2018

Heavy Rain-Producing Mesoscale Convective Systems in a Changing Climate

Sean Spratley
Iowa State University

Heavy Rain-Producing Mesoscale Convective Systems in a Changing Climate

Sean Spratley

Department of Geological and Atmospheric Sciences, Iowa State University, Ames, Iowa

William Gallus – Mentor

Department of Geological and Atmospheric Sciences, Iowa State University, Ames, Iowa

ABSTRACT

It has been thought that the behavior of heavy-rain producing mesoscale convective systems would change in a future climate scenario. This could have important implications, because these systems have many effects on the central United States, from providing necessary rainfall to producing hazards such as wind and flooding. Specifically, this study looked at how the frequency, intensity, and tracks of heavy-rain producing mesoscale convective systems (MCSs) would change in a future climate scenario. To do this, cases of heavy-rain producing MCSs were determined for both the present climate and a future climate scenario using regional climate data. These cases were defined using precipitation data that met or exceeded both an aerial and intensity threshold. The tracks were determined using the median starting and ending latitude of each MCS, the frequency was determined using the number of MCSs in each climate period, and the intensity was determined using the maximum precipitation rate from each MCS. Upon conducting the study, it was found that heavy-rain producing MCSs are likely to take tracks further to the south in a future climate scenario, and their maximum precipitation intensities are likely to increase. No conclusions could be made about the frequency of MCSs in the future climate. This means that there will likely be more flooding problems associated with MCSs, and the locations that receive the most beneficial rainfall from MCSs will likely shift southward. Due to the range of different climate scenarios and different factors causing MCSs globally, the results of this study are specific to the central United States with this particular climate scenario.

---

1. Introduction

Mesoscale convective systems are an important weather phenomenon in the United States. In addition to causing many problems with flash flooding, these systems provide a significant proportion of the summer rainfall to the central United States (Ashley et al. 2003). However, climate change is likely to affect many of the conditions in which these systems develop. In doing so, it is also expected to affect specific characteristics of these systems such as their frequency, location of occurrences, and intensity.

Because these systems affect people living in the central United States in so many ways, it is essential to understand how climate change will affect them so that scientists can better predict them in the future, and people who may feel the effects of these changes can start preparing for them now.

A mesoscale convective system is defined as a large-scale cluster of thunderstorms in which the thunderstorms within it interact in a way that allows it to maintain its organization (Ashley et al. 2003). This organization enables these systems to persist for much longer than individual thunderstorms. These systems that occur in the central United States frequently develop just to the east of the Rocky Mountains and tend to reach their peak intensity during the overnight hours (Tuttle and Davis 2005). This peak timing is quite unusual, as thunderstorms usually reach their maximum intensity in the late afternoon or early evening. Tuttle and Davis speculate that this region and time of day is favored for the development of these systems due to the prominence of the low-level jet, which is common in this region and is primarily a nocturnal phenomenon, although other features such as fronts and drylines also play a role. In addition to being unusual for convective weather phenomena, the nocturnal nature of these systems can amplify some of the other problems they cause. For example, it can be harder to see whether a roadway is flooded at night than it would be during the day. Therefore, the frequent nighttime occurrence of these systems makes people more likely to drive through a dangerously flooded road than they otherwise would, increasing the risk of fatalities.

Mesoscale convective systems can sometimes be very problematic. They are responsible for many of the severe weather and flash flooding events occurring in the United States (Parker and Johnson 2003). Sometimes, a series of these systems will strike the same area repeatedly within a short period, increasing the likelihood of flash flooding (Tuttle and Davis 2005). These flash flooding events can claim many lives, and they also cause millions of dollars in damage and displace people for months at a time. However, these systems can also be beneficial. They account for a significant amount of warm season precipitation in the Central United States. This precipitation is essential for crop growth, and it also helps to provide drinking water for many people. Because of all of this, it is important that scientists understand how these systems work so they can provide accurate forecasts on when and where they will develop, as well as their intensity. However, changing overall conditions could cause forecasting these systems to become more complicated in the future.

One thing that will likely have many impacts on the weather is climate change. Although scientists are aware that climate change is causing the planet to overall become warmer with time, predicting how trends in mesoscale convective systems will change in the future is a difficult task. However, observational data has shown that some changes are already occurring in the trends of these systems. One observational study found that found that during the period from 1979-2014, the frequency of springtime (April-June) MCSs was increasing in areas north of the region with the highest overall

MCS frequency, suggesting that MCSs have been trending further to the north in recent years (Feng et al. 2016). This study also found that the overall frequency of MCSs in the central US was increasing from one decade to the next. Furthermore, this study found that extreme hourly precipitation rates (precipitation rates exceeding the 95th percentile) have increased during this period (Feng et al. 2016). All of this shows that climate change is likely causing a northward shift in the overall tracks of these systems, and it is also causing their frequency and intensity to increase. However, this particular study only examined springtime MCSs and did not include mid-late summer ones.

These climate change-induced changes to these systems carry enormous potential consequences for the people living in the central United States. If climate change led to an increase in the intensity of mesoscale convective systems, it would likely lead to there being more catastrophic flooding events in the areas that receive them the most. This could lead to significant damages and potentially more loss of life for the people living in these areas. If the frequency of these systems were to decrease, this could lead to increased drought in the areas that depend on them for rainfall, which would be problematic for the farmers that depend on this rainfall for their crops to grow. Similarly, if the regular tracks of these systems were to shift further to the north, this would lead to increased rainfall some places while it would decrease the rainfall in other places. This could cause significant changes to what places had the most optimal amounts of rainfall for farming. If any of these scenarios were to play out, it would have significant impacts on the ways of life of the people living in these areas. Also, due to the difficulty in making such major lifestyle adjustments, it would take years for people to be ready for the impacts. Therefore, rather than merely waiting for the future climate to come, it is important to figure out how these systems will respond to climate change as soon as possible so that people can prepare for the consequences.

This study addresses these concerns by comparing the characteristics of mesoscale convective systems in our current climate to their characteristics in a future, human-induced climate scenario. Specifically, this study will look at three different trends: 1.) How will the frequency of heavy-rain producing mesoscale convective systems change in the future climate? 2.) How will the intensity of these systems change in the future climate? 3.) How will the overall tracks of these systems change in a future climate?

2. Data and Methods

To determine whether there were any significant differences between the present and future climate, cases of MCSs needed to be determined for both climates. These two climates then needed to be compared. To determine which cases to use, a region of interest was chosen that included the area between 30 and 50 degrees north and 85 and 105 degrees west which stretches from the Rockies to the Ohio Valley of the United States. This is the region within the United States in which MCSs are most likely to develop and persist (Tuttle and Davis 2005).

Two different data sets were used, including one from the present climate and one from the future climate. For both sets, ten years of 6-hourly precipitation data were used. Both sets were also at 12 km horizontal resolution. This resolution was chosen because it was the smallest resolution of a climate model that was readily available. For the present climate, data from the RegCM4 was used, which was a regional climate model downscaled from the HadGem (HadGem). This model run was based on historical data and included data from the years 1986-1995. For the future climate, the data was based on the RCP8.5 future climate simulation and included data from the years 2076-2085. The RCP8.5 simulation was the scenario in which no changes significant changes were made to human emission levels and caused the average forcing caused by radiation to increase to 8.5W/m^2 by 2100 (Riahi 2011). This scenario is commonly referred to as the "business as usual" future climate scenario depicted by the IPCC. Additionally, this study focused on warm-season MCSs, so it focused on the months of June, July, and August. Due to the setup of the model, each of these months in the simulation contained precisely 30 days.

To determine where MCSs were in the dataset, several thresholds were used. Within any 6-hourly period, an area of at least 20 grid points spanning east-west and five grid points spanning north-south receiving at 12.7 millimeters (one-half of an inch) of precipitation over a 6-hour period was necessary to consider the case to be a heavy-rain producing MCS. This threshold was chosen to account for the organized nature of an MCS (Ashley et al. 2003), as well as the movement of the MCS during that period. Additionally, at least one data point within the set of contiguous data points had to receive at least 25.4 millimeters (one inch) of precipitation over the 6-hour period. This was chosen to ensure that the systems being examined were convective in nature and not just stratiform. Finally, all of these criteria had to be present for at least two consecutive 6-hour periods in order to qualify as an MCS and the two areas needed to have at least one grid point of overlap. These determinations were made using plots generated by code (Caruthers 2018). In total, 108 cases were selected for the present climate, and 106 cases were selected for the future climate.

To look for differences in the two climate periods, statistics were calculated on the frequencies, tracks, and intensities of the MCSs for the two climate periods. This was done both for the overall climate period and for June, July, and August individually. The tracks were determined by taking the centroid latitude and longitude of both the start and the end 6-hour periods of the MCS. The frequencies were determined by calculating the number of MCSs per year for the two climate periods. The intensities were determined based on the maximum 6-hourly precipitation rate for each MCS. For each of these attributes, the average, standard deviation, median, and inner quartile range were calculated. After that, a t-test was used to determine if there were any statistically significant differences between the two climate periods. For these t-tests, an alpha level of 0.05 was used, meaning that it had to be at least 95% likely that the results were different in order to conclude that there were statistically significant differences of

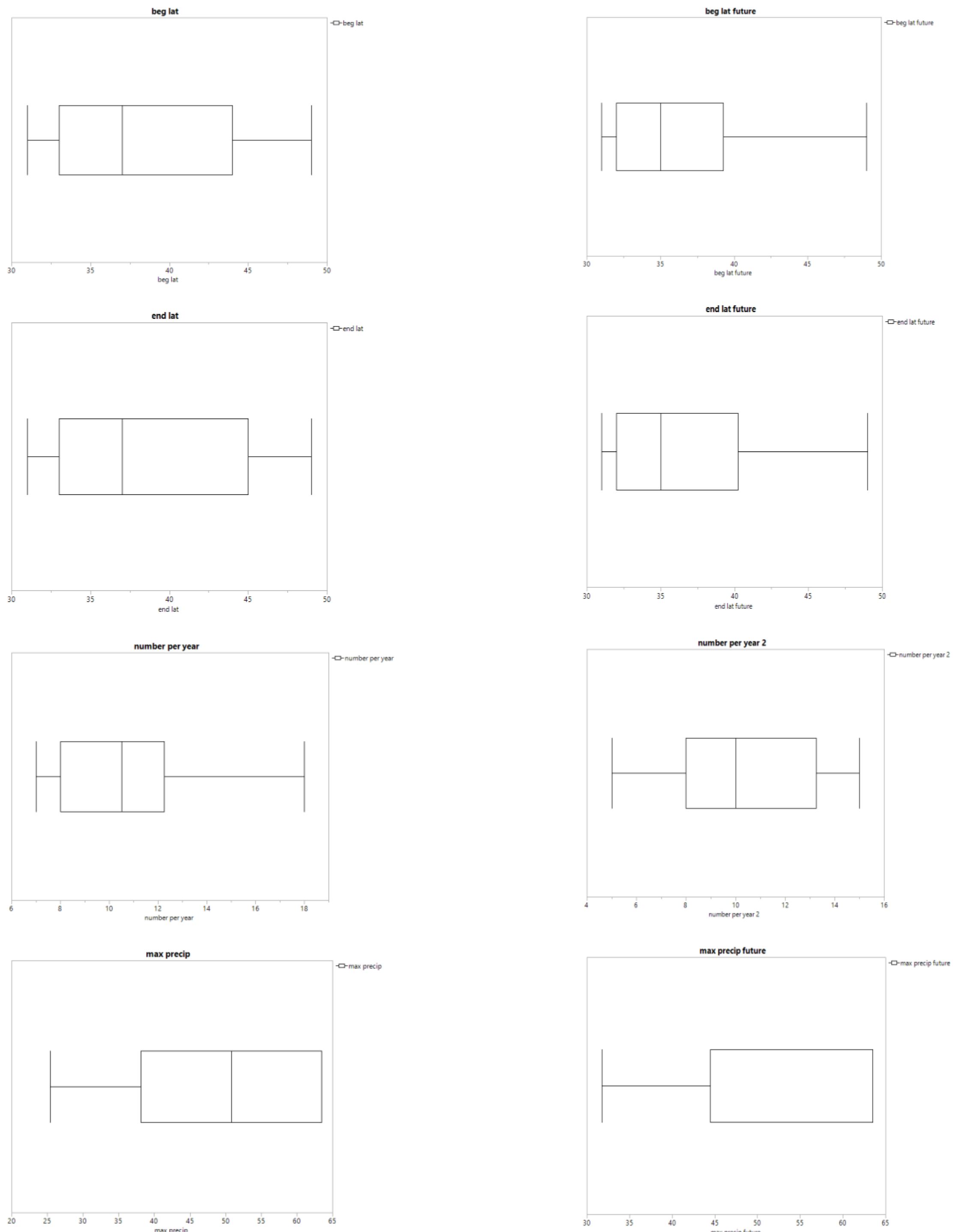

Figure 1a-h: Side-by-side box plots of the beginning latitude, ending latitude, frequency, and intensity of heavy-rain MCSs in the two climate periods. The column on the left represents the present climate, while the column on the right represents the future climate.

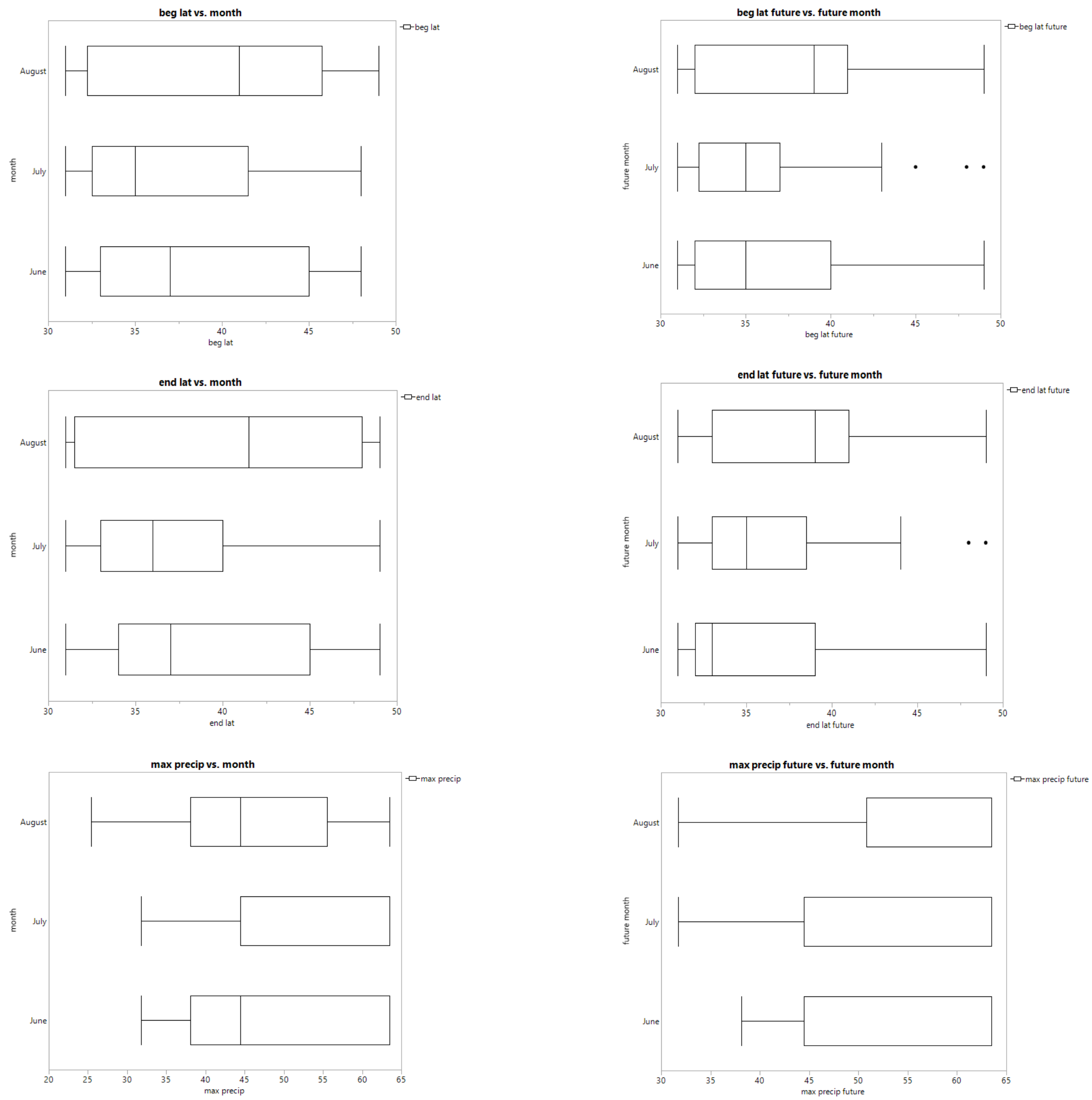

Figure 2a-f: Side-by-side box plots of the monthly breakdowns of the beginning latitude, ending latitude, frequency, and intensity of heavy-rain MCSs in the two climate periods. The column on the left represents the present climate, while the column on the right represents the future climate.

frequency, latitude, or intensity of MCSs for the two climate periods. As with the calculations of the individual statistics, these t-tests were performed for both the overall climate periods and each of June, July, and August within them.

3. Results

Figures 1a-d show the boxplot distributions of the beginning latitude, ending latitude, frequency, and maximum intensity of the present climate MCSs, and figures 2a-c show the boxplot distributions of these same characteristics broken down by month. Figures 1e-h show the boxplot distributions of the beginning latitude, ending latitude, frequency, and maximum intensity of the future climate MCSs. Figures 2d-f show the boxplot distributions of the beginning latitude, ending latitude, and maximum intensity broken down by month.

Statistics including the mean, standard deviation, median, and inner-quartile range were calculated for the starting latitude, ending latitude, annual frequency, and maximum 6-hourly precipitation intensity for all of the MCSs in each climate scenario. They were calculated for both the overall climate periods and for each individual month. Looking at these statistics (Appendix A), the averages of all of these characteristics in the future climate tended to have smaller standard deviations than those of the present climate. This trend was apparent for both the overall statistics and the statistics that were broken down by month. This implies that the frequencies, intensities, and tracks of these MCSs will vary less in a future climate. However, when specifically looking at intensities by month, the standard deviations decreased from June to August in the present climate, while they increased from June to August in the future climate. This implies that the intensities of MCSs will exhibit more variability later in the summer in a future climate, whereas they exhibit more variability earlier in the summer in the present climate, potentially making the tracks of future climate MCSs more difficult to predict. Additionally, the beginning and ending latitudes of MCSs in both the present and future climates tended to have lower medians than means overall. When broken down by month, this trend held up for the months of June and July, but it flipped for the month of August for both the present and future climates. This implies that the latitudes for both climates were skewed by a few northern outliers during both June and July, but they were skewed by southern outliers during August. These outliers being in both climate periods could potentially have the effect of reducing the apparent shift in overall tracks. Furthermore, the average ending latitudes of the MCSs were to the north of the beginning latitudes in the present climate, but they were to the south of the beginning latitudes in the future climate. This shows that MCSs are more likely to track to the south of their starting points in the future climate than they are in the present climate, whereas they are more likely to track to the north of their starting points in the present climate. It also shows that the track that an MCS follows will be affected more by changes in the climate than the latitude at which an MCS develops.

The starting latitudes, ending latitudes, annual frequencies, and maximum 6-hourly precipitation intensities were also compared between the two climate periods to test for statistically significant differences. These comparisons were also done for both the overall climate periods and for each individual month. Looking at the statistical comparisons of the two climate periods as shown in Appendix B, on average the beginning latitude of the heavy-rain producing MCSs in the future climate was south of the average beginning latitude of the MCSs of the present climate, and this difference was statistically significant at the 95% confidence level. Breaking this down by month, the average beginning latitude of the future climate was south of the average beginning latitude of the present climate for June, July, and August. However, June was the only month where this difference was statistically significant at the 95% confidence level. For the ending latitude, the average latitude of the MCS cases in the future climate was also south of the average ending latitude of the MCSs of the present climate, and this difference was statistically significant at the 95% confidence level. Breaking this one down by month, the average ending latitude of the future climate was again to the south of the average ending latitude of the present climate for June, July, and August. As with the beginning latitude, only the difference for June was statistically significant at the 95% confidence level. All of this shows that heavy-rain producing MCSs in this future climate scenario would likely have overall tracks that are to the south of these MCSs in the present climate. This is mostly due to a southward shift in the MCS tracks in June, but it could be attributed to southward shifts during July and August as well.

For the frequency, there were on average fewer heavy-rain producing MCSs per year in the future climate than there were in the present climate, but this difference was not statistically significant at the 95% confidence level. Breaking this down by month, there were fewer MCSs per year in the future climate in the month of June, more MCSs per year in the future climate in the month of July, and fewer MCSs per year in the future climate in the month of August. However, as with the overall frequency, none of these differences were statistically significant at the 95% confidence level, although this lack of significance could be due to the small sample size of data for annual frequency. This implies that there would not likely be any significant changes in the annual frequency of heavy-rain producing MCSs in this future climate scenario.

For the maximum intensity, the average maximum 6-hour precipitation rate for the MCSs of the future climate was higher than the maximum precipitation rate of MCSs in the present climate, and this difference was statistically significant at the 95% confidence level. Breaking this down by month, the average maximum precipitation rate in the future climate was higher than the average maximum precipitation rate of the present climate for June, July, and August. The differences for the months of June and August were statistically significant at the 95% confidence level, but the difference for the month of July was not significant at this level. This shows that the maximum 6-hourly precipitation rate in heavy-rain producing MCSs is likely to increase in this future climate scenario, especially during the months of June and August.

4. Discussion and Conclusion

The purpose of this study was to determine how heavy-rain producing MCSs' behavior in a future climate scenario would compare to their behavior in the present climate. This study concluded that there was a significant southward shift in both the starting and ending latitude of these MCSs in the future climate overall, although only June saw a significant southward shift when broken down by month. This implies that there will likely be significant changes to which regions of the country receive the most rainfall from MCSs in the future climate, and this change will be the most pronounced in the month of June. This could significantly impact farmers, as they may eventually need to relocate in order to ensure that their crops receive the rainfall they need to grow. This study did not find any conclusive evidence of any changes to the frequency of MCSs in the future climate. Finally, this study found that the maximum intensity of heavy-rain producing MCSs saw a significant increase in the future climate overall, and the increase was significant for both June and August when broken down by month. This implies that there will likely be a significant increase in flooding caused by MCSs in a future climate. Compounded with the southward shift in the tracks of these MCSs, this means that people who live in areas that are not currently prepared for potential flooding caused by these systems are likely to be dealing with this flooding in the future.

The present climate data was based on historical data, so it presented a reasonably accurate representation of the attributes of MCSs that were examined in this study. Also, the sample size of MCSs in both the present and the future climate scenarios was large enough to ensure that significant differences in the two time periods did not occur by chance. Although the criteria used here to determine an MCS should work reasonably well to determine organized precipitation systems, the methodology did have some limitations. Although the 12 km resolution was a relatively fine resolution for regional climate data, it still would not necessarily resolve certain mesoscale features embedded in the thunderstorms associated with MCSs. Also, the future climate simulation was based on the most extreme future climate simulation predicted by the IPCC. Although there would be no way to predict this for sure, this scenario would not necessarily be realistic depending on what happened with carbon dioxide emissions. Additionally, the data for the future climate based on a simulation and not on observational data. This does mean that the results would be subject to change depending on what kind of simulation was used. Furthermore, the methodology for defining an MCS was somewhat arbitrary and may have excluded cases that scientists generally would consider to be MCSs, or vice-versa. Another caveat is that only ten years of data from each climate was used, rather than the 20 or 30 years that would be better representative of a climate period. This means that the results from one or both of the climate periods may have been skewed one way or another due to natural variability occurring within a climate period.

Some future work may include looking at looking at changes in these same characteristics of MCSs for additional months of the year, such as April, May and September. This would enable scientists to make comparisons between seasons, as well as individual months. It would also allow them to determine whether certain regions see changes in what time of the year they receive most of their MCSs. Additionally, future studies may also look at changes in type and evolution of MCSs in a future climate scenario. Furthermore, future studies may look into what specifically causes the changes in MCS characteristics that occur in a future climate scenario. All of this would allow scientists to continue to develop an understanding of how the behavior of mesoscale convective systems will change in the future climate.

Acknowledgments: The author would like to thank Dr. William Gallus for serving as a mentor and for devoting time to discuss the project and offer advice on how to approach the topic at hand. The author would also like to thank Alexandra Caruthers for providing the code necessary to generate the plots used to define cases of MCSs.

References

Allen, R.P., B.J. Soden, 2008: Atmospheric Warming and the Amplification of Precipitation Extremes. Science, 321, 1481-1484, doi: 10.1126/science.1160787

Ashley, T.M., P.D., S.T., E.P., J.D., and A.J. Grundstein, 2003: Distribution of Mesoscale Convective Complex Rainfall in the United States. Mon. Wea. Rev., 131, 3003-3017, https://doi.org/10.1175/1520-0493(2003)131%3C3003:DOMCCR%3E2.0.CO;2

Caruthers, Alexandra (2018) ncl script to calculate 6-hour precipitation [computer program] https://www.ncl.ucar.edu/

Feng, Z., L.L., S.H., R.H., C.B., and K. Balaguru, 2016: More Frequent Intense and Long-Lived Storms Dominate the Springtime Trend in central US rainfall. Nature Communications, 1-8, doi: 10.1038/ncomms13429 (2016).

Hadley Centre Global Environment Model: HadGem, RegCM4 Data Download. Iowa State University

Riahi, K., Rao, S., Krey, V. et al. Climatic Change (2011) 109: 33. https://doi.org/10.1007/s10584-011-0149-y

Schumacher, R.S., R.H. Johnson, 2005: Organization and Environmental Properties of Extreme-Rain-Producing Mesoscale Convective Systems. Mon. Wea. Rev. 133, 961-976, https://doi.org/10.1175/MWR2899.1

Tuttle, J.D., C.A. Davis, 2005: Corridors of Warm Season Precipitation in the United States. Mon. Wea. Rev., 134, 2297-2317, https://doi.org/10.1175/MWR3188.1

	mean	std dev	median	IQR
beg latitude	38.44	5.89	37	33-44
beg latitude future	36.3	4.92	35	32-39.25
end latitude	38.73	6.27	37	33-45
end latitude future	36.4	5.14	35	32-40.25
max precip	50.27	12.19	50.8	38.1-63.5
max precip future	56.37	9.67	63.5	44.45-63.5
frequency	10.7	3.3	10.5	8-12.25
frequency future	10.5	3.21	10	8-13.25
beg latitude june	38.74	5.84	37	33-45
beg latitude june future	36.26	5.2	35	32-40
beg latitude july	37.08	5.14	35	32.5-41.5
beg latitude july future	36.63	4.24	35	32.25-37
beg latitude august	39.79	6.67	41	32.25-45.75
beg latitude august future	38.11	5.7	39	32-41
end latitude june	39.03	6.15	37	34-49
end latitude june future	35.92	5.6	33	32-39
end latitude july	37.14	5.43	36	33-40
end latitude july future	36.04	4.34	35	33-38.5
end latitude august	40.36	7.15	41.5	31.5-48
end latitude august future	38.26	5.83	39	33-41
max precip june	47.7	12.72	44.45	38.1-63.5
max precip june future	55.52	9.41	63.5	44.45-63.5
max precip july	55.09	11.5	63.5	44.45-63.5
max precip july future	56.89	9.8	63.5	44.45-63.5
max precip august	47.85	10.58	44.45	38.1-55.56
max precip august future	56.82	10.25	63.5	50.8-63.5
frequency june	4.3	2.67	4.5	2-6.25
frequency june future	3.4	1.84	3.5	1.75-5
frequency july	3.7	1.77	4	2.5-4.25
frequency july future	4.8	2.82	5	2.75-8
frequency august	2.8	1.87	3	1-4.25
frequency august future	1.9	1.2	1.5	1-2.5

Appendix A: Table containing individual statistics relating to the MCSs determined for the two climate periods. The mean, standard deviation, median, and inner quartile range are included for the beginning latitude, ending latitude, frequency, and intensity for each climate period. These statistics were calculated for both the overall climate period and broken down into individual months.

	difference	p-value
beg latitude overall	-2.11	0.003
end latitude overall	-2.31	0.0024
max precip overall	6.05	0.0001
frequency overall	-0.2	0.4546
beg latitude june	-2.64	0.0347
beg latitude july	-1.21	0.1482
beg latitude august	-1.68	0.2122
end latitude june	-3.29	0.0153
end latitude july	-0.89	0.234
end latitude august	-2	0.1718
max precip june	9.44	0.0001
max precip july	2.75	0.1243
max precip august	9.02	0.0087
frequency june	-0.9	0.2269
frequency july	1.1	0.1874
frequency august	-0.9	0.1548

Appendix B: Table containing values used to compare the beginning latitude, ending latitude, frequency, and intensity of the MCSs determined for the two climate periods. The first column shows amount that the value increased from the present climate to the future climate. The second column shows the p-values that were used to determine whether the differences were statistically significant. These were calculated for both the overall climate periods and the monthly breakdowns.