EXTREME DEWPOINT TRENDS ARE INCREASING ACROSS MUCH OF THE UNITED STATES

by

James Cody Burroughs

A thesis submitted to the faculty of
The University of North Carolina at Charlotte
in partial fulfillment of the requirements
for the degree of Master of Science in
Meteorology

Charlotte

2021

Approved by:

____
Dr. Jacob Scheff

____
Dr. Matthew Eastin

____
Dr. Brian Magi

ABSTRACT

JAMES CODY BURROUGHS. Extreme Dewpoint Trends Are Increasing Across Much of the United States (Under the direction of DR. JACOB SCHEFF)

As temperatures continue to increase all over the world, extreme weather events and the extreme observations associated with them are becoming more prevalent. This should imply that higher moisture content values are occurring across the globe, which could have severe impacts on everyday human activity and could even cause some areas of the world to become uninhabitable in the future. This research looks to analyze ASOS station data across the continental United States to determine if extreme summertime dewpoints are rising at a significant rate. Dewpoint data was gathered for the months of June through September from 114 stations in the US during the 73-year time period of 1948-2020. The data was then sorted into percentiles and the highest percentiles were examined. Results have shown that for the median percentile of dewpoints, 57 of the 114 stations experienced significant positive trends, while for the 95^{th} percentile, 45 of the 114 stations had positive significant trends. The Northeast, Upper Plains, West Coast, and Gulf Coast are the areas of the country that showed the largest positive trends. The interior West is notably experiencing a negative trend in extreme dewpoints, and the Mid-Atlantic region into Georgia is experiencing near neutral trends. Although each of the areas that have positive increases are changing at a similar rate, the area of most concern is the Gulf Coast. This is because the base maximum dewpoints already are the highest in the country. With the 95^{th} percentile of dewpoint trend in the area reaching 3˚F/70 year period, this could lead to human health concerns if this trend continues into the future.

ACKNOWLEDGMENTS

I would like to express the deepest appreciation to my committee chair, Dr. Jacob Scheff. He has guided me from day one after my return back to college in 2019. His enthusiasm for teaching and research is unmatched. He has taught me that success comes through hard work and determination. He has shown patience and been understanding throughout many challenges that I faced throughout the entire project. Without his knowledge and guidance, this thesis would not have been possible.

I would like to thank my committee members, Dr. Matthew Eastin and Dr. Brian Magi. Their feedback and direction allowed this project to be properly focused and structured. They taught me that it is better to put much effort into one idea, rather than minimal effort into many ideas. Their passion for research is evident, and their ideas for this project allowed it to be successful.

Lastly, I would like to thank my family. For the past 2 and a half years, my wife Victoria has done a tremendous job allowing me to achieve my goals of going to graduate school and completing this project. Without her support and love, none of this would have been possible. My two kids, Ana and Landon, were the driving force of my return to school, and they are what kept me pushing through to this moment.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

Humidity is one of the most impactful weather measurements on the human body. Even in extremely high air temperatures, humidity determines how bearable it is to do strenuous activities outdoors. A direct measurement of humidity is dewpoint (Samenow 2016). Dewpoint measures the temperature at which the air must be cooled to reach saturation and form dew. Therefore, the dewpoint will never exceed the air temperature because once the air reaches saturation, it cannot become any more saturated. Also, this means that the temperature can never fall below the dewpoint.

Even though dewpoint is very informative, the two primary measures of atmospheric moisture are relative humidity and specific humidity (Brown and DeGaetano 2013). Relative humidity is the ratio between the moisture content in the air and the maximum amount the air can hold at that given temperature. However, relative humidity is not necessarily a true indicator of the amount of moisture in the air. For example, a cold day can still have high relative humidity values, even with low amounts of moisture content in the air. Specific humidity is the ratio of water vapor mass to the total moist air parcel mass but can be complicated to explain to the public, so it is mainly used for calculations.

There is yet another atmospheric moisture measurement type, which is called wet-bulb temperature. It is defined as the temperature at which a parcel of air is cooled adiabatically to saturation at constant pressure by the evaporation of water into it, with all latent heat being supplied by the parcel (American 2021). Wet-bulb temperature incorporates both temperature and moisture in its measure, which allows it to more accurately represent the temperature that the human body can cool itself off to by sweating. Coffel et al. (2018) explains that although the body is efficient at cooling itself in very high air temperatures, this is only if the moisture levels are low.

High moisture levels are the main cause of heatstroke due to the human body not being able to allow sweat to evaporate off the skin and cool the core body temperature. This is important because heat stress is the leading cause of fatalities from natural phenomena (Sherwood and Huber 2010). If the wet-bulb temperature values exceed the human skin temperature of 35˚C (95˚ F), the human body would have significant trouble dissipating heat. Therefore, this is considered the threshold of human tolerance to heat stress. Coffel et al. (2018) mentions that recent extreme wet-bulb temperatures between 29˚-31˚C (84-88˚F) combined with intense heat waves have caused tens of thousands of deaths around the globe. The areas that are most at-risk in the world for high wet-bulb temperatures and their effects are the Southeast U.S., Northeast India, East China, and West Africa. These areas are also very densely populated, which increases the risk of a large scale effect on human health. With these threats, wet-bulb temperatures are being used more frequently to index heat stress (Sherwood 2018).

Although wet-bulb measurements are helpful, dewpoint is the largest influence on wet-bulb temperatures, especially in summer conditions that are hot and humid. Dewpoint also is directly measured by weather stations, has a minimal diurnal cycle, and is a good indicator of human comfort (McKinnon and Poppick 2020). These reasons are why dewpoint is the most commonly reported atmospheric moisture parameter (Brown and DeGaetano 2013). This familiarity allows the average person to easily relate the moisture content of the air to air temperature and understand how it will affect them.

Due to the above, our research will focus on just dewpoint temperatures. We are examining trends in extreme dewpoints in the continental United States during the months of June through September. Meteorological summer months of June through August were chosen because they typically have the highest dewpoint values. This is due to temperatures being the highest in the Northern Hemisphere at that time along with a strong Southerly flow from the warm Gulf of Mexico influencing much of the country. The month of September was added due to the strong tropical influence that the Eastern half of the country experiences during the peak of the Atlantic hurricane season. Specifically, we are evaluating the trends and distributions of the most extreme dewpoints at 114 ASOS weather stations over a time period of 1948-2020.

Station data is extremely useful to understand local weather conditions, even though this can come with possible errors. A change in location of a particular station can have an effect on instrumentation readings, and even a static site for the duration of the time period can be influenced by the surrounding environment changing. This can lead to unobserved humidity biases (Raymond et al. 2020). The stations chosen for this project were evaluated in MATLAB by sorting the daily maximum dewpoint data into the months of June through September for all 73 years. Then maps were created to perform a spatial analysis of both extreme base percentile dewpoints and dewpoint trends of those percentiles to determine significance. This will give a clear picture of moisture content across the US.

CHAPTER 2: BACKGROUND

A weather outbreak can have many different forms. Severe weather or an arctic blast of cold air are often thought of as being the only types of an “outbreak”. However, any weather type can be labeled as this. Samenow (2016) discusses an extremely moist air mass that encompassed the entire Eastern United States in August of 2016. Almost every city east of the Great Plains was experiencing dewpoints over 70 degrees Fahrenheit. The invasion of moisture was strong enough, that in southeastern Texas there were multiple reports of 80+ degree dewpoints. Dewpoints of this magnitude are rarely, if ever, seen in most of the U.S., as will be explained in the results of this project. When dewpoints are as high as they were in August of 2016, the air temperature is unable to cool off much at night. Keeping in mind that the temperature can never fall below the dewpoint, this means that overnight temperatures stay very warm, which led to forecasts of record high lows across the South. These extreme values can cause other intense weather, such as thunderstorms that produce very heavy rainfall. During this 2016 event, there were forecasts for rain-rates in thunderstorms to be 3 to 4 inches per hour. The precipitable water in the air was measured as being in the top percentile of historical values across the Gulf States, even higher in some areas than when a tropical cyclone passes through. So, what caused this extreme moisture influx? The answer was a strong Bermuda high pressure system off the East Coast of the United States. High pressure systems have a clockwise flow around them, and this clockwise flow brings in rich moisture from the warm Gulf of Mexico and Atlantic Ocean across the entire southern half of the United States. This along with water temperatures in the Gulf of Mexico and Atlantic Ocean being warmer than normal was a recipe for record dewpoints. With events like the one mentioned above, we look back at some studies that have already been completed on dewpoint trends, causes of extreme moisture outbreaks, and risks that high moisture content can cause.

Bentley and Stallins (2008) referenced one of the most infamous cases of an extreme heat/dewpoint event, where over 700 deaths occurred across 19 different states in July of 1995. Of these deaths, 87% were in the Midwest and 65% were in Chicago alone (Kunkel et al. 1996). This outbreak also caused electricity usage records for utilities in the area (Changnon et al. 2006). The high moisture values were determined to be influenced by evapotranspiration from crops as well as recently wetted soil. This meant that there was a substantial amount of low-level moisture present. This along with low Turbulent Kinetic Energy (TKE) values meant that it was a recipe for high dewpoints. Bentley and Stallins (2008) looked at extreme dewpoint events across the Midwest by evaluating 46 stations and using a decision tree to determine the level of severity and coverage across the area. They decided that a minimum of 22˚C (72˚F) was required over at least a 2-day period at a particular station and if 4 or more stations did this, it was labeled an extreme dewpoint period. If more than 50% of the stations experienced this, it was deemed an extreme dewpoint event.

These high values of low-level moisture are becoming more frequent. From 1980-2000, there was significant increases in time that the dewpoint was over 24˚C (75˚F) as compared to the 20 years prior. Bentley and Stallins (2008) looked at data from 1960-2000 and discovered that 9 extreme dewpoint events occurred during that time. It was also determined that during these events, a major contributor to these higher dewpoints was evapotranspiration and a capping inversion near the surface that trapped the moisture content there, making it unable to mix up into the atmosphere. This was done by evaluating TKE values. If the values were low, this meant that the Planetary Boundary Layer (PBL) mixing was also low, again keeping moisture levels higher near the surface. Evidence suggested that although Gulf of Mexico moisture might have played a role in some of these events in the Midwest, it was primarily due to the shallow mixing layer, plentiful soil moisture, and evapotranspiration.

Synoptically speaking, 850hPa fields showed that a ridge was present over the Midwest during these events, with a trough forming on the western edge of the ridge. This caused the ridge to first amplify and then push southward. In later stages, it weakened, and height fields indicated that disturbances generated across the upper Midwest which then pushed the ridge southward and backed the flow westward. Surface analyses indicated that extreme dewpoint events in the Midwest were caused by a low pressure forming in the Upper Great Plains that propagated into the Upper Midwest. They determined that these are the essential characteristics of an extreme dewpoint event located in the Midwest. Although urban heat islands can affect air temperature significantly, and did so in the 1995 event for Chicago, Kunkel et al (1995) stated that the urban moisture levels were actually lower than the rural areas, indicating evapotranspiration was a leading cause of the extreme moisture content that led to this deadly outbreak.

The trends of dewpoints over time vary based on the seasons. This was shown in a study by Robinson (2000) using data from 1951-1990. There were 178 stations that were analyzed across the U.S. during this time period for each season. The coverage was not equal across the U.S., as gaps were noted in a few areas. One issue the paper noted was that by using hourly data, a single “snapshot” of dewpoints at a certain time meant that stations were spread across four different time zones. This was corrected by splitting the set of 4 time zones into 2 zones, with a snapshot of each zone having only a one hour difference between them, respectively. This is not something that will be an issue in this project, due to the use of daily maximums instead of hourly observations. Results showed that summertime dewpoint trends were minimal with only a slight increase across the middle of the country. In springtime, most of the U.S. had an increasing trend of dewpoint temperature with the largest increase occurring in the Southwestern U.S. with a 4˚C/100 years rate increase. The one exception was the Southeastern U.S., which had a negative trend for spring. Winter results showed a mostly negative trend, except for the Southwestern United States. When a smaller data sample was used from 1961-1990, the pattern was similar, but the values for the Southwest and Southeast were more positive and negative, respectively.

What the results of this study show is that a dewpoint trend should not be done on a yearly time scale, but rather needs to be broken down into seasonal evaluations for more accurate results. The time period of the data is also important, as measurement accuracy can affect some of the dewpoint trends. Data before the late 1940’s is scarce, and the instrument changes over time certainly can skew the data by restricting the sample size and giving inaccurate readings. Indications suggested that a 1˚C increase in dewpoint temperature may have occurred merely due to instrumental changes. From 1951-1990, a general dewpoint trend for the U.S. was 0.5˚C/100 years. For just 1961-

1990, it was 2.0˚C/100 years. Results from this and other previous studies were determined to be very sensitive to the time period used for evaluation.

Brown and DeGaetano (2013) discuss how five different types of dewpoint temperature instrumentation over the years have affected measurements and they discuss the trends of annual maximum and minimum dewpoint. Psychrometers were the instruments used between the 1930's and 1960's to record dewpoint, a dial hygrometer was used from the 1960's until the 1980's, then a hygrometer with a chilled mirror was used until the 2000's where a Vaisala humidity sensor is now used to record dewpoint measurements. These changes have been shown to affect the dewpoint readings at some stations between 1961 to 1995, but their influence was inconsistent, so the data is still useful to use. They split the continental U.S. into 6 geographic sections: the Northeast, Southeast, Midwest, Great Plains, Northwest, and Southwest. Data was selected if the records at a station were at least 90% complete. Trends were evaluated for dewpoints from 1947-2010 at 145 stations. Of them, 73 were classified as rural stations, and the other 72 were urban. The results showed that there was no significant dewpoint trend across the U.S. for the annual average. However, regional trends were more apparent and showed an increase in the central U.S. in the months of March, April, and May. The northern half of the country saw the largest increase in trends, both in rural and urban settings. The largest negative dewpoint trends were confined to the Southeastern U.S. in wintertime. The study showed that minimum dewpoint increases across the stations were actually more widespread than were maximum dewpoint increases. It also found that the Western U.S. is drying out while the central and eastern US is becoming more moist since 1980. As with other studies, the Midwest is the area that shows the largest trend upward for dewpoint. One of the most interesting conclusions from this study is that moisture content across the United States actually decreased from 1947-1979, but from 1980-2010 is when the moisture levels began to rise.

The research done by Brown and DeGaetano (2013) also most closely resembles my research and therefore was a foundation on which this project was built. Their research looks at trends of annual maximum dewpoints across the country and makes a trend map similar to the ones in this project. The key difference is that my research does not focus on the annual maximum dewpoint, but it examines multiple high percentiles and evaluates the trends of each. Brown and DeGaetano (2013) also uses a time period of 1947-2010 that includes 145 stations and split them into categories of urban and rural. Our project consists of 114 stations but for a longer time period of 1948-2020. My research will look at extreme values only during the months of June through September, whereas they looked at a broader picture of dewpoint and temperature changes and focused on the maximum, minimum, and averages for yearly data but only the averages for seasonal data. Brown and DeGaetano (2013) found that only the Midwest had increases in yearly average moisture content over the time period. Their maps indicate that the Southeast annual maximums only slightly increased. They also indicated that the summer averages did increase as well.

The mention of a shift around 1980 to an increasing dewpoint trend is shared amongst different studies. Changnon et al. (2006) states in their study of the Midwest, that extreme dewpoint events were becoming more frequent after 1980, and that more hours in a day had extreme dewpoint values as compared to previous events preceding

1980. Freychet et al. (2020) found this to also be the case in east China, particularly with the minimum dewpoints on extreme days being much higher. However, Coffel et al. (2018) mentions that future changes in wet-bulb temperatures are expected to be smaller, more uniform, and have less variation than air temperature projections show. It also suggests that annual maximum wet-bulb temperatures will increase the same amount as mean daily maximum wet-bulb temperatures. Regardless of the rate of increase, areas that already experience high moisture content are nearing critical marks. Im et al. (2017) notes that the Persian/Arabian Gulf area experiences the highest recorded wet-bulb temperatures on Earth with values exceeding 28˚C (82˚F) normally and occasionally approaching the critical 35˚C (95˚F) mark. By the end of the century, these areas along with portions of India are expected to have wet-bulb temperatures that are above the threshold of human tolerance.

Freychet et al. (2020) conducted a similar research project to this thesis by using 756 station records from 1979-2017 and evaluated wet-bulb temperatures in China. It mentions that wet-bulb temperatures are not provided in observational records, and that they must be computed. They concluded that wet-bulb temperatures were very high in Southeast China, reaching record highs of 29˚C (84˚F) for over 6 hours at a time. The highest value found was 31˚C (88˚F). Most of the higher values were found in lower elevation areas. They noted that the most extreme wet-bulb temperature events were due to an increase in dry-bulb temperatures. Specific humidity also increased during these events as well, which contrasts with European analyses. Results from Freychet et al (2020) back up what other studies have shown, which is a stronger increase in daily minimum moisture content as compared to daily maximum moisture content. However, this contrasts with Schwartzman et al. (1998), that discusses how daytime dewpoints in the warmer seasons increased as compared to nighttime dewpoints in their research of the U.S. and Canada. These contrasts are what makes the findings from this thesis important because there is a clear lack of uniformity when it comes to moisture content and its trends.

Raymond et al. (2020) also discusses global wet-bulb temperatures and how frequently they are closing on the threshold of human tolerance of 35°C (95°F). Areas that have seen the highest wet-bulb readings are located in South Asia, the coastal Middle East, and along the western coast of Mexico near the Gulf of California. This is similar to the results that Im et al. (2017) and Freychet et al. (2020) noted. The paper states that the frequency of wet-bulb temperatures hitting marks of 27, 29, 31 and 33 degrees Celsius has more than doubled in occurrences between 1979 and 2017. It also suggests that El Nino events can trigger higher than normal wet-bulb temperatures but not the most extreme values of wet-bulb temperature for the tropics and subtropics. They project that the wet-bulb temperatures will regularly exceed the critical 35°C (95°F) threshold by the third quarter of the 21st century in parts of South Asia and the Middle East.

To this point, the research papers mentioned above have either dealt with moisture trends in the eastern half of the U.S. or dealt with extreme moisture values found in other places around the world such as China. However, in the Western United States, the moisture content differs drastically from the Eastern United States. McKinnon et al. (2021) talks about how for the Western U.S., the theory suggesting that, global warming would cause specific humidity to increase, might not be true in desert regions. They also mention that some stations in the Southwestern U.S. have negative mean dewpoint trends. They determined that on hot days in summer, the specific humidity decreases are more pronounced than on average temperature summer days. With the desert areas already being semi-arid, evapotranspiration is lower on these hot summer days, and with soil moisture decreasing since the 1980's, this indicates that a negative moisture trend is occurring on these hot summer days, which is more frequent due to global warming.

Wildfires in the Western U.S. are due to a direct relation to a lack of moisture content, as a drought in 2011 shows (Williams et al. 2014). The extreme drought led to record-breaking wildfire that burned areas across the Southwestern United States. They determined that a combination of higher than normal temperatures and below average rainfall and dewpoints was directly related to the increase in wildfires in the same area. Although in other years low dewpoints did not cause significant wildfire coverage, for 2011, it was the driving force. Vapor Pressure Deficit (VPD) is the saturation vapor pressure minus the actual vapor pressure. Results showed that for March – July of 2011, there was a record high VPD, and extremely low dewpoints were responsible for 45% of the VPD anomaly. Low dewpoints also led to dry soil, which diminishes evapotranspiration, and can lead to extremely high temperatures. Although their paper does not talk about trends of moisture, it does indicate that moisture content in recent years has been at record lows and led to extreme wildfire events. One could infer that with record low moisture content in recent years, along with station data from McKinnon et al. (2021), that moisture trends across the Southwestern U.S. are decreasing and are due to the desert environment.

This current research project will help climatologists to better understand the growing risk of moisture content in the air and how quickly the rate of change of extreme moisture content is compared to the rate of change of extreme temperatures in the United States. This comparison is for multiple high percentiles of dewpoint temperature so that climatologists will have data of not just the trend of the annual maximum dewpoint as Brown and DeGaetano (2013) discussed, but also for other high percentiles that give a wider perspective of moisture trends in the U.S. as compared to extreme temperatures. With a good sample size of stations and with a time period of over 70 years used in this research, the trends and causes found are able to provide specific regions of the United States with their own data so that areas of greatest change can be highlighted.

CHAPTER 3: METHODS

Data was selected for this project from 114 different ASOS stations across the U.S. from the years 1948-2020 using the Iowa Environmental Mesonet website (Iowa 2021). The stations are listed in Table 1. Daily maximum dewpoints were collected at each station, then MATLAB was used to sort the data into the 122 days of June through September for each year of the period. The dewpoints used in this project are in Fahrenheit for two different reasons. First, the data collected is already in Fahrenheit, and any conversions could decrease accuracy if decimals are rounded. Secondly, since this is a research project focusing on US surface observations, Fahrenheit is customary in the U.S. for this purpose. Therefore, it is more relatable to keep the data in Fahrenheit.

There were many questionable data points, particularly for values at the high end of the distribution, at different stations across the country. These were evaluated individually, and a determination was made whether the value was legitimate or an instrument error. All questionable data points and how each were handled are listed in Table 2. For this reason, maximum dewpoints are not used to evaluate long-term trends on this research, but instead the 95th percentile is used. For any dewpoint value noted as suspect, such as a value that was higher than any other value for any other year during the time period, then the days leading up to and surrounding the date in question were evaluated to determine if there was a gap in dewpoint greater than 5 degrees for the day in question. If the difference was less than 5 degrees, the value was compared to the same day value for other stations in the area. If the surrounding station(s) had a similar value to the original station's value, then the value was kept as a plausible observation. If the difference was greater than 5 degrees, then the value was considered erroneous and thrown out leaving the value for that day blank. The only exceptions to this were if a dewpoint value was 3-4 degrees higher than any other dewpoint recorded over the time period. If this was the case, for coastal cities in the Southeast, a simple check for a tropical system being in the area was done to see if it could have caused the suspect value in question, as noted in one of the examples below. For non-coastal cities, surrounding stations were again checked to see if the day in question also had values that were a few degrees higher than the days surrounding the date in question. If a nearby station was not available, such as stations in remote areas in the Western U.S., then the 5 degree threshold was used to compare the days surrounding the date in question to determine legitimacy.

A few examples are listed below to indicate the process used for checking of potentially erroneous data. Memphis, TN had a dewpoint reading of 90 on July 8th, 1996. This was deemed an instrument error, as no other dewpoint value for any year was above 84 and the maximum dewpoint of the day before and after were 76 and 71, respectively. Miami had a dewpoint reading of 84 on June 26th and 27th of 1995. This was odd considering there were no dewpoint readings greater than 80 for any other daily maximum in any year aside from those dates. This was first thought to be an instrument error as well, considering the day prior's maximum dewpoint was 79 and the day after was only 75. However, after checking surrounding weather stations for Miami, it was determined this reading was accurate due to other stations reading dewpoints as high as 83 due to a tropical system being in the area. A second date of July 5, 1970, for

Miami was also an outlier with a dewpoint reading of 85, but this was deemed an instrument error, as no other station in the area reported dewpoints even near 80 for that date.

Missing data was also an issue when evaluating the stations across the country. In the early 2000's, there was substantial missing data for numerous sites. This is most likely due to a widely implemented instrument upgrade where the hygrometer with a chilled mirror was replaced with a Vaisala humidity sensor, as Brown and DeGaetano (2013) discussed. Some years at certain stations had 30+ days of missing data per year during the months of June through September in the early 2000's. With those months consisting of 122 days total, that means each day of lost data can hurt the validity of the calculations due to each day making up approximately 0.82% of the yearly data. With some years missing 30+ days, this meant that the results could be inaccurate if the years' data was still used. Therefore, a threshold of 13 days, or >10% of the total 122 days evaluated for each year, was used to determine if a stations' data from a year was used or not. If 13 or more days of data was not available for a given year during the months of June – September, then the entire year was not included in the trend analyses. If a station had 8 years of data, or >10% of the 73 years total, that was not included or was missing, then that station was not included in the project. This is based off of Brown and DeGaetano (2013) that used stations whose records were at least 90% complete.

After data was collected and sorted, a base analysis was conducted to get an idea of the general distribution of dewpoints across the US. Cumulative distribution plots were created for the stations, which show the distribution of percentiles of dewpoint for each station and how they compare to each other, as in Figure 1. Then, a map was created that shows the 50^{th} percentile of dewpoint across the entire 73-year period for each station (Figure 2). A color-coded dot was placed at each station location using longitude and latitude to show the spatial pattern of values. This map shows a single value that evaluates the entire 8,906 days of data and represents the 50^{th} percentile of dewpoint of those days. The same map was also created for the 85^{th}, 90^{th}, 95^{th}, 99^{th} and 99.9^{th} percentiles as shown in Figures 3-7. The scale ranges for the dewpoint temperature of each figure are not uniform to greater emphasize smaller differences between stations.

After the base analysis was completed, a year-by-year analysis was then performed to look at dewpoint trends. First, a graph was plotted for each station consisting of the 50^{th}, 85^{th}, 90^{th}, 95^{th}, and maximum percentile values for each year of the time period. Trend lines were also plotted on the station graphs for each percentile and p-values are listed to determine the significance of the trends. A graph was made for each station, but in the interest of space, only 8 figures (Figures 8-15), are used as examples in this thesis. Next, a trend map for each of the 50^{th}, 85^{th}, 90^{th} and 95^{th} percentile dewpoints in degrees Fahrenheit per 70-year period was created with color-coded representation, as shown in Figures 16-19. The 99^{th} and 99.9^{th} percentiles were not included for the trends maps as both values would simply be the maximum value recorded for each year due to each year consisting of only 122 days of data. If this one maximum yearly value is inaccurate, then the trend map results would also be inaccurate. Using a slightly lower percentile means that if even a few days in a year are inaccurate, it will not affect the results. This is in direct contrast to the research that

Brown and DeGaetano (2008) performed, where they looked at the maximum yearly dewpoint values. We believe this to be an unreliable method of evaluating dewpoints, therefore we did not include those results in our findings. Each trend map shows a numeric value for the slope of the trend lines of each percentile on the station plot graphs over a 70-year period, which indicates how many degrees Fahrenheit that the percentile is increasing over the time period. Trends were determined to have significance by using MATLAB to perform a linear correlation between the variables of years and dewpoints of a particular percentile for a station. Basic statistics then tells us that the p-value of a correlation is equal to the p-value of a regression. Therefore, the p-value calculated gives us the p-value of the trend in dewpoint with time. After performing these calculations for each percentile examined across all stations, the significant trend values that were less than 0.05 for a specific percentile were circled in a large black circle and the station location dot was increased in size. Stations that had an insignificant trend of greater than 0.05 were also circled but very lightly only to indicate the location of the station more clearly on the map.

CHAPTER 4: RESULTS

The results from this project varied based on geographical location. Stations in lower latitudes, such as Brownsville, TX, had a smaller range of very high dewpoints in the cumulative distribution plot (Figure 1) while stations further north, such as Sioux Falls, SD, had wider ranges for their dewpoints. Stations in drier climates, such as Reno, NV had very low dewpoints for the entire range, and areas with a marine climate, such as San Francisco, CA, had a very small range of dewpoints.

The base percentile maps each had dewpoint values that were as expected with the higher values residing in the Southeastern states along the Gulf Coast and Atlantic Ocean while the Midwest and Northeast areas of the country saw slightly lower values for all percentiles. Dewpoints for stations in the western half of the country largely was determined by the topography of where the station was located. The higher elevations had lower dewpoints while areas further south had higher values due to the influence of the monsoon season. The 50th percentile dewpoint map (Figure 2) show the Gulf States having values around 75 degrees Fahrenheit. There is a sharp drop off to the mid-latitude states where the dewpoint values of the 50th percentile are around 68 degrees, and it continues to drop down to values in the low 60's in the Northeast and Northern Michigan. West of the Rockies, dewpoints at this percentile are generally in the 40's and 50's. The 85th, 90th, 95th and 99th percentile maps (Figures 3-6) all indicate similar patterns to the 50th percentile map but with slightly higher values for each percentile. It should be noted that the scale range is different for each base percentile map to greater show the spatial details of each station's dewpoint value.

For the 99.9th percentile map (Figure 7), the pattern slightly changed in that the values in the Midwest were very similar to the Gulf States, with dewpoints as high as 82. This would tend to indicate that the Midwest is seeing more extreme dewpoint events causing these high values. The Northeast had values in the upper 70's, which is only about 5 degrees off of the Gulf States highest values. This also indicates that for areas east of the Rocky Mountains, extreme dewpoints are all within a fairly close range, regardless of location. The western half of the country experienced a wide variety of dewpoints. Stations in the Rocky Mountains had dewpoint values in the low 60's and stations in the Southwest had values in the mid to upper 70's. There were a few areas that did not follow the pattern of the lower latitudes having the highest dewpoints. The Upper Plains had very high values for dewpoints compared to other stations at the same latitude in the Northeast, particularly in the highest percentiles, as mentioned previously. On the opposing end, the Appalachian region and surrounding areas had lower dewpoint values than the areas on either side of the mountain range for the 90th, 95th, 99th, and 99.9th percentiles. From Atlanta to Pittsburgh along the Appalachian Mountains, the area had dewpoint values that were 1-3°F less than surrounding areas, particularly noticeable at the 99.9th percentile. Although high elevation may have played a role in some of the stations having a lower dewpoint value, such as Elkins, WV, there were other stations that were not in high elevation, such as Atlanta, GA and Pittsburgh, PA, that also experienced these lower values. One stark contrast in Figure 7 of the 99.9th percentile dewpoints was that two stations in West Virginia were almost 5°F apart! This is not an error, due to each station being at very different elevation levels. This is also evident in parts of the Western U.S., where topography drastically changes across every state.

Each station's line graph depicting dewpoint percentile and their trend lines widely varied, again based on their location. Figures 8-15 show some examples of these plots. Figure 8 shows the aforementioned Appalachian region's neutral to negative trend for Charlotte, NC. Chicago, IL (Figure 9) was an anomaly compared to all other stations evaluated in the region due to having a negative trend across all percentiles. Not only did all other stations around it have positive trend values, but they were also significant. One possible reason why this station has a negative trend could be that a station move was performed which would be indicated by the sudden downward shift in the dewpoints after the early 2000's. This could also be due to new instrumentation or the environment around the station changing as well. Reno, NV (Figure 10) shows that a few stations had significant negative trends. This is most likely due to the semi-arid region and lack of evapotranspiration as Williams et al. (2014) discussed. This is not surprising, due to the previously evaluated negative moisture trends that McKinnon et al. (2021) and Brown and DeGaetano (2013) discovered. Sioux Falls, SD (Figure 11), in the Upper Plains, had one of the largest increasing slopes found in our research, with all percentiles increasing at least 3 degrees Fahrenheit. Brownsville, TX (Figure 12) also experienced a significant positive increase in dewpoints, but this plot shows that at the lower latitudes, the range of dewpoints was quite small. The Northeast was another area that experienced significant positive trends, as Boston, MA (Figure 13) demonstrates. Figure 14 is of San Francisco, CA, and it shows a positive trend. Stations like San Francisco along the West Coast experienced similar trends due to being west of the Sierra Nevada/Cascade Mountain ranges. This is in contrast to the negative trends that the stations in the interior West are having. Most stations had consistent slopes for each of the percentiles on the line plots, but Figure 15 of Bangor, ME, shows an example where the maximum percentile had an opposite trend of the other percentiles. This could be due to erroneous data or rare meteorological events that caused a difference for the maximum value as compared to the other percentiles. This is another example of why a maximum trend map or a 99th percentile trend map is not included in these results due to the possible inaccuracy.

The trend maps are the most telling of all the results. Figure 16 shows the 50th percentile trend map. The entire Northeast had an increasing dewpoint trend with the majority of stations there being significant in their trends. Dewpoint increases were around 1-2°F/70-year period. The Southeast also shows an increase in dewpoint trend, but to a lesser extreme than the Northeast with about half of the positive trend values being significant and trend values closer to 1°F/70-year period. The Plains and Midwestern regions showed the strongest positive trends of >3°F/70-year period. The Dakotas as well as Nebraska had multiple stations with dewpoint trends of up to a 5°F/70-year period when looking at the station plots. However, there were also a couple stations, most notably Chicago, that experienced a slightly negative trend. Areas west of the Rocky Mountains that were inland, experienced significant negative trends, while stations along the West Coast had positive dewpoint trends with stations located in the southern latitudes had significant positive trends.

For the 85th percentile trend map (Figure 17), results were distributed similarly, with the northern half of the country having significant positive trends in dewpoint, but the number of stations that experienced the significant trends dropped to about half of what the 50th percentile map showed. The trends also shifted down to a 0.0-1.5°F increase for most stations in the Northeast as compared to the 50th percentile trend map. The Upper Plains still experienced the highest positive trend values, still showing trends of >2°F/70-year period. Stations along the Gulf Coast also continued to have significant positive value dewpoint trends around 1-2°F/70-year period. The one area in the eastern half of the country that was an anomaly to the rest of the map was the Mid-Atlantic region. Only two stations had a positive significant trend value, while the majority had near neutral trend values in that area. For the Western US, there was not much change in the interior areas, but the coastal stations continued to have strong positive trends with most now being significant.

Figure 18 shows the 90th percentile trend map, and the results looked very similar to the 85th percentile map, with only a slightly more neutral trend occurring in the Mid-Atlantic region. From Baltimore to Montgomery, no station has a significant trend value, and all are near neutral with 3 stations having negative trend values. The Northeast continues to see significant positive trend increases in dewpoint. However, the area of significance is limited to southern New England into the Ohio Valley. Both the Gulf States and Midwestern regions had similar increases to the 85th percentile maps with little to no changes for most stations. Again, the anomalies of the map are the Mid-Atlantic/Upper South regions as well as the interior West. The interior West also had a few more stations that trended negative as compared to the 85th percentile trend map.

The 95th and highest percentile trend map (Figure 19) shows that there is a tendency with the percentile trend maps. The higher the dewpoint percentage of trend maps, the closer many stations become to having a neutral or negative trend value in the Eastern U.S., while some of the negative trending stations in the interior West now have significant negative trends. This map also shows the same pattern as the other maps, with significantly positive trends ranging between 1-3°F/70-year period for the upper Plains, Northeast, West Coast, and Gulf Coast, while the Mid-Atlantic region continues to have a neutral to slightly negative trend.

The trend mentioned above with the higher percentiles having less significant positive dewpoint trends is most evident in the Eastern United States. Over 50 stations east of the 110°W longitude line were positively significant in the 50th percentile, while only around 35 were for the 95th percentile. With that being said, the 50th percentile trend map (Figure 16) had only 16 of the 114 stations have a negative trend. The 85th percentile (Figure 17) had the least number of stations with a negative trend at only 11, but two were significant trends. The 90th percentile trend map (Figure 18) had 16 negative trending stations, again with two significant. The 95th percentile trend map (Figure 19) had 17 stations with a negative trend, with 3 stations significant. For each percentile map, over half of the negative trending stations were located in the interior West between the Rocky Mountain and the Cascades/Sierra Nevada Mountain ranges. Also, three stations in the eastern half of the country had negative trending dewpoints for each percentile examined. These were: Nashville, TN, Chicago, IL, and Columbus, GA. The reasons that Chicago could have experienced negative trends were mentioned previously, however, the reasons for Nashville and Columbus are unclear. Neither station plot indicated a station move unlike Chicago’s. However, there was a noticeable dip in dewpoints for all percentiles in 2008 for both stations. Whether this dip was due to an instrumentation upgrade, or a larger synoptic feature would need to be researched. It is plausible that this dip is part of the reason for the negative trend of dewpoints. Columbus, GA was the only station east of the Rocky Mountains to have a significant negative trend, and that was only for the 95^{th} percentile. Two stations in the West had significant negative trends for each percentile: Boise, ID and Reno, NV, with each having a near 2°F/70-year negative trend. Therefore, the result of this research suggests that, as a whole, the U.S. is increasing in dewpoint trend, with the Northeast, the Gulf Coast, and the upper Plains experiencing the most significant increases, while only two areas experienced a neutral to negative increase, the interior Western U.S., and the mid-Atlantic region stretching into Georgia.

CHAPTER 5: DISCUSSION

After examining the results, there were several key points to discuss. The continental United States has a wide variety of dewpoints, even in the months of June – September. Areas along the Gulf Coast experienced very small changes between their lowest percentile dewpoints and their maximum dewpoints, as the cumulative distribution plot in Figure 1 showed. Any area east of the Rocky Mountains was clearly influenced by Gulf of Mexico moisture with dewpoints being 20+ degrees higher than areas west of the Rocky Mountains, as the base percentile maps indicate (Figures 2-7). This clearly shows how the mountains are a "Continental Divide". The only exceptions to this were stations located along the southwestern border, such as Albuquerque, NM, and stations along the southern Pacific Coast, which had dewpoints more similar to areas in the Northeast. These were most likely due to the monsoon season and Pacific Ocean influences, respectively. The 50th percentile map (Figure 2) indicated that stations at the lowest latitudes have the highest average dewpoints, which was expected. The 99.9th percentile map of dewpoints (Figure 7) indicates that every station analyzed that was east of the Rocky Mountains has recorded dewpoints of at least 75°F. This is a confirmation of the article that Samenow (2016) discussed about a humidity outbreak that occurred and how influential the Gulf of Mexico and Atlantic Ocean moisture can be.

Some trend results are what we would expect, such as the trend maps (Figures 16-19) showing that stations with influence from the Gulf of Mexico have similar increases with one another. Only two regions of the map indicated trends of neutral or negative values, particularly in the highest percentiles. These were the Mid-Atlantic region into the Carolinas and Georgia, and the area between the Rocky Mountains and the Cascades/Sierra Nevada Mountain ranges. These stood out by not seeing the same increases in dewpoints as all other stations surrounding the areas did. Compared to the region in the West, the anomalous area in the Eastern U.S. is much smaller and less significant. The reason for this neutral trend is unclear, but considering its proximity to the Gulf of Mexico, it would be expected to have an increase as other stations have near it. For the area in the Western U.S., the dry climate with desert dominating the area is most likely the cause. The one common factor between the two areas of decline in dewpoint trend is that both areas are influenced by mountain ranges. However, the eastern area does not extend up the entire range of the Appalachian Mountains. Further research would need to be performed to evaluate if mountains are the cause.

After examining the negative trends, the positive trends are the more concerning for human health. The 50th percentile map (Figure 16) is the most uniform map in this research, seeing how the majority of stations experienced positive trends, with many being significant. The most notable area of increase was in the Northeast with dewpoint increases of around 2°F/70-year period. Population is extremely dense in the area, and although the 50th percentile of dewpoints may not cause significant problems for those who live there, it does indicate that the median dewpoint is rising, thereby impacting many millions of lives in some capacity. If this trend of the 50th percentile becomes the trend of the 95th percentile in the future, then this will have a bigger impact than the even larger dewpoint trends in the Midwest region because population there is more widely scattered, and many areas are used for farming and vegetation. For the Midwest, the extreme trend increases of >3°F/70-year period are most likely due to the local crops and irrigation of them as Bentley and Stallins (2008) discussed.

The 95th percentile trend map (Figure 19) is the most important map when it comes to human health, because these extreme values are what stresses the human body the most. It also gives an idea of how moisture content at the highest levels could change in the future. Less than half of the stations showed a positive significant increase, but where they were significant seemed to be clustered together. As with the other trend maps, positive significant trends were seen in the Northeast with increases around 2°F/70-year period, the Midwest/upper Plains increasing at 2-3°F/70-year period, and the Gulf Coast increasing at about 2°F/70-year period. Although the areas in the Northeast and Midwest/Upper Plains had some of the highest trends on the map, they also have lower base dewpoints than does the Gulf Coast. The 95th percentile dewpoints for the Upper Plains are at most 75°F, whereas at the Gulf Coast, the same percentile dewpoints are at 80°F. Therefore, for human health reasons, the largest area to be concerned about is the Gulf Coast. With the 95th percentile dewpoints already around 80°F, and trends indicating an increase in dewpoint of up to 3°F/70-year time period, this could mean that if moisture trends continue at this pace, these areas could one day have dewpoints that approach the threshold of human tolerance to heat stress of 95°F (35°C). This could cause any outdoor activities to be near impossible and human health hazards to occur during these extreme moisture events. Coffel et al. (2017) discusses this by saying that wet-bulb temperatures between 84-88°F (29-31°C) have already caused tens of thousands of deaths and that evidence suggests physical labor is unsafe over 90°F (32°C).

Previous research on summertime dewpoint temperatures across the United States tended to indicate that only small trends occurred and only in the central U.S. (Robinson 2000). My thesis has shown that the trend has increased in the decades since, to where a large portion of the Eastern U.S. experienced significant trends in dewpoint for summertime, such as the Upper Plains region, as the trend map figures show (Figures 16-19). One reason our results have changed is that the time period Robinson used was from 1951-1990. Our research includes data from 1948-2020. Three decades of additional data can drastically alter results, especially when other dewpoint trend analyses, such as Changnon et al. (2008), indicated a more positive dewpoint trend in the decades after 1980.

The trend that Changnon et al. (2008) indicates is of a shift occurring around 1980 where moisture content in the U.S. began to rise more rapidly in the decades following as compared to the decades prior to 1980. This trend was also evident for moisture trends evaluated in China (Freychet et al. 2020). This is most notably seen in Figure 20, where an upward shift in dewpoint of 5-7 degrees occurred for Cheyenne, WY right around 1980. Although there were some stations that had a slight increase around 1980, there were more stations that did not. In fact, there were a number of stations that experienced an unusual dip in dewpoints during the early to mid-1980's, as seen by the example of New Orleans, LA in Figure 21. This dip could be due to a larger weather phenomenon, or it could be an instrument change. Further research would need to be performed to determine the cause. Therefore, the trend of an upward shift in dewpoints around 1980 would appear to be more of a localized result, rather than a nationwide trend.

Results from McKinnon et al. (2021) compared similarly to this project. They found that there were some stations across the Southwest U.S. that had experienced negative dewpoint trends and that the intense heat during summer can cause this trend. Williams et al. (2014) provided a case example of how in 2011 a record high VPD that was driven by extremely low dewpoints across the Southwestern U.S. caused a record setting wildfire season. The results from our thesis do indicate that dewpoints have decreased in the West, particularly in the interior regions. The dewpoint trend maps (Figures 16-19) show the interior West having most stations trending negatively. Station dewpoints analyzed at the 50th percentile also indicate a negative trend across the northern section of the Southwest United States.

Brown and DeGaetano (2013) was the only previous study that looked at trends of dewpoints across the United States. Their results are not able to be directly compared to mine, due to their use of the maximum dewpoint percentile, but there are still several aspects to note. They found that in the central U.S. was where the largest trends were for their study. Even though those results were for March – May, the results from my research still show that the central part of the country is the area with the highest trends in dewpoint. They also noted that the northern half of the country saw the largest increase in trends, and that compares somewhat to this thesis' findings of the Upper Plains having the largest increases found. The biggest difference between this research and Brown and DeGaetano's study is that they focused on the maximum dewpoint instead of the 95th percentile. The maximum percentile can be inaccurate, even if one sorts through the data to eliminate assumed instrumentation errors. The results from our research after evaluating max dewpoint trends, showed there was a significant difference in the maximum trend map as compared to the 95th and 90th percentile trend maps. The maximum trend map (Figure 22) had 24 stations with negative dewpoint trends. This is 7 stations higher than the 95th percentile trend map and 8 higher than the 90th percentile trend map. However, the maximum dewpoint trend map did show similar results to what Brown and DeGaetano (2013) found, which was that most of the country experienced minimal trends for dewpoints, with only the Midwest having an increase. This indicates that by just looking at the maximum dewpoint instead of an extreme percentile, that the results were skewed for their research.

CHAPTER 6: CONCLUSION

In summary, dewpoint distribution across the U.S. largely was determined by geographical location. Areas in the southern latitudes experienced higher dewpoints with smaller ranges, while areas further north had lower values but wider ranges. The Eastern half of the United States had very high dewpoints with even areas at the northern-most latitudes having dewpoints around 75°F at the 99.9th percentile. The Western U.S. experiences much lower dewpoints, especially in the interior portions. Most stations followed this pattern with the exception of the Appalachian region from the Mid-Atlantic down into Georgia, which experienced slightly lower values.

Dewpoint trends also widely varied from the Eastern U.S. to the Western U.S., with most areas in the east experiencing positive trends, save the Appalachian region in the higher percentiles. Areas in the west differed by that the interior West experienced negative trends, some significant, for all percentiles, while the West Coast continued the majority trend of the country by having significant positive trends, particularly at higher percentiles. The Upper Plains, Northeast, and Gulf Coast all had significant positive trends for all percentiles. The most concern lies with the Gulf states, as their base dewpoints are already quite high with the highest dewpoint values being in the low 80's. With this area also experiencing positive significant dewpoint trends of up to 3°F/70-years at the 95th percentile, this could lead to this part of the country being the highest risk to human health in the future.

Dewpoint, wet-bulb temperature, and all parameters of moisture are a significant factor in everyone's lives, even if you do not live in an area that sees extremely high moisture values. If dewpoints continue to increase as the trend map results from this project show, this could lead to human and economic impacts. Although not everywhere experienced these increases, more areas across the U.S. are becoming more humid and quickly. This is not something that can be ignored, because just like global warming, lives will be affected. Some areas of the U.S. would become higher energy consumers due to immense need for air conditioning and if moisture content reaches high enough, areas could even become uninhabitable. Perhaps a different concern aside from the highest dewpoint percentile values, is that of the 50th percentile dewpoint values. The 50th percentile trend map (Figure 16) indicated that 57 of the 114 stations experienced significant increases for the median dewpoint values during the summer months across the time period. This implies that for longer durations and for a larger number of days per year, that dewpoints are continuing to rise across a large portion of the country. Due to this, more energy consumption is needed for human comfort and sustainability, even when human health is not as large of a concern for median dewpoints. Regardless, trends in dewpoint are important to monitor going forward due to the results found in this research.

CHAPTER 7: FUTURE WORK

The results gathered from this project could give lead to other future projects as well. A similar study of moisture trends across the U.S. but using wet-bulb temperatures instead of dewpoints would be a good project to compare to this one because daily maximum wet-bulb temperatures usually do not occur at the same time as maximum dewpoint temperatures. Also, wet-bulb temperatures more closely relate to what the human body feels, so results from such a project would be beneficial for more than just statistical trend evidence. Other future project ideas would be doing a similar evaluation to this thesis of dewpoints/wet-bulb temperatures but on a global scale to see if trends are similar across all parts of the globe. A project that used climate models to project moisture content could also beneficial as well. Evaluating other seasons of moisture content would be very informative to see if seasons determine whether moisture trends up or down in certain parts of the world, even though this does not affect human lifestyle the same way that summer dewpoints do. Comparing the dewpoint trends from this paper to summertime temperature trends would also be a revealing project to see if both are trending at the same rate or if they have significantly different trends. A month by month breakdown of dewpoints and their trends individually would be beneficial to see how any differences may occur across various weather stations for different months in summertime due to the varying summer seasons that the U.S. displays. Case studies for areas noted in this research that experienced extreme dewpoint trends could be performed to see what caused these extreme trends.

References

American Meteorological Society, 2021: Glossary of Meteorology. Accessed 14 December 2021, https://glossary.ametsoc.org/wiki/Wet-bulb_temperature

Bentley, M. L., and J. A. Stallins, 2008: Synoptic Evolution of Midwestern US Extreme dewpoint events. *Int. J. Climatol.*, **28**, 1213-1225, (www.interscience.wiley.com) DOI: 10.1002/joc.1626.

Brown, P. J., and A. T. DeGaetano, 2013: Trends in U.S. Surface Humidity, 1930–2010. *J. Appl. Meteor. Climatol.,* **52**, 147–163, https://journals.ametsoc.org/doi/pdf/10.1175/JAMC-D-12-035.1.

Changnon, D., M. Sandstrom, M. Bentley, 2006. Midwestern High Dew Point Events 1960-2000: *Physical Geography*, **27**(6), 494-504, https://www.tandfonline.com/doi/abs/10.2747/0272-3646.27.6.494

Coffel, E. D., R. M. Horton, A. de Sherbinin, 2018: Temperature and humidity based projections of a rapid rise in global heat stress exposure during the 21st century. *Environ. Res. Lett.* **13**, 014001, https://iopscience.iop.org/article/10.1088/1748-9326/aaa00e

Freychet, N., S. F. B. Tett, Z. Yan, Z. Li, 2020: Underestimated Change of Wet-Bulb Temperatures over East and South China. *Geophysical Research Letters*, 47, e2019GL086140. https://doi.org/10.1029/2019GL086140

Im, E., J. S. Pal, E. A. B. Eltahir, 2017. Deadly heat waves projected in the densely populated agricultural regions of South Asia. *Sci. Adv.*, 2017. **3**: e1603322, DOI: 10.1126/sciadv.1603322

Iowa State University of Science and Technology, 2021: IEM Computed Daily Summary of Observations. Iowa Environmental Mesonet, Accessed 1 May 2020, https://mesonet.agron.iastate.edu/request/daily.phtml?network=NC_ASOS

Iowa State University of Science and Technology, 2021: Network Location Tables. Iowa Environmental Mesonet, Accessed 1 May 2020, https://mesonet.agron.iastate.edu/sites/networks.php?network=NC_ASOS&format=html

Kunkel, K. E., S. A. Changnon, B. C. Reinke, R. W. Arritt, 1996. The July 1995 Heat Wave in the Midwest: A Climatic Perspective and Critical Weather Factors. *Bull. Amer. Meteor. Soc.*, 1996. **77**, 1507-1518, https://journals.ametsoc.org/view/journals/bams/77/7/1520-0477_1996_077_1507_tjhwit_2_0_co_2.xml

McKinnon, K. A., A. Poppick, 2020. Estimating Changes in the Observed Relationship Between Humidity and Temperature Using Noncrossing Quantile Smoothing Techniques. *Journal of Agricultural, Biological and Environmental Statistics*., 2020. DOI 10.1007/s13253-020-00393-4

McKinnon, K. A., A. Poppick, I. R. Simpson, 2021. Hot extremes have become drier in the United States Southwest. *Nature Climate Change*., 2021. **11**, 598-604. https://doi.org/10.1038/s41558-021-01076-9

Raymond, C., T. Matthews, R. M. Horton, 2020: The emergence of heat and humidity too severe for human tolerance. *Science Advances*, **6**(19), 1-17. https://www.science.org/doi/10.1126/sciadv.aaw1838

Robinson, P.J., 2000: Temporal trends in United States dew point temperatures. *Int. J. Climatol.*, **20**, 985–1002, https://rmets.onlinelibrary.wiley.com/doi/pdf/10.1002/1097-0088(200007)20:9%3C985::AID-JOC513%3E3.0.CO;2-W.

Samenow, J., 2016: Extreme humidity: The entire eastern U.S. is a wet blanket. The Washington Post, Accessed 1 May 2020, https://www.washingtonpost.com/news/capital-weather-gang/wp/2016/08/11/the-entire-eastern-u-s-is-a-wet-blanket/.

Schwartzman, P. D., P. J. Michaels, P. C. Knappenberger, 1998: Observed changes in the diurnal dewpoint cycles across North America. *Geophysical Research Letters*, **25**(13), 2265-2268. https://agupubs-onlinelibrary-wiley-com.librarylink.uncc.edu/doi/pdfdirect/10.1029/98GL01843

Sherwood, S. C., 2018: How Important is Humidity in Heat Stress?. *Journal of Geophysical Research: Atmospheres*, **123**, 11808–11810. https://doi.org/10.1029/2018JD028969

Sherwood, S. C., and Matthew Huber, 2010: An Adaptability Limit to Climate Change Due to Heat Stress. *PNAS*, **107**(21), 9552-9555, https://doi.org/10.1073/pnas.0913352107

Williams, A. P., R. Seager, M. Berkelhammer, A. K. Macalady, M. A. Crimmons, T. W. Swetnam, A. T. Trugman, N. Buenning, N. Hryniw, N. G. McDowell, D. Noone, C. I. Mora, T. Rahn, 2014: Causes and Implications of Extreme Atmospheric Moisture Demand during the Record-Breaking 2011 Wildfire Season in the Southwestern United States. *J. Appl. Meteor. Climatol.,* **53**, 2671-2684, https://doi.org/10.1175/JAMC-D-14-0053.1

Table 1. List of ASOS stations from which data was collected.

Location	ID	Latitude	Longitude	Elevation (m)
Albany, NY	KALB	42.75757	-73.80361	89
Albuquerque, NM	KABQ	35.0419	-106.6155	1620
Arcata, CA	KACV	40.97811	-124.10861	66
Atlanta, GA	KATL	33.6301	-84.4418	315
Atlantic City, NJ	KACY	39.45758	-74.57717	20
Baltimore, MD	KBWI	39.17536	-76.66833	47
Bangor, ME	KBGR	44.80744	-68.82814	59
Billings, MT	KBIL	45.8069	-108.5422	1088
Birmingham, AL	KBHM	33.56546	-86.74488	192
Boise, ID	KBOI	43.56667	-116.24056	874
Boston, MA	KBOS	42.36057	-71.00973	9
Brownsville, TX	KBRO	25.91461	-97.42313	6
Buffalo, NY	KBUF	42.9408	-78.7358	215
Burlington, IA	KBRL	40.77293	-91.12549	213
Burlington, VT	KBTV	44.47	-73.15	104
Caribou, ME	KCAR	46.87	-68.02	190
Casper, WY	KCPR	42.908	-106.46442	1612
Cedar City, UT	KCDC	37.7	-113.1	1714
Charleston, WV	KCRW	38.3794	-81.59	299
Charlotte, NC	KCLT	35.22255	-80.95431	228
Cheyenne, WY	KCYS	41.15564	-104.81047	1871
Chicago, IL	KORD	41.98754	-87.93193	200
Cleveland, OH	KCLE	41.405	-81.85278	233
Colorado Springs, CO	KCOS	38.80581	-104.70078	1881
Columbia, SC	KCAE	33.9419	-81.1181	69
Columbus, OH	KCMH	39.99139	-82.88083	247
Columbus, GA	KCSG	32.51611	-84.94222	121
Concord, NH	KCON	43.19528	-71.50111	105
Dallas, TX	KDAL	32.84711	-96.85178	148
Dayton, OH	KDAY	39.90611	-84.21861	305
Des Moines, IA	KDSM	41.53395	-93.65311	294
Detroit, MI	KDET	42.40919	-83.00986	190
Dodge City, KS	KDDC	37.76312	-99.96542	790
Dubuque, IA	KDBQ	42.39835	-90.70914	329
El Paso, TX	KELP	31.81111	-106.37583	1194
Elkins, WV	KEKN	38.88528	-79.85278	609
Eugene, OR	KEUG	44.12458	-123.21197	114
Fargo, ND	KFAR	46.92528	-96.81111	274
Farmington, NM	KFMN	36.74361	-108.22917	1677
Fort Smith, AR	KFSM	35.33658	-94.36744	141
Fort Wayne, IN	KFWA	40.97805	-85.18713	248

Fresno, CA	KFAT	36.78	-119.7194	100
Glasgow, MT	KGGW	48.2138	-106.6214	700
Grand Island, NE	KGRI	40.96754	-98.30964	563
Grand Junction, CO	KGTJ	39.13417	-108.54	1475
Hartford, CT	KBDL	41.9381	-72.6825	55
Helena, MT	KHLN	46.6056	-111.9636	1188
Houston, TX	KHOU	29.63747	-95.28245	14
Jackson, MS	KJAN	32.32	-90.08	101
Jacksonville, FL	KJAX	30.49406	-81.68786	9
Key West, FL	KEYW	24.55611	-81.75956	1
Knoxville, TN	KTYS	35.8181	-83.9858	299
La Crosse, WI	KLSE	43.88	-91.25	199
Lander, WY	KLND	42.81524	-108.72984	1694
Las Vegas, NV	KLAS	36.08006	-115.15225	664
Little Rock, AR	KLIT	34.7273	-92.23573	79
Los Angeles, CA	KLAX	33.93816	-118.38653	32
Louisville, KY	KSDF	38.17439	-85.736	149
Lubbock, TX	KLBB	33.66364	-101.82278	988
Mason City, IA	KMCW	43.15438	-93.3261	370
Medford, OR	KMFR	42.3811	-122.8722	405
Memphis, TN	KMEM	35.06111	-89.985	87
Miami, FL	KMIA	25.78805	-80.31693	4
Miles City, MT	KMLS	46.42797	-105.88625	801
Minneapolis, MN	KMSP	44.88537	-93.23131	265
Minot, ND	KMOT	48.25938	-101.28033	523
Mobile, AL	KMOB	30.68833	-88.24556	67
Montgomery, AL	KMGM	32.30064	-86.39397	62
Nashville, TN	KBNA	36.11889	-86.68917	180
New Orleans, LA	KMSY	29.9933	-90.2511	9
North Platte, NE	KLBF	41.12191	-100.66896	844
New York City, NY	KJFK	40.63861	-73.76222	7
Oklahoma City, OK	KOKC	35.3889	-97.6006	397
Omaha, NE	KOMA	41.31028	-95.89917	296
Pendleton, OR	KPDT	45.69506	-118.84144	456
Phoenix, AZ	KPHX	33.43428	-112.01158	337
Pierre, SD	KPIR	44.38269	-100.28597	522
Pittsburgh, PA	KPIT	40.49147	-80.23286	373
Portland, OR	KPDX	45.59083	-122.60028	12
Portland, ME	KPWM	43.64243	-70.30442	19
Providence, RI	KPVD	41.7219	-71.4325	19
Raleigh, NC	KRDU	35.8922	-78.7819	118
Rapid City, SD	KRAP	44.04533	-103.05736	965
Red Bluff, CA	KRBL	40.1519	-122.2536	108
Reno, NV	KRNO	39.48389	-119.77111	1539
Richmond, VA	KRIC	37.5115	-77.32336	54

Roanoke, VA	KROA	37.31724	-79.97368	345
Rock Springs, WY	KRKS	41.59422	-109.06519	2060
Sacramento, CA	KSAC	38.5069	-121.495	8
Salt Lake City, UT	KSLC	40.78	-111.97	1288
San Antonio, TX	KSAT	29.53369	-98.46978	242
San Francisco, CA	KSFO	37.61897	-122.37489	5
Santa Maria, CA	KSMX	34.9	-120.45	73
Sault Ste Marie, MI	KANJ	46.47922	-84.36839	218
Savannah, GA	KSAV	32.12758	-81.20214	15
Scottsbluff, NE	KBFF	41.87403	-103.59564	1203
Scranton, PA	KAVP	41.33347	-75.72267	289
Seattle, WA	KSEA	47.44469	-122.31437	137
Shreveport, LA	KSHV	32.4472	-93.8244	79
Sioux Falls, SD	KFSD	43.57694	-96.75361	429
South Bend, IN	KSBN	41.70722	-86.31639	237
Spokane, WA	KGEG	47.6216	-117.528	721
St. Louis, MO	KSTL	38.75245	-90.3734	171
Syracuse, NY	KSYR	43.11119	-76.10631	124
Tallahassee, FL	KTLH	30.3954	-84.35135	21
Tampa, FL	KTPA	27.9619	-82.5403	3
Tonopah, NV	KTPH	38.05052	-117.09043	1654
Topeka, KS	KTOP	39.07	-95.62	270
Traverse City, MI	KTVC	44.74164	-85.58236	190
Tucson, AZ	KTUS	32.12027	-110.93798	779
Tucumcari, NM	KTCC	35.18278	-103.60319	1239
Wilmington, DE	KILG	39.67278	-75.60083	24
Wilmington, NC	KILM	34.27	-77.9	10
Winnemucca, NV	KWMC	40.90194	-117.80722	1315

Table 2. List of potentially erroneous data that was analyzed to determine legitimacy. If a value was kept, it was due to either the day(s) surrounding the date in question at the station or the day in question of a nearby station having a dewpoint value within 5 degrees Fahrenheit of the questionable value. If a value was excluded, it was due to those values not being within 5 degrees, unless otherwise noted below.

Location	Date	Value (°F)	Determination
Albany (KALB)	7/27/97 8/4/98	79 83	Excluded Excluded
Albuquerque (KABQ)	7/16/97	72	Excluded
Arcata (KACV)	8/24/00 9/2/83	128 68	Excluded Kept due to high values that week
Atlantic City (KACY)	6/25/52 6/26/52 7/2/55 9/2/56	85 85 84 84	Excluded Excluded Excluded Kept
Billings (KBIL)	6/12/53 7/8/54 6/26/96 6/28/97	75 72 71 69	Kept Excluded Kept Excluded
Birmingham (KBHM)	7/12/89 7/27/97 8/16/07	83 93 81	Excluded Excluded Excluded
Boise (KBOI)	7/13/07	84	Excluded
Burlington (KBRL)	7/19/92 9/8/96	86 86	Excluded Excluded
Caribou (KCAR)	7/19/75 7/20/77	86 78	Excluded Kept
Casper (KCPR)	8/13/98	69	Excluded
Cedar City (KCDC)	8/1/59 6/4/64 6/20/74 6/24/74 6/25/74 7/14/96	73 75 81 90 93 84	Excluded Excluded Excluded Excluded Excluded Excluded
Charlotte (KCLT)	9/26/17	82	Excluded
Cheyenne (KCYS)	7/21/18	69	Kept
Colorado Springs (KCOS)	9/25/96 7/24/98	69 70	Excluded Excluded
Columbia (KCAE)	8/31/55 7/30/58 8/12/83 6/29/00 7/23/91	82 82 83 81 82	Excluded Excluded Excluded Excluded Kept

Columbus (KCSG)	7/13/77 7/14/77 6/5/78 6/17/91 6/19/91	83 85 86 80 83	Excluded Excluded Excluded Excluded Excluded
Dallas (KDAL)	8/12/85 7/20/86 7/21/86 6/7/93 7/17/97 9/9/97 9/18/98 6/15/99 6/26/99 8/24/99	85 83 84 82 90 91 83 84 84 86	Excluded Excluded Excluded Excluded Excluded Excluded Excluded Excluded Excluded Excluded
Dayton (KDAY)	6/26/59	82	Excluded
Des Moines (KDSM)	9/6/98 7/26/97	84 82	Excluded Kept
Detroit (KDET)	8/3/96 6/29/97 7/14/97 9/15/98 6/11/99 6/13/99 7/1/99 8/10/02 6/7/05 8/6/96	82 82 91 84 86 86 82 81 86 81	Excluded Excluded Excluded Excluded Excluded Excluded Excluded Excluded Excluded Kept
Elkins (KEKN)	8/2/54-9/30/54	32	All values were 32 for this period, so they were excluded due to probable instrumentation error
El Paso (KELP)	8/19/78	78	Excluded
Eugene (KEUG)	6/21/58 6/15/61 6/16/61 7/22/96 7/4/97	71 73 72 73 72	Kept Kept Kept Kept Excluded
Fargo (KFAR)	7/19/11	83	Kept
Farmington (KFMN)	9/5/49 7/6/68-9/2/68	75 32	Kept All values were 32 for this period, so they were excluded due to probable instrumentation error
Fort Smith (KFSM)	7/2/57 7/29/58 8/28/79	83 83 85	Both kept due to high dewpoints that week. Excluded
Fresno (KFAT)	8/16/96 7/1/97 7/6/07	79 83 75	Excluded due to no surrounding stations within 5 degrees even though day prior was 5 degrees off Excluded Excluded

Glasgow (KGGW)	6/24/65 8/18/00 6/25/12	76 77 74	Excluded Excluded Excluded
Grand Island (KGRI)	7/4/80	83	Excluded
Grand Junction (KGTJ)	9/21/05	74	Excluded
Hartford (KBDL)	7/16/80 9/9/99 8/18/02 7/27/05	85 84 82 81	Excluded Excluded Excluded Kept
Helena (KHLN)	7/17/55 7/4/75 6/9/96	70 69 73	Kept Kept Kept
Houston (KHOU)	7/24/81 9/8/81 8/1/82 9/3/83 8/3/96 8/12/96 7/10/97 6/26/98 7/20/98 7/25/05 7/11/97 7/12/97	85 83 85 84 84 85 87 85 94 85 83 82	Excluded Excluded Excluded Excluded Excluded Excluded Excluded Excluded Excluded Excluded Kept Kept
Jacksonville (KJAX)	6/9/78 8/1/84	85 84	Excluded Excluded
Key West (KEYW)	8/6/75 6/8/79 8/9/79 6/30/85	84 88 87 84	Excluded Excluded Excluded Kept
Knoxville (KTYS)	8/4/65 8/3/05 6/30/17 6/19/18 7/4/80	79 82 84 87 81	Excluded Excluded Excluded Excluded Kept
La Crosse (KLSE)	7/3/77 7/4/77 6/26/78 7/5/78 9/14/00	81 83 85 85 113	Excluded Excluded Excluded Excluded Excluded
Lander (KLND)	7/7/75 7/23/79 7/9/18	67 68 64	Excluded Excluded Kept
Little Rock (KLIT)	6/7/79 7/6/77 7/18/82	85 82 83	Excluded Kept Kept
Los Angeles (KLAX)	6/27/76	73	Excluded
Lubbock (KLBB)	7/3/58 7/26/13	81 79	Excluded Excluded

Mason City (KMCW)	7/31/96-9/30/96 6/1/97/-7/31/97 6/1/98-9/30/98	Low 30's Mid 30's Low 30's	All values were in the 30's which indicated an instrument error for each case
Medford (KMFR)	7/23/94 8/1/09	72 72	Excluded Kept
Memphis (KMEM)	9/5/97 8/17/97 6/13/97 7/8/96	89 84 84 90	Excluded Excluded Excluded Excluded
Miami (KMIA)	7/5/70 6/11/05 6/26/95 6/27/95	85 171 84 84	Excluded Excluded Both dates were kept due to a tropical system being in the area attributing to these values at other nearby stations.
Miles City (KMLS)	7/10/74 7/28/87 6/1/97 7/10/18 9/15/19	74 75 79 75 78	Excluded Kept Excluded Kept Excluded
Minot (KMOT)	7/23/97	86	Excluded
Mobile (KMOB)	7/29/63 8/1/69 7/13/72 7/3/74 7/16/75 7/29/99	83 84 83 85 84 86	Excluded Excluded Excluded Excluded Excluded Kept
Montgomery (KMGM)	8/14/01 8/15/01 8/17/01 8/18/01 9/20/01	85 86 85 86 85	All kept due to extremely high dewpoints in the area for the week Kept
Nashville (KBNA)	7/14/15 8/15/95	81 82	Excluded Kept
New Orleans (KMSY)	9/23/80	88	Excluded
New York (KJFK)	8/13/16	84	Excluded
North Platte (KLBF)	9/11/01 7/17/10 7/16/11	81 81 80	Excluded Kept Kept
Pendleton (KPDT)	7/11/75 9/7/98	71 72	Excluded Excluded
Phoenix (KPHX)	7/28/94 7/5/06 7/29/10	82 81 80	Excluded Kept Excluded
Pierre (KPIR)	8/13/97 7/15/98 6/20/99	142 84 246	Excluded Excluded Excluded
Portland (KPDX)	6/4/78 7/22/06	72 72	Excluded Kept

Providence (KPVD)	8/1/75 8/22/76 7/16/77 7/21/77	80 80 81 81	Kept Kept Both kept due to extremely high values that week
Raleigh (KRDU)	7/24/65 8/10/07 7/31/06 8/1/06	81 82 81 81	Excluded Excluded Kept Kept
Rapid City (KRAP)	8/19/04 9/13/17	91 131	Excluded Excluded
Reno (KRNO)	8/11/01	70	Excluded
Richmond (KRIC)	8/5/80 8/2/79 8/29/03	83 84 81	Excluded Kept Kept
Roanoke (KROA)	8/13/75	79	Excluded
Rock Springs (KRKS)	8/17/68 8/19/68 7/28/78 9/1/83 9/6/83 7/23/89 7/25/89	63 64 69 66 63 64 64	Excluded Excluded Excluded Excluded Kept Kept Kept
Sacramento (KSAC)	8/7/89 6/19/92 7/12/99 8/24/99 8/12/86	75 79 83 86 77	Excluded Excluded Excluded Excluded Kept
Salt Lake City (KSLC)	7/28/93	71	Excluded
San Antonio (KSAT)	7/28/79 6/17/95	84 82	Excluded due to no surrounding stations within 5 degrees even though day prior was 5 degrees off Excluded
San Francisco (KSFO)	9/19/00	92	Excluded
Santa Maria (KSMX)	9/7/58 9/3/17	71 73	Kept Kept
Savannah (KSAV)	9/13/73	85	Excluded
Scranton (KAVP)	9/2/52 6/25/53 6/26/53 6/25/97	79 79 83 85	Excluded Excluded Excluded Excluded
Seattle (KSEA)	8/13/73 7/30/00	69 83	Excluded Excluded
Scottsbluff (KBFF)	6/27/03 7/16/03 7/20/03 7/21/03 9/17/13 9/18/13 6/28/14	77 79 82 82 79 83 79	Excluded Excluded Excluded Excluded Excluded Excluded Excluded

Shreveport (KSHV)	9/9/62 8/17/79	85 83	Excluded Excluded
Spokane (KGEG)	7/28/96 7/21/97 7/20/12 8/1/18	79 73 67 68	Excluded Excluded Excluded Excluded
South Bend (KSBN)	7/23/01	83	Excluded
Tallahassee (KTLH)	8/11/83 7/18/96 8/31/05	86 84 84	Excluded Both dates were kept due to a tropical system being in the area attributing to these values at other nearby stations.
Tampa (KTPA)	8/10/85 8/5/00 8/6/00 8/14/75 8/22/80 6/17/91	84 84 86 82 83 82	Excluded Excluded Excluded Kept Kept Kept
Tonopah (KTPH)	7/21/56 9/5/59 8/26/01	71 72 71	Kept due to high values that week for KTPH and surrounding stations Excluded Kept
Topeka (KTOP)	8/6/62	83	Excluded
Tucson (KTUS)	8/3/89	77	Kept
Tucumcari (KTCC)	5/31/02 6/2/02 6/8/02 6/13/02	82 81 85 81	Both kept due to high values all week Excluded Excluded
Wilmington (KILM)	6/9/51 7/30/69 9/20/77 7/20/83	84 84 84 88	Excluded Excluded Excluded Excluded

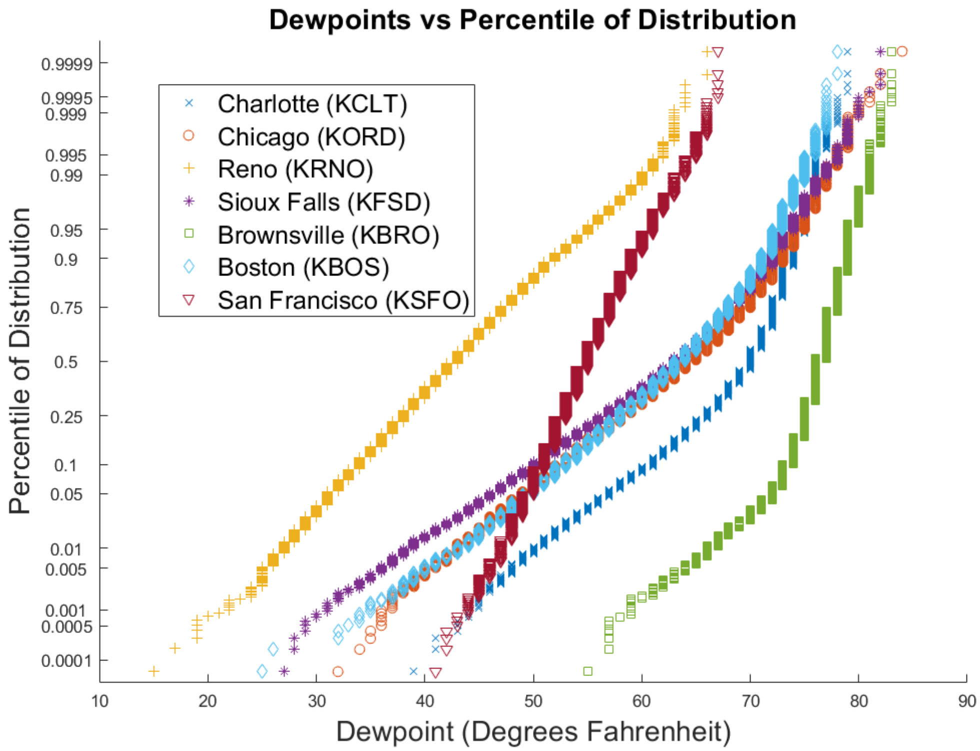

Figure 1. Cumulative Distribution of dewpoints from 1948-2020 for seven example stations in the months of June through September.

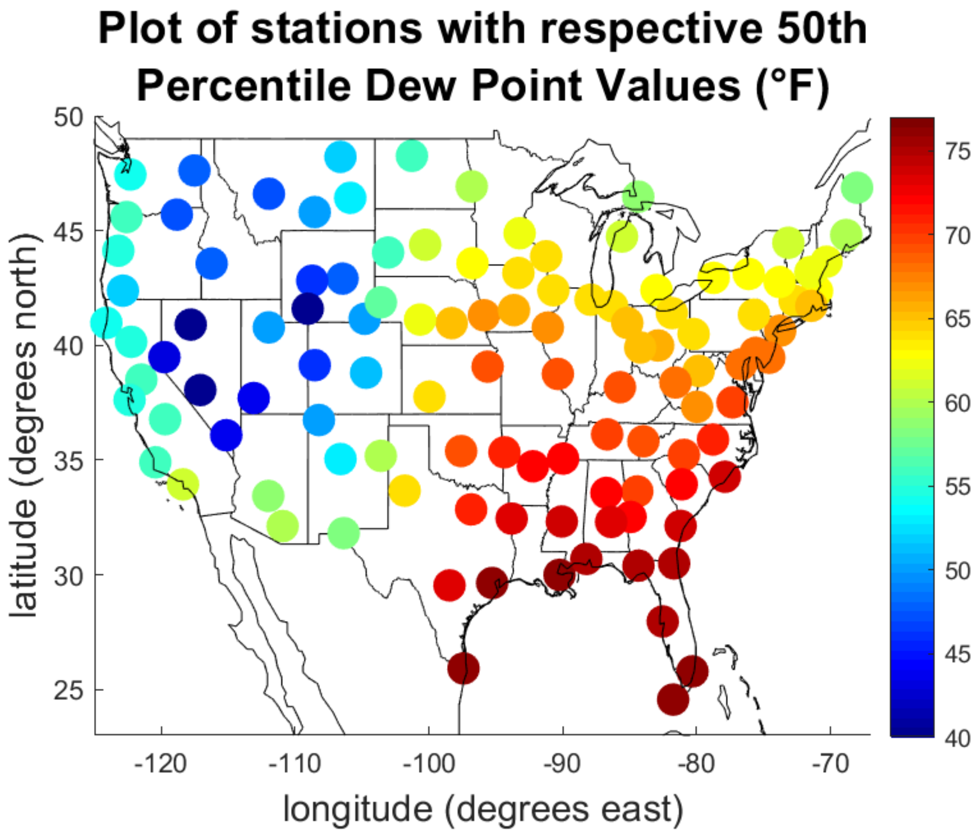

Figure 2. Plot of the 50th percentile of June - September dewpoint temperature at each station.

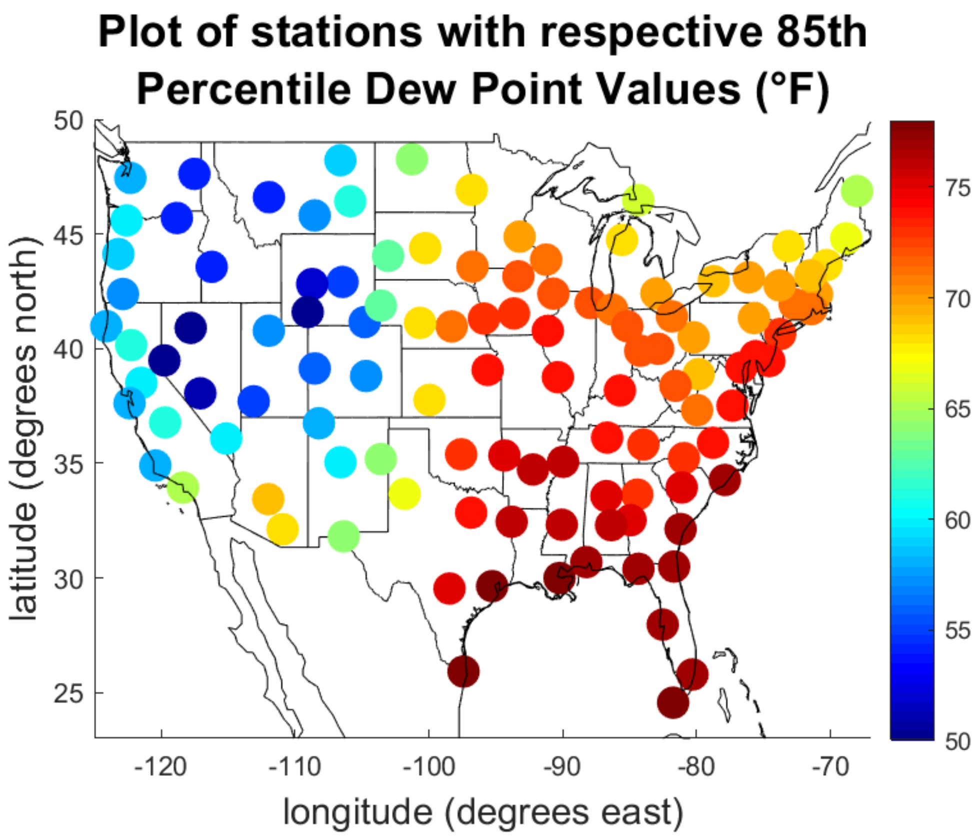

Figure 3. Plot of the 85th percentile of June - September dewpoint temperature at each station.

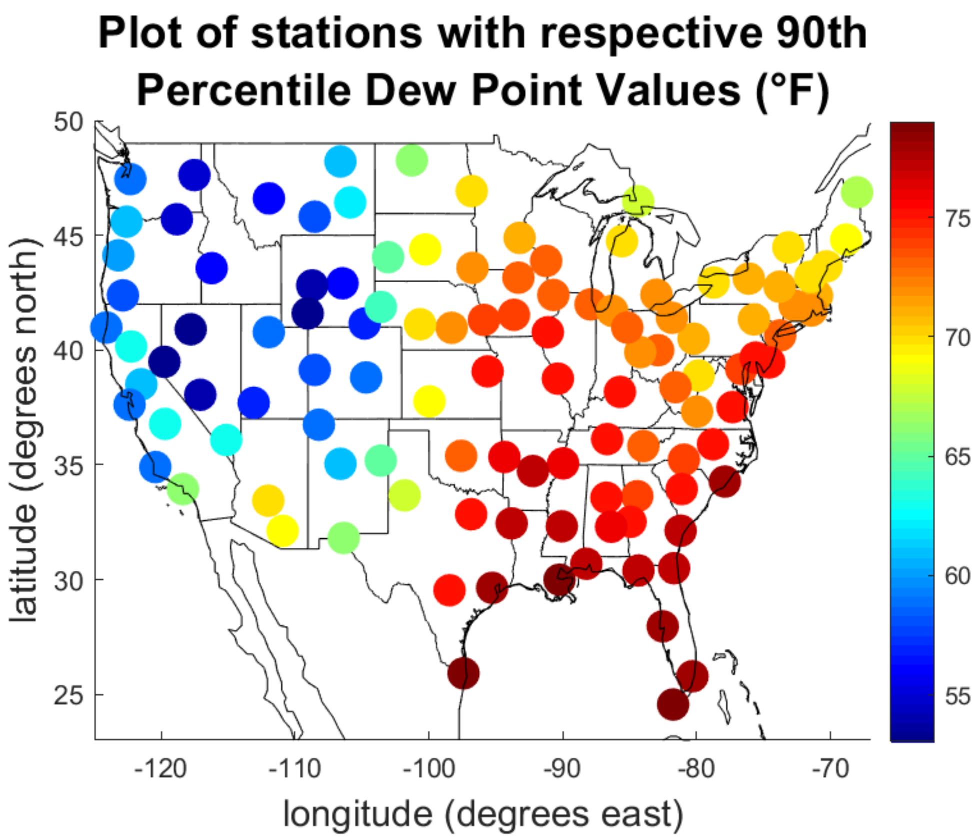

Figure 4. Plot of the 90th percentile of June - September dewpoint temperature at each station.

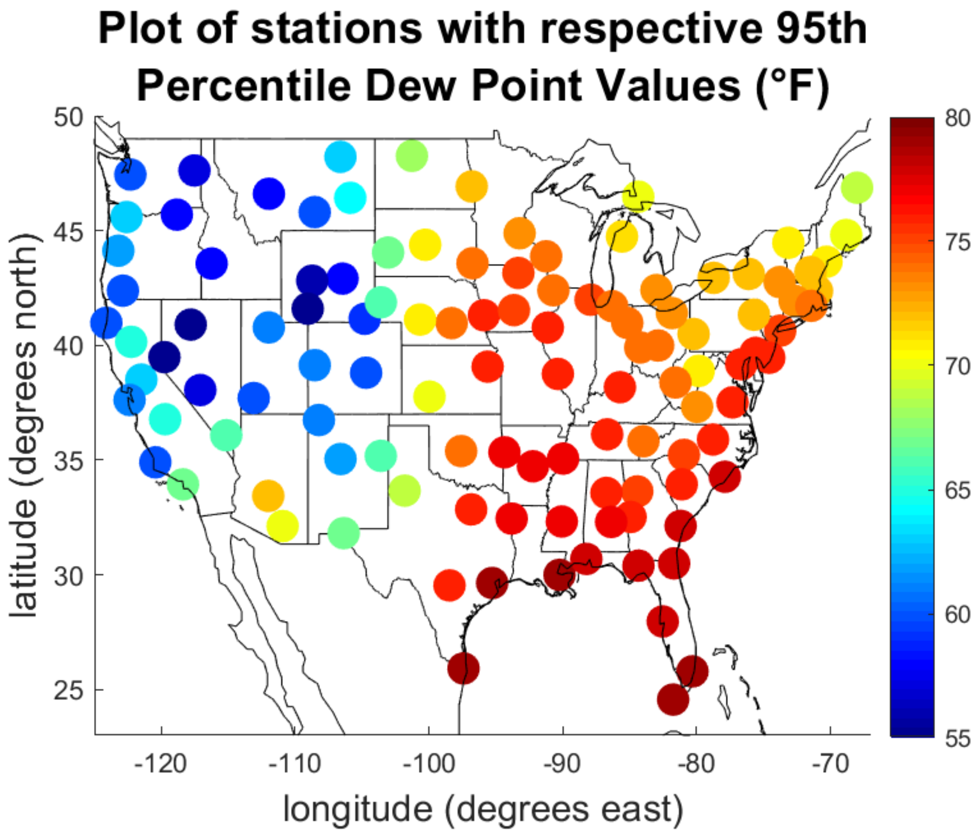

Figure 5. Plot of the 95th percentile of June - September dewpoint temperature at each station.

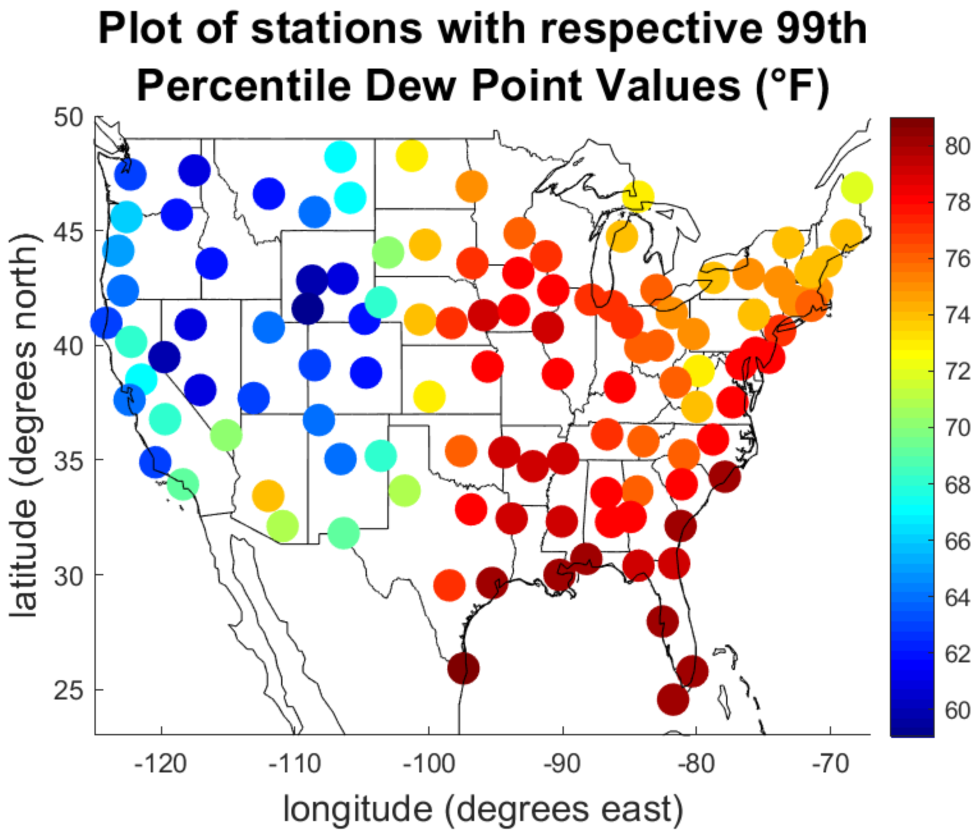

Figure 6. Plot of the 99th percentile of June - September dewpoint temperature at each station.

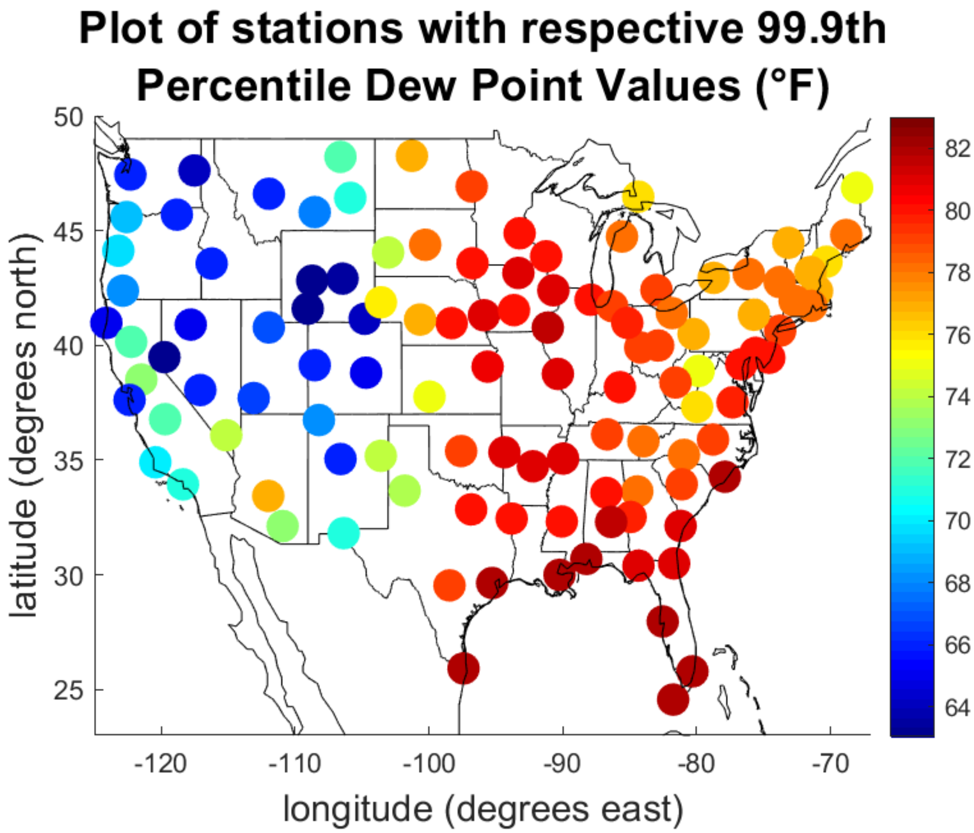

Figure 7. Plot of the 99.9th percentile of June - September dewpoint temperature at each station.

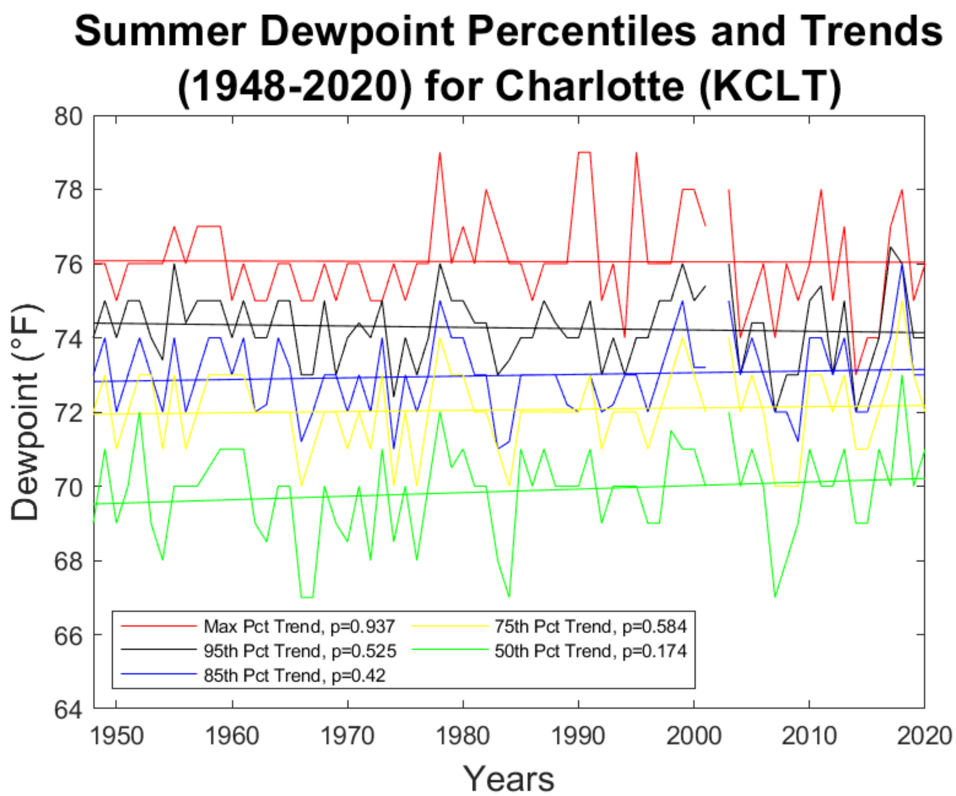

Figure 8. Yearly June - September dewpoints for the 50th, 75th, 85th, 95th and maximum percentiles and their respective trend lines for Charlotte, NC.

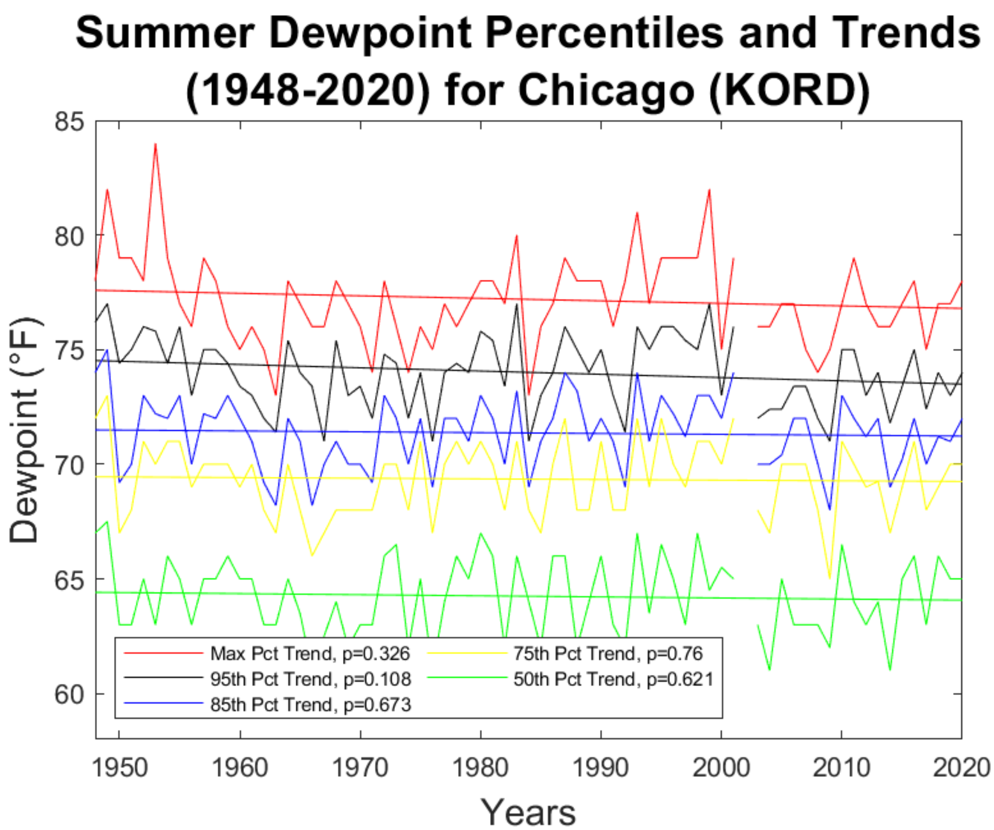

Figure 9. Yearly June - September dewpoints for the 50th, 75th, 85th, 95th and maximum percentiles and their respective trend lines for Chicago, IL.

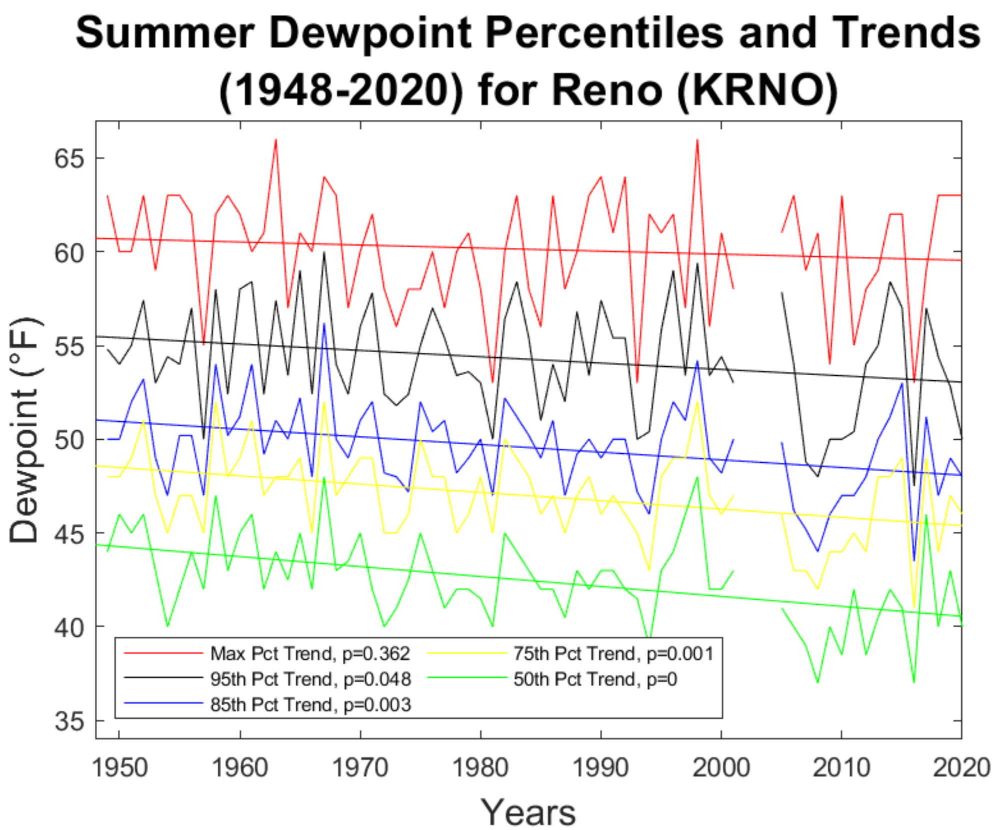

Figure 10. Yearly June - September dewpoints for the 50th, 75th, 85th, 95th and maximum percentiles and their respective trend lines for Reno, NV.

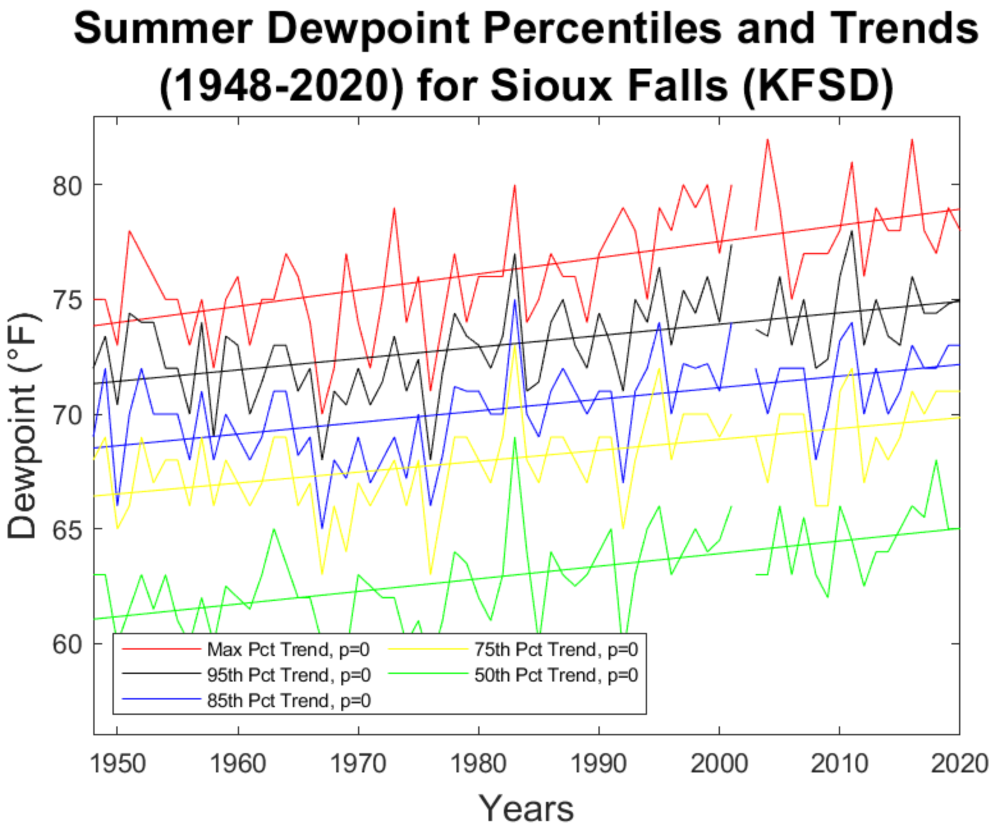

Figure 11. Yearly June - September dewpoints for the 50th, 75th, 85th, 95th and maximum percentiles and their respective trend lines for Sioux Falls, SD.

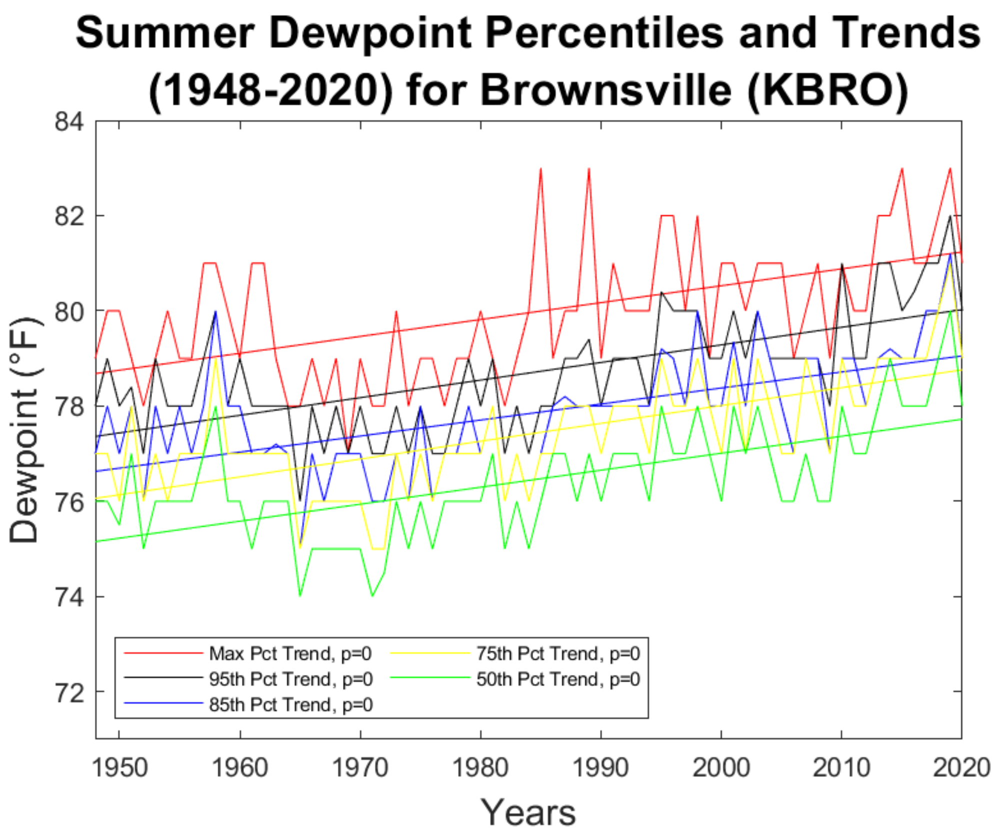

Figure 12. Yearly June - September dewpoints for the 50th, 75th, 85th, 95th and maximum percentiles and their respective trend lines for Brownsville, TX.

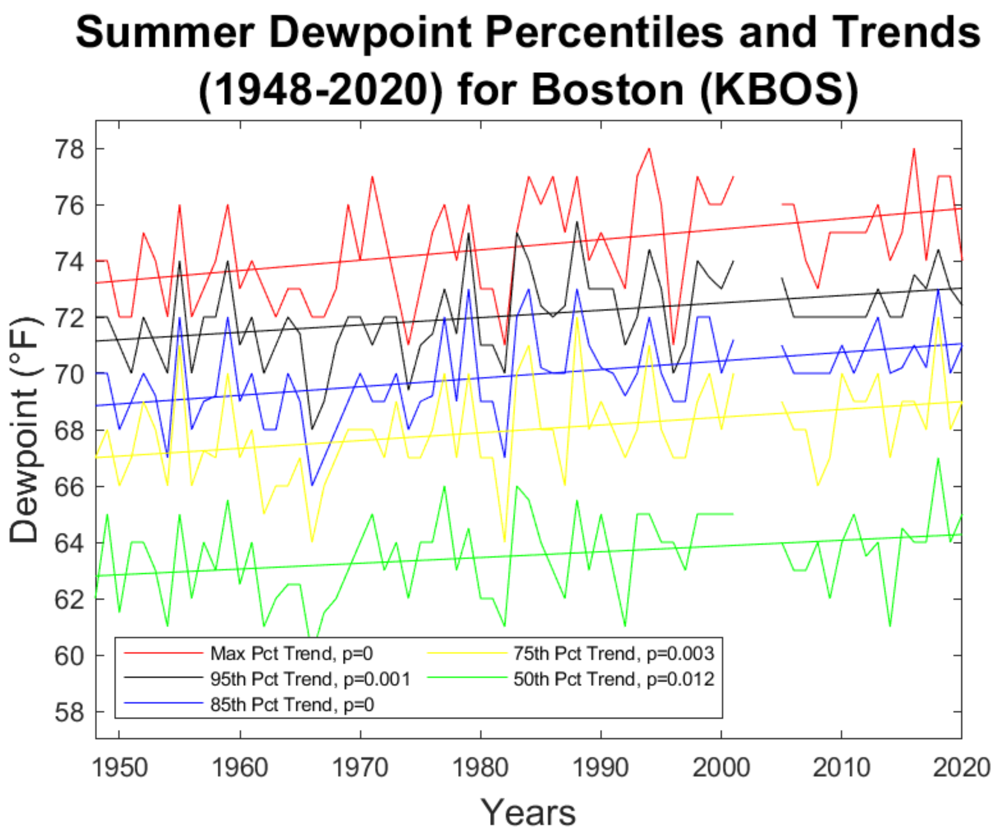

Figure 13. Yearly June - September dewpoints for the 50th, 75th, 85th, 95th and maximum percentiles and their respective trend lines for Boston, MA.

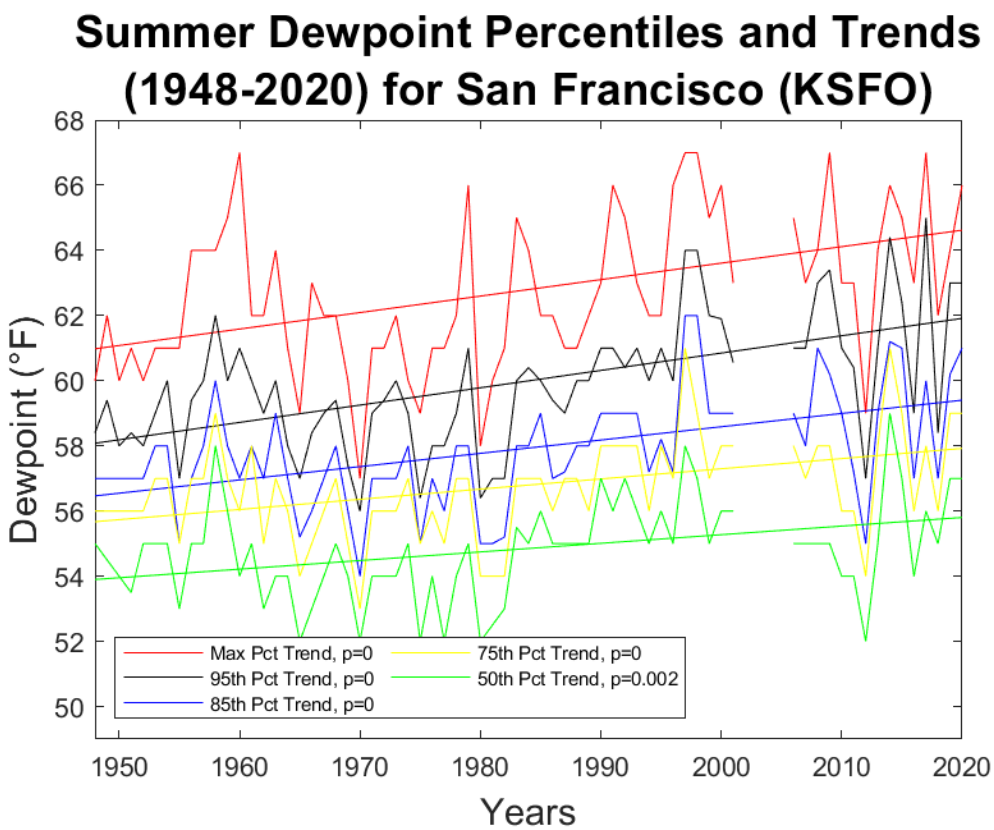

Figure 14. Yearly June - September dewpoints for the 50th, 75th, 85th, 95th and maximum percentiles and their respective trend lines for San Francisco, CA.

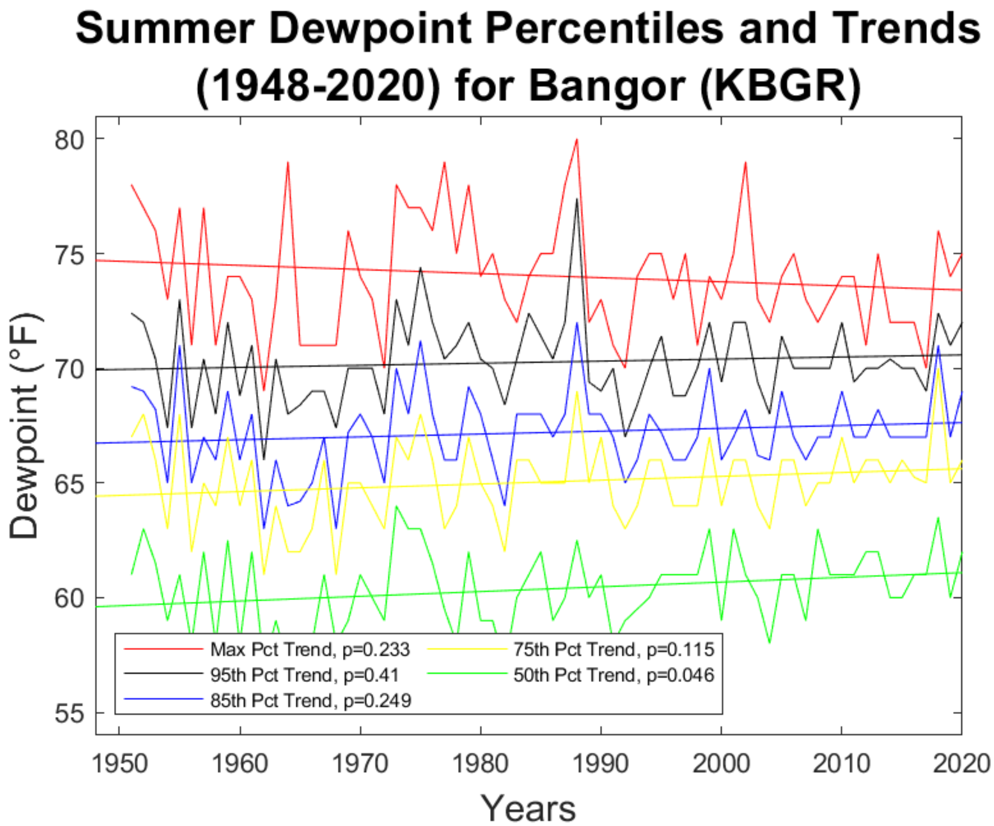

Figure 15. Yearly June - September dewpoints for the 50th, 75th, 85th, 95th and maximum percentiles and their respective trend lines for Bangor, ME.

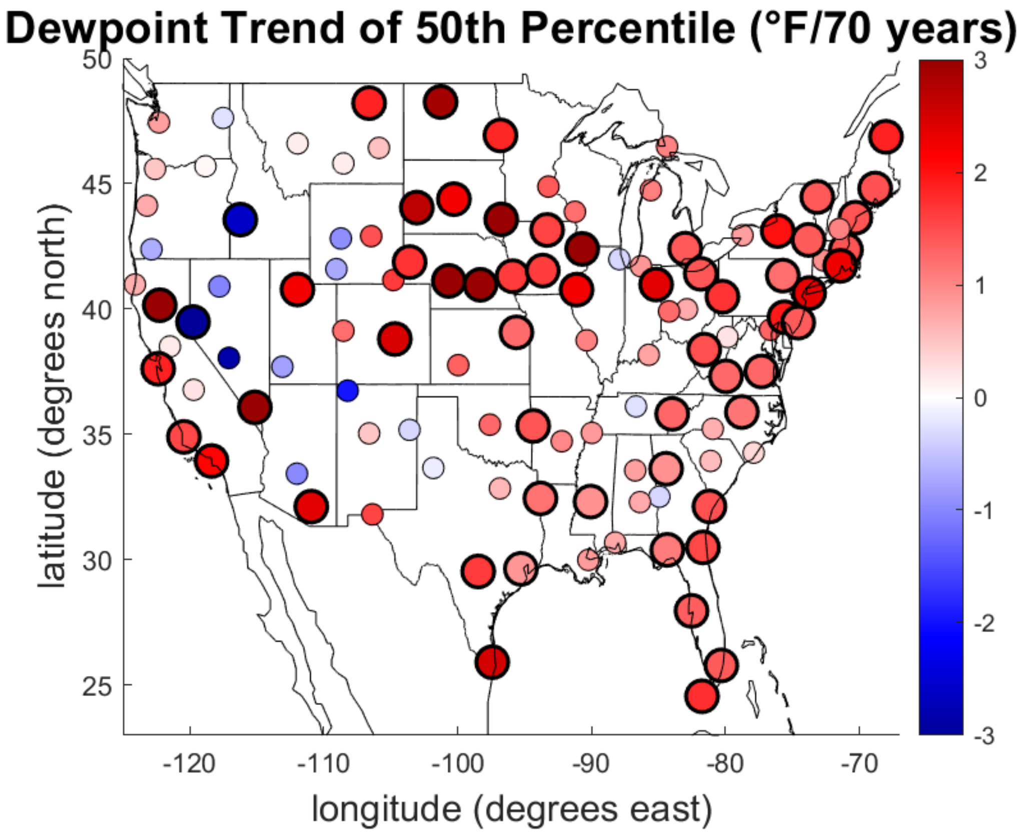

Figure 16. Plot of the 50th percentile trend of dewpoint temperature for June - September at each station (˚F/70 years). The heavier black circles indicate stations that have significant trends.

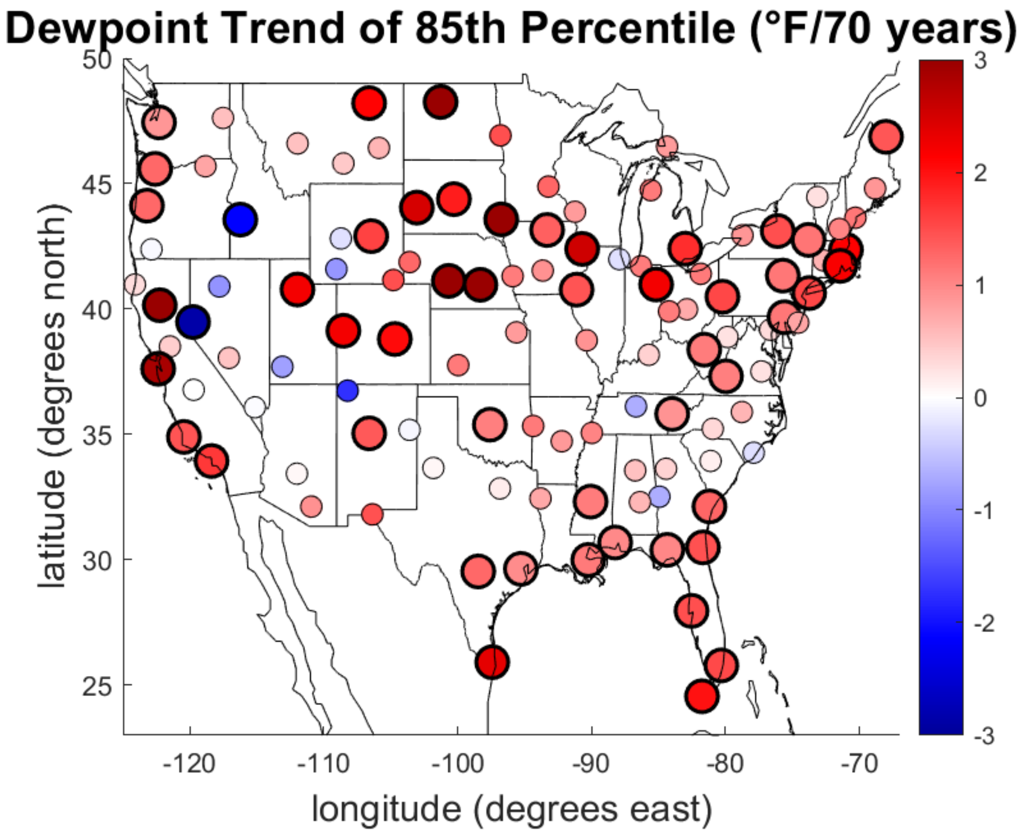

Figure 17. Plot of the 85th percentile trend of dewpoint temperature for June - September at each station (˚F/70 years). The heavier black circles indicate stations that have significant trends.

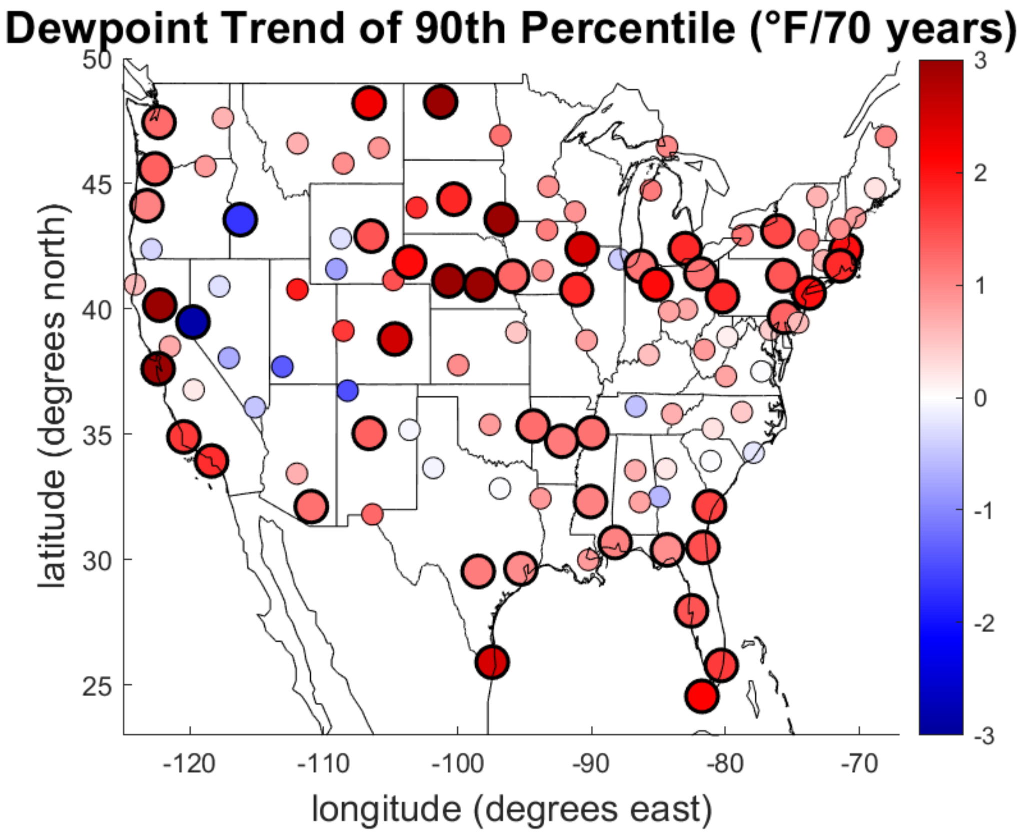

Figure 18. Plot of the 90th percentile trend of dewpoint temperature for June - September at each station (˚F/70 years). The heavier black circles indicate stations that have significant trends.

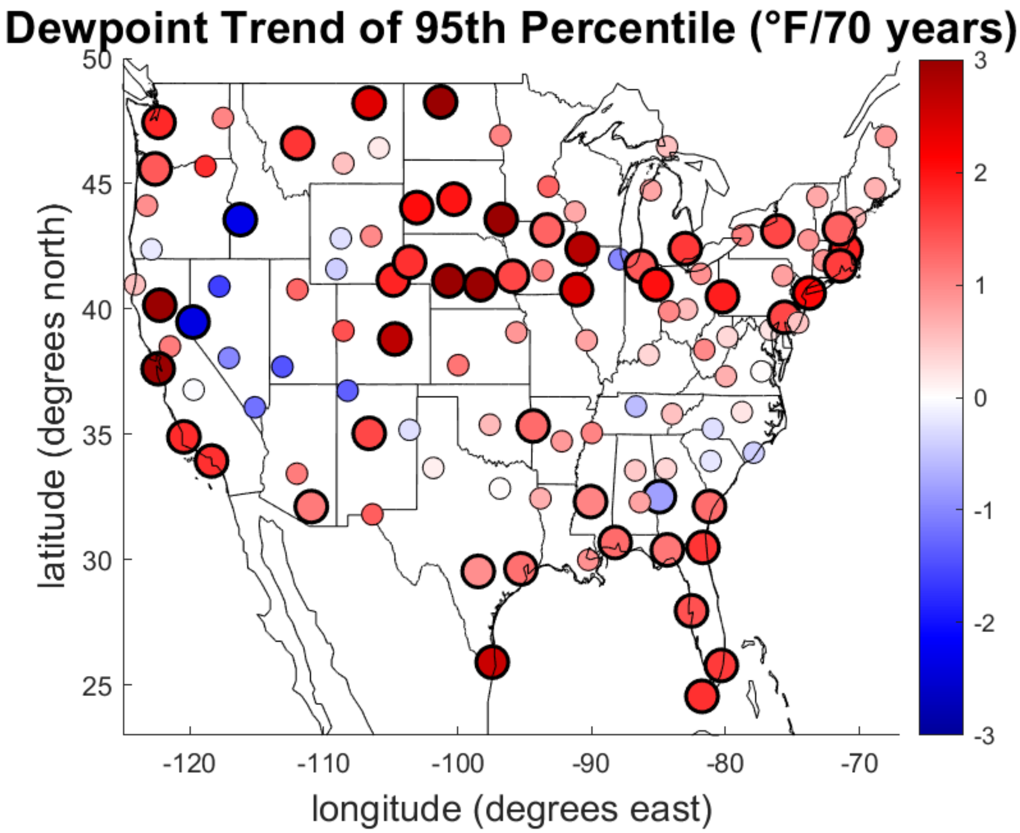

Figure 19. Plot of the 95th percentile trend of dewpoint temperature for June - September at each station (˚F/70 years). The heavier black circles indicate stations that have significant trends.

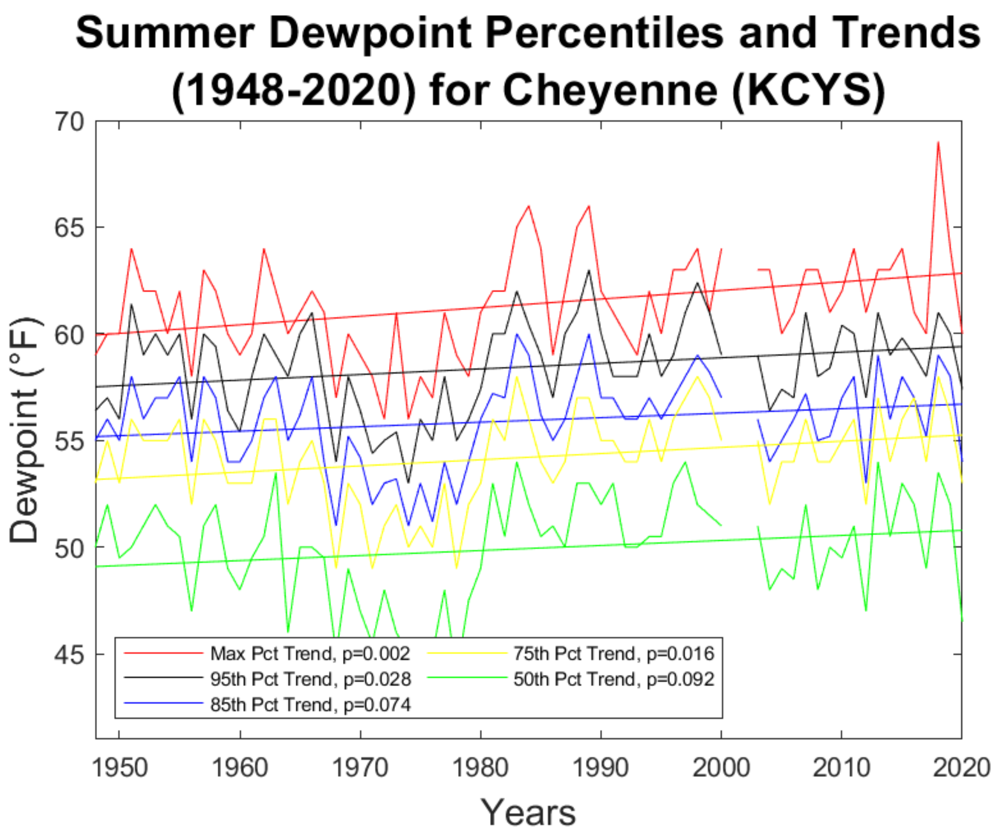

Figure 20. Yearly June - September dewpoints for the 50th, 75th, 85th, 95th and maximum percentiles and their respective trend lines for Cheyenne, WY.

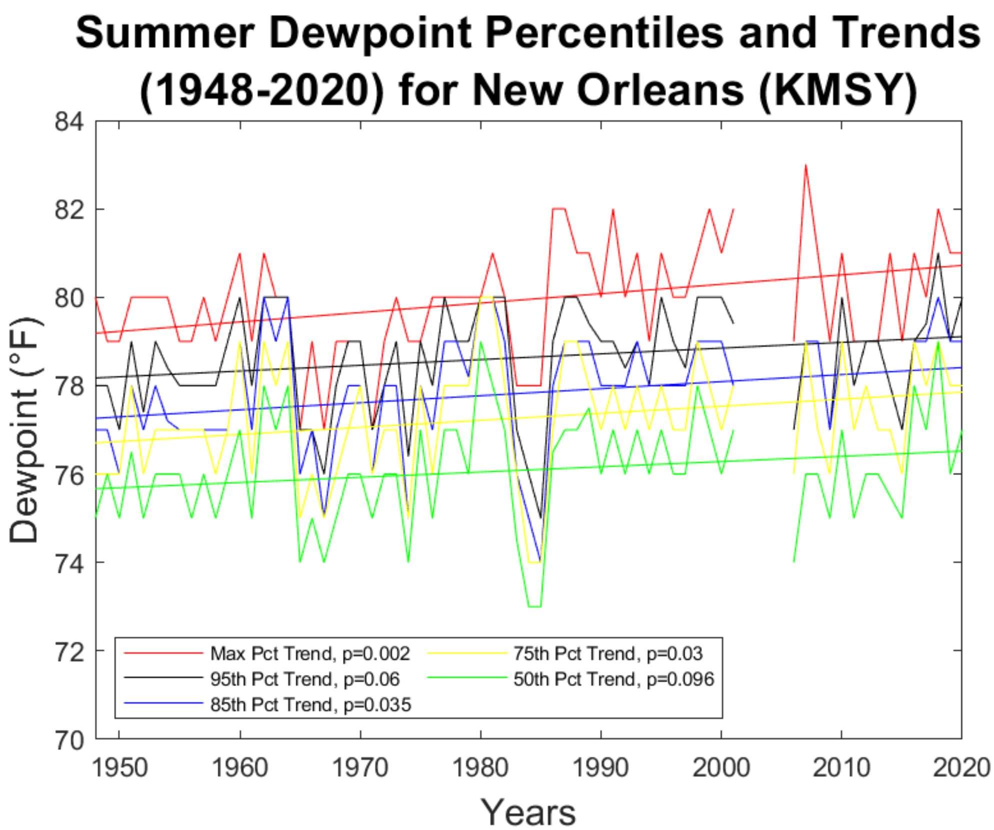

Figure 21. Yearly June - September dewpoints for the 50th, 75th, 85th, 95th and maximum percentiles and their respective trend lines for New Orleans, LA.

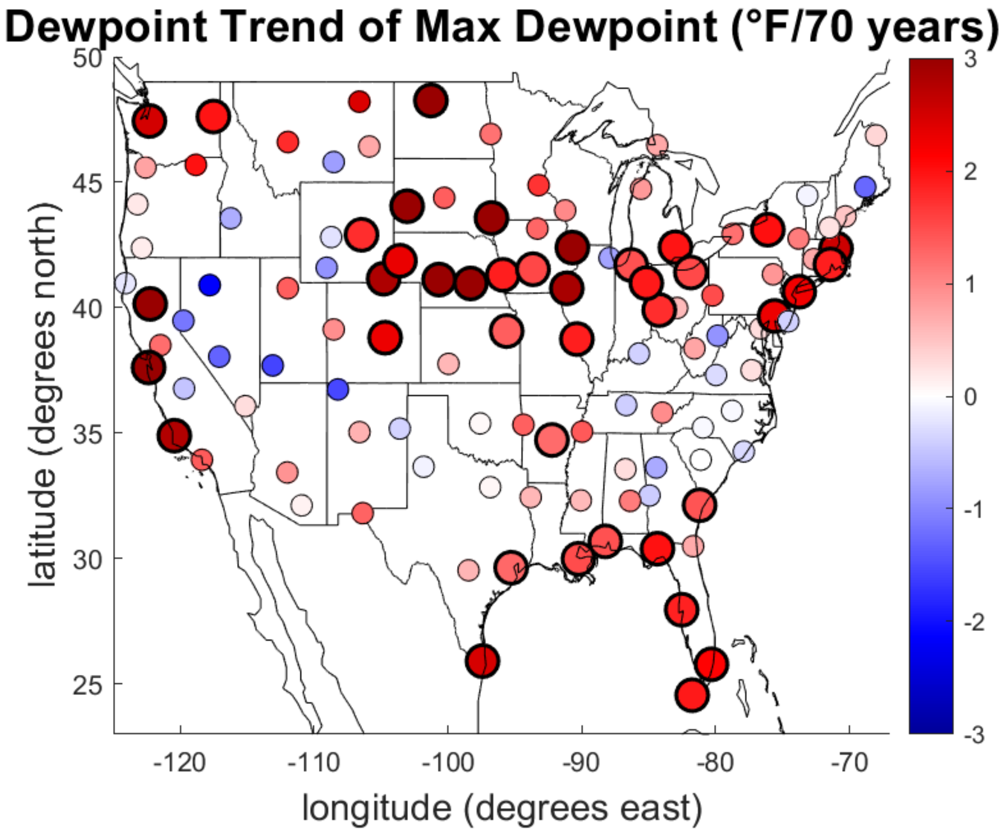

Figure 22. Plot of the Maximum percentile trend of dewpoint temperature for June - September at each station (˚F/70 years). The heavier black circles indicate stations that have significant trends.