Exploring Local Tornado Alleys for Predictive Environmental Parameters

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Abstract

Recent publications have noted small, local “tornado alleys” scattered across the eastern two-thirds of the United States but have not attempted to explore in-depth reasons for these local maxima. Other publications are noting possible effects of local topography upon approaching mesocyclonic storms. Using ArcGIS Spatial Analyst and information gained in past models constructed for Oklahoma and Arkansas, I propose to first remove population bias from the dataset and explore the surface in and around these alleys to see if any environmental parameters, such as vegetation/land use, soil families, elevation/roughness, certain landforms and orientations, or other surface features, are common to all of the areas.

Introduction

In the past I have explored possible correlations between changes in the local topography and/or land use, cover, and soils and tornadogenesis in Arkansas and Eastern Oklahoma (Passe-Smith 2004 and 2005). The findings were encouraging and in keeping with studies which note the importance of capturing these localized changes in models predicting severe weather. What was troubling, however, was threefold: 1) the validity of the data set of tornadoes I was using; 2) the fact that I analyzed only touchdown points (in part due to statements which note they are the most reliable) rather than the entire path length; and 3) the strong likelihood that the existence of populations can (falsely) be the best predictor of tornadoes.

With regard to the validity of the data, many researchers agree that the Storm Prediction Center's data is not very spatially accurate, especially as one goes back in time. The current SPC director, Joe Schaefer, and forecaster Roger Edwards note (1999)

> Since each entry in the database has an associated latitude/longitude, these data can be used to perform site-specific analyses. However, because of the inherent biases in the data…[o]ne should carefully examine local inhomogeneities before ascribing meteorological significance to them. Perhaps, local 'hot spots'…do exist, but the data is such that it is generally impossible to distinguish a difference in the hazard between one side of a town to the other (Schaefer and Edwards, 1999).

To those who are used to working with geographic coordinates, an obvious source of error is the fact that their decimal degree coordinates are given with only two decimal places of accuracy. The Texas Commission on Environmental Quality states, for example, believes "In order to meet the TCEQ minimum accuracy standard of 25 meters, latitude and longitude coordinates should be carried out to at least 4 places for decimal degrees" (2006). However, there are other issues, including reports from untrained witnesses resulting in wrong time, place, storm, and strength, especially prior to the late 1970s (Doswell and Burgess, 1988); "overburdened National Weather Service staff" whose training is "woefully inadequate" add to the problem (Doswell and Burgess, 1988). I mention these things only to explain errors that might be noted readily, and put forth a disclaimer that all studies using this data are likely incomplete and no hard-and-fast rules or findings should be forthcoming.

The issue of population bias has been dealt with in previous works by Passe-Smith (2004, 2005), and can be summed up as noted by Harold Brooks of the National Severe Storms Laboratory in Norman, Oklahoma:

> Population biases, *especially for weak tornadoes*, have been addressed previously (e.g., Grazulis 1993; King 1997) and are certainly present here. The relative minimum over southwestern Kansas and the Oklahoma panhandle may be a result of low population density and lack of interstate highways and the associated reporting problems (Brooks *et al*., 2003; emphasis mine).

This study suggests one way to deal with these problems is to single out long-path, strong tornadoes, as noted by Concannon *et al*. (2000):

> [T]he dataset for significant and violent tornadoes may have more reliability over that for the weak tornadoes. The fact that more people are likely to observe an intense tornado due to its larger size and longer path length reduces the number of "missing" significant or violent tornadoes within the dataset.

This methodology was used by Broyles and Crosbie (2004) to identify smaller tornado alleys within the United States. Following their lead, for this research I will use, as did Broyles and Crosbie, only tornadoes rated F3 to F5 (Fujita scale) but include path lengths of over 20 miles; the authors used 25, but had more tornadoes to work with (went back to 1880) and may include data some deem not reliably long-track (tornado families counted as one, etc.). I did not feel that pre-1950 data is reliable enough to work with at this time. The most important reason to use only these storms, as Broyles and Crosbie point out (2004, 1), is that they have the highest destruction potential and, thus, are responsible for most deaths, injuries, and property damage by tornadoes. I will shortly present just how lopsided that figure is. Finally, Broyles and Crosbie end their work with a desire to explore why these alleys exist; they mention and depict some major features such as river valleys; in keeping with the reasoning reviewed below, I will examine the data for explanatory environmental parameters.

Grazulis, 1991, for example, believes what he defines as a tornado maximum in the Arkansas River Valley might be related to its relief. Bosart *et al.* (2004) discuss tornadogenesis as a storm moved over the Hudson River Valley from the Catskill Escarpment. Although the change in elevation in their study is larger than that which would occur in many of the target areas herein, the idea that terrain-channeled surface wind can enhance shear might be evidenced by these local strong tornado alleys. Doswell (2001, 1982) also stresses the importance of small scale terrain-related phenomena which enhance convection on a local scale. Horizontal convective rolls (HCRs), associated with enhanced convection along updraft branches, may or may not be related to terrain. In Southern California, enhanced convection and even funnels are thought to be associated with a phenomena related to HCRs called the “Island Effect” related to terrain (Small, 1999). Weckwerth found absolutely no relation between terrain and storm formation along HCRs in Florida. A horizontal convective roll seen on the 1.5° elevation base reflectivity from Frederick, Oklahoma was likely a mechanism for initiating the convection which became the storm that produced 14 tornadoes, including one F5 tornado that devastated the Oklahoma City area May 3, 1999, killing 36 people and injuring nearly 600 (Thompson and Edwards, 2000); thus, any interaction between a roll and enhanced updraft could be crucial. Another possibility is the alignment of river valleys; Bosart *et al.* (2004) depict strong increases in shear within a supercell thunderstorm as it moved across both the Hudson River Valley, again as it crossed the Housatonic River Valley. They believe the terrain might channel the south-southeasterly flow ahead of the storm in a manner that increases the shear available to the oncoming supercell, resulting in a long-track, F3 tornado in an area in which tornadoes are not that common.

Again, the relationship between land use/cover and tornadogenesis have been covered in great detail elsewhere (Passe-Smith 2004; Passe-Smith 2005). Briefly, abrupt surface changes in vegetation (native and crop) have been found by Esau and Lyons (2002) to produce convective clouds absent of any difference in topography; Raddatz and Cummine (2003) connected interannual variability in evapotranspiration rates in crops and the number of tornado days in the Canadian prairie agricultural region. Weaver and Avissar (2001) show convincingly that over an area 250 kilometers square in Oklahoma and Kansas, again with almost no elevation change, that diurnal thermally induced circulations occur in areas of differential land use. Finally, Xue *et al.* (2001) describe the successful integration of vegetation type, coverage, and leaf-area index, among many other variables, into a model to predict with resounding success, among other events, the January, 1999 tornado outbreak in Arkansas. Thus, vegetation change—especially between natural and cultivated plants—should perhaps show up as a predictor.

Methodology

All tornadoes with no F-scale were removed from the Storm Prediction Center's (SPC) tornado data (online at http://www.spc.noaa.gov/wcm/ONETOR5004.txt). I generated the tornado paths using ArcInfo and the begin/end points provided by the SPC, resulting in 14,634 paths since 1950. I then selected by attribute only those with F-scale equal to or above 3, and path length over 20 miles. After projecting the paths into Albers Equal Area (USGS) I allowed the GIS to do the work for me by using Spatial Analyst's density calculator, set to square miles. The resultant map of strong, long-path tornado density is shown in Figure 1, overlain with all 846 F3 or greater, long-track tornadoes from 1950 through 2004. The numbers represent, basically, the square miles of tornado affecting any given square mile (example: .157 square mile of tornado affected each square mile of the most dangerous area in the country, South Central Mississippi).

I then used the raster calculator to select all areas greater than four standard deviations above the mean (mean .0097, standard deviation .0188) and converted these to vector polygons to use as my study areas. I calculated the mean direction of travel of the tornadoes and used this figure to compute two vector octants to either side of this line, in order to investigate the environment long-track tornadoes encountered at or shortly before touchdown. These octants (45 degrees on either side of the mean direction line) and the study areas are shown in Figure 2.

From these boundaries, I was able to define coordinate pairs with which to obtain land cover and elevation data from the USGS's Seamless Data Distribution site (http://seamless.usgs.gov/website/seamless/viewer.php) over several days. These variables were chosen to evaluate each of the target areas using the environmental factors gleaned from the literature above.

Spatial Analyst's zonal statistics were used to count the most common or mean raster value within each study area for land cover data; a 20-kilometer buffer was extended around each polygon to calculate the number of tornadoes, long/strong tornadoes, and fatalities and injuries in each. I further used zonal statistics in two study areas (Area 1, on the Kansas-Nebraska border, and Area 7, South Central Mississippi, two areas with distinctly different climates, landscapes, growing seasons, etc.) to examine the 5 kilometers before touchdown (created by adding 180° to the tornado's trajectory)

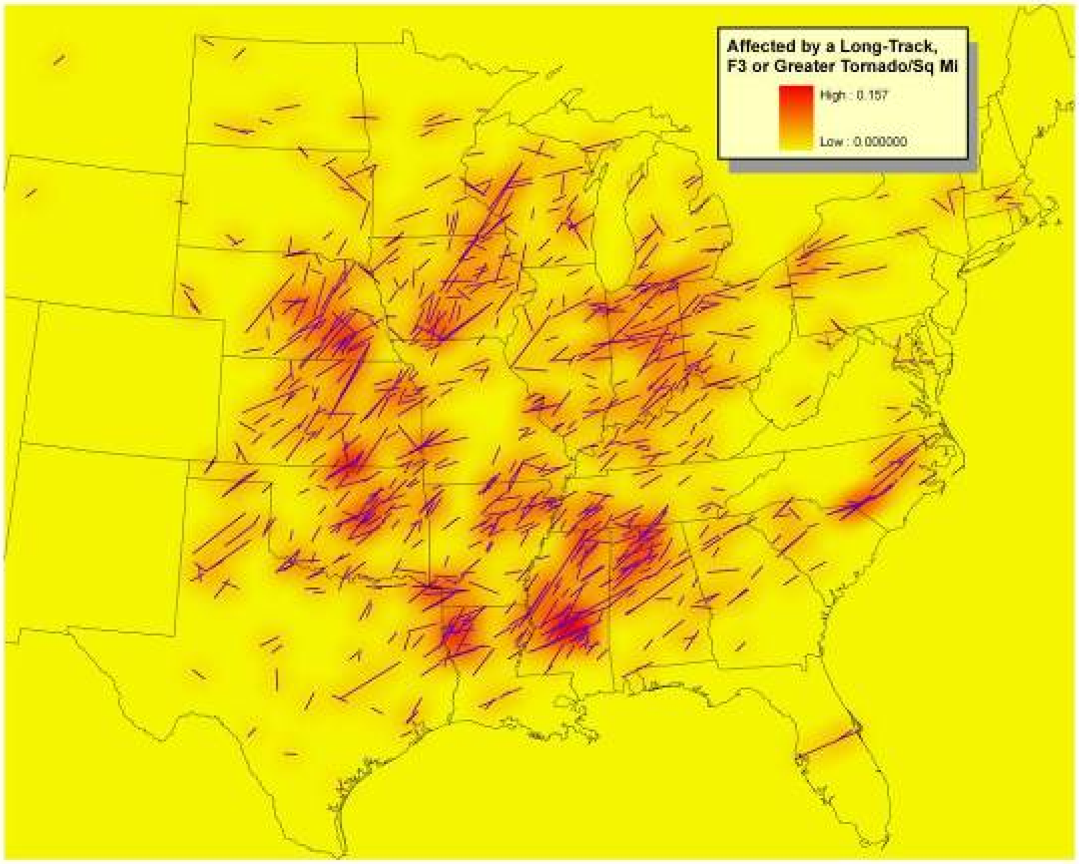
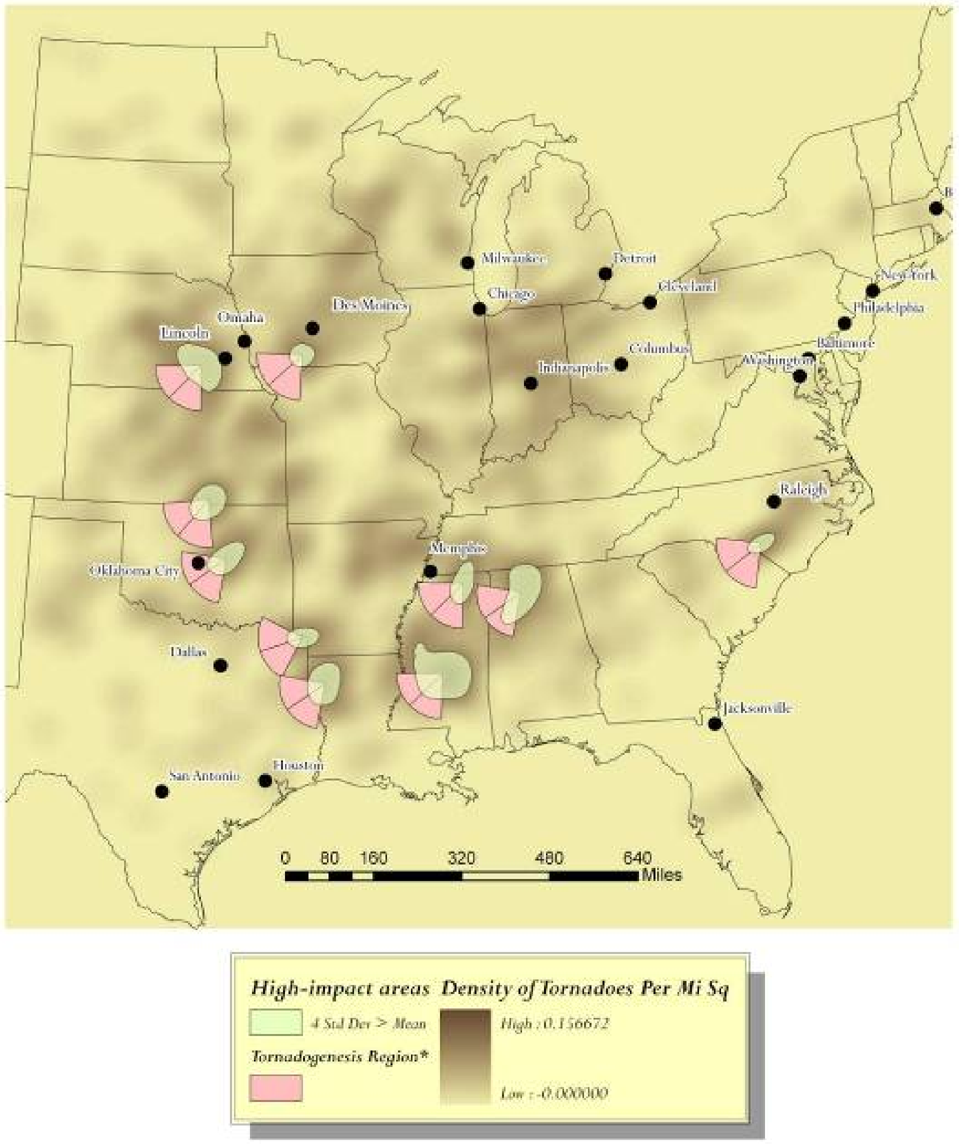


Figure 1: Square miles of long-track, strong tornado affecting each square mile, 1950-2004, and generated tornado paths.

and the path after touchdown for differences. For instance, will slope be higher and/or land cover trees before touchdown, and abruptly be flatter and crop post-touchdown? I also rely on 2D and 3D visualization to examine the ten areas that were above 4 standard deviations. Finally, spatial statistics are used to derive the mean direction of a proxy for the orientation of valleys, streams clipped from a country-wide set obtained from a USGS



*Division between tornadogenesis octants shows mean direction of long-track, F3 or greater tornado travel for all tornadoes 1950-2004

Figure 2: Areas impacted by long-track, F3-or greater tornadoes. Note only one large city, Oklahoma City, lies within one of these regions.

online site at http://water.usgs.gov/maps.html. Only streams within counties where long-track strong tornadoes had an origin were included; these areas do not necessarily coincide with the National Elevation Dataset or NLCD land cover boundaries obtained. A rose diagram script authored by Shan Chen (2005) was obtained from the ESRI website at http://arcscripts.esri.com/details.asp?dbid=13473 to aid in the visualization of the orientation data.

Findings

First, the importance of looking primarily at long track strong tornadoes can be demonstrated by examining the tornado statistics within and around these high-impact areas. The importance of discovering any environmental parameter which might increase lead times for warnings and aid in more correctly modeling local vagaries in terrain or land cover is evident from the data presented in Table 1; the impacted areas are in order

Table 1: Tornadoes, Fatalities, and Injuries within 20 KM of High-Impact Areas

Within 20 km	**SoCent MS**	**OK/KS**	**NW LA**	**SE NE**	**NW AL**	**CENT OK**	**N MS**	**TX/ AR**	**IA/MO**	**NC/SC**
Tornadoes (total)	247	127	122	212	179	134	65	58	45	49
Deaths (total)	463	228	45	24	177	60	216	14	9	54
Injuries (total)	5674	1615	892	549	2665	1137	2359	106	161	1413
Long-track F3 or more tornadoes (% total)	30 (12%)	18 (14%)	20 (16%)	23 (11%)	27 (15%)	18 (13%)	15 (23%)	14 (24%)	14 (31%)	11 (22%)
Deaths (long-strong)	406 (88%)	208 (91%)	38 (84%)	18 (75%)	132 (75%)	43 (72%)	206 (95%)	7 (50%)	7 (78%)	28 (52%)
Injuries (long-strong)	4968 (86%)	1287 (80%)	492 (55%)	291 (53%)	1686 (63%)	775 (68%)	2205 (93%)	86 (81%)	151 (94%)	997 (71%)

of their tornado path density, high to low, i.e., the South Central Mississippi area has the highest long/strong tornado density in the country, a finding that matches that of Broyles and Crosbie (2000). Due to differences in the datasets, other findings vary somewhat, but for the most part closely match those found in these authors' work, including southeastern Nebraska, northwestern Louisiana, central Oklahoma, northwestern Alabama extending slightly into Tennessee, northern Mississippi, and the North/South Carolina border. Where they differ is Broyles and Crosbie (2000) include an area crossing Springfield, Illinois and one in northeastern Arkansas; while I show high numbers, they are not extreme. My map includes a region in southwest Arkansas/northeastern Texas and a separated region in north-central Oklahoma and south-central Kansas that do not show in the former authors' work. This replication is reassuring that the methods used by both are sound.

Topography

Figures 3 through 12 are three-dimensional renderings of the tracks of long/strong tornadoes that entered the high-density area, touchdowns of long-strong tornadoes

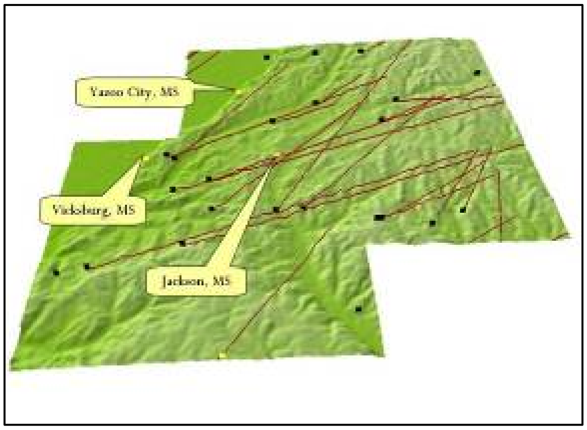


Figure 3: South-Central Mississippi; elevation range from 2 (dark green) to 221 meters (light greens).

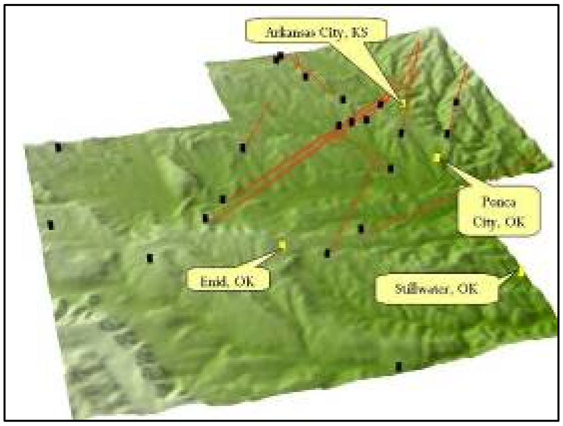


Figure 4: North-Central Oklahoma/South-Central Kansas; elevation range 250 to 601m.

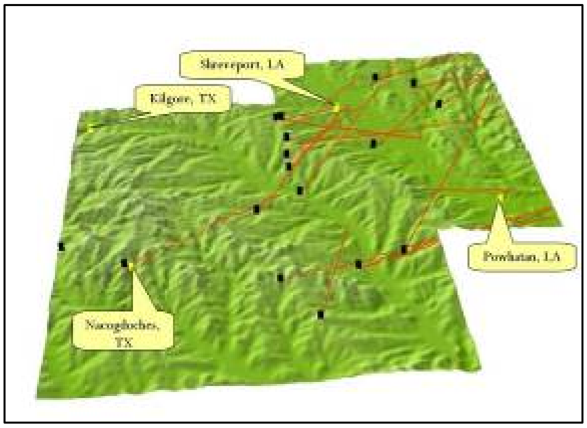


Figure 5: Northwest Louisiana/E Texas; elevation range 24 to 221 meters.

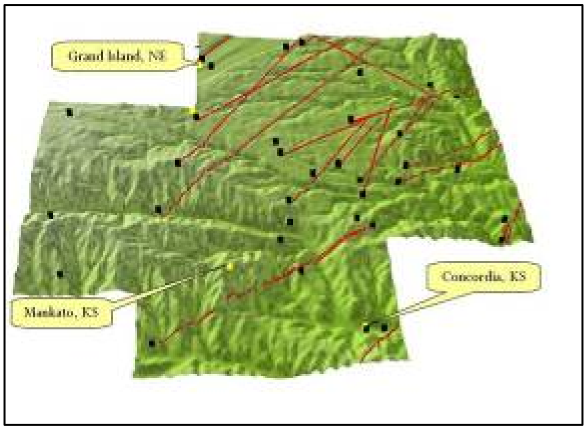


Figure 6: SE Nebraska, NE KS; elevation range 351 to 686 meters.

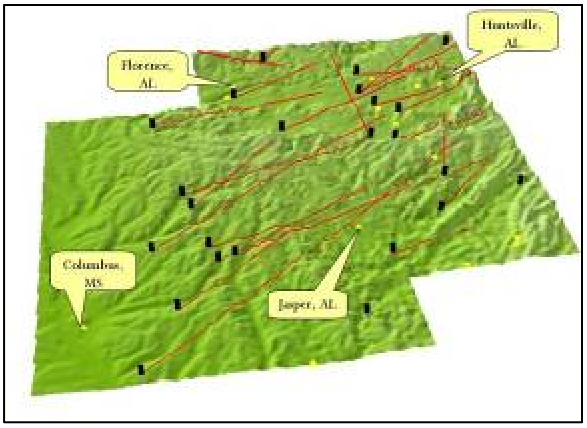


Figure 7: NW Alabama/NE MS; elevation range 27 to 501 meters.

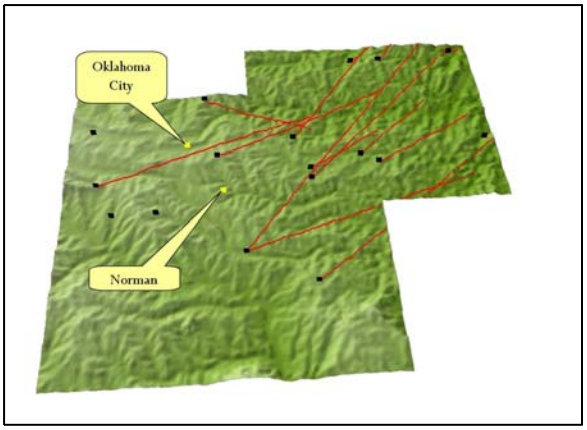


Figure 8: Central Oklahoma; elevation range 184 to 473 meters.

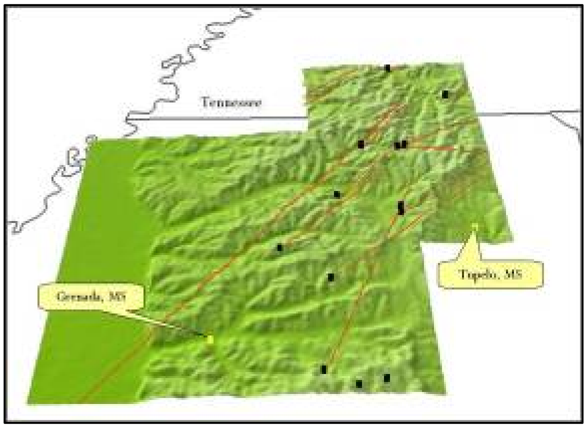


Figure 9: N Mississippi/SE Tennessee; elevation change 30 to 242 meters.

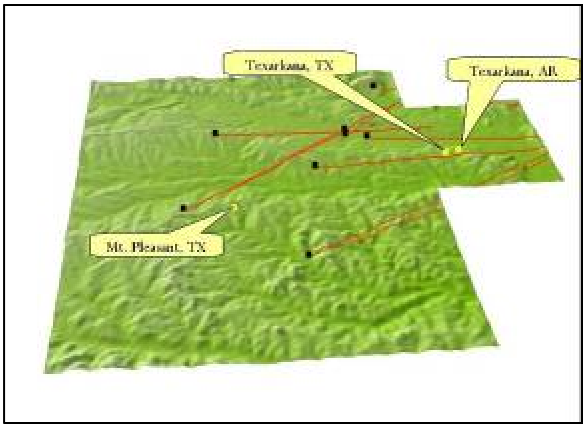


Figure 10: NE Texas/SW Arkansas; elevation change 49 to 207 meters.

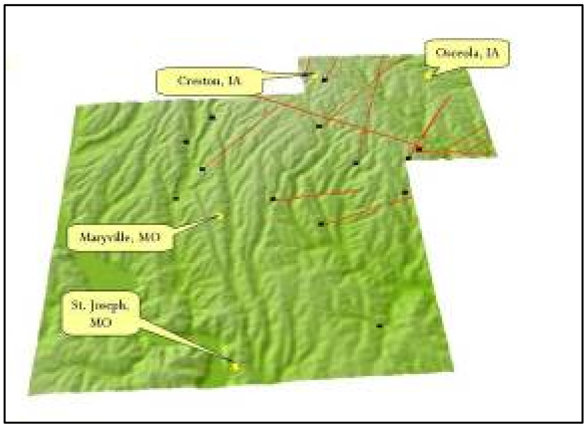


Figure 11: SW Iowa/NW Missouri; elevation change 223 to 417 meters.

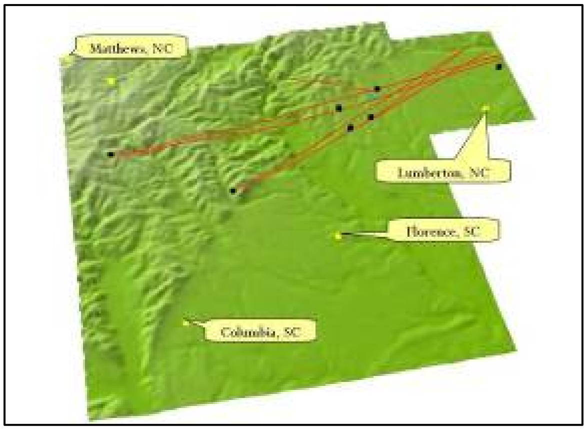


Figure 12: SE North Carolina/NE South Carolina; elevation change 2 to 249 meters.

and reference cities overlain on the elevation surface. Visualizing these areas shows that almost all are crossed by major river valleys; many of these valleys appear to run somewhat perpendicular to the direction of parent storm/tornado trajectory; there is an area of elevation change in each area, often considerable given the surroundings (i.e., from 2 to 249 in the North/South Carolina ‘hotspot’ area).

It was not easy to determine if valleys as a rule run perpendicular to tornado tracks. While it is easy enough to obtain a mean direction or orientation with ArcInfo, obtaining vector lines without tracing each valley bottom was not. I settled for using a USGS stream file as a proxy. This was less than satisfactory because it included small streams with little elevation change, but for a preliminary analysis it did well. The following rose diagrams (Chen, 2005) show the orientation of both tornado tracks and streams in the region delimited by all counties which had long-strong tornado touchdowns, again in the order of highest to lowest density of long-strong tornadoes.

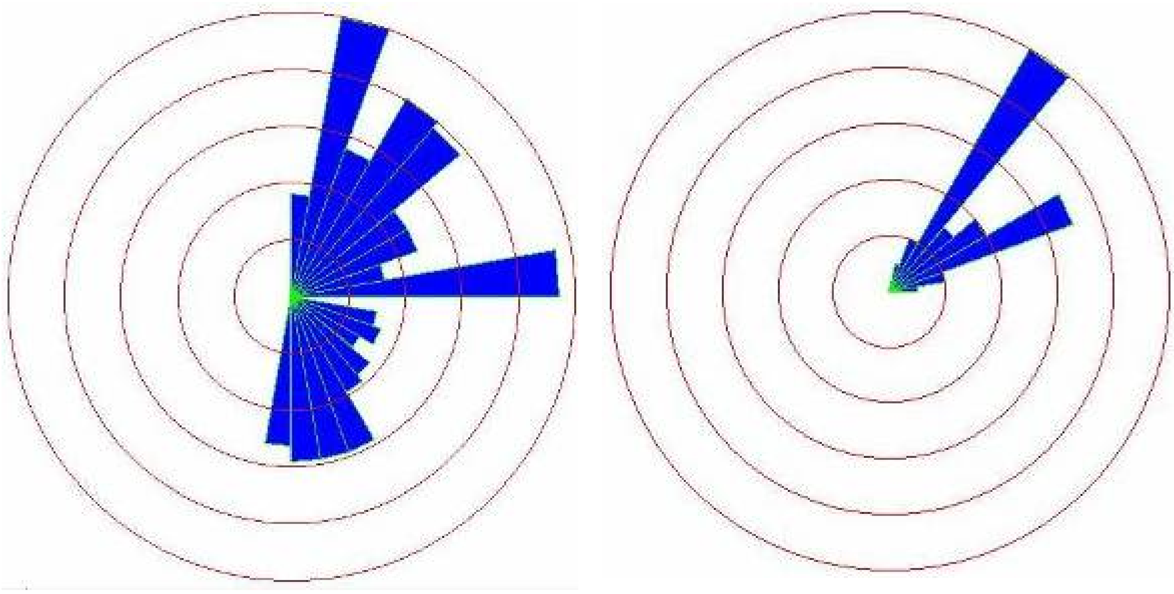


Figure 13: South-central Mississippi shows most tornadoes (right) travel parallel or between the orientation of most river valleys (left). The easterly-trending valleys might funnel southeasterly winds, increasing shear, but there is weaker support for either horizontal rolls or shear.

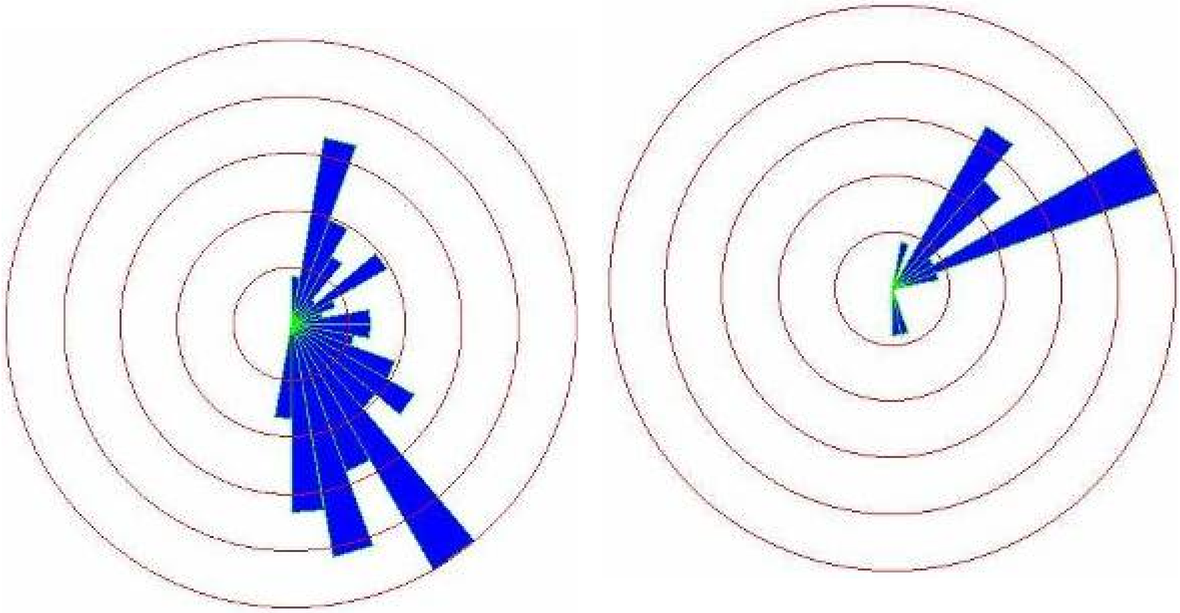


Figure 14: An example of trajectories that are nearly perpendicular from the north-central Oklahoma/south-central Kansas hotspot; this configuration could support both horizontal rolls and strongly increased shear.

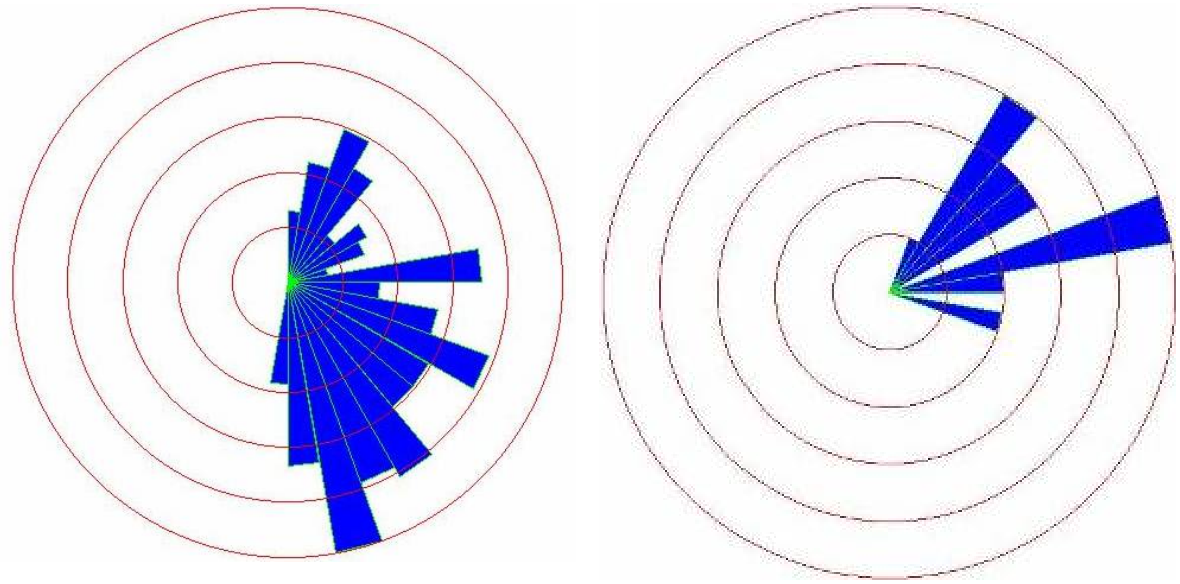


Figure 15: Unlike other southern locales, northwestern Louisiana also displays a highly perpendicular orientation of streams (L) versus tornado trajectory (R).

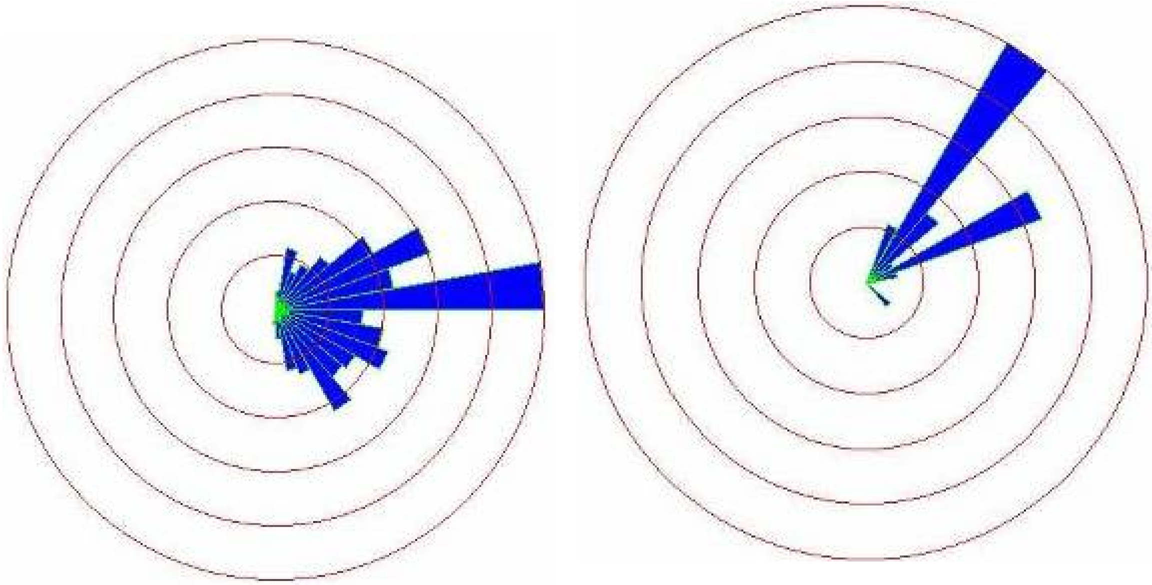


Figure 16: Nebraska-Kansas hotspot river valley orientation (L) and tornado travel direction (R). Again, enhanced shear is possible here; a southeasterly wind might be funneled in an easterly direction, while storm movement is almost due northeast.

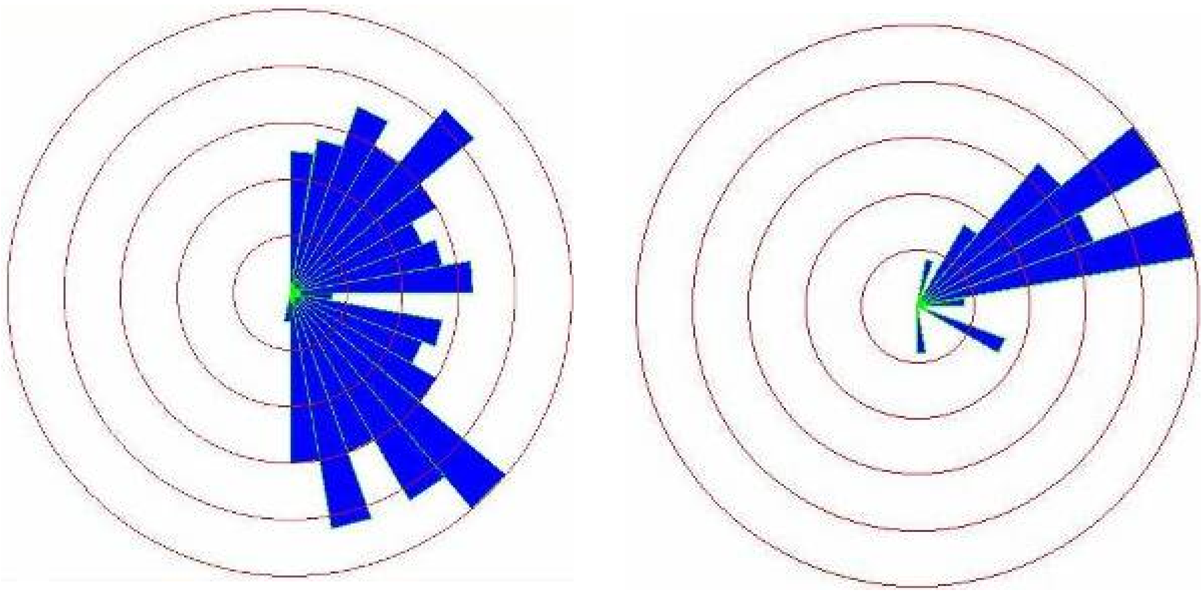


Figure 17: Northwest Alabama hotspot; while more variety in stream orientation (L), there is still a great number which are perpendicular to tornado trajectory (R). A better operationalization of valleys would help in the South, where rivers abound.

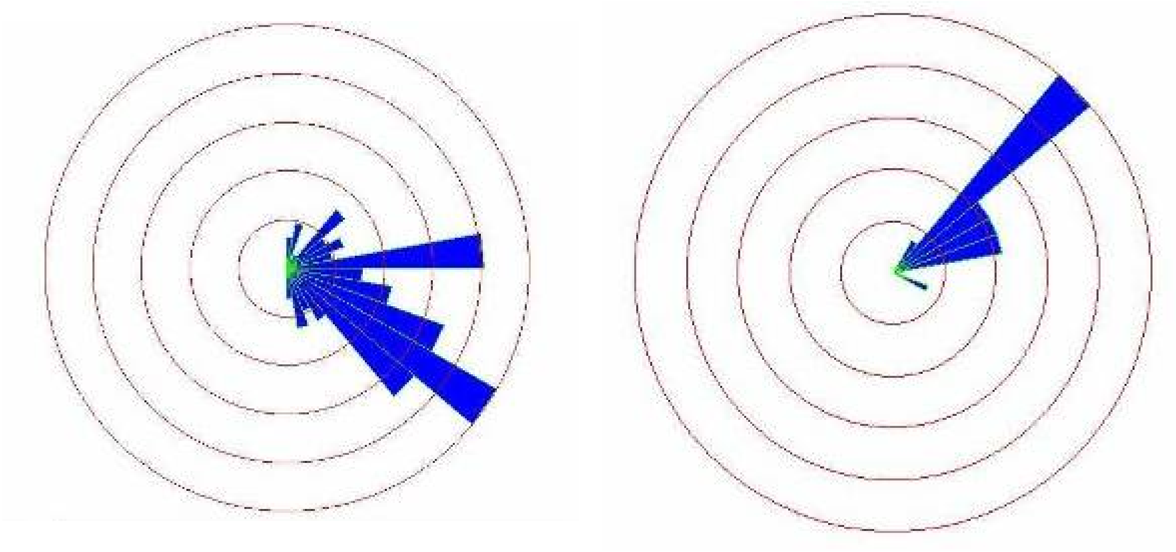


Figure 18: Central Oklahoma streams (left) and Central Oklahoma long-track, strong tornadoes (right); like north central Oklahoma, these tornadoes do tend to cross stream channels in a perpendicular fashion.

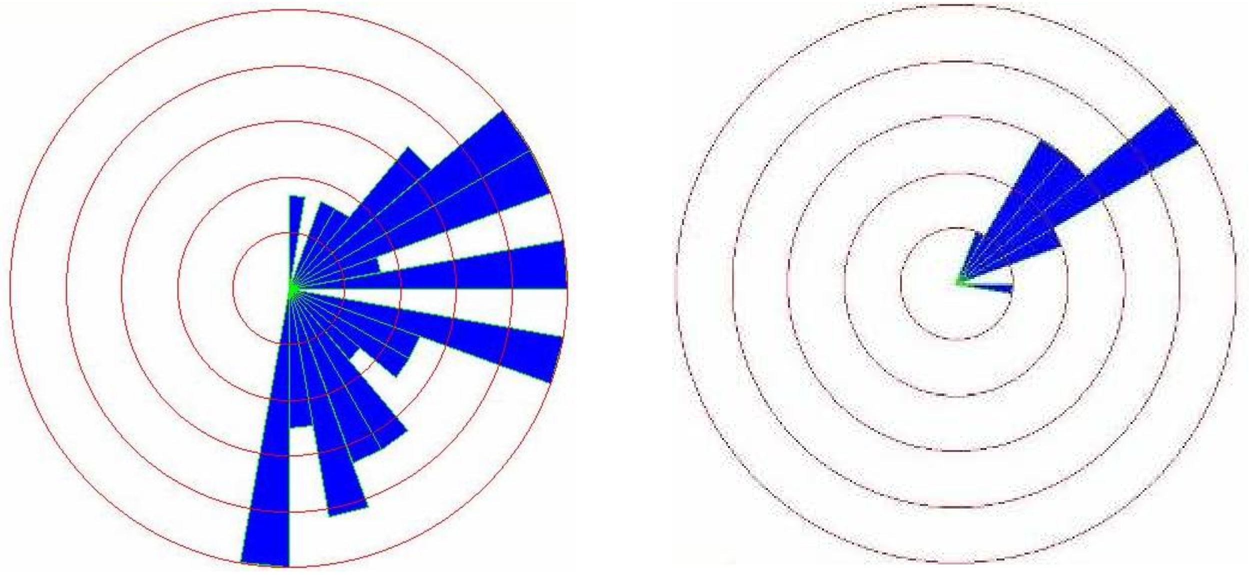


Figure 19: Northern Mississippi crosses many waterways; viewing this figure in conjunction with Figure 9, it seems most *major* waterways are more or less perpendicular to tornado trajectory (R).

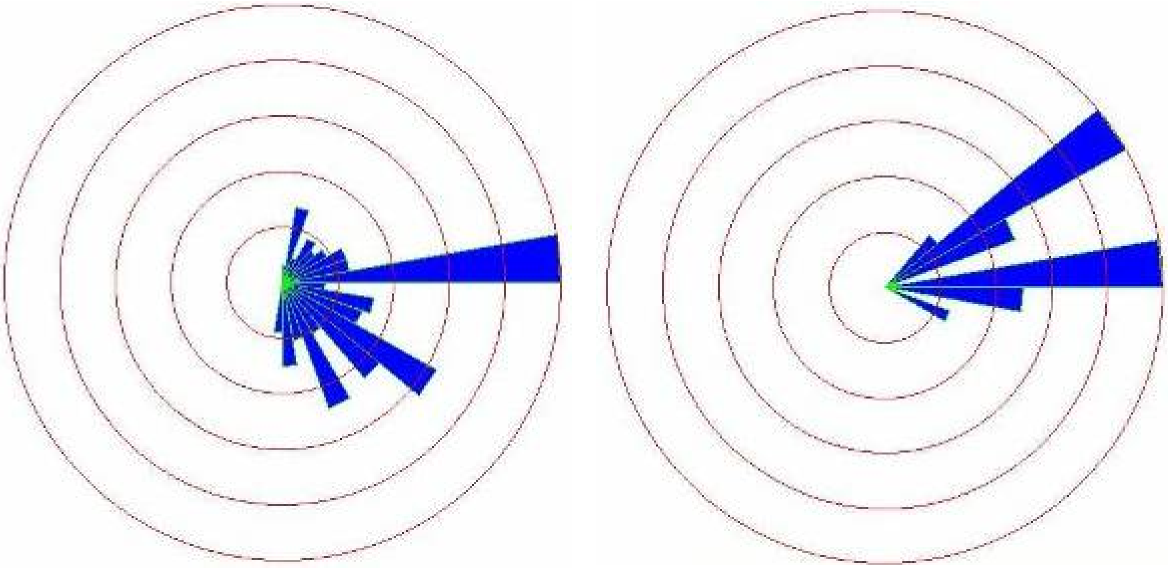


Figure 20: However, here in the Southwest Arkansas-Northeast Texas hotspot, the streams seem parallel (for the most part) to the tornadoes. This area, while in a major river valley (the Red), does not lend support to either theory.

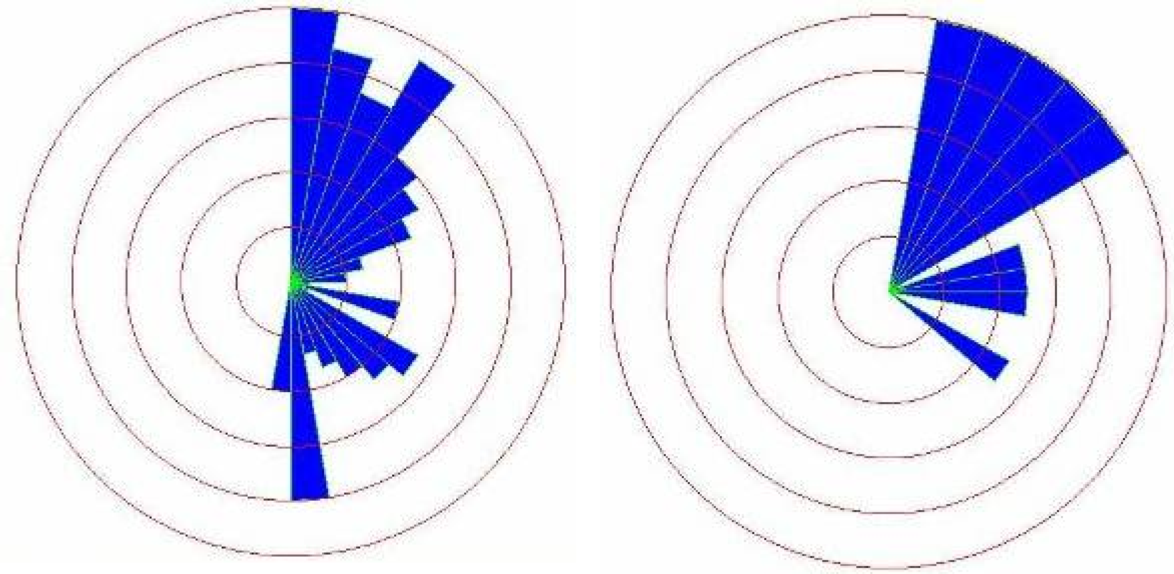


Figure 21: Iowa-Missouri area stream orientation (L) and long/strong tornado direction. Here we see a more parallel orientation; looking at Figure 11, more major waterways run due N/S, so there is some support for shear, but it is weaker than in other Plains areas.

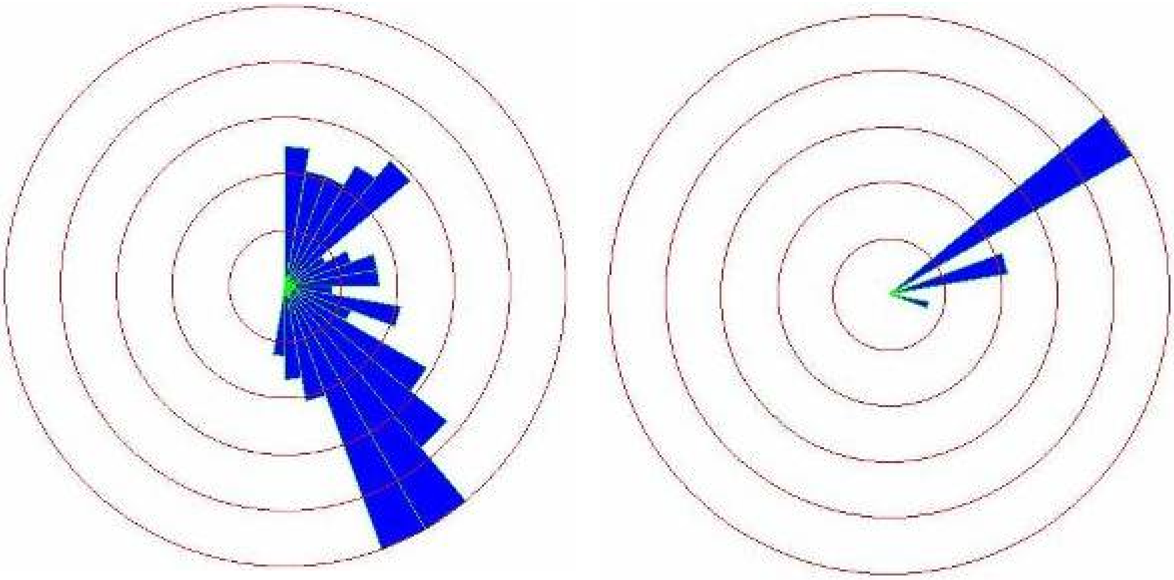


Figure 22: North/South Carolina border hotspot tornado trajectories and river valley orientation (left). Once again, predominant river orientation is nearly perpendicular to tornado trajectory.

In conclusion, there is a considerable amount of evidence that valleys, particularly perpendicular to the direction of storm movement, increase shear and/or possibly are responsible for horizontal convective rolls enhancement. Since all of the high-risk areas in this paper are in an area of incline, it is possible these rolls could be in part responsible.

In order to look more closely at changes in the pre- and post-tornado environment, I extended the tornado paths 50 kilometers out (approximately one hour) from touchdown in two study areas: the Nebraska/Kansas high-impact zone, and the south-central Mississippi zone. Because these zones are different climatologically and thus have different vegetation, topography, soils, etc., findings that show marked changes in both would be more meaningful. As noted in the methodology section, the mean and range of various raster values was assessed for both the 50-kilometers leading up to touchdown and the entire path subsequent to tornadogenesis.

For the Nebraska/Kansas study area, the results are as follows: mean elevation pre-touchdown is 514 meters, with an average range of 66 meters. After touchdown, the mean elevation is 488 meters, with a range of 71 meters. There is some evidence tornadoes form as the parent storms move off of higher terrain; the rougher terrain visible in Figure 4 in the *pre*-tornado environment is not reflected. In only two cases are tornadoes on higher terrain after touchdown. The mean slope is 1.89 before touchdown, and 1.65 after, and range of slope is very close; very little information is given here. In Mississippi, the mean elevation for pre-touchdown environment is 86 meters, while post-touchdown is 104 meters, the opposite of Nebraska/Kansas. Further, no tornadoes begin on lower ground in this region. We could see evidence of horizontal convective roll enhancement west of the tornadogenesis area at the east bank of the Mississippi, but the rougher terrain (the range of elevations is also greater) east of the Mississippi could be funneling southerly winds to increase shear *or* the vegetation change from the flat Delta landscape to the ‘Piney Woods’ may enhance convection, discussed in detail below. The mean slope is *greater* prior to touchdown (3.01 v. 2.45), indicative of the aforementioned rise.

Land Use/Land Cover

The first comparison was between the land cover in areas considered to be “pretornado,” or over which tornadogenesis begins, and is shown in Table 2. It includes the octants derived from the directional means of the tornado paths, shown in Figure 2. There was not much to support a change between the two regions: five high-impact areas were the same majority land use/land cover. It is interesting to note, though, that the two regions with the *highest* long-strong tornado density had different pre- and post-tornado land cover; south-central Mississippi changes from forest to pasture/hay, while north-central Oklahoma/south-central Kansas supports possibility that natural v. planted vegetation enhances convection, as the pre-tornado environment is predominantly small grains and the post-touchdown environment is grass/herbaceous vegetation. Northwest Louisiana is fairly uniform across the pre- and post-touchdown environs; close

Table 2: Majority Land Use/Cover in Impact and Tornadogenesis Areas

	SoCent MS	**OK/KS**	**NW LA**	**SE NE**	**NW AL**	**CENT OK**	**N MS**	**TX/ AR**	**IA/MO**	**NC/SC**
North Octant	41 Decid forest	83 Small grains	81 Past/ hay	82 Cult. crops	41 Decid forest	71 Grass/ herb	41 Decid forest	81 Past/ hay	82 Cult. crops	42 Everg forest
South Octant	42 Everg forest	83 Small grains	43 Mixed forest	82 Cult. crops	41 Decid forest	71 Grass/ herb	82 Cult crops	81 Past/ Hay	81 Past/ hay	82 Cult crops
Impact Area	10 Past/ hay*	71 Grass/ herb	43 Mixed forest	82 Cult. crops	41 Decid forest	71 Grass/ herb	41 Decid forest	81 Past/ hay	81 Past/ hay	42 Everg forest

* 2001 LULC data was available for areas in Mississippi; codes are different

examination of the pattern of touchdowns here shows a majority are at the border between Texas and Louisiana before it becomes the Sabine River, perpendicular to the direction of storm travel. Perhaps Shreveport NWS verification teams prefer not to leave the state when looking for touchdown sites; otherwise, there is no explanatory variable that can be found in my data that explains this configuration.

As above, changes in the pre- and post-tornado environment were assessed for both the 50-kilometers leading up to touchdown and the entire were path subsequent to tornadogenesis. These two areas are shown in Figures 23 and 24. Figure 23 shows that generally, there is a considerable change in land use in Nebraska/Kansas from grassland/herbaceous vegetation, which is likely natural, to cultivated crops, and Figure 24 shows an even more marked change from cultivated crops to forests and pastures in Mississippi as one moves east from the Mississippi River.

For land cover, the zonal statistics summary of findings is as follows:

Nebraska	Majority Land Cover
Pre-tornado	15 cult. crops
	4 grass/herb
Post-touchdown	21 cult crop
	2 grass/herb

Mississippi shows almost no change between pre and post touchdown trajectories; both majorities are evergreen forest (pre = 12 and post = 14). Of the five Nebraska/Kansas tornadoes that varied in majority cover pre- and post-touchdown, all went from cultivated crop to grass/herbaceous vegetation; of 16 of the 29 pre- to post-touchdown changes in Mississippi, 9 are from crop or pasture to forest of some type.

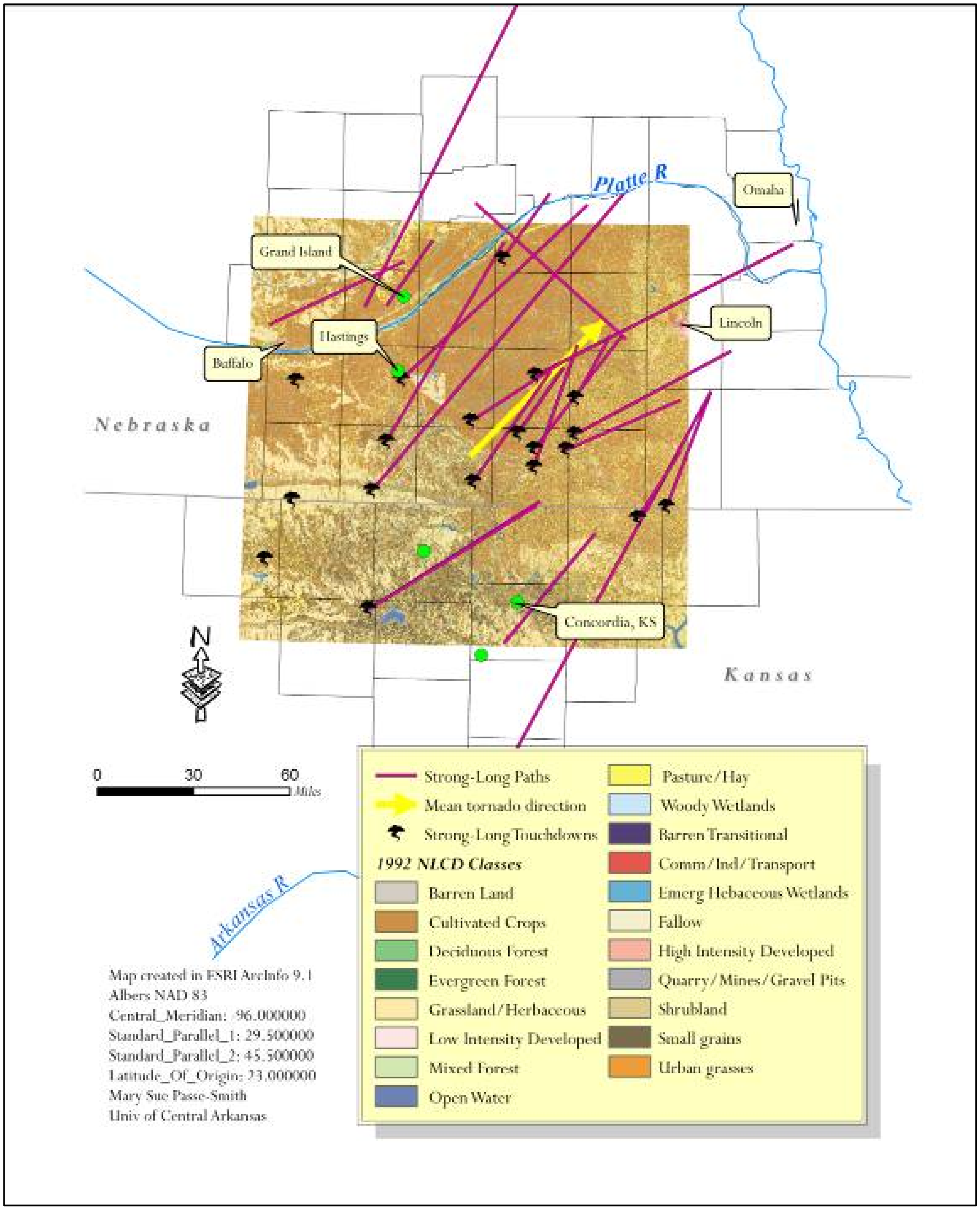


Figure 23: Nebraska/Kansas high impact tornado area, with land use/land cover data, all F3 or higher, over-20 mile tornado paths and touchdowns (no liftoff data included), the directional mean travel of tornadoes, and reference cities.

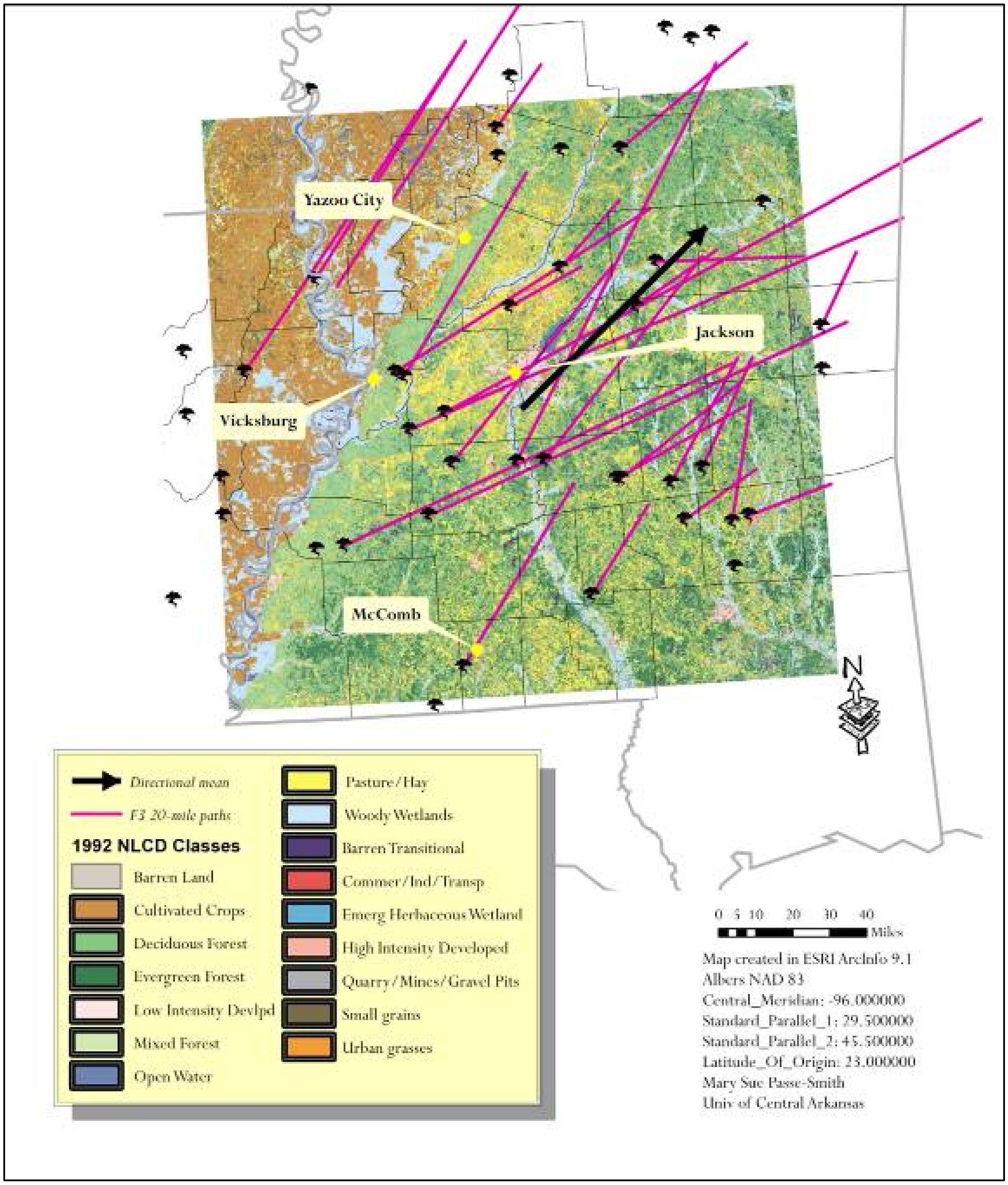


Figure 24: South-Central Mississippi high impact tornado area, with land use/land cover data, all F3 or higher, over-20 mile tornado paths and touchdowns (no liftoff data included), the directional mean travel of tornadoes, and reference cities.

There is thus weak support here for vegetation change encouraging tornadogenesis, but, with all the caveats related to the veracity of the data itself, is certainly not strong enough to say anything more about. The border-instigated tornadoes in Northwest Louisiana, for example, call into question reporting practices that might reflect jurisdictions rather than actual touchdown sites or are simply coincidence. A very clean tornado data set, more geographically and temporally specific pre/post environments inclusive of the entire pre/post tornado tracks, and better operationalization of all parameters, especially valley alignment, would be the next steps in this study. With that in mind, a micro-study of each area, with close examination of the tornado data using media and other sources; correction of errors; correct operationalization of the pre-tornado and post-tornado environments; the inclusion of soil data or surface geology (excluded from this study due to the size and differences in availability of soil data), would all be in order before any definitive statements could be made about similarities between U.S. tornado alleys.

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Oklahoma data

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Data source Iowa

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