Jordan Schuster and Rohan Jha

Prof. Jung-Eun Lee

Final Project

19 December 2019

Is global warming leading to more afternoon convection in American cities?

Introduction

Atmospheric convection is, broadly, a result of energy imbalance: when there is more energy at the surface than at higher altitudes, it might rise and transfer energy to higher altitudes, which can result in rainfall and sometimes thunderstorms. Therefore, if the surface becomes hotter (or moister) on average, we might expect convection to occur more often. We are interested in the following research question: has global warming led to more afternoon convection and subsequently more afternoon rainfall in American cities? We hypothesize that it has, especially in the summer and in cities that are warmer and more humid. First, we will discuss the scientific basis for our research question and hypothesis in greater depth, i.e. why we would expect global warming to lead to increases in afternoon convection and rainfall. Then, we will discuss related work. And finally, we will discuss the data analysis we performed and our findings.

Background

Moist static energy (MSE) is defined as follows:

$$S = c_p\mathbf{T} + \mathbf{g}z + L_v q$$

We note that (MSE) is a function of (1) temperature T, (2) height z, and (3) moisture in the air, q. When the atmosphere is stable, MSE will be constant or higher at higher altitudes, and as discussed above, the atmosphere will be unstable, and convection might occur when MSE is higher at low altitudes because this high-energy air will rise and energy will be redistributed to higher altitudes.

This will take place when this low altitude air is hotter or more humid than given by the moist adiabatic lapse rate. Intuitively, this means that the low altitude air is hotter than expected for its height. We hypothesize that this will occur more often with global warming because air near the surface has the potential to be hotter and more humid (the saturation pressure of water vapor will increase with temperature by the Clasius-Clapeyron relation) and the energy *gradient*, therefore, might be more prone to being imbalanced. The afternoon is the hottest and most humid point of the day, so we would expect the most convection in the afternoon, and therefore, proportionally more rainfall. We discuss some related work below that gives further evidence for this relationship between temperature and afternoon rainfall. We also hypothesize that the effects of global warming on afternoon convection will be stronger in warmer months and in cities that are hotter and more humid because the surface because the energy gradient has the potential to be larger in these settings.

To summarize, we hypothesize:

1. Global warming has led to an increase in afternoon convection across cities and seasons.
2. The increase in afternoon convection is stronger in warmer months and warmer cities.

Related work

Aiguo Dai (2001) shows that thunderstorms are much more common in the tropics, over land, and in moist regions. This means that surface temperature (which is higher in the tropics and over land) and moisture (which is higher in the tropics and in moist regions) is correlated with the incidence of thunderstorms, which is a result of greater convection. Zesper and Nesbitt also write in a large-scale study of rainfall data (2003): “An increase in conditional rain rates in non-MCS systems, in particular, corresponds to an afternoon peak in convective rain fraction.” Both these papers lend evidence for our hypothesis that global warming (which leads to hotter and moister conditions) might lead to more convection, particularly in the afternoon, which is the hottest and moistest part of the day.

Dai writes in a different paper (2001) that “the late-afternoon maximum for showery precipitation and thunderstorms over land areas is consistent with the late-afternoon maximum CAPE that results primarily from solar heating on the ground during the day” (1127). CAPE is a measure of the instability of the atmosphere. Dai, therefore, writes that higher surface temperatures are leading to more instability and presumably more convection. This, again, lends evidence to our hypotheses.

In another work (1999), Dai notes increases in summer afternoon precipitation in the Southwest and the Midwest (while he notes decreases in the Southeast). We seek to update these results for a greater number of regions and with fifteen more years of data. And Zhou (2002) looks at the diurnal cycle of rainfall in different parts of China but doesn’t analyze the effects of climate change.

Data analysis

Providence

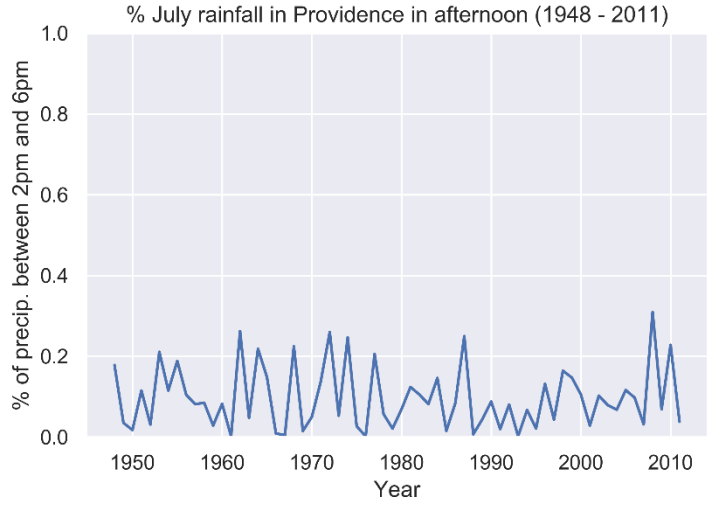
We start by analyzing the rainfall in Providence, RI. Our data comes from NOAA and contains the hourly precipitation for a given station, in addition to the hourly temperature. After importing the data from the website, we performed two separate analyses.

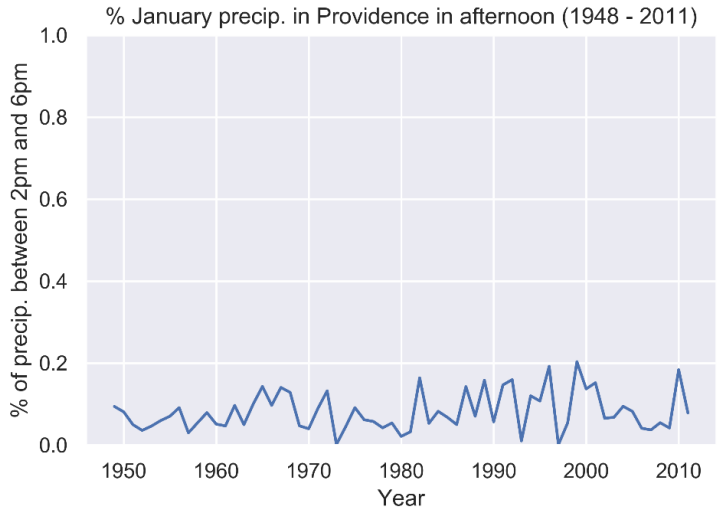
Precipitation alone

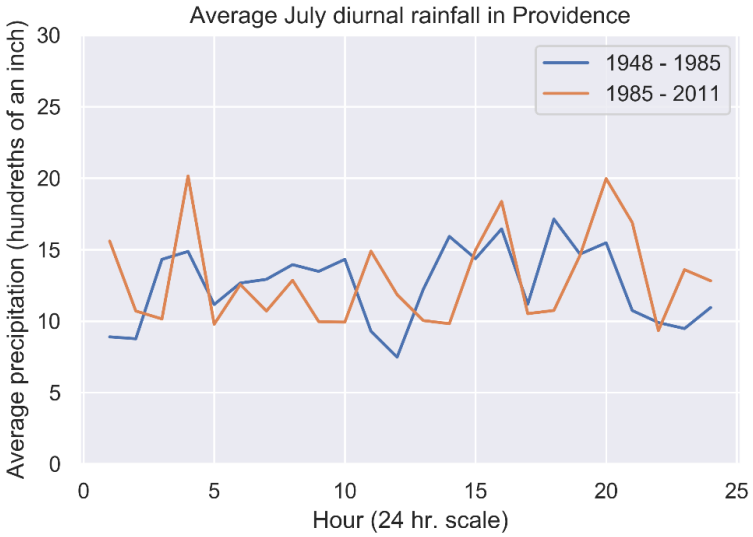
The first question was whether the ratio of rainfall that occurs in the afternoon has changed from a time period considered 'pre-climate change' (before 1985) and that in which the effects of climate change are thought to be visible (after 1985). The precipitation data for Providence specifically is from 1948 to 2011. We did a statistical analysis, we found that there was a significant difference between the percent of rainfall in *January but not in July* that occurred in the afternoon in 1948-1990 vs. 1990-2011.

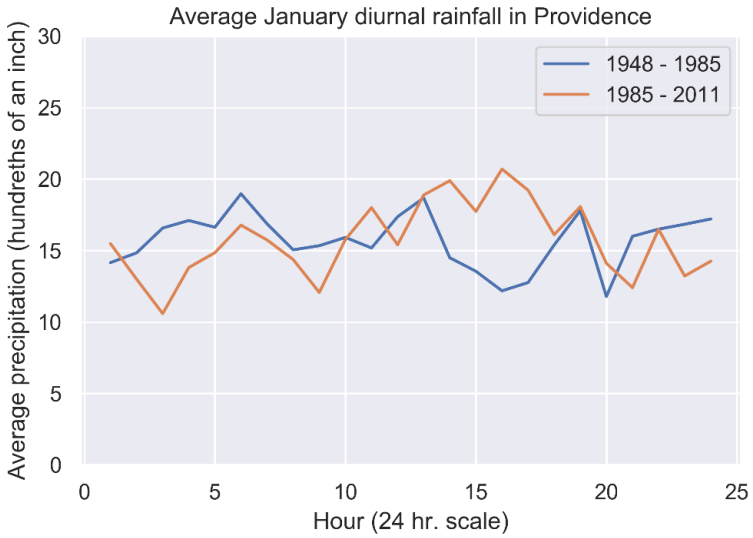
In particular, we computed the percent of rainfall in January and July (separately) that occurred in between 2pm and 6pm for each year in our dataset, and we performed a T-test to determine whether the difference in the proportions before and after 1985 was significant. This

returned a p-value of 0.039 for January and 0.726 in July (the proportion of afternoon rainfall actually decreased). We provide graphs that show the proportion of afternoon rainfall in July and January, respectively, for each year in our dataset. They are consistent with the results of our statistical test: we see an increase for January but not July. We also provide graphs that show the average diurnal cycles for July and January, respectively, before and after 1985. These also corroborate our results. In January precipitation becomes more concentrated in the afternoon; in July, we observe sharper peaks at 4pm and 8pm but the overall proportion of afternoon rainfall does not seem to increase.







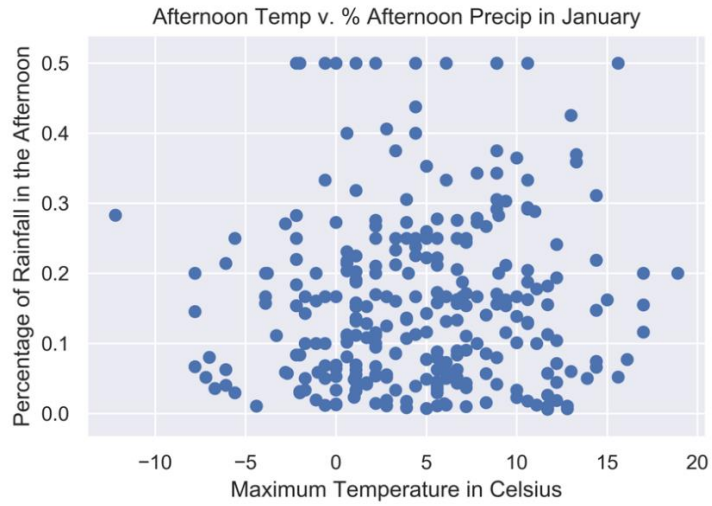


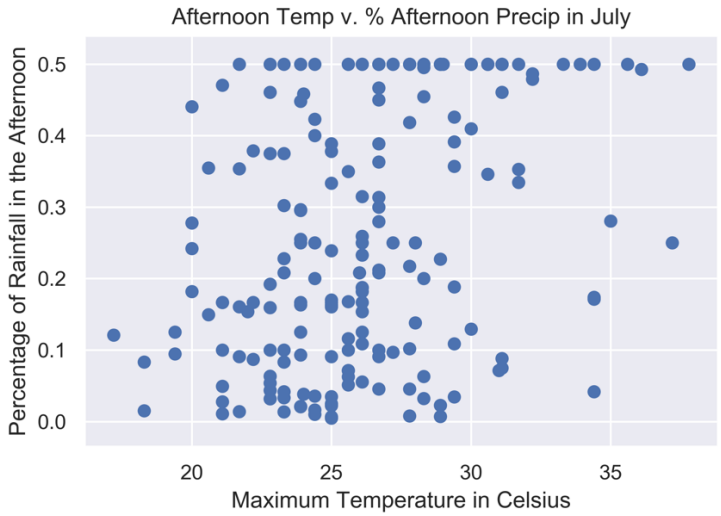
Precipitation and temperature

Next, we investigated the relationship between temperature and proportion of afternoon precipitation in Providence, RI. We compared the proportion of afternoon precipitation to the temperature. Because this was be challenging, particularly matching the stations to each other and finding the data for the right time periods, we only conducted this analysis for Providence. Specifically, we made a scatterplot with a point

for each year and temperature on one axis (we tried afternoon temperature and maximum daily temperature, which is highly correlated with afternoon temperature) and the percent of precipitation in the afternoon on the other axis. Then, we performed a statistical analysis to assess whether they were in fact correlated. Again, we repeated for January and July. The results were not significant; there was no clear correlation between the temperature and the percent of afternoon rainfall.

After viewing these results, we decided that it might be more productive to have more data points, so we looked at the daily values for each year within the given month. We took the percent of the afternoon rainfall and the maximum temperature for the given day. We removed any values where there was no rainfall. After doing this, we made the below plots. We performed statistical analysis, and we found that for January the R-value was small and the p-value was not significant (0.0769 and 0.2045 respectively). However, for July, while the R-value was still relatively low at 0.3613, the p-value is incredibly small at 3.7678e-08. We conclude that temperature certainly influences afternoon rainfall, but the correlation is not that strong. However, maximum temperature is only one way to get at the effects of global warming. It might be more meaningful to look at humidity, average temperature, morning temperature, etc., and these metrics could reveal stronger correlations.





Repeating the analysis for other cities

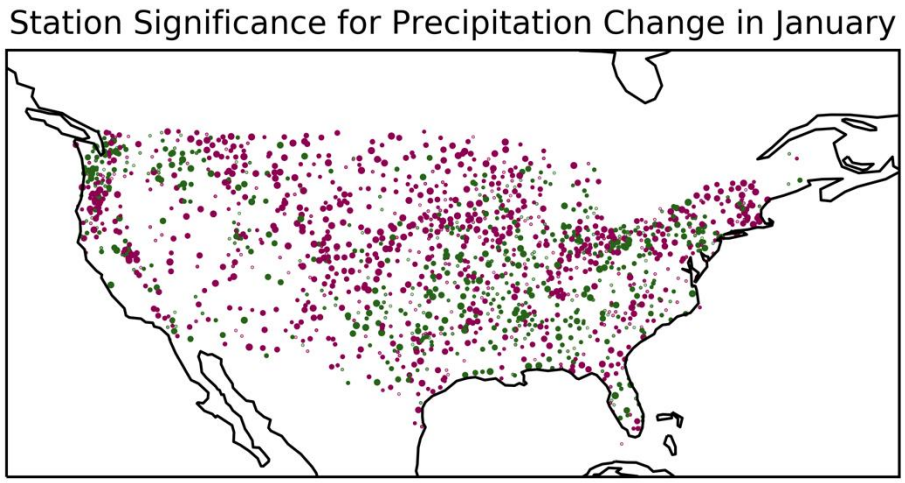
We repeated our tests of significance for all stations that have precipitation data. Specifically, we downloaded all the hourly precipitation data, and found the coordinates for each station using a table given by NOAA with the coordinates for each COOP station (we discarded the data if the coordinates couldn't be found). Then, if there was data for 15 years before and after 1985, we conducted a one-sided T-test to determine whether

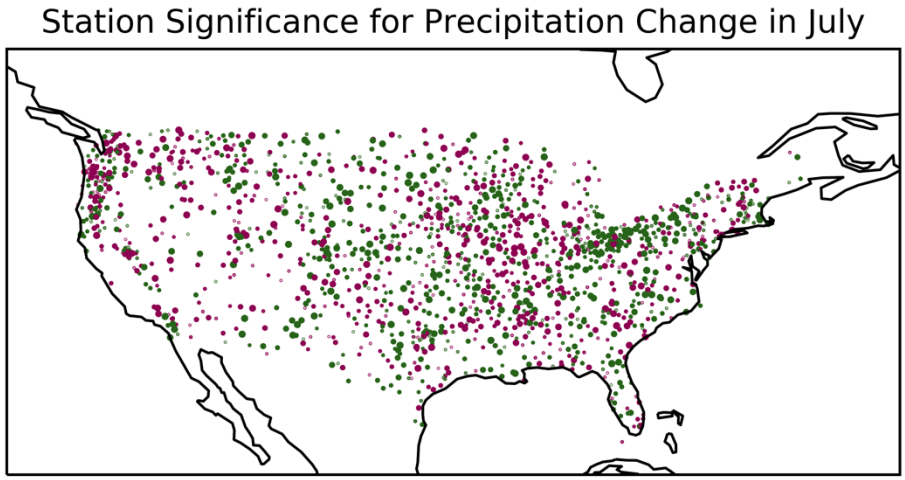
the proportion of rainfall between 2pm and 6pm increased after 1985. Again, we did this separately for January and July.

We found that the proportion of afternoon precipitation in January increased in roughly 60% of 1,600 stations, which suggests there's a nationwide trend. However, the proportion for July was only 50%, which means there hasn't been a general increase, or that the patterns are more regional.

In the maps below, there's a dot for each station: purple means that the proportion of afternoon rainfall has *increased*, while green means *decreased*. The size of the dot is proportional to the sixth power of the p-value subtracted by one, which is done to emphasize those points where there's significance. For January, we see that the proportion of afternoon precipitation has increased, often significantly, in the Midwest and much of the West Coast and the Northeast. For July, however, the patterns are less clear with significance in fewer places. We again find that afternoon precipitation has increased in the West Coast for the most part, and we find that it's decreased in parts of the Great Lakes region. We only ran our statistical tests for one time range (2pm to 6pm), so it's possible that later time ranges, for example, would yield clearer results.

In conclusion, we find some evidence in the January map for our high-level hypothesis that afternoon rainfall has generally increased. The takeaways from the July map, however, are less clear. The fact that there's been more of an increase in January is evidence against our hypothesis that there would be more of an increase in warmer months and places – in addition to the fact that the increases have been higher in the northern parts of the country.





Purple = increased
Green = decreased

Conclusion

We find that there has been a significant increase in afternoon rainfall in the winter but not the summer in Providence. This latter fact is evidence against our hypothesis that there has been a greater difference in afternoon rainfall in the summer. We also found a weak correlation between afternoon temperature and proportion of afternoon rainfall in Providence, which suggests that global warming might have more of an effect in the next decade. The correlation was much weaker in the winter. Finally, we saw some evidence of widespread increases of

afternoon rainfall in January (in the northern parts of the country), but not as much in July, which again is evidence against our hypothesis that there would be more increases in afternoon precipitation in warmer months and places.

Citations

Dai, A. (2001). Global precipitation and thunderstorm frequencies. Part I: Seasonal and interannual variations. *Journal of climate*, *14*(6), 1092-1111.

Dai, A. (2001). Global precipitation and thunderstorm frequencies. Part II: Diurnal variations. *Journal of Climate*, *14*(6), 1112-1128.

Dai, A. (1999). Recent changes in the diurnal cycle of precipitation over the United States. *Geophysical Research Letters*, *26*(3), 341-344.

Nesbitt, S. W., & Zipser, E. J. (2003). The Diurnal Cycle of Rainfall and Convective Intensity according to Three Years of TRMM Measurements. *Journal of Climate*, *16*(10), 1456-1475.

Zhou, T., Yu, R., Chen, H., Dai, A., & Pan, Y. (2008). Summer precipitation frequency, intensity, and diurnal cycle over China: A comparison of satellite data with rain gauge observations. *Journal of Climate*, *21*(16), 3997-4010.