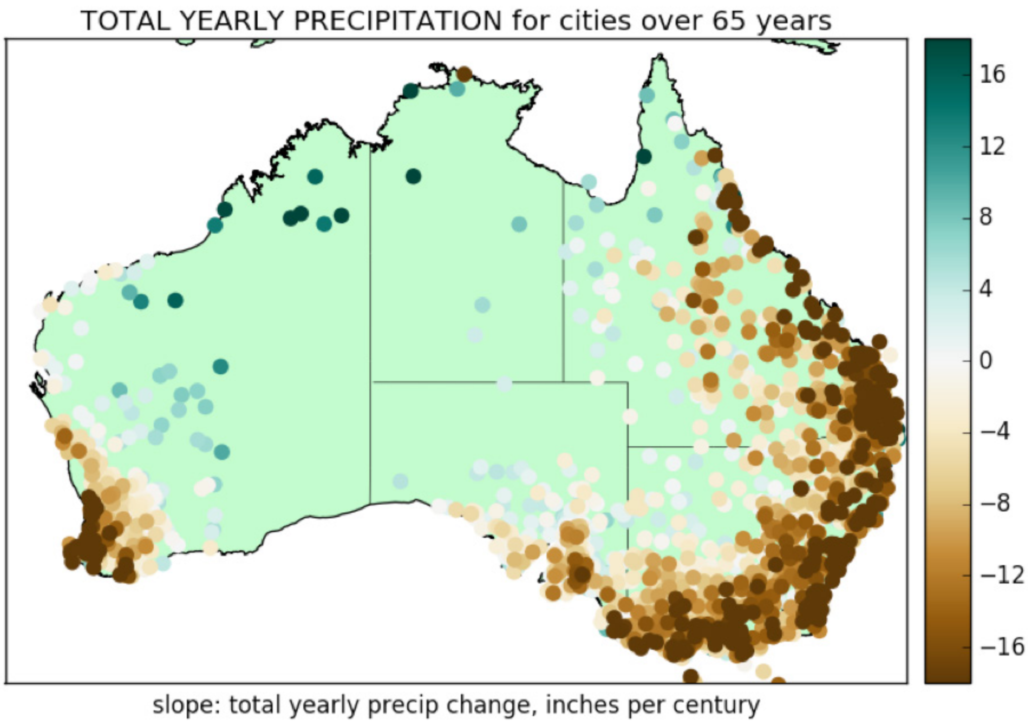


Figure 19. The change in yearly high temperature in the Australia

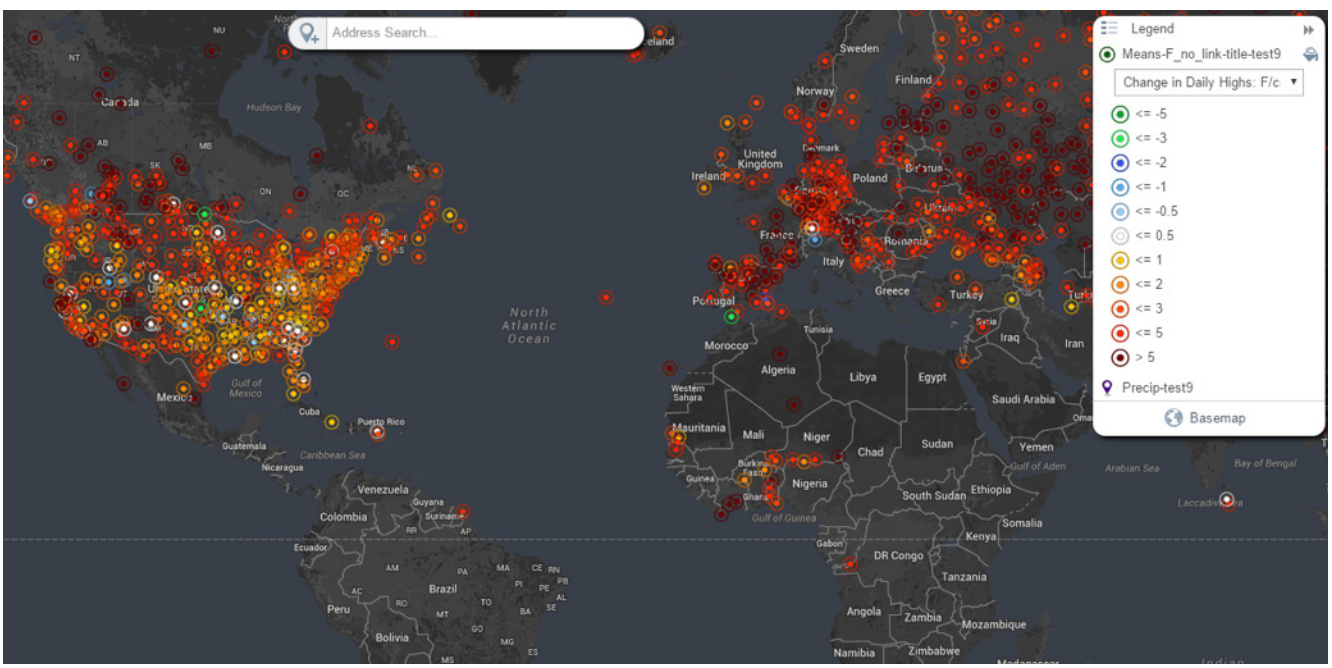


Figure 20. Online interactive map, planned for use as a museum display. See http://lillianpetersen.github.io