Topographic Implications for Tornado Climatology

Kirk Pearson
Geology, Oberlin College
Oberlin, OH 44074
kirk.pearson@oberlin.edu

SUMMARY

Reports of North America's infamous tornado alley date back to the mid-17th century, yet its mythic image is somewhat misguided. Based on large-scale data analysis, the United States lacks a singular "alley" of storms and instead contains a patchwork of high density tornado clusters (Frates 2012). Each of these clusters has a statistically significant outlier in regards to tornado frequency— the most dense of these outliers has over one thousand times the national average. While these clusters have been previously described, little is known about why specific North American locations have such incredible tornadic potential. An understanding of these conditions could lead to better accuracy in storm prediction and increased safety for highly prone regions.

The following study reports on similarities between these clustered regions and describes a model for regional tornado prediction based on topography and precipitation. Due to the highly unpredictable and short-lived nature of these storms, tornado climatology typically analyzes historical datasets of storm pathways (Smith and Marsh 2016). Data from the NOAA Severe Weather Project is used to calculate the pathways of all reported tornadoes from 1950 though 2015. Storms are visualized in ArcGIS by algorithmically graphing a line between each storm's two terminal points (Figure II). Tornado clusters are quantified by calculating the density of storm pathways in every region of the continental United States.

A U.S. map is then generated that colors areas based on tornado likelihood (Figure III). Virtually all areas with high storm density, including the tornado clusters, are located in the midwest and Great Plains. This is due to the regions being disproportionately flat, balanced in moisture levels, and bordered by two major mountain ranges to the east and west (Brooks 2004). These conditions generate high cyclostrophic balance— an atmospheric state that gives rise to the vast majority of tornadoes (Frye and Mote 2010).

Plotted on a North American map, the five high-density clusters do not share any obvious geographic similarities. However, tornado frequencies do not correspond exclusively to latitude (Mercer et al. 2008) as much as other limiting factors, such as topography (Weaver 2012) and precipitation (Galaway 1979). By overlaying a digital elevation map as well as annual rainfall data, similarities between tornado clusters become much more apparent. Zonal statistics are calculated on these high potential regions, illuminating the correlation between tornado clustering and these environmental characteristics.

The five largest U.S. tornado clusters all share narrow topographic and climactic ranges (Figures VII and VIII). These factors attain a balance of optimal storm cohesion, updraft, and low atmospheric density. While several other factors that contribute to tornado

climatology have been described, such as soil moisture (Frye and Mote 2010), decade-long weather oscillations (Enfield et al. 2001) and global climate change (Diffenbaugh et al. 2008), this study suggests that storms can be predicted with significant acuity as a function of local topography and precipitation. This is especially significant as both of these statistical measures are easily collected in virtually all regions of the world— even those that do not have official geographic databases.

With this model, a map of all regions on Earth that satisfy the elevation and climate ranges is generated (Figure IX). Not only does this model bear striking resemblance to maps of tornado distribution (Brooks 2004), but also suggests at the possible presence of tornado clusters in underreported areas. These areas, such as Southeast Africa and Patagonia, have few official storm reporting services as well as low population densities. This model suggests the presence of never before described tornado alleys, that very possibly exist despite the lack of reported incidents.

INTRODUCTION

The North American tornado alley spans the majority of the midwest and Great Plains, in the plateau between the United States' two major mountain ranges (Figure II). This region reports more tornadoes than any other in the world by a large margin, due to the area's ideal tornadic conditions (Weaver et al. 2012). Air currents from both coasts experience a rapid drop in pressure due to the quick geomorphic transition from mountain to plain. This decrease leads to a proportional increase in fluid velocity (Brooks et al. 2003), destabilizing the currents of cooler air. Rising condensation from these air currents leads to intense updraft and increased stratospheric moisture. The resulting storms, called supercells, form when uprising warm air meets two rapidly moving currents (Rasmussen et al. 1998). Depending on the storm's level of moisture, a supercell's rotation may increase due to especially high cyclostrophic balance. If rotation is at a high enough velocity, downdrafting winds will pull the cloud vortex to the ground, forming the tornado's visible wind column.

Storms across tornado alley are not randomly scattered, but tend to have a preference for a small number of very specific locations (Figure III). Understanding the propensity of these clusters to form tornado-rich supercells allows for us to correlate storm probability with other local factors. As supercells depend greatly on moisture levels and elevational stability, we can look for correlations between regional topography and precipitation on number of tornadoes reported.

This study seeks to find a relationship between geography and tornado presence and to use this function as a model to predict tornado frequency across the globe. North America is an excellent place to base the study off of, due to both its high number of storms and availability of reliable, government-regulated data.

METHODS

The NOAA Severe Weather Project was founded in 1950 to increase understanding of deadly storms and aid the ability to predict them. Since then, the database has come to amass over one hundred thousand reported tornadoes in the continental United States (Smith and Marsh 2016). In addition to the estimated wind speeds, damage, and death counts, the dataset also contains geocoordinates of the start and endpoints of

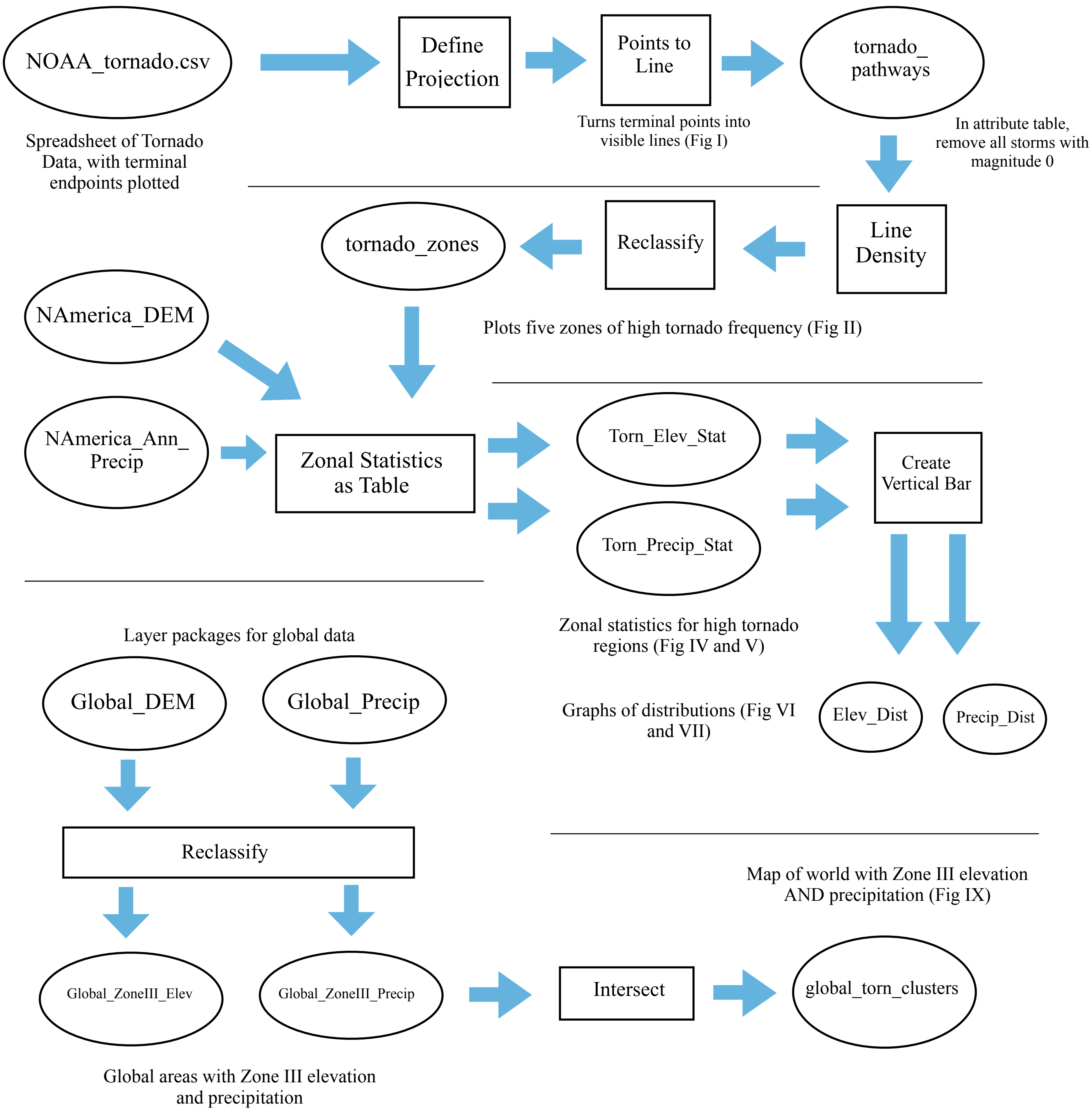


Figure I: A workflow of this study in ArcGIS, intended for the ease of replication.

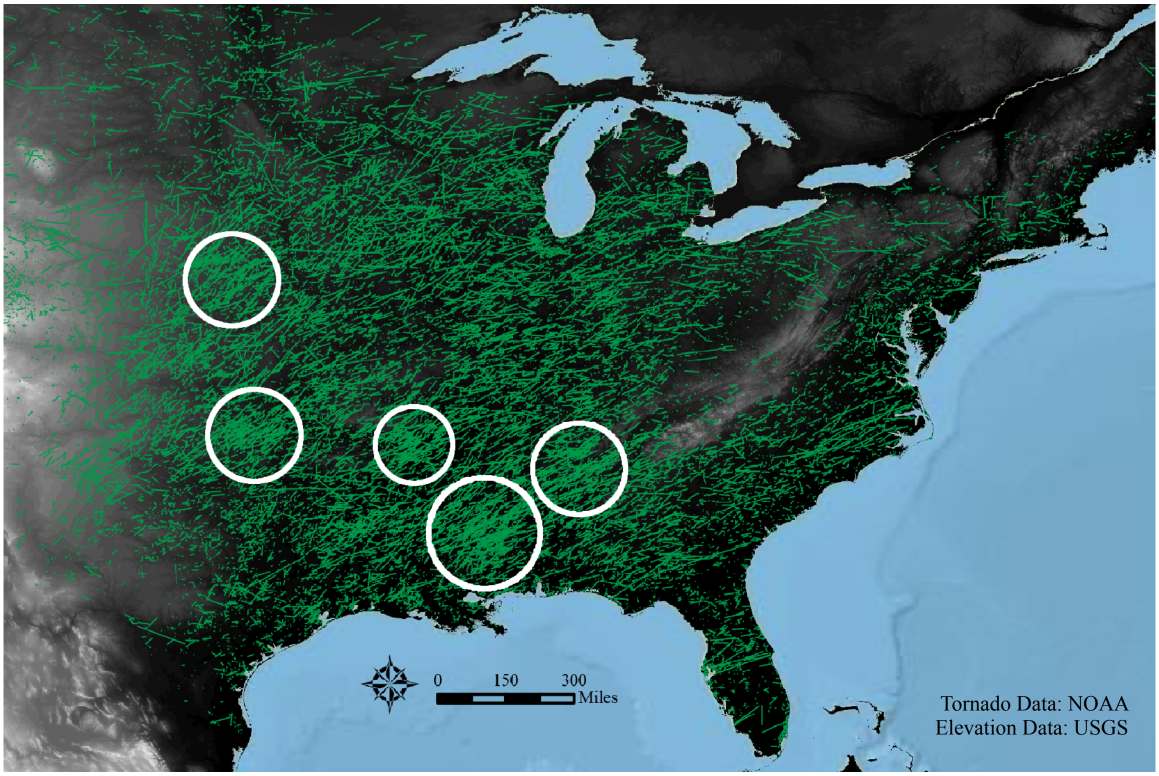


Figure II: An image of all NOAA-reported EF1-EF5 tornadoes (1950-2015) with highest density clusters circled.

each tornado pathway (workflow starting with Figure I). Isolating tornadoes with an EF0 ranking on the Enhanced Fujita-Pearson scale — those with wind speeds under 72 mph (Glickman 2000), a map that connects all terminal points shows us the distribution of all EF1-EF5 tornadoes reported to the database (Figure II).

The software ArcGIS can be used to categorize the map of storm distribution into areas of varying storm density using the line density algorithm (Figure III). Zone I regions represent the entire study area and are not indicated on the map. Zone II regions indicate low density, and are most obviously a reflection of topography. The Rocky Mountain region, for example, has an elevation where air currents are too stable for tornadoes to form (Weaver et al. 2012). The region highlights the rough outline of tornado alley. Zone III regions, the densest 5%, show the areas with especially high risk. Zones IV and V pose the highest risk for tornado formation, having densities respectively in the top 1% and 0.1% of the study area.

It should be noted, however, that cluster identification is fraught with multiple categorization issues. A study by Michael Frates, for instance, finds four clusters instead of five as it concerns itself only with EF3-EF5 tornadoes with a 20-mile path. As the map of storm densities (Figure III) does not discriminate between tornadoes based on their magnitude, allowances must be made in order to prevent bias in statistical methods. This study, focusing on all non-EF0 tornadoes, does *not* claim that high-frequency clusters have the most deadly tornadoes. The average storm magnitude in each of the clusters shows a small range of 1.77-1.95 on the Enhanced

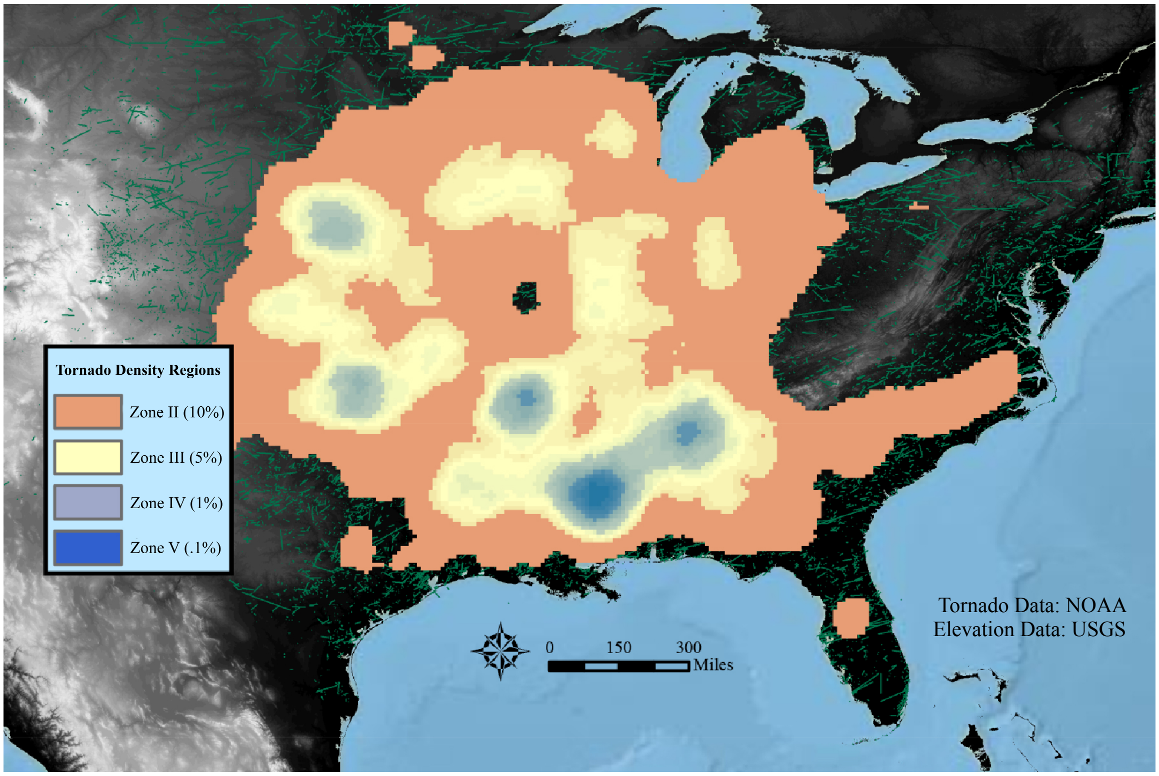


Figure III: An image of U.S. tornado density against topography. Zone I regions (the lowest density) are not shown. Zone II shows regions with the 10% highest density, Zone III with the highest 5% and so forth.

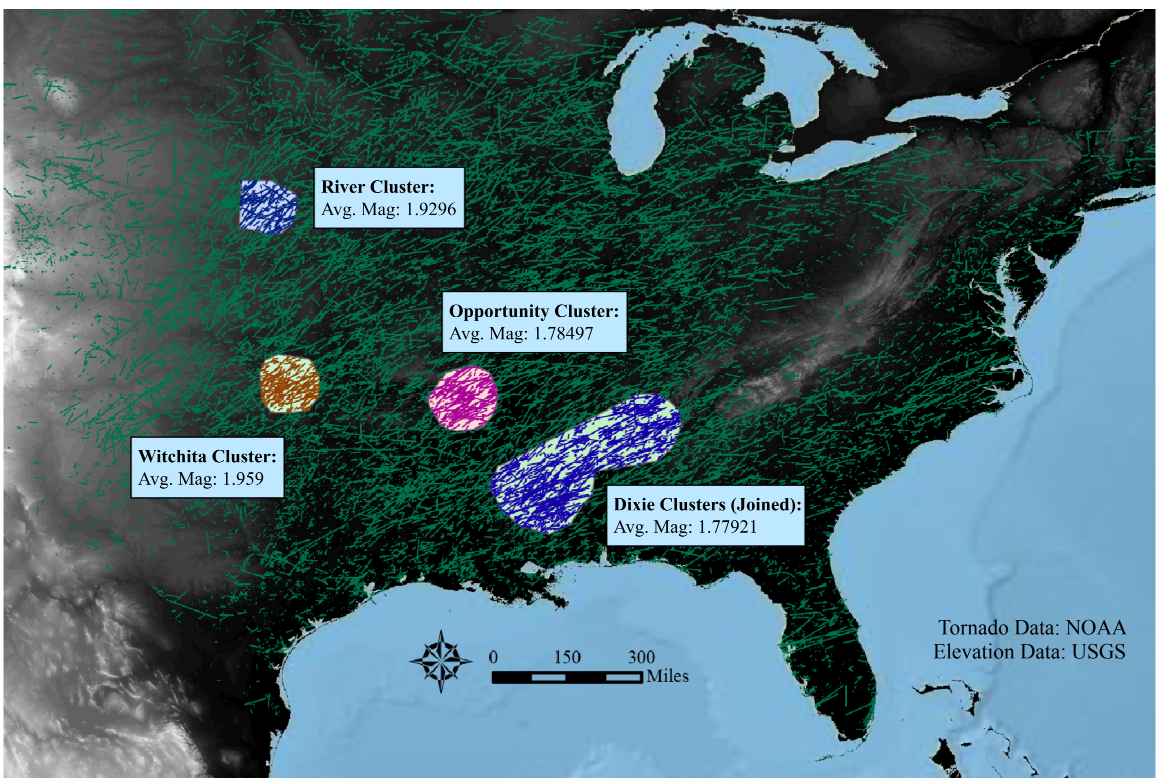


Figure IV: An image that shows the average magnitude of tornadoes on the Enhanced Fujita-Pearson Scale (EF1-EF5), *purely to illustrate that high density regions need not be regions with abnormally high magnitudes.*

Fujita-Pearson scale (Figure IV).

Once a cluster classification was developed, high risk regions (Zones III-V, the 5% highest density) were defined as the regions of study. DEM data from the United States Geological Survey (USGS) was projected alongside high-storm regions and clipped (USGS 2015). The zonal statistics algorithm in ArcGIS allowed for a quantification of each cluster's local maxima and minima, as well as the topographic variability between all regions.

Precipitation data was obtained from the National Weather Service (NWS) and analyzed in an identical fashion (NWS 2016). As American tornadoes are significantly more common during Spring and early Summer months (Tippett et al. 2012), the study chose to tabulate annual rainfall amounts so as to not skew temporal variability. While this method does not take historical drought data into account, which is widely regarded to increase storm frequency at the onset of rainfall (Galaway 1979), this condition was seen as negligible at the scale of this study.

RESULTS AND ANALYSIS

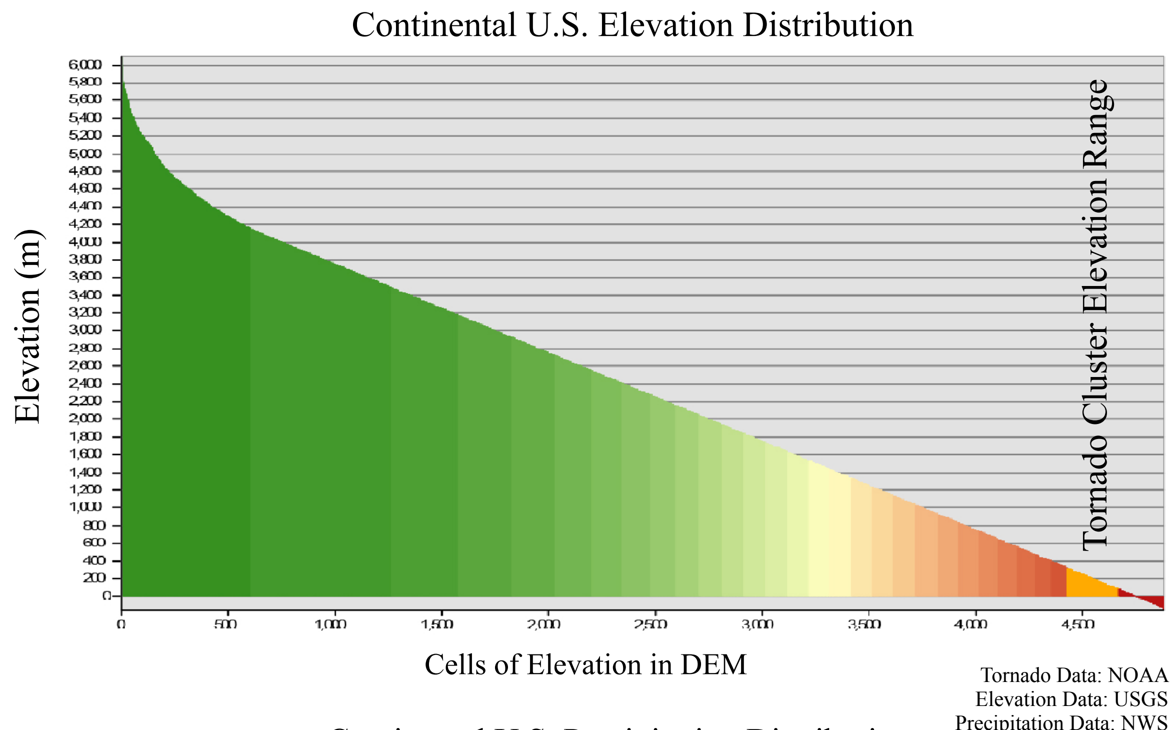
Once trends in precipitation and topography were tabulated for the five clusters, their ranges indicated a strong tendency to form in regions with particular elevations and rainfall (Figures V and VI).

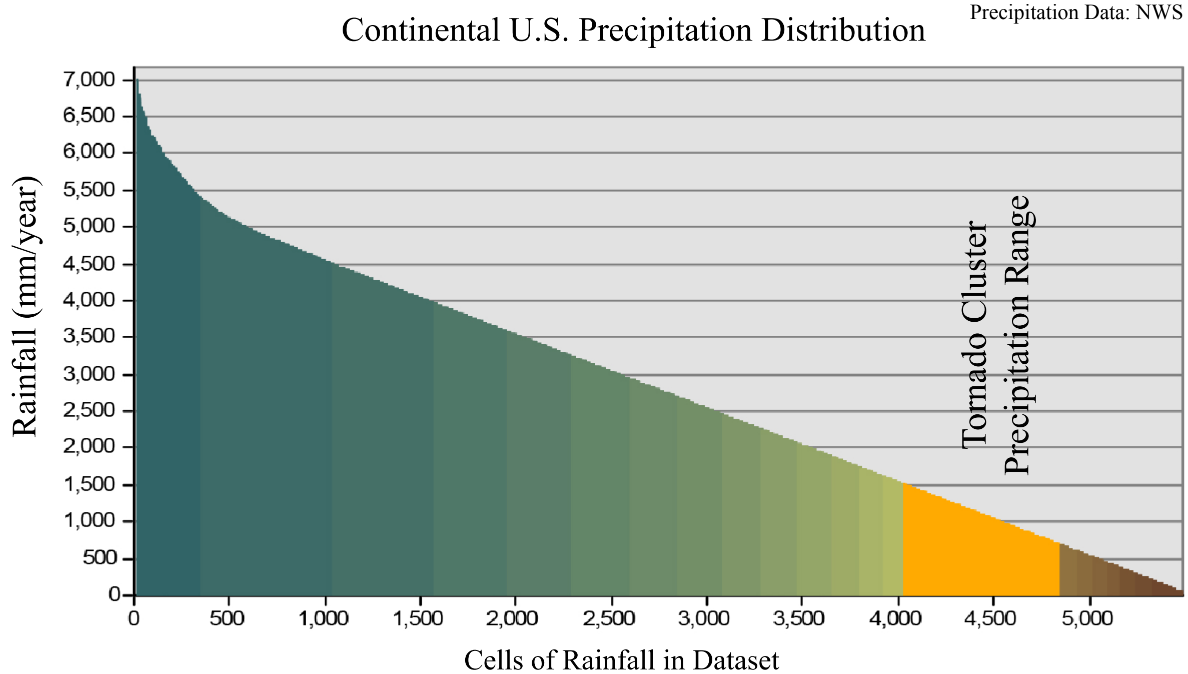
	Minimum Elevation (m)	**Maximum Elevation (m)**	**Range (m)**
Zone I (All Data)	-84 (Continental Min.)	4305 (Continental Max.)	4389
Zone II	2	1429	1427
Zone III	16	866	850
Zone IV	23	618	595
Zone V (Highest Density)	55	339	284

Figure V: The topographic ranges of each of the five zones of tornado density, analyzed through the ArcGIS Zonal Statistics algorithm.

	Minimum Rainfall (mm/year)	**Maximum Rainfall (mm/year)**
Zone I (All Data)	55 (Continental Min.)	5711 (Continental Max.)
Zone II	411	2305
Zone III	507	1707
Zone IV	629	1690
Zone V (Highest Density)	1266	1581

Figure VI: The rainfall ranges of each of the five zones of tornado density, analyzed through the ArcGIS Zonal Statistics algorithm.





Figures VII and VIII: Histograms that show relative distributions of elevation and precipitation in the continental United States. Ranges of high-density tornado clusters are indicated in orange.

Topographic distribution of Zone V clusters shows a strong bias towards a narrow range just above sea level (Figure V). This evidence is supported in a study by Dr. Scott Weaver et al., who claim warm currents of air have an optimized velocity at certain low elevations (Weaver et al. 2012). Low topographic profiles tend to have low cyclostrophic balance, as rising currents of warm air are seldom met with shearing force winds. Even in very rare cases, elevations below sea level have updrafts that are too low velocity for severe storms to be a common occurrence. High elevations, such as mountain ranges, have an even lower likelihood for tornadoes (Brooks et al. 2003) as wind conditions have statistically low turbulence and low updraft.

Clusters also tend towards a small range of wetter regions (Figure VI). This level of rainfall suggests a tipping point between storm cohesion and cloud cover. While moisture is indeed vital for atmospheric cohesion, heavy clouds reduce sunlight, limiting updraft-fueling convection currents (Craven et al. 2002). The range proposed by these data suggests a optimal balance between strong updraft and a low-laying level of moisture.

Plotted along histograms (Figures VII and VIII), we can view the limited regions of the United States that satisfy both the topographic and precipitative conditions. When highlighted against the country's total topographic and climactic distributions, the graph roughly suggests the correct relative area of tornado alley compared to the area of the United States.

Using these data ranges as proxies for tornado cluster locations, a global map was rendered in ArcGIS that showed all locations that satisfied *both* the Zone III topographic and climactic ranges. Based exclusively on the relationship between North American tornado clusters and their associated geographies, the map shows an estimate of highly tornado-prone areas highlighted in red (Figure IX). A comparison of this map along with studies of global tornado frequency (Brooks 2004) shows a very high correlation between the two images (Figure X). In addition to successfully highlighting the North American tornado alley, the South American *Pasillo de los Tornados*, and the Bangladeshi tornado cluster, the map successfully shows other regions that have more nuanced pathways.

DISCUSSION

While this study suggests possible correlations between geography and tornado presence, the two-dimensional classification offers several limitations in regards to assessing global storm frequency. As discussed with the limitations of cluster identification, regions with high tornadic potential do not necessarily harbor the most severe or dangerous tornadoes (Figure IV). The world map visualization merely suggests the possibility of a high number of storms—many of which might be incredibly weak.

Despite its standardization, the Enhanced Fujita-Pearson scale is not without its issues. Primarily, a tornado can only be measured on the scale after it has already occurred. Furthermore, as the scale is based off a quantification of wreckage, the tornado cannot be measured if it occurs in an area without damageable infrastructure. For example, an incredibly high-velocity EF5 tornado might only be classified as an EF2 if its pathway was considerably removed from infrastructure. Unfortunately, modern meteorological techniques simply cannot measure wind speeds for tornadoes with great acuity due to both storm ephemerality and the grave danger of active tornado research.

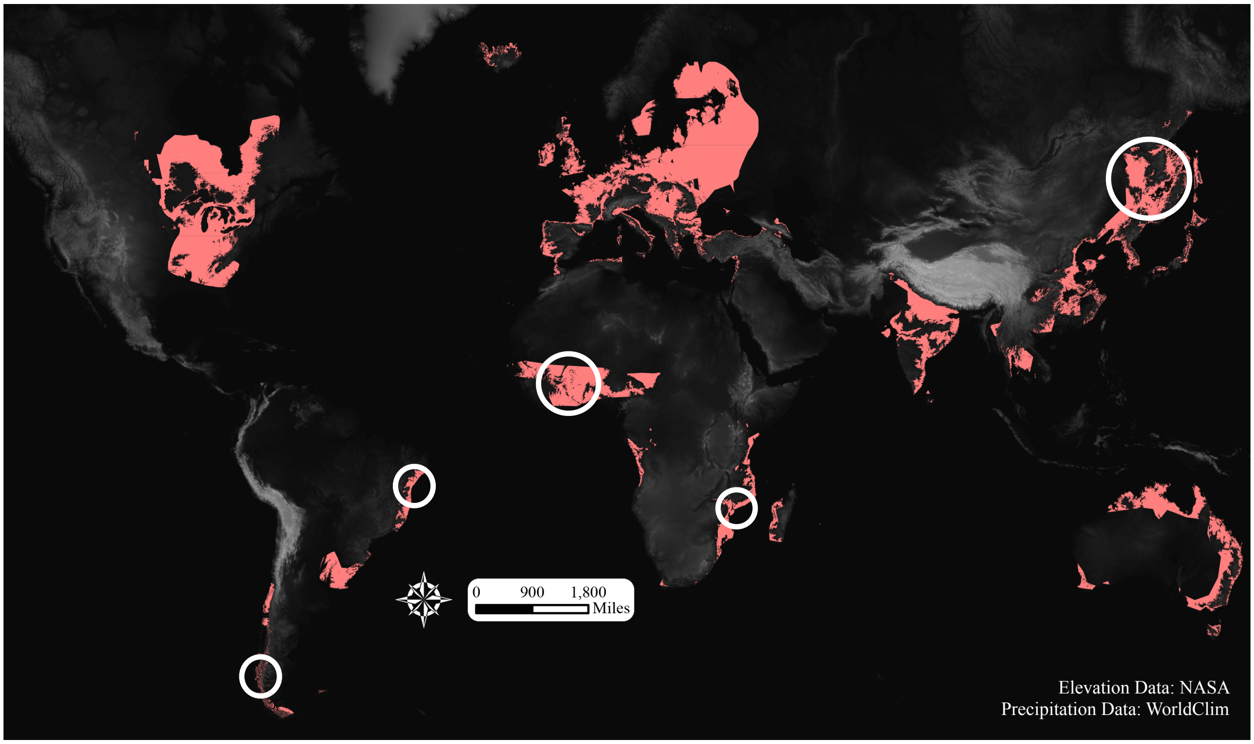


Figure IX: Areas of the world that satisfy Zone III topographic and precipitation ranges. Unreported areas with hypothesized tornado clusters are circled.

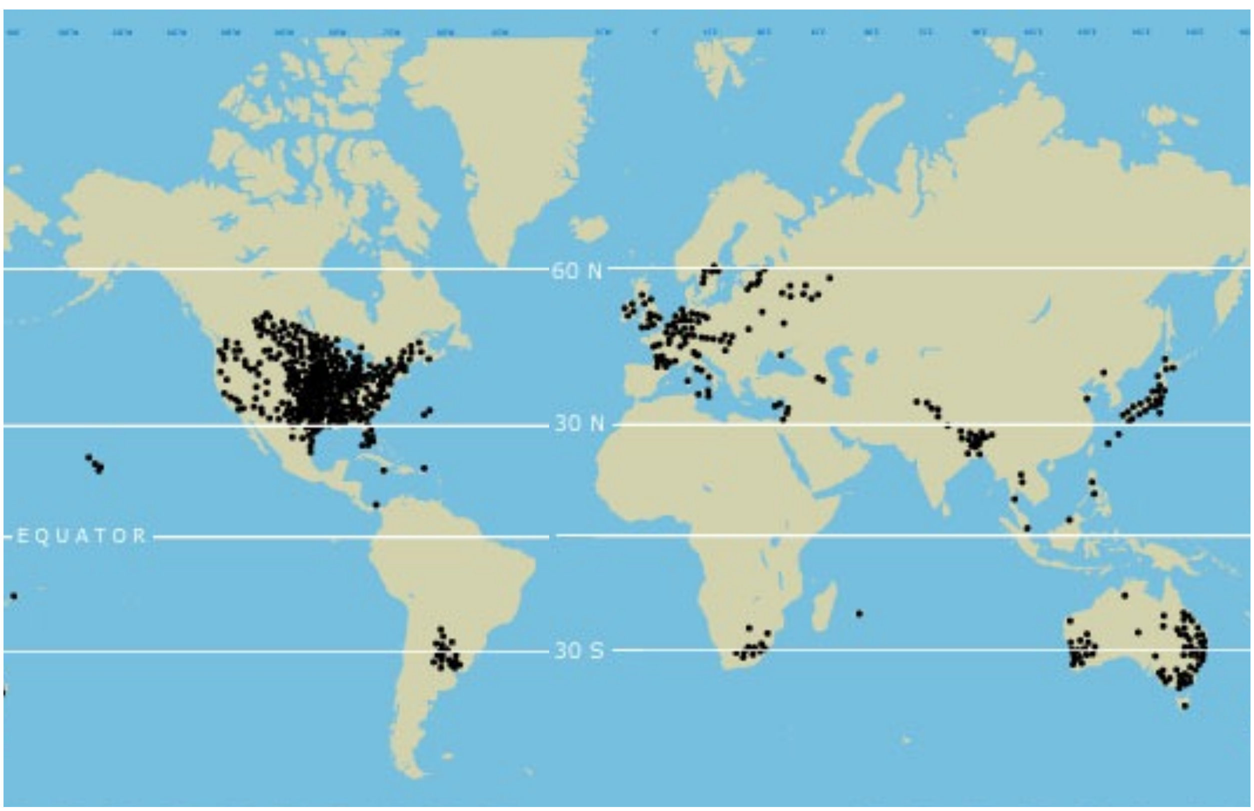


Figure X: Map of global tornado frequency (Source: PBS Nova, based on Brooks 2004).

A further issue is the fact that the study did not take into account the wind funneling effect caused by the United States' two major mountain ranges. The increased wind velocity caused by those ranges is regarded as being a major contributor to cyclostrophic balance (Weaver 2012). Continued analysis of tornado clustering should focus on finding similar topographic patterns that effectively "funnel" low-velocity winds into currents with significant shearing force against rising updraft. This does, however, offer some insight into the plausibility of the Patagonian and Mozambican tornado clusters, as both would seemingly experience wind funneling by by the Andes and Namuli cordilleras, respectively.

CONCLUSIONS

Based on the correlations found, tornadic potential can be viewed as a function of topography and climate with high precision. This suggests that further refinements to this model could potentially help predict storms in areas where high-resolution weather data is unavailable.

Furthermore, the generated world map suggests the presence of additional tornado alleys that might exist. For example, Mozambican and Patagonian tornadoes are seldom to never reported on, due to both very sparse populations and lack of government reporting agencies. Likewise, North Korea's high tendencies might suggest a meteorological quirk that goes internationally unnoticed due to lack of civilian access to reporting services.

Although this study is not high-resolution enough to be entirely comprehensive, it does suggest that tornadoes might be predicted based off of regional geographic fingerprints. It stands to reason that geography-based storm prediction models could help better prepare global organizations for targeting clusters and prioritizing aid.

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