NOT IN KANSAS ANYMORE: ANALYZING THE SHIFT OF TORNADOES IN THE UNITED STATES

By

SIDNEY HARNEY

MASTER OF SCIENCE
GEOGRAPHIC INFORMATION SYSTEMS TECHNOLOGY
FINAL PROJECT

THE UNIVERSITY OF ARIZONA

2025

ACKNOWLEDGMENTS

I thank my family and loved ones for their unconditional support throughout my educational and professional career. I thank the researchers and scientists who have committed their lives to helping understand severe weather to improve warning times and keeping the public safe. Lastly, my sincerest gratitude extends to the University of Arizona and specifically Professor Yoga Korgaonkar for his support and guidance during my time at the institution.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

CAPE	Convective available potential energy.
NARR RDA	North American Regional Reanalysis Research Data Archive.
S-R Helicity	Storm-relative helicity.
STP	A calculated significant tornado parameter statistic based on surface-based convective available potential energy, surface-based lifting condensation level, storm relative helicity, and bulk wind difference.

ABSTRACT

Tornadoes are a potential threat to life no matter how much one prepares. Many people in high-risk areas can become desensitized to this threat, but tornadoes are significant everywhere and can occur with zero notice. These high-risk areas rely on infrastructure and resource management to best deal with the consequences of tornadoes. Identifying the areas at high risk of tornadoes can better equip officials with the knowledge to aid residents with recovery more efficiently. Geographic Information Systems can be utilized to leverage historical data to identify these high-risk areas and predict which areas will see an increase in frequency and intensity based on future weather pattern predictions. To accomplish this task, a suitability analysis model is appropriate with an accompanying time series map that highlights how tornadoes have shifted geographically over time. This is centralized into three study areas: The Great Plains, Tornado Alley, and Dixie Alley. The results show which general study area has increased in intensity, as determined by the Enhanced Fujita Scale and overall frequency. Ultimately, tornadoes have shifted in frequency from the Great Plains and historical Tornado Alley to Dixie Alley, but everywhere has increased in intensity, with the past five years showing an increase in violent tornadoes.

Keywords: GIS, Tornadoes, Suitability Model, Dixie Alley, Tornado Alley

INTRODUCTION

Tornado Research Significance

"I heard things slamming my house, then the sheetrock overhead fell down and it sounded like my roof lifted and came back down. I heard the sound of nails being pulled out of wood, glass breaking, and then the scariest sound I've ever heard, and pray that I never hear again. It was a groan. A moaning. And I can only describe it as evil" (Taylor, 2021). Many other stories like Adam Taylor's are being shared everyday as tornadoes rip through vulnerable, unaware communities. Tornadoes are destructive rotating air columns which cause extensive damage to infrastructure and human life. Each year, more than 1,000 tornadoes hit the United States alone causing over one billion dollars in damages (Smith, 2025). These range anywhere from Enhanced Fujita 0 (EF0) to Enhanced Fujita 5 (EF5) in magnitude with winds between 45 to over 300 miles per hour. Although such destruction is seen year after year, tornadoes are an unavoidable part of life and research seems to fade as society becomes numb to the effects as each outbreak occurs. There is a need to continue to research tornadoes and mitigate the impacts. Tornado Alley is no longer the tornado capital as these weather phenomena are shifting to a new area. This shift is occurring at an alarming rate in areas which are underprepared and denser. Anyone who moves to Tornado Alley is aware of the enhanced risk and prepares their lifestyle accordingly. However, these new areas in the southeast have not had this same kind of exposure historically. The infrastructure to withstand tornado force winds has not been built in certain areas and, in some cases, has not been re-built after past tornadic activity. Tornadoes are shifting to unsuspecting people and scientists must help these people understand the danger they face. Thus, this analysis hypothesizes a shift in tornado activity away from The Great Plains and Tornado Alley to Dixie Alley which may lead to more destruction and death in less prepared areas.

Literature Review

Tornadogenesis is not a new concept and the literature surrounding tornadoes is plentiful. The National Centers for Environmental Information (NCEI) publishes the Storm Prediction Center's (SPC) data on natural disasters at the end of each year and maintains a website to display this data. On the site they conclude that 2024, with high probability, will have the second-most confirmed tornadoes on record with close to 1.817 tornadoes, the current record from 2004 (NCEI, 2025). Although the highest season on record is 2004, recent trends show that tornadoes are increasing in frequency. These frequently destructive tornadoes leave nothing but devastation in their wake. Yet, this weather phenomenon keeps occurring without lowering fatality incidents, cost of recovery, and community resilience. The tornado season in 2013 produced $3.6 billion in damages (Kantamaneni et al., 2017). Despite the high cost in damages, building practices have remained unchanged. Experts are not in favor of high-cost building methods to offset a perceived low tornado risk. These old practices can lead to even more fatalities in the future as tornadoes shift to Dixie Alley. This can be even more problematic since Dixie Alley is home to over seven million more people than Tornado Alley (Gagan et al., 2010). Homeowners and officials do not believe the risk of being hit directly by a tornado gives reason to pay more for a tornado resistant house. Even in tornado prone areas like Tornado Alley, tornado resistant housing is not common practice among construction companies. Tornado resistant material has existed for decades in the aerospace, military and nuclear industries but has yet to shift to everyday uses. Developed in 1959, maraging steel, in small concentrations, can withstand over 400 mile per hour winds (Kantamaneni et al., 2017). If tornado resistant housing hardly exists in the historically most active area for tornadoes, the new shift in tornado activity will only increase fatalities and damages with an underprepared society at the mercy of the changing weather.

The American Meteorological Society (AMS) has studied this exact phenomenon leading up to 2024 in the organization's journal. Since 1951, tornado activity has shifted from the Great Plains into the southeast United States even into the colder months in favor of traditional warmer months (Coleman et al., 2024; Figure 1-1). The study also highlights the spatial shift in tornadogenesis events, tornado days, and tornado path lengths (Figure 1-1) towards Dixie Alley. The addition of tornado path lengths adds to the validity of the study as a longer tornado path puts more of the public at risk. A tornado path which is 50 miles in length drastically increases the risk compared to a tornado which is only ten miles in length.

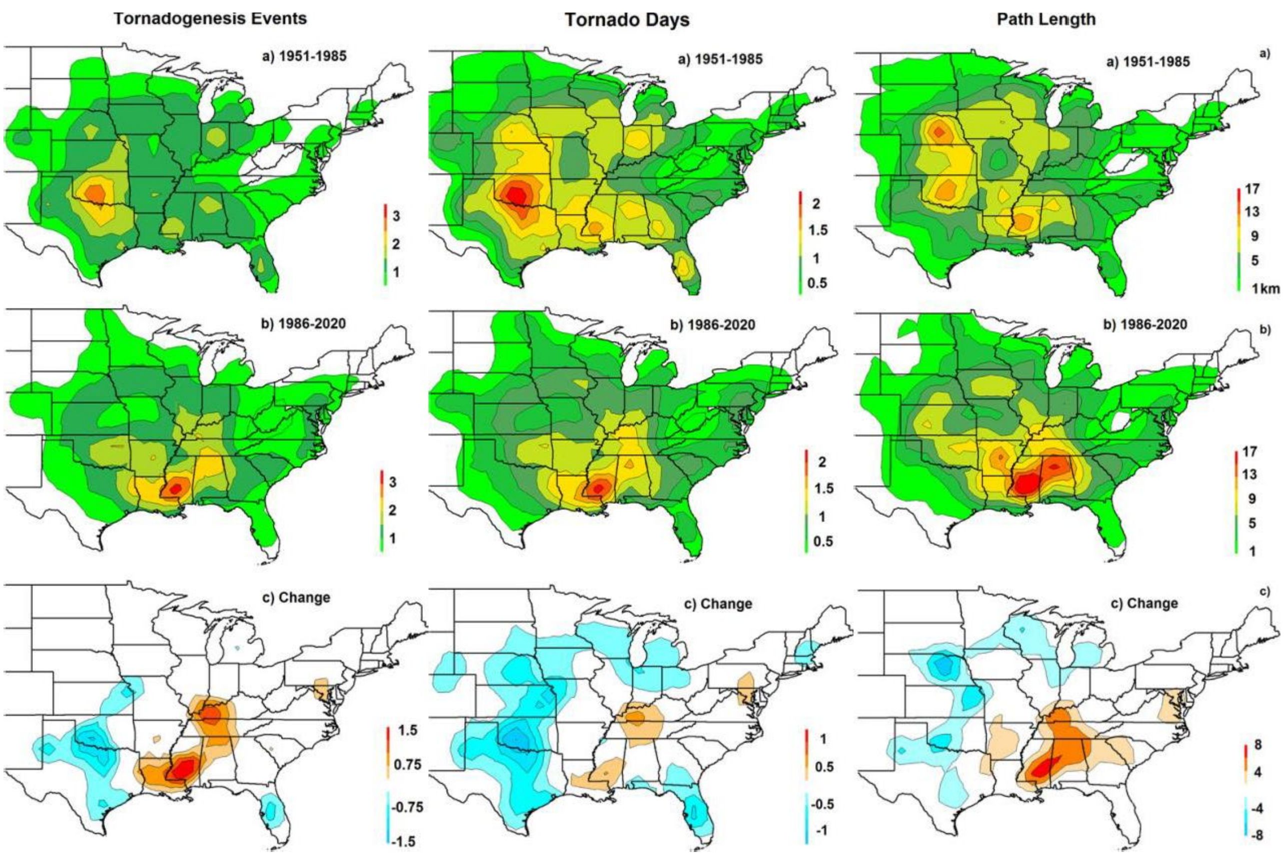

Figure 1-1. Tornadogenesis events, tornado days, and tornado path lengths by observations comparing years 1951-1985 to 1986-2020 (Coleman et al., 2024).

In addition to an increase in frequency, location, and intensity, compounding events is another factor that is causing financial burden on the United States regarding tornadoes. This last factor being compounding events. In terms of frequency, we can model the increase in overall totals and monthly totals, but also the totals within specified outbreaks. Compounding impacts are current recovery and aid efforts being disrupted by further natural disasters to exacerbate the current state of the area (National Academies of Sciences, Engineering, and Medicine, 2024). There is an increase in these compounding impacts as well as areas being repeatedly hit by tornadoes while still recovering or being recently rebuilt. For example, El Reno, Oklahoma, has been struck by devastation twice as two separate EF5 and EF3 tornadoes decimated the town in 2011 and 2013 respectively (US Department of Commerce, 2021). El Reno is a community that would not have been completely rebuilt before sustaining another violent tornado barely two years later. These compounding disasters cause mass tragedy and increase the cost of weather events like hurricanes and especially tornadoes. Understanding communities with the greatest risk factors can help officials determine necessary preventative actions to build stable infrastructure like tornado resistant housing or buried utilities to help community resilience in the wake of an extreme weather event.

There are several studies and research regarding the destruction, formation, and impacts of tornadoes, but each study is different in nature. Some studies look at analyzing past data from a factual context (McCarthy & Schaefer, 2004). Other research analyses aim to identify the correlating factors which cause tornado formation (Houser). Lastly, predictive analyses might analyze recent trends in tornado data to potentially forecast the future weather patterns (Gensini, 2018). The latter analyses are far less common and even fewer try to predict the future trends in favor of looking at past 5-year or 10-year trends. Past trends for tornado data outlined a noticeable shift in areas of high tornado environment potential (Gensini, 2018). As shown in Figure 1-2, by calculating and mapping a STP based on crucial formation criteria, this study found an increase in potential activity across Dixie Alley and the Midwest compared to west of the 95th Meridian (Gensini et. al., 2017). Similarly, the same study found an increase in annual tornado reports across a similar geographic region (Figure 1-3). This STP is based upon significant predictors of tornado formation from the observed daily maximums. These predictors include surface-based convective available potential energy, surface-based lifting condensation level, storm relative helicity, and bulk wind difference (Gensini et. al., 2017).

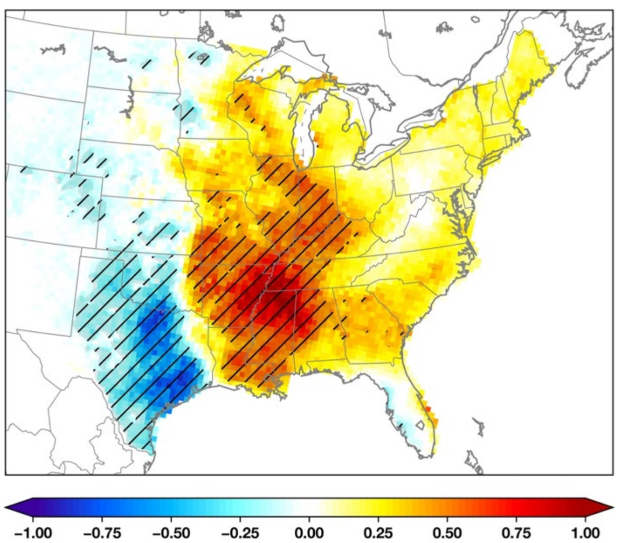

Figure 1-2. Trending tornado activity observed from the STP during 1979-2017 (Gensini, 2018).

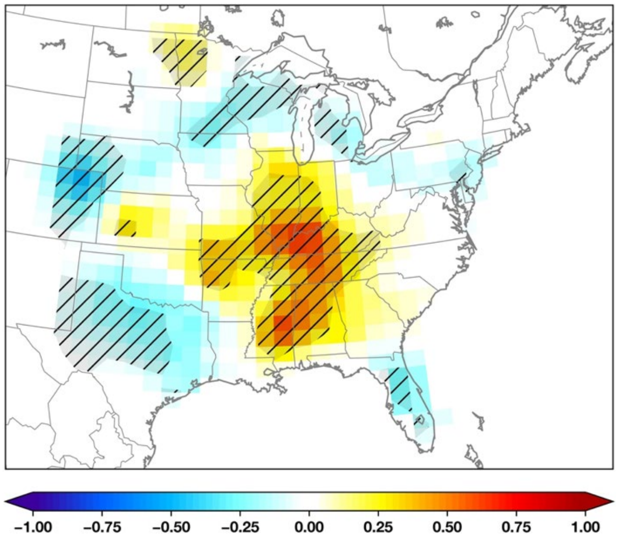

Figure 1-3. Trend of annual tornado reports based on data from 1979-2017 (Gensini, 2018).

Lastly, the study found the temporal resolution of tornado activity and how it shifts throughout the entire season (Figure 1-4). Gensini et al (2018) found that a northern shift in tornado environment occurs as the tornado season goes through the cycle whereas the southern activity is dominant during the early months of December, January, and February. The study does acknowledge it is not predicting but simply analyzing recent trends compared to historical data. Another study has noted the shift away from tornado activity during traditionally warm months in favor of a shift to the cold season (Coleman et al., 2024).

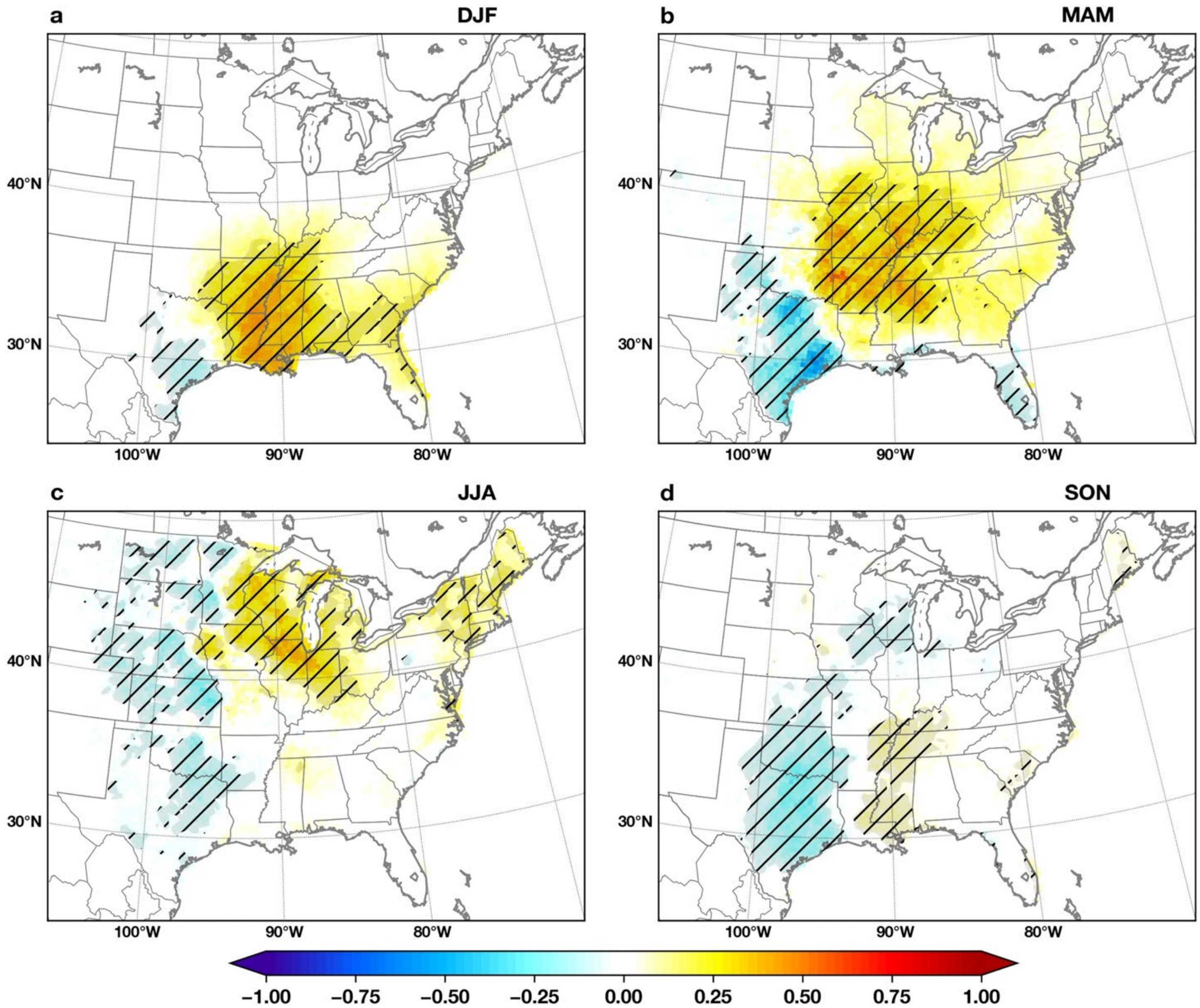

Figure 1-4. Map layout illustrating sums of daily max STP in three-month increments (Gensini, 2018).

The previous analysis is helpful to note shifts in recent times, however, data exists to potentially give researchers a method to predict weather patterns based on other predictive weather data. This gap exists in the current scientific realm and if executed properly, can provide beneficial information to the public and their safety. Another limitation with the research and study of tornadoes exists in the collection of data. Data collection was heavily reliant on newspaper clippings and photographs prior to the introduction of the Fujita-Scale (F) in 1973 by the National Weather Service (NWS). However, some NWS offices were still conducting damage surveys deriving from the media. Any tornado which did not make major headlines would therefore most likely not be counted and lost to time. There was no official record keeping for magnitude on a normalized scale until the Enhanced Fujita scale (EF) in 2007 (Coleman et. al., 2024). Although there is no methodology to rectify the loss of records, to not admit this existed would be a greater fallacy.

This study aims to find a suitable method to predict tornadogenesis using climate projection data. Models for climate analysis are utilized to decide procedures in engineering and government which guide building and resource management. Any analysis which can help predict the vulnerable regions will aid in a better recovery. This study will analyze where tornadoes are currently forming and check the best model to predict these regions to better inform officials and aid in recovery and preparedness.

METHODS

Study Area

Over the course of this analysis, the study areas include Tornado Alley, Dixie Alley, and the Great Plains. Traditionally, Tornado Alley has seen the most activity throughout the 20th century. In more recent years, tornado activity has migrated towards Dixie Alley instead of the Great Plains and Tornado Alley. Researchers and scientists have now dubbed a new Tornado Alley based on the trends seen in the last 30 years. The historical Tornado Alley includes the areas in red whereas the new Tornado Alley is seemingly shifting away from the Great Plains in tan to Dixie Alley in green (Figure 2-1). These areas have the highest risk of tornadoes (Figure 2-2) according to the Federal Emergency Management Agency (FEMA). Similarly, Florida has a high tornado vulnerability index, however, many of the tornadoes that occur in Florida happen because of hurricanes which strike the region every year. Florida's high number for tornado reports as Hurricane Milton caused over twice the daily tornado record (Ferrell, 2025). Outside of these regional phenomena that can skew tornado statistics, tornadoes remain a viable threat to most of the United States. This author does note there is significant overlap between the Great Plains and the historical Tornado Alley, however, there is no intersect for Dixie Alley with either of the other areas.

There are varying differences as to the exact locations of the aforementioned regions, however this analysis abides by regional definitions provided from former NSSFC Director Allen Pearson who created the term Dixie Alley, NCEI for the Great Plains based on their climate divisions, and Air Force weather officers Major Ernest J. Fawbush and Captain Robert C. Miller who first utilized the term Tornado Alley as a research project and correctly issued the first ever tornado warning in history (Gagen et. al., 2010; Grice, 1999).

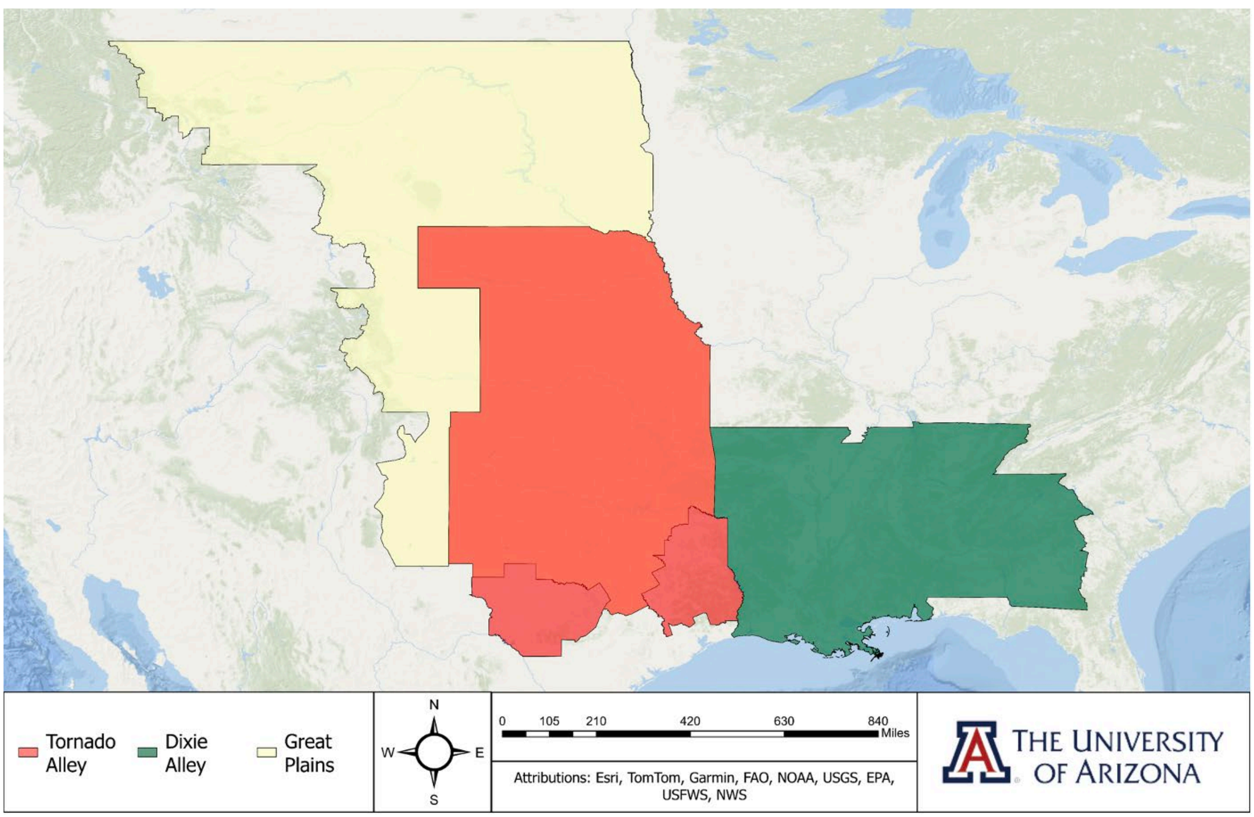

Figure 2-1. Study areas for the research study based on original and official definitions.

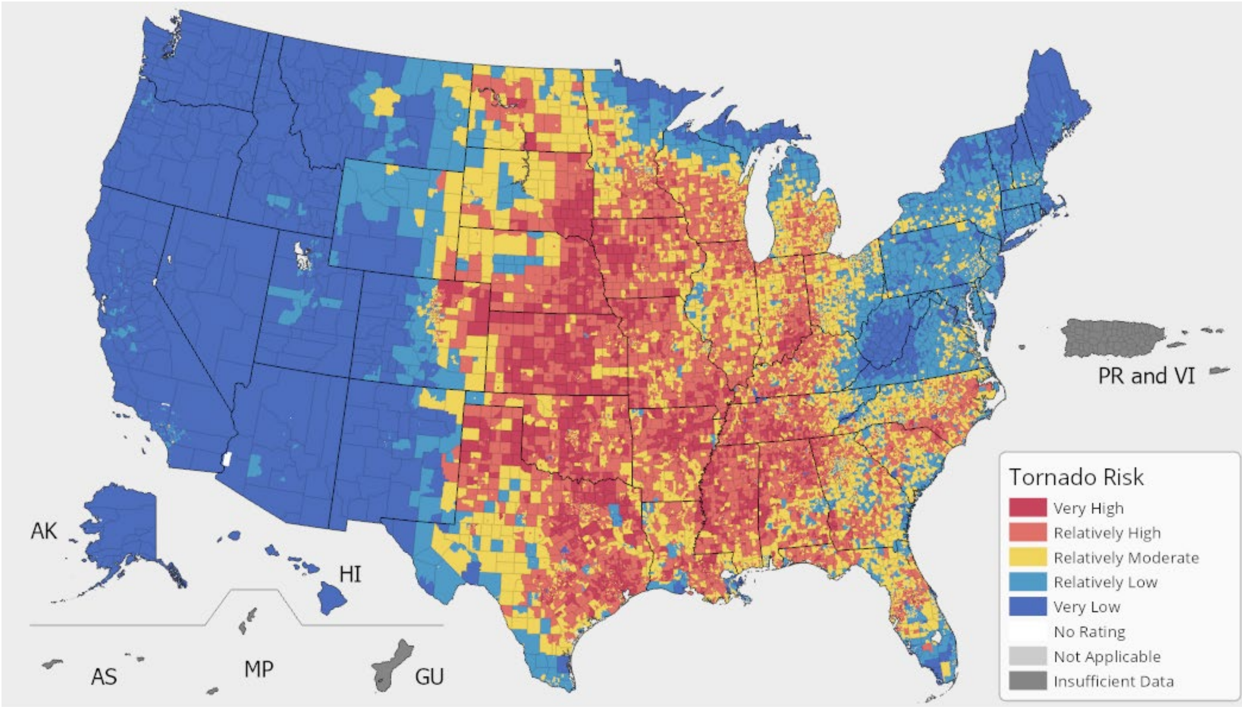

Figure 2-2. National Risk Index specific to tornado vulnerability (FEMA, 2023).

Data

Historical tornado records from 1950-2023 were collected from FEMA (Table A-1). These records come in the format of a feature service hosted in the Living Atlas of ESRI's ArcGIS Online platform. This feature service contains information on magnitude, time variables, location, injuries, fatalities, starting longitude and latitude, ending longitude and latitude, etcetera. The Living Atlas also provided a United States boundary layer for counties (Table A-4). The layer is dissolved into the entire border for the United States. This feature service contains data on county names, geometries, and state names.

Coupled Model Intercomparison Project Phase 6 (CMIP6), the most recent iteration from the Working Group on Coupled Modelling (WGCM), data for forecasted temperatures was collected from the Earth System Grid Federation (ESGF) from 2015-2064 for the SSP2-4.5 scenario. This study will subset the data to the years 2021 and 2030. This model is a middle of the road risk assessment which puts this study in a less extreme scenario while not underestimating the changing climate (The SSPs Scenarios, 2025). This model is an update to the RCP4.5 model and maintains a radiative forcing of 4.5 W/m^2 by 2100. For this model, the Earth's radiation absorption will increase by 4.5 W/m^2 compared to the radiation that leaves the Earth (Radiative Forcing, 2025). This dataset contains the monthly means for temperature and dewpoint.

Monthly mean temperature and dewpoint data, in Kelvin, comes from the NCEI's NARR RDA for the year 2021 at the surface and two meters above the surface respectively. Additionally, Convective Available Potential Energy (CAPE) and Storm Relative Helicity (S-R Helicity) statistics are also collected from the NCEI's NARR RDA for the same year. CAPE at the surface level has units of J/kg. S-R Helicity between 0-3000 meters above the surface has units of m^2/s^2. Data is then reprojected from their original coordinate system into the NAD 1983 (2011) geographic coordinate system.

Methods

This study can be broken down into the following steps (Figure 2-3): (1) Tornado Trends and Statistical Analysis – where a time series map of tornado locations in the USA and their magnitudes from 1950-2023 were displayed along with the visualization of the extent and tornado counts in the Great Plains, Dixie Alley and Tornado Alley regions, (2) Tornado Risk Assessment for 2021 – where a risk assessment model is run to identify a high risk region which occurred during the year 2021, (3) Tornado Risk Prediction for 2030 – where projection data is used for the risk assessment model to determine which regions tornadogenesis will be greatest in during the year 2030. Three risk assessment models make up this study's analysis. One to assess the environment in 2021, one to assess the accuracy of the CMIP6 data, and a future prediction. All analyses tools were executed using ArcGIS Pro.

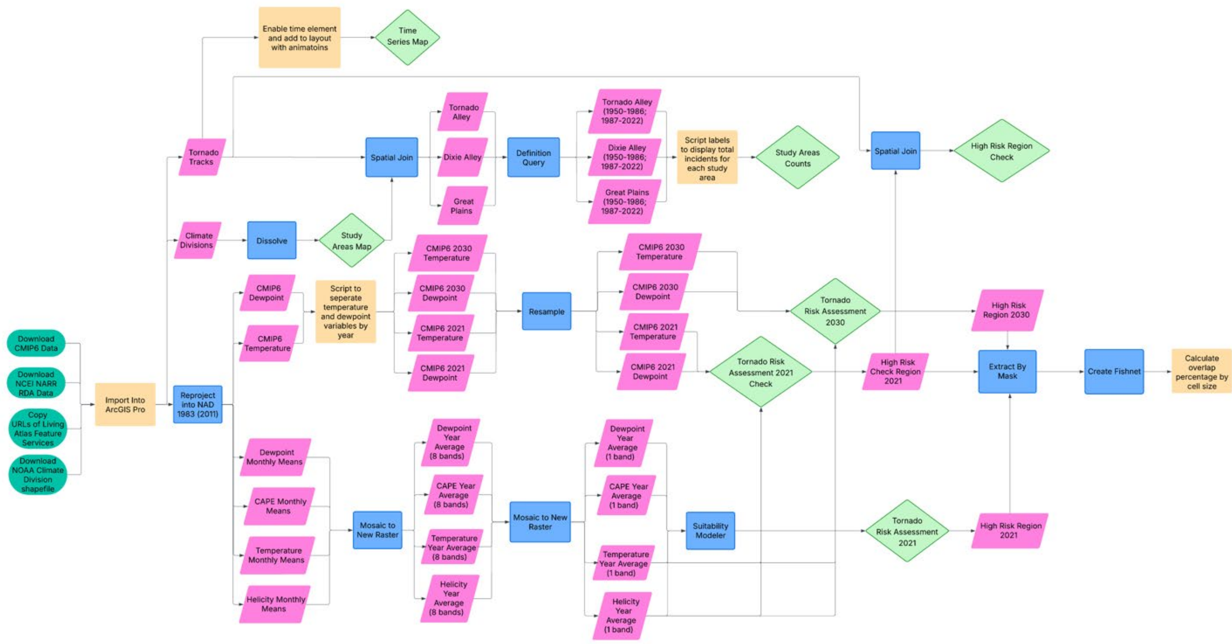

Figure 2-3. Methodology flowchart.

Tornado Trends and Statistical Analysis

The time series map used ESRI's ArcGIS Pro with the functionality built into the software to enable a temporal resolution as well as the animation capabilities. The authoritative data for tornado paths from FEMA were loaded into ArcGIS Pro. This Shapefile contained a comprehensive view of all tornadoes counted by the National Oceanic and Atmospheric Administration (NOAA) with data on the magnitude, path lengths, dates, and other crucial information. The symbology was standardized based upon magnitude and this symbology was kept for the time series map. The time field was set in UTC -7:00 time zone to represent the time zone which the University of Arizona falls into. An animation was then created for the time series map with the addition of a time stamp and a legend. This animation was then exported from the software.

The NCEI's US Climate Divisions Shapefile was imported in ArcGIS Pro to select and dissolve the divisions into one area to define the Great Plains region using a Definition Query.

Similarly, Tornado Alley and Dixie Alley are defined using the same methodology with their respective definitions (Figure 2-1). A tornado summation was then computed using a spatial join and the dissolve geoprocessing tool to view the total incidents in each of these areas from 1950-2022. The spatial join tool joined the individual tornado path polylines and added them to the table of each study area if the paths cross into the area. This study included any tornado path that enters each study area even if the tornado did not originate or dissipate in the study area. The dissolve tool summed the join count and produced the total incident counts of tornadoes in each area for the defined period. The same process using the spatial join and the dissolve tools also created this map.

Tornado Risk Assessment for 2021

The study then proceeded to compare the criteria for tornadogenesis formation with study area statistics. This study focused on the year 2021, the latest data from NCEI NARR RDA. Datasets for this portion of the analysis included average monthly temperature, average monthly dewpoint, CAPE, and S-R Helicity. The wgrib program (www.cpc.ncep.noaa.gov/products/wesley/wgrib.html) was used to extract and read the raw data from GRIB files. GRIB files for each month were filtered to extract data for the four variables of interest. The GDAL library (https://gdal.org) was used to convert these GRIB files into a usable TIFF format in ArcGIS Pro. The Clip Raster tool was used to clip all four criteria layers to the study area extent. Then, the Mosaic to New Raster tool combined all study areas for each month and each criterion, using a mean statistic to produce a yearly average with eight bands. These eight bands represented the average monthly means for each three-hour time interval starting at midnight. These eight raster bands were averaged and converted to a single band raster for the 2021-year average per study area. Lastly, the method required combining the three-study area yearly averages into one raster using the average. Finally, the four individual variable raster layers were input into a Suitability Modeler. The modeler transformed the raster cells into classification intervals with equal weighted inputs to determine the areas of suitability. In this study, the suitability scale was set as one to five with a value of five considered as the highest risk for tornadogenesis and one considered as very low risk. The suitability modeler classification scales for each variable were decided after extensive research. The NWS website included predefined classifications for convective season environmental parameters and indices including CAPE and S-R Helicity (US Department of Commerce, 2015; NOAA's National Weather Service - Glossary). Based on this classification and the scales of the rasters after processing, each threshold for tornadogenesis was set at the high-end value for the third interval. CAPE had a threshold at around 2500 J/Kg, however, with the average across the year caused the scale to have a maximum value at 254 J/Kg. For this analysis, the higher the CAPE, the more likely a tornado will occur which is true no matter the scale. These intervals are 50 J/Kg starting at zero and ending at the maximum. Dewpoint had a threshold at 12 degrees Celsius, temperature at 15 degrees Celsius, and Helicity at 150 meters squared per second squared.

To corroborate these models, two other maps were created. The first map extracted the highest risk region for further analysis. This highest risk region polygon was spatially joined with the tornado tracks data to find tornados which crossed into this high-risk region during 2021. The areas, both inside the high-risk polygon and outside, were compared by normalizing tornadoes per square area that reveal the number of tornadoes occurring in these areas per US Survey square mile. The second map creation used the WGCM's CMIP6 climate prediction models for temperature and dewpoint for 2021 and were input into a separate Suitability Modeler with the same CAPE and S-R Helicity raster datasets to check whether the CMIP6 models would have accurately predicted the tornado environment in 2021.

Tornado Risk Prediction for 2030

The final step was to load predictor data to the future environment suitability modeler. Future predictions of temperature and dewpoint from CMIP6 models were used supplementary to the 2021 CAPE and S-R Helicity parameters as there were no predictor datasets available for the latter variables. The subset of each predictor variable, temperature and dewpoint, were calculated using Python to average the monthly means for each variable during 2021. Clipping adjusted the subsets to the entire study area for both variables. A Suitability Modeler performed a high-risk analysis to identify locations more likely to experience increased tornado formation potential in the future. The identical transformation and classification intervals for all high-risk assessment models across all variables were maintained to preserve statistically accurate results.

RESULTS

Tornado Trends and Statistical Analysis

The results of the basic study area statistics show an increase in tornadoes from the first period, 1950-1986, to the second period, 1987-2022. Although The Great Plains sees the highest total tornado incidents across all areas, the study will account for a more comprehensive view. Not only does total incidents matter, but also incidents per square mile and incident increases and decreases.

The Great Plains have by far the largest area with 718,654 US Survey square miles compared to Tornado Alley with 400,317 US Survey square miles and Dixie Alley at just 274,936 US Survey square miles. Dixie Alley, in area, makes up only 68.6% of Tornado Alley and 38.3% of The Great Plains. This can account for a non-normalized perspective when looking at total incidents as the study areas are not equal in area. To account for this difference, in terms of tornadoes, The Great Plains sees 0.02726 tornadoes per US Survey square mile. This is lower than both Tornado Alley and Dixie Alley which has 0.03908 tornadoes per US Survey square mile and 0.03959 tornadoes per US Survey square mile, respectively (Figure 3-1). This means that Dixie Alley does see the most tornadoes per the area of each tornado region.

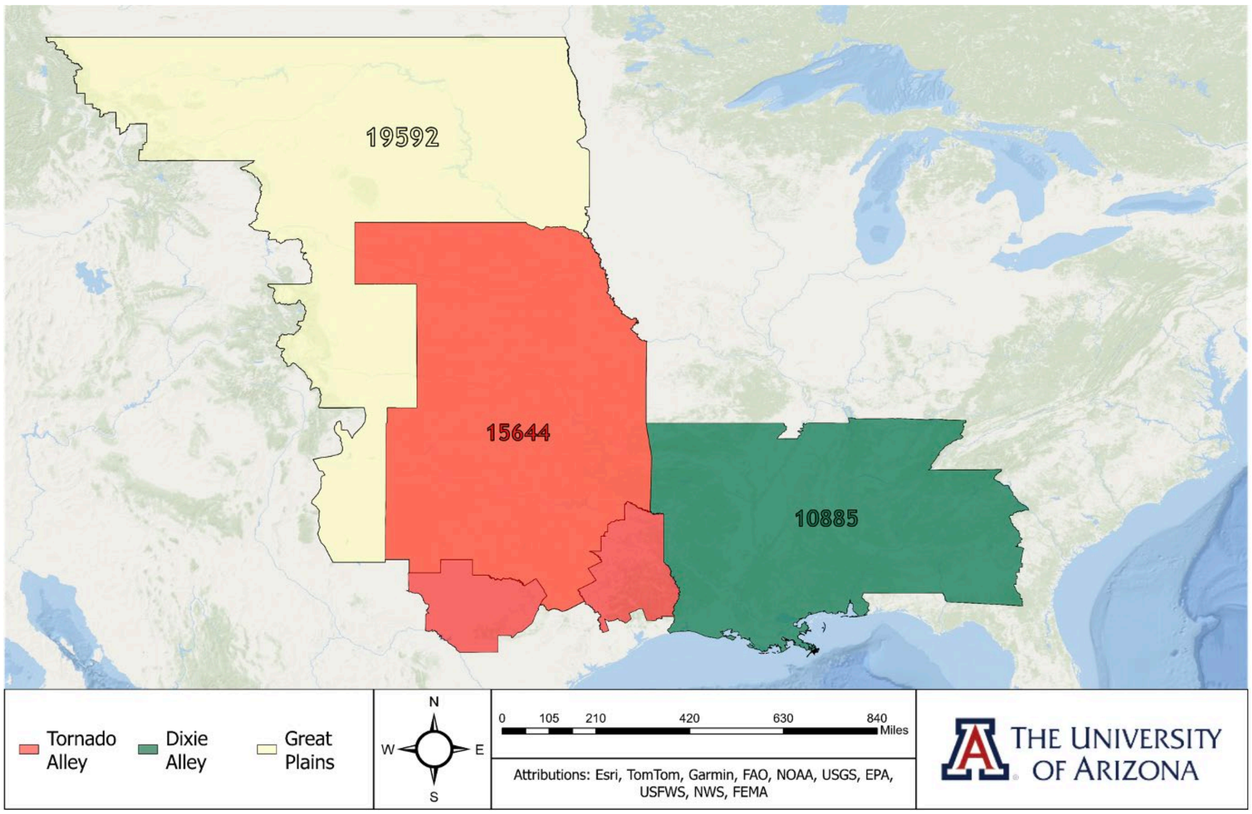

Figure 3-1. Visualization showing the total number of tornadoes to have crossed into each study area from 1950-2022.

Figure 3-2 highlights the total incidents of tornadoes broken down into two equal time periods each spanning 36 years. The first period includes 1950-1986 and the second period starts in 1987 and ends in 2022 inclusively. This shows the increase in tornadoes over the most recent 36 years compared to the earlier 36-year period. The spatial trends between these three areas are drastically different. From each 36-year period, the study areas have seen varying increases and decreases. The Great Plains saw a 0.09% decrease in tornadoes from 1950-1986 and 1987-2022. This is equivalent to 18 tornadoes. Tornado Alley had a 0.17% increase in tornadoes which equates to 28 tornadoes for the area. Of most importance is Dixie Alley with a 24.7% increase in tornadoes across the two periods with 2,979 more tornadoes. Not only is this historically increasing, but recently as well. Within the last 6 years, 2017-2022, alone Dixie Alley has seen 1,975 tornadoes whereas Tornado Alley has had 1,236 tornadoes and The Great Plains has had 1,467 tornadoes. In this case, despite significantly less area, Dixie Alley has seen a drastic increase in tornado incidents within the last 6 years compared to the others. It is worth noting that as time passes, data collection, radar, and warning systems have all improved and can potentially account for a partial uptick in tornadoes. However, it is not believed to have a significant impact in any study area to severely skew the results of this study.

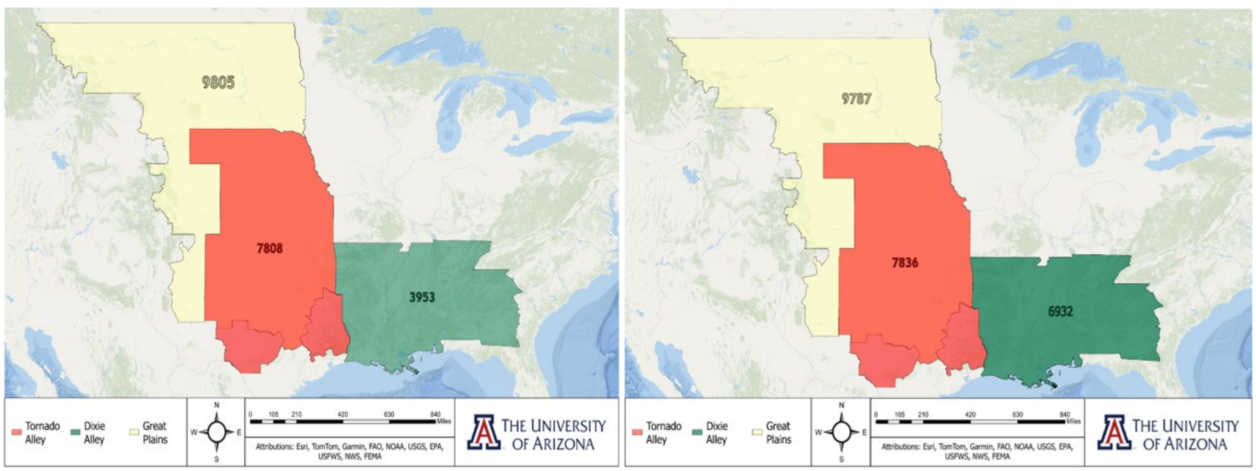

Figure 3-2. Side by side comparison of total tornadoes of each study area from 1950-1986 (left) and 1987-2022 (right).

Tornado Risk Assessment for 2021

The tornado risk assessment for 2021 has indicated parts of the US which are more vulnerable to tornadogenesis events. During the year 2021, the criteria raster datasets indicate there is a high-risk environment present in Dixie Alley. Variables which indicate this high-risk environment include CAPE (Figure 3-4), Temperature (Figure 3-5), and Dewpoint (Figure 3-6). S-R Helicity does show a decrease in this environment for this year and instead favors the northern Midwest, specifically Iowa and Minnesota (Figure 3-3).

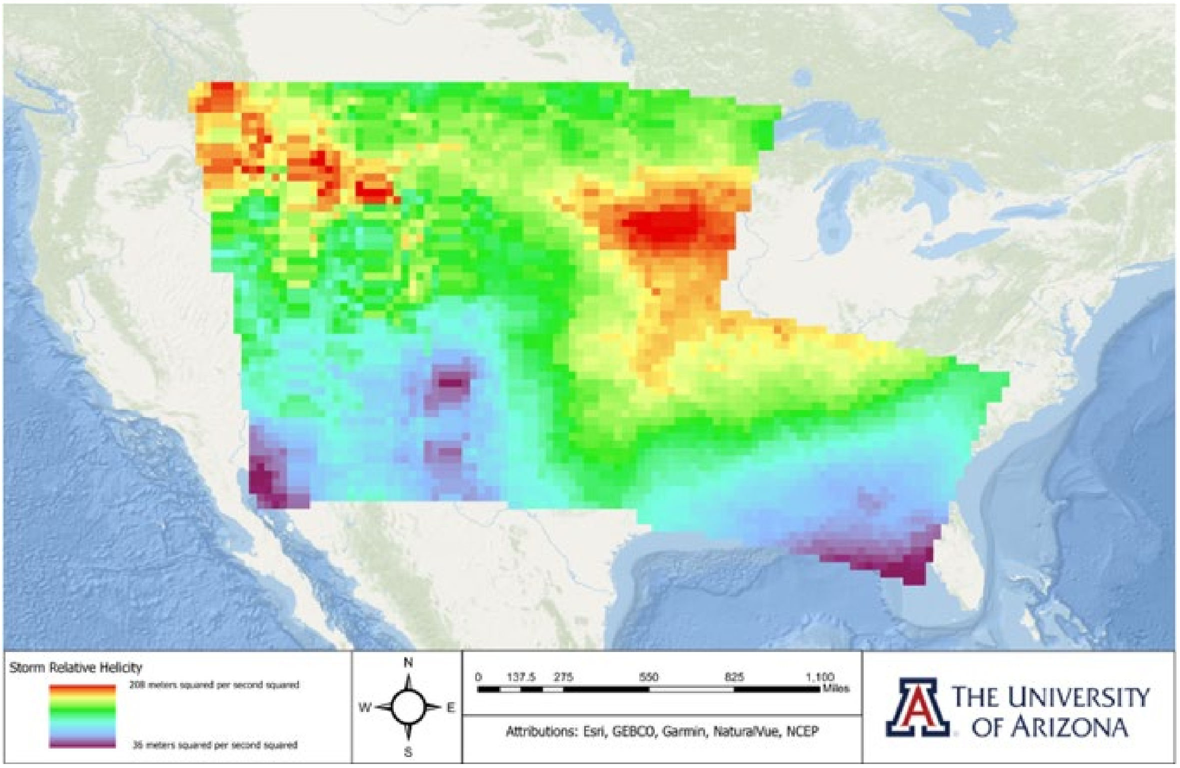

Figure 3-3. Raster layer for representing storm relative helicity average for the year 2021.

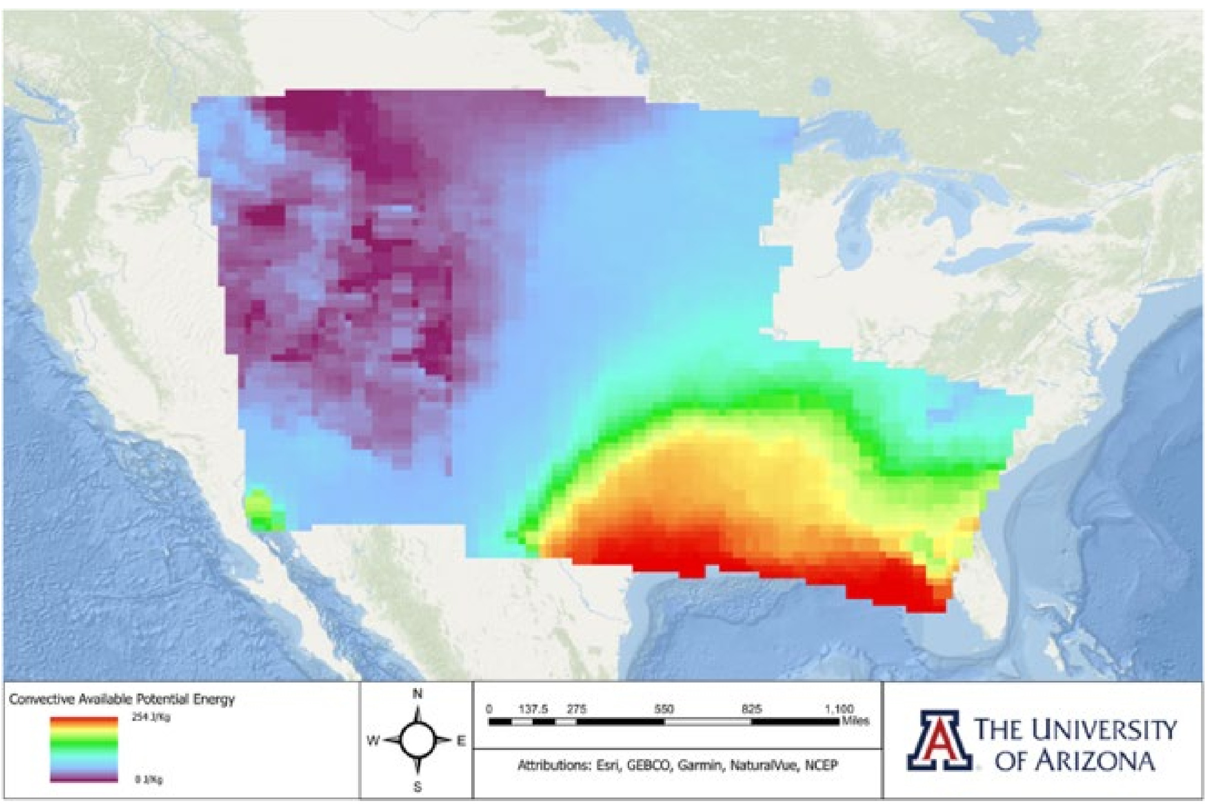

Figure 3-4. Raster layer for representing observed average environment for CAPE during the year 2021.

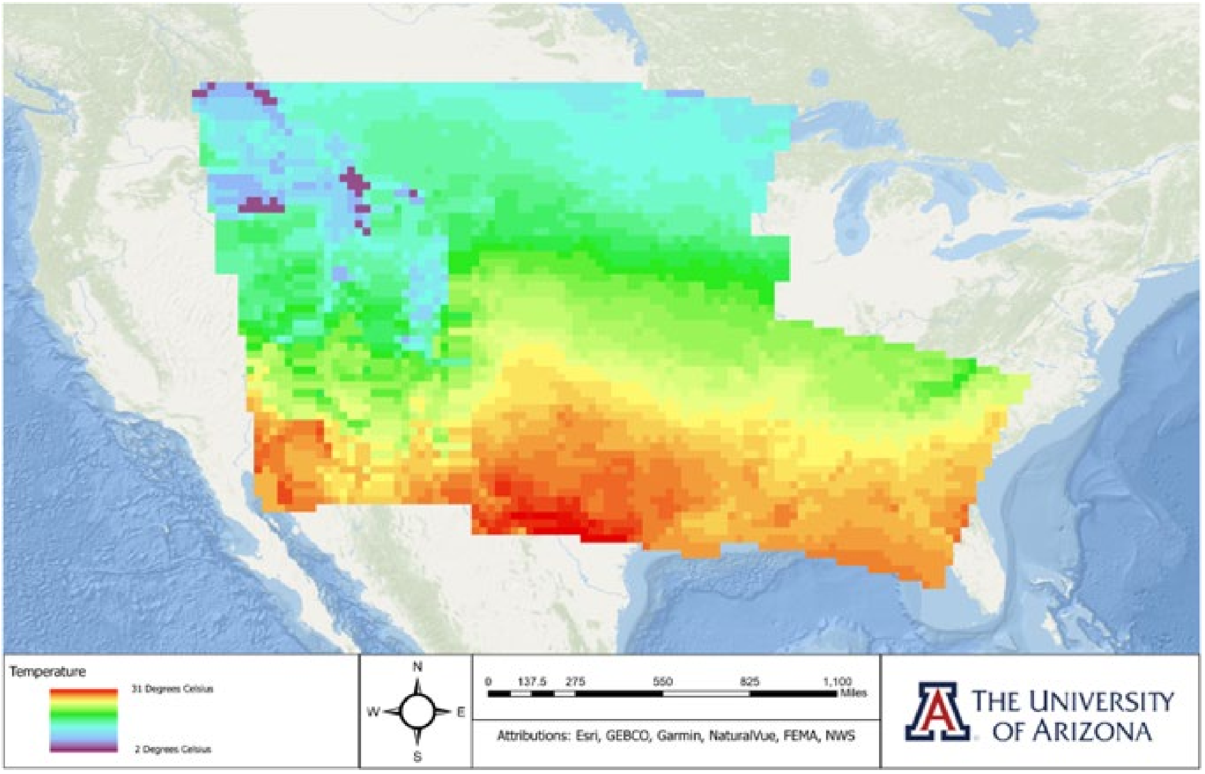

Figure 3-5. Raster layer for representing surface level temperature average across the year 2021.

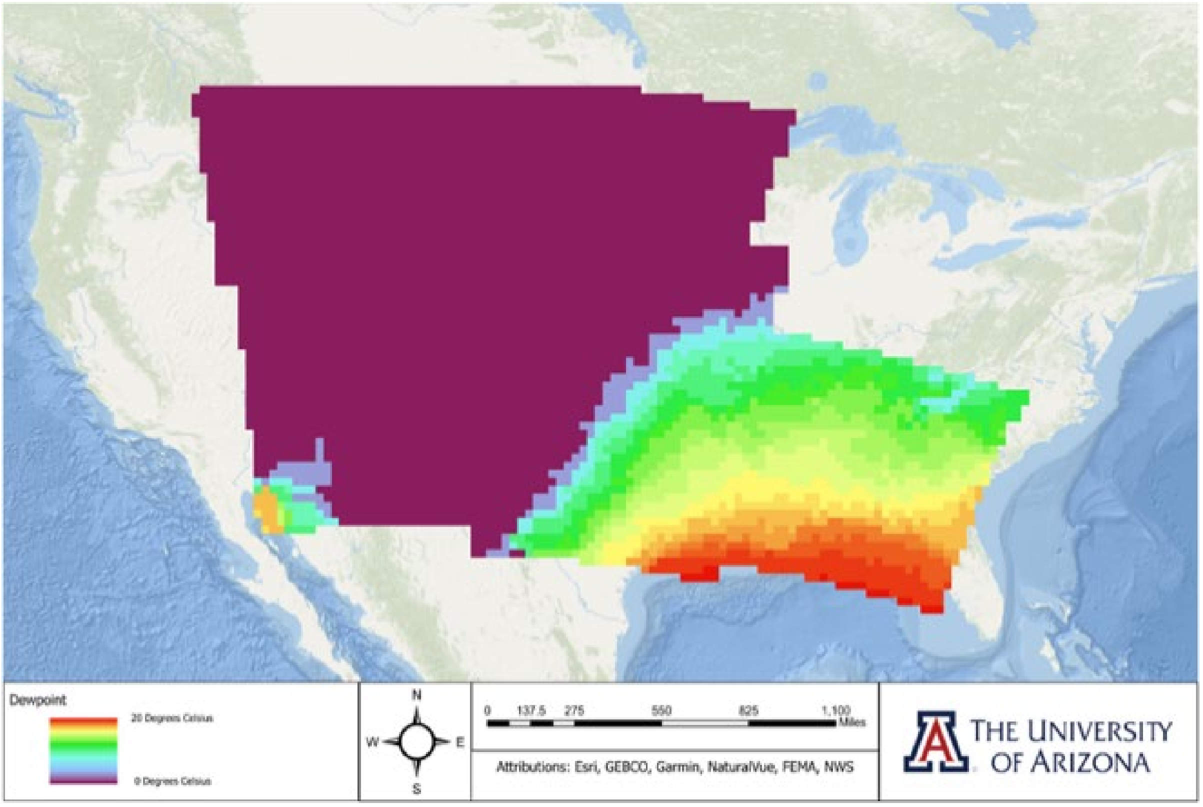

Figure 3-6. Raster layer for representing dewpoint average for the year 2021.

The 2021 tornadogenesis risk assessment shows a strong overlap with Dixie Alley. using observed data for 2021, Dixie Alley shows the highest risk region in gray and occupies 59% of the area in Dixie Alley, whereas the region only occupies 20% of the area in Tornado Alley and only 7% in The Great Plains (Figure 3-7). This indicates that the highest potential for tornado development during 2021 occurred in the majority of Dixie Alley when compared to the other study areas. Much of this overlap is with the majority of Louisiana, Tennessee, and Mississippi. Texas contains the high-risk region overlap for The Great Plains and Tornado Alley exclusively.

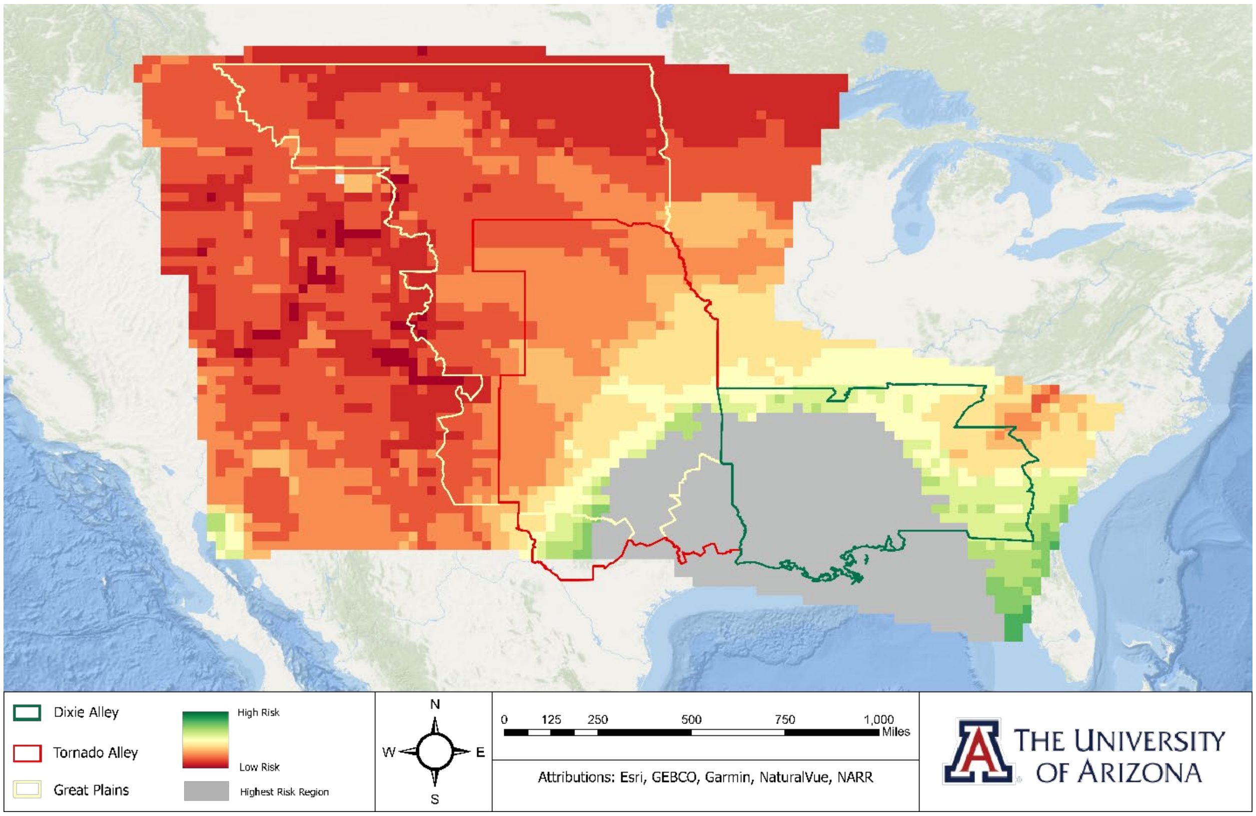

Figure 3-7. Current environment for high and low risk tornado potential mapped with the outline of each study area.

While comparing the 2021 observed tornado environment (Figure 3-7) to the 2021 corroboration model using CMIP6 data for 2021 (Figure 3-8), the latter has a high-risk region occupying 43% of Dixie Alley, 23% of Tornado Alley, and 8% of The Great Plains. CMIP6 data reflected a medium, non-extreme model which predicted a smaller risk region than what transpired in 2021. One can conclude a similar effect will occur for the 2030 prediction. Using a more severe CMIP model may better suit analysis for tornadogenesis but will need to be studied further to find the best prediction models.

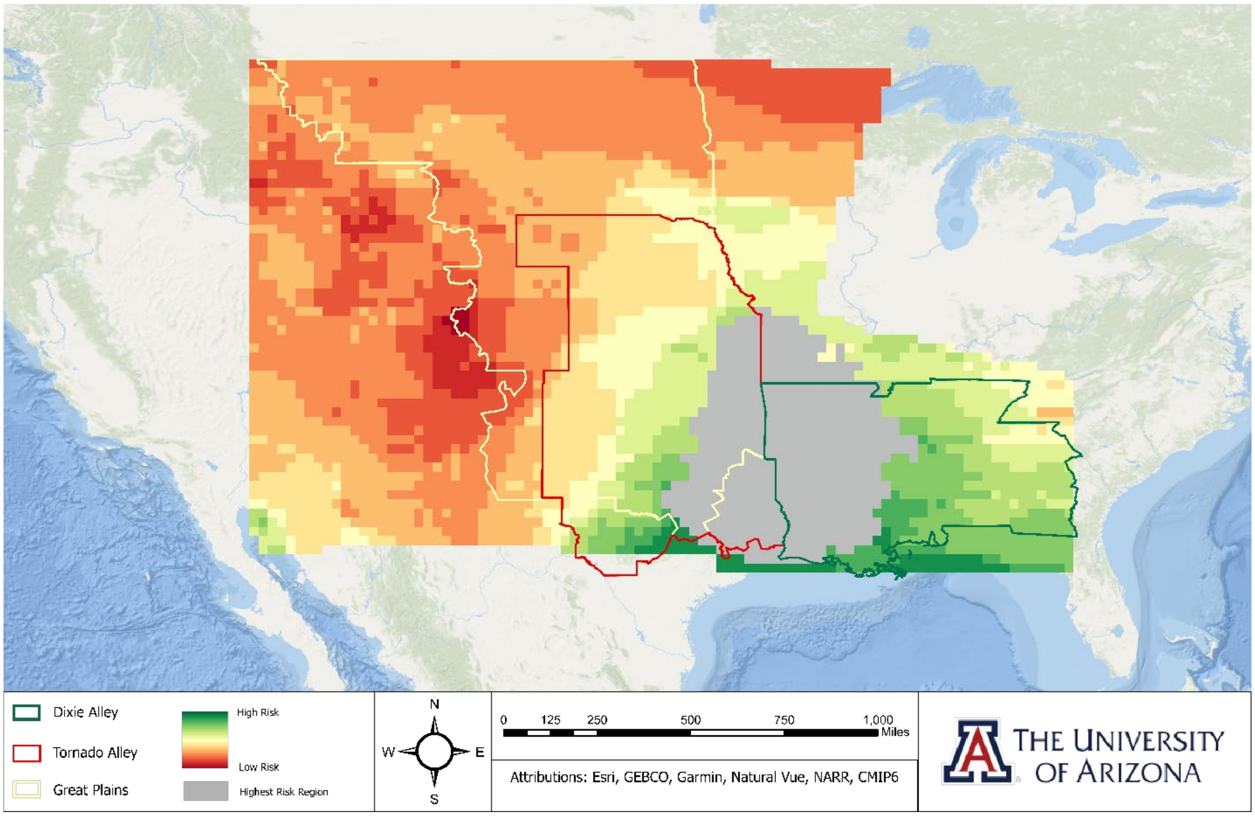

Figure 3-8. Risk assessment analysis using CMIP6 data for temperature and dewpoint for 2021.

The second corroboration map (Figure 3-9) uses a normalized process to verify whether the results from the 2021 predictor high-risk analysis (Figure 3-8) correctly identifies the statistical counts of tornadoes from that year. This map takes a normalized approach by analyzing tornadoes per square mile in both the high-risk region, shown in the gray high-risk region, and the rest of the United States. Figure 3-9 highlights the difference in tornadoes per square mile with the CMIP6 predicted high-risk region from 2021 had two more tornadoes per square mile than the rest of the contiguous United States, even though there were more total tornadoes outside this high-risk polygon. It is also worth noting that the high-risk polygon does not directly overlap with the entirety of Dixie Alley nor the high-risk region from the observed 2021 high-risk assessment. These statistics' difference would increase further if this map used the Dixie Alley study area polygon or the observed 2021 high-risk assessment region.

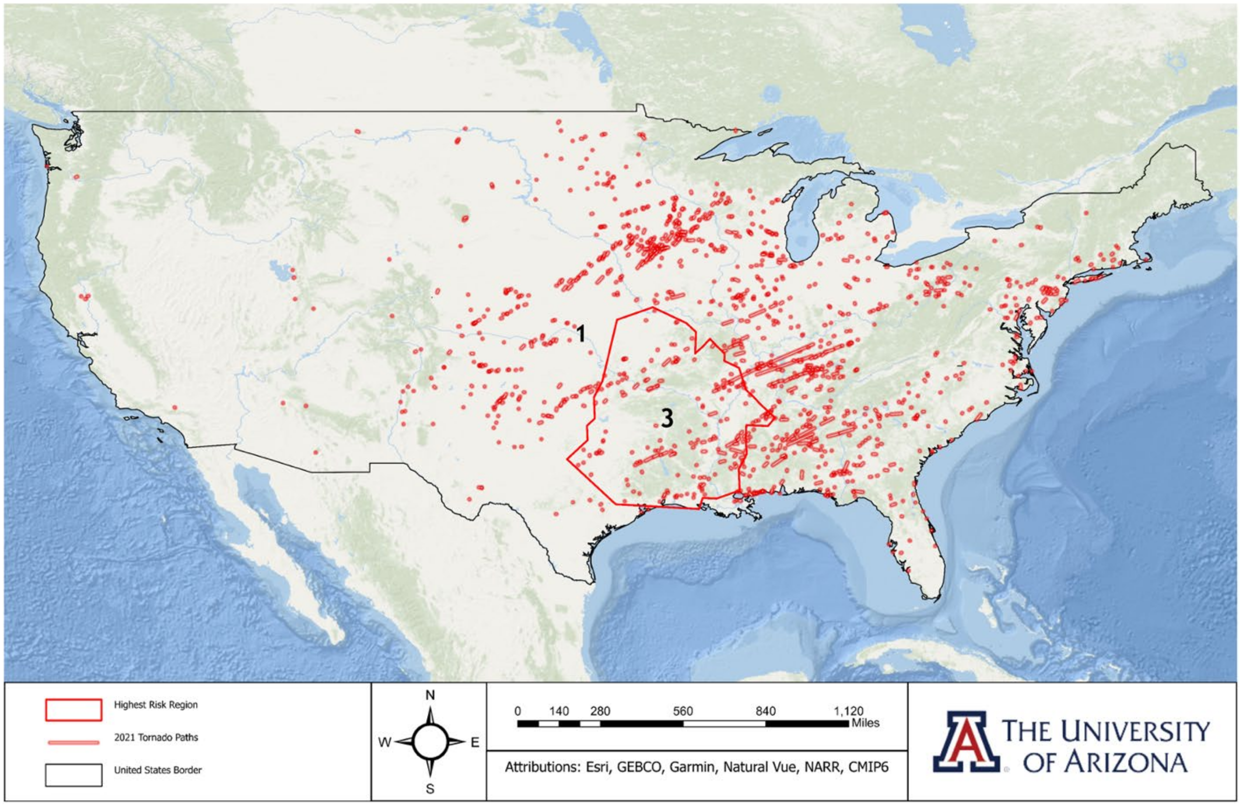

Figure 3-9. High risk region comparison of 2021 tornadoes per survey square mile with entire the United States.

Tornado Risk Prediction for 2030

For the predictor risk model for 2030, the study finds a similar result to the models from 2021. As is with the previous model for 2021, 2030 sees the highest risk for tornadogenesis to occur in Dixie Alley. For the 2030 risk assessment model (Figure 3-10), the highest risk is 39% of Dixie Alley and only 24% of Tornado Alley. Although there is a prediction that activity will decrease in Dixie Alley in favor of Tornado Alley, this shift is marginal and still emphasizes that Dixie Alley should experience more tornado activity for the next five years. This increase is to remain, affecting areas in Louisianna, Mississippi, and parts of Alabama and Georgia. This also highlights the fact that Dixie Alley does have a higher risk of tornadogenesis than both Tornado Alley and The Great Plains despite having a lower area. There is a 40% overlap between the 2030 future prediction and the 2021 CMIP6 high-risk predictor model. This likeness indicates the strength which CAPE and S-R Helicity have in both models, given that both models share these two variables.

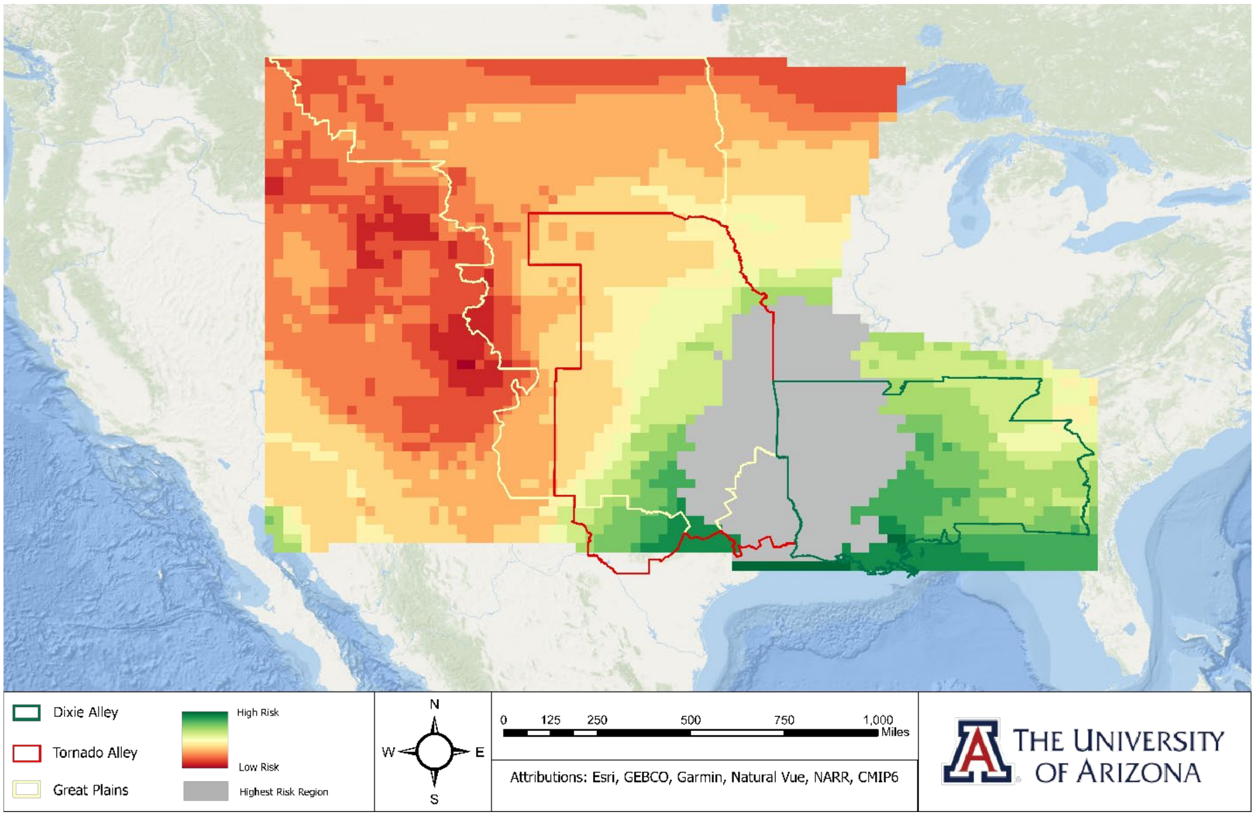

Figure 3-10. Future risk assessment analysis for 2030 using CMIP6 data for temperature and dewpoint and 2021 data for CAPE and S-R Helicity.

CONCLUSION

Conclusion

This study sought to research where and how tornadoes form in the United States and where they will form in the future. This was achieved by identifying key variables which measure tornadogenesis. By combining these variables into a model to view the areas with different risk classifications, the study was able to visualize which areas have a higher risk and predict the future risk. The highest overlap for all the models remained within the region defined as Dixie Alley. There has also been a very significant increase statistically favoring a high-risk scenario occurring in Dixie Alley at 24.7% whereas the other study areas do not increase above

0.2%. This study does contain limitations due to data availability and inconsistent definitions. There is no set definition for areas like Dixie Alley and Tornado Alley. Many analysts and geographers alter these areas based on specific needs and even as the geographical phenomenon change. As the name suggest, Tornado Alley generally focuses on areas with a traditionally high concentration of tornadoes. This definition is loose and can change as areas see an increase and decrease in tornadoes. A separate analysis of tornado frequency and contrasting Tornado Alley areas could better place this region with a higher accuracy. Predictor datasets for variables like CAPE and S-R Helicity could improve the 2030 prediction in terms of accuracy instead of using older, observed calculations.

Ultimately, this study has found an increase in tornadogenesis events within Dixie Alley compared to traditional tornado prone areas such as Tornado Alley and The Great Plains. Officials in these areas should plan for this continued change and determine proper building procedures and community resilience to combat the changing climate. This method can also be used by offices such as NOAA and the NWS to analyze current and future weather including not just tornados, but other weather phenomenon as well. Dixie Alley will continue to be the breeding ground for tornadoes not just in the coming years, but until 2030 and potentially beyond. This trend is lingering and will need to be studied to further understand the impacts this shift in environment will have to society and nature.

LIST OF REFERENCES

Coleman, T. A., Thompson, R. L., & Forbes, G. S. (2024). A comprehensive analysis of the spatial and seasonal shifts in tornado activity in the United States. *Journal of Applied Meteorology and Climatology*, *63*(6), 717–730. https://doi.org/10.1175/jamc-d-23-0143.1

Danabasoglu, Gokhan (2019). NCAR CESM2 model output prepared for CMIP6 ScenarioMIP ssp245. Earth System Grid Federation. doi:https://doi.org/10.22033/ESGF/CMIP6.7748 .

EC-Earth Consortium (EC-Earth) (2019). EC-Earth-Consortium EC-Earth3 model output prepared for CMIP6 ScenarioMIP ssp245. Earth System Grid Federation. doi:https://doi.org/10.22033/ESGF/CMIP6.4880.

FEMA. (2023). *FEMA's National Risk Index Map*. Tornado. Retrieved March 2, 2025, from https://hazards.fema.gov/nri/tornado.

Ferrell, J. (2025, January 3). *2024 tornado season was 2nd worst on record, driven by Hurricanes*. 2024 tornado season was 2nd worst on record, driven by hurricanes. https://www.accuweather.com/en/severe-weather/2024-tornado-season-was-2nd-worst-on-record-driven-by-hurricanes/1710598

Houser, J. (n.d.). *Tornadogenesis*. Dr Jana Housers Research Page. https://u.osu.edu/janahouser/tornadogenesis/

Gagan, J. P., Gerard, A., & Gordon, J. (2010). A historical and statistical comparison of "Tornado Alley" to "Dixie Alley.". *Natl. Wea. Dig*, *34*(2), 145-155.

Gensini, V.A., Brooks, H.E. Spatial trends in United States tornado frequency. *npj Clim Atmos Sci* **1**, 38 (2018). https://doi.org/10.1038/s41612-018-0048-2

Grice, G. K., and Coauthors, 1999: The Golden Anniversary Celebration of the First Tornado Forecast. *Bull. Amer. Meteor. Soc.,* **80**, 1341–1348, https://doi.org/10.1175/1520-0477(1999)080<1341:TGACOT>2.0.CO;2.

Kantamaneni, K., Alrashed, I., & Phillips, M. (2017). Cost vs. safety: A novel design for tornado proof homes. *HBRC Journal*, *13*(2), 223–232. https://doi.org/10.1016/j.hbrcj.2015.05.004

McCarthy, D., & Schaefer, J. (2004). *Tornado trends over the past 30 years*. TORNADO TRENDS OVER THE PAST THIRTY YEARS. https://www.spc.noaa.gov/publications/mccarthy/tor30yrs.pdf

National Academies of Sciences, Engineering, and Medicine. 2024. *Compounding Disasters in Gulf Coast Communities 2020-2021: Impacts, Findings, and Lessons Learned*. Washington, DC: The National Academies Press. https://doi.org/10.17226/27170.

National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce. 2005, updated monthly. NCEP North American Regional Reanalysis (NARR). Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://rda.ucar.edu/datasets/d608000/. Accessed† 5 Apr 2025.

NCEI. (2025). *Annual 2024 tornadoes report*. Annual 2024 Tornadoes Report | National Centers for Environmental Information (NCEI). https://www.ncei.noaa.gov/access/monitoring/monthly-report/tornadoes/202413#:~:text=According%20to%20data%20from%20NOAA's,reported%20100%20or%20more%20tornadoes.

NOAA's National Weather Service - Glossary. (n.d.). https://forecast.weather.gov/glossary.php?letter=h

"Radiative Forcing." 2025. *MIT Climate Portal*. Accessed April 24. https://climate.mit.edu/explainers/radiative-forcing.

Smith, A. B. (2025, January 10). *2024: An active year of U.S. billion-dollar weather and climate disasters*. NOAA Climate.gov. https://www.climate.gov/news-features/blogs/beyond-data/2024-active-year-us-billion-dollar-weather-and-climate-disasters

"The SSP Scenarios." 2025. *DKRZ*. https://www.dkrz.de/en/communication/climate-simulations/cmip6-en/the-ssp-scenarios.

Taylor, A. (2021, March 22). *Tornado survivor stories*. National Weather Service. https://www.weather.gov/safety/tornado-survivors

US Department of Commerce, NOAA. 2015. "ENV Parameters and Indices." *National Weather Service*. NOAA's National Weather Service. https://www.weather.gov/lmk/indices#:~:text=The%20EHI%20attempts%20to%20combine,EHI%20is%20a%20dimensionless%20number.

US Department of Commerce, N. (2021, June 30). *Tornadoes in or near El Reno, Oklahoma (1875-present)*. National Weather Service. https://www.weather.gov/oun/tornadodata-city-ok-el_reno

APPENDIX A

METADATA TABLES

Table 1. Historical tornado tracks feature layer.

Dataset:	Esri U.S. Federal Dataset's Tornado Tracks
Last Updated:	2023-07-13
Owner:	Esri
Description:	Tornado tracks with information provided on start and end time, magnitude on the Fujita or Enhanced Fujita scale, fatalities, injuries, length, and width.
Coordinate System:	World Geodetic System 1984 (WGS 1984)
Projection:	Geographic Coordinate System
Type of Geometry:	Vector

Table 2. NARR RDA.

Dataset:	2021
Last Updated:	2012
Owner:	NCEI
Description:	Climate data including monthly means for temperature and dewpoint, CAPE indices, and S-R helicity.
Coordinate System:	World Geodetic System 1984 (WGS 1984)
Projection:	Geographic Coordinate System
Type of Geometry:	Raster

Table 3. CMIP6 SSP245 Climate Dataset.

Dataset:	2015-2100
Last Updated:	2021
Owner:	Working Group on Coupled Modeling
Description:	Temperature and dewpoint predictor data.
Coordinate System:	World Geodetic System 1984 (WGS 1984)
Projection:	Geographic Coordinate System
Type of Geometry:	Raster

Table 4. USA Counties

Dataset:	Esri USA Counties Feature Service
Last Updated:	2023-07-13
Owner:	Esri
Description:	USA Counties
Coordinate System:	World Geodetic System 1984 (WGS 1984)
Projection:	Geographic Coordinate System
Type of Geometry:	Vector