Modeling the Tornado Threat in Arkansas with GIS

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ABSTRACT

Past efforts to explain Arkansas' relatively high tornado fatality rates using geographic methods conclude that many of Arkansas' population centers are, evidently coincidentally, located in local 'tornado alleys.' This distribution might simply reflect a bias in reporting due to the rural nature of the state. When evaluating personal risk, the public's sole information source is often media displays delimiting "Tornado Alley," most of which exclude Arkansas. Utilizing ESRI's Spatial Analyst extension and statistical analysis, I will test the above hypothesis by demonstrating the relationship between population (density of settlements and census blocks) and tornado reports. An attempt will then be made to model the actual distribution by assuming an even distribution of population and analysis of anomalous regions (i.e., high tornado/low population) to determine if features such as elevation, slope, aspect, or land use might aid in modeling tornado distribution.

The Problem

The focus of this research is to review the distribution, risk, and factors such as topography and land cover and their relation to the formation of tornadoes in the state of Arkansas in order to create a model of tornado risk within the state. The problems related to risk analysis are not trivial; since the stated goal of the National Weather Service is to save lives, portraying risk, even crudely, to the public is a major concern. But what goes on behind the scenes among those responsible for forecasting and informing the public is an interesting and ongoing debate over the ability to obtain accurate data. A recent *National Geographic* article's title spells out the importance of such questions clearly: "To do good risk analysis, you have to know how often bad things happen," summarized with a statement that knowledge of true risk occurrence rates shapes personal choices and can affect how public resources are used (Warren, 2003).

Most risk maps available to the general public do not include Arkansas in a high tornado risk area, or in "Tornado Alley." Online and print media sources such as *The Weather Channel*, *USA Today,* and *Places Rated Almanac* either leave the state out entirely or do not include hazards in consideration of the attractiveness of a place to live. Even experts disagree or give somewhat confusing information; for example, University Corporation for Atmospheric Research (UCAR) educational website at http://www.windows.ucar.edu shows a map of "Tornado Alley" as the Great Plains states, with Arkansas and many other Southern states in "common areas" of tornado occurrence, but states in the caption that "most of the tornadoes in the southern United States near the Gulf of Mexico are the result of hurricanes." If one considers him or herself in "the South" the importance of the caveat "near the Gulf of Mexico" could easily be lost, and the definition of "near" is also questionable. Intensive research might result in the eventual collection of sufficient information considered reliable enough with which to construct an accurate map of this so-called "Tornado Alley," but the general public does not normally read research papers in scientific journals and weigh all of the facts.

Mark Monmonier stressed in *Cartographies of Danger* (1997) that people should be armed with a 'proceed with caution' or 'no-go' map, but those that exist are often highly misleading. For example, many use a "high-medium-low" risk format which allows the viewer to interpret "low" as "no" if that is where they want or need to live; isarithmic maps do not define what lies between an area of three and five tornadoes–are there four? None? Twenty-seven, but no one to report them? He argues that these misreadings can be a fatal mistake in that a feeling of relative safety could result in complacency. In the early twenty-first century, Arkansas ranks only fourteenth in number of tornadoes, and tenth in tornadoes per square mile and tornadoes per year from 1950 to 1997, for 1950-2002, but ranks fourth in total deaths and deaths per square mile; third in per-tornado fatalities, and second per 100,000 population, using the average population over the period 1950-2000.

Daniel McCarthy (2003), of the Storm Prediction Center, feels the public storm database, "Storm Data," is not complete or, at times, useful. These facts are reiterated by Greg Stumpf and Caren Marzban of the Severe Storms Lab in a recent assessment: "Tornado verification is problematic in… regions with low population density, and mountainous and forested regions where access to damaged areas can be restricted" (2000, p. 130). Many authors (for example, Grazulis *et al*., 1993; McDonald and Allen, 1981; Grazulis, 1993 and 1991) believe Arkansas specifically has experienced far more tornadoes than are reported in the database. They also note that problems with verification likely compound as one moves back in time, making the data increasingly unlikely to be representative of reality. This leaves those assessing risk with the awkward situation of basically having to model data with which to model; in other words, extrapolate from known data. The use of Geographic Information Systems (GIS) to aid in the understanding of the distribution is lacking in the literature and yet these tools allow depiction of the earth's surface at a scale never possible in the past. This study will utilize the abilities of GIS to grid data and statistically explore several hypotheses that relate topography and land use/land cover and soil type to tornado distribution, as well as explore the use of population to help predict where tornadoes might occur. The resulting findings will hopefully produce a more complete model of tornado risk in Arkansas.

The Population Issue. If the distribution of population has affected tornado counts in Arkansas, why not, as Grazulis *et al.* (1993) have done, use the areal density of tornadoes in the most populated county in the state, Pulaski, and extrapolate this figure to the state as a whole? This method produces a figure of 2037 as opposed to the reported 597 from 1959-1989, which seems overstated. It also does not take into consideration any physiographic reason for a lack or inducement of tornadoes. However, the use of elevation and slope as variables related to the instigation of tornadoes suffers from the issue that these variables are also strongly related to settlement of humans, as well as with land use. Both tornado touchdowns and population occur at statistically significantly lower elevations and slope percentages than would be expected given the background values (Passe-Smith, 2004), and because populations are necessary for the reporting of tornadoes and are, indeed, by far the most highly correlated variable with tornadoes, it becomes almost impossible to separate out which influences which. Further, this elevation connection could bring into play the differences in vegetation and agricultural usage in valleys as opposed to areas with high relief. This factor, or evidence to contradict it, must be considered; a brief look at the origin and physical distribution of tornadoes follows.

A Brief Review of Literature on Tornadogenesis

The three major environmental conditions necessary for a supercell thunderstorm of the type that produces a damaging tornado are convective available potential energy (CAPE), especially from the surface to a height of three kilometers; change in wind direction and speed with height (shear), including storm-relative helicity in the 0-1km level, and a significant forcing mechanism (Rasmussen, 2003). The CAPE is *potential* energy, or the ability of an air parcel to rise once it can attain the level of free convection. Tornadoes often occur in situations where the atmosphere is "capped" by a layer of cooler, stable air above the surface; if the parcel can break through this layer, explosive convective development can occur in minutes. Rasmussen (2003) states that in recent studies, it has been found that the CAPE in combination with low-level shear is one of the best forecast parameters for tornadic supercells. Supercell thunderstorms can, however, maintain a strong rotation for hours without producing a tornado, and tornadoes can be produced within minimal environmental conditions, including weak shear and low CAPE (Doswell *et al.,*1993; Korotky *et al.,* 1993). Thus, it is apparent that other factors come into play to influence the formation, strength, and longevity of tornadoes. The importance of low-level factors in Rasmussen (2003) points to the possibility that surface features play a role in tornadogenesis.

Topography. One reason cited for the uneven distribution of tornadoes in Arkansas is the diverse topography of the state (Hehr and Baldwin, 1985, for example). Grazulis (1991) also puts forth the possibility that the clear tornado maximum he depicts along the I-40 corridor in the Arkansas River Valley might be related to relief, and that the valley itself may actually cause thunderstorms to produce tornadoes. Rydell and Kloesel (2003) observed radar images which showed local intensification of storms as they moved over southward-opening valleys in the Hill Country of Texas in six of eight cases they studied. Doswell (2001, 1982) also stresses the importance of small scale terrain-related phenomena which enhance convection on a local scale, as well as the difficulty in pinning down a near-chaotic state of affairs at the surface. He mentions specifically (2001) topographic effects on convective development such as horizontal mesoscale vortices created by wind interacting with terrain and flow changes associated with differences in surface roughness, but cautions that the line between a major outbreak of severe convective weather and no convection at all might be associated with very small differences in very spatially specific surface features. Gibson and VonderHaar (1990) found that convection is enhanced across upsloping features of relatively small rise (i.e., 180 meters across 9 kilometers or less) at the Alabama-Tennessee border during summer, and areas of low elevation that are bodies of water or swamps are *not* favorable for cloud development in the summer, as they are usually cooler than the surrounding air. Ray *et al.* (1995) used Doppler radar data in North Carolina to reveal numerous pre-existing boundaries associated with sea breezes, outflows, thermal and moisture discontinuities, orographic features, and horizontal rolls which triggered increased convective activity in 94 percent of the cases they studied. Since convection has been shown to be enhanced in areas of relatively small rise in other areas of the Southern U.S., topography will be included in the modeling process.

Land Use and Land Cover Patterns. Closely related to the above findings are those which focus on the effect of abrupt surface changes in land cover as one important variable in instigating or strengthening convection. Esau and Lyons (2002) show remarkable images illustrating the effect on the atmosphere of the “Bunny Fence” in southwest Australia, where the abrupt change in vegetation from natural eucalyptus-scrub to wheat fields produce convective clouds within one kilometer of the fence on the natural vegetation side. There is no difference in topography on either side of the fence: soil type and elevation are identical. Raddatz and Cummine (2003) connect interannual variability in evapotranspiration rates and the number of tornado days in the Canadian prairie agricultural region. These differences are postulated to be related to changes in magnitude of the CAPE resulting from evapotranspiration of wheat; in mid-July of 2000 CAPE was found to increase from 1850 to 3500 $J\ kg^{-1}$. A change of this magnitude sharply raises the potential for severe weather and possibly tornadoes from minimal to high. Their regression equation of moisture flux apparently resulting from changes in spring wheat phases of growth and their accompanying evapotranspiration rates with tornado days has an R^2 of .84, quite high. In differing annual regimes–cool, moist summers, hot dry summers, etc.–the number of tornado days stayed more closely in step with the wheat phenology than with any other factor. Their findings indicate that at different times of year the stage of crop development must be considered when using land cover as a variable in models; they also find that stomatal conductance plays the predominant role in the redistribution of energy into the boundary layer above vegetative surfaces. White *et al*. (2000) state that there are major differences between agricultural and natural vegetation when considering stomatal conductance, but not between natural types; this finding will help operationalize the land cover variable in the proposed model.

Weaver and Avissar (2001) show convincingly that over an area 250 kilometers square in Oklahoma and Kansas, almost flat to remove any possible influence of topography, that diurnal thermally induced circulations occur, the driving force of which is the heterogeneity of the land cover resulting from differential uses of the land. These thermal changes are completely independent of unusual large-scale conditions but can significantly affect large scale weather.

In environments where tornado probability is considered low, it is thought that some small-scale process can create a local environment that can induce tornadogenesis; since 95 percent of tornado days are not synoptically evident, local effects are quite important. Indeed, Xue *et al*. (2001) describe the successful integration of vegetation type, coverage, and leaf-area index, among myriad other variables, using satellite images and the Normalized Difference Vegetation Index (NDVI), as well as soil type, into the ARPS to predict with resounding success, among other events, the January, 1999 tornado outbreak in Arkansas. In that the surface moisture budget and, thus, CAPE, are reliant upon vegetation as well as humidity, dew, previous precipitation, and soil moisture, sharp vegetative and/or soil boundaries could very well mark areas of increased intensification at the convective storm level. Thus, an attempt to connect tornado touchdowns to land use variability and, to check for moisture-holding capability, soil types will be made; further, different seasons will be examined in that leaf conductance changes across time. Increased surface roughness associated with buildings has also been proposed as a factor increasing convection and precipitation in urban areas (Diem and Brown, 2003); urban land use may thus prove to be a factor for reasons other than increased reports due to increased population density.

Methodology

In order to use the population issue as a predictor, I first used ArcView Spatial Analyst to calculate the number of tornado touchdowns per census tract; 392 tracts had touchdowns and 231 had none. I extracted the data for each tract into Microsoft Excel to analyze, using linear regression, the relationship between increased population, quantified as houses per square mile and increased touchdowns per square mile. I also looked for patterns of correlation of touchdown numbers with different land use predominance or variety within each tract. These findings will help guide model construction.

To construct a model based on the above literature, I utilized the following statewide data sets:

- Fall, 1999 Land Use/Land Cover (LULC) from the Arkansas Soil and Water Conservation Commission and the University of Arkansas' Center for Advanced Spatial Technologies (CAST). This map depicts the land use and land cover of Arkansas as it occurred in the fall of 1999, and is derived from Landsat TM 5 scenes and extensive ground-truth information. The actual dates of the photos used to construct the Fall, 1999 LULC are 9/9/1999 through 11/16/1999. Thus, only tornadoes occurring during those dates (albeit for all years) will be selected for study. The data were available through the State of Arkansas and CAST's GeoStor free spatial data clearinghouse.

- Spring, 1999 LULC, which encompasses a one-month period. **Beginning_Date**: 4/7/1999; **Ending_Date**: 5/7/1999. As above, tornadoes occurring between those dates (not year-specific) will be studied.

- National Elevation Dataset (NED) from the U.S. Geologic Survey (USGS), via GeoStor.

- Tornado touchdowns, 1950-2002. From this set compiled from several sources (Storm Prediction Center, USGS, and the National Climate Data Center), 253 tornadoes which occurred between April 7 and May 7 were extracted for the Spring data set, and 70 tornadoes occurring between September 30 and November 16. The entire set will be used for the final model analysis.

- STATSGO soil map for Arkansas, from the Natural Resources Conservation Service, also obtained through GeoStor. Soils were grouped by Map Unit ID (MUID); those with the same Map Unit name were grouped together; all tornadoes were used in the analysis.

Each of these layers was categorized using Jenks' optimalization via ArcEditor 8.3 and tornadoes within each category were determined using Spatial Analyst's zonal statistics. These were compared with expected values, given the areal proportion of the state in each category (for example, 53 percent of the state is of some type of forested land cover (deciduous, conifer, mixed, etc.) and thus, 53 percent of tornadoes would be expected to occur within the boundaries of this category. A chi-square statistic was then calculated and its significance determined; only those variables which had significant ($p \leq .01$) differences from the background were used, and weights were assigned based on the most different categories (i.e., if "Crop" land use had far more tornadoes than would be expected, it was weighted positively). I constructed one model based on those variable categories with higher-than expected numbers, such as the five soil types with far more tornadoes than would be expected given the land area each encompassed. I also constructed one exclusionary model, based on any area that was *not* in the most negative category. For example, the five soil types that had far fewer numbers of tornadoes than would be expected were excluded; all other soil types were left in the model. Assessment was done in the same manner as weighting: if more tornadoes occurred in the highest weighted categories and fewest in the low, the model was assumed to be successful. The best model was then compared with all touchdowns; areas with high likelihood of tornadoes but without any touchdowns would be a focus point for assessing how many uncounted tornadoes might exist in the state.

Findings

Using data extracted from census tracts, a scatterplot of the natural log of houses per square mile in each tract and the natural log of touchdowns per square mile, both strongly skewed distributions before transformation (Y=touchdowns per mi^2, X=houses per mi^2) is presented in Figure 1, and shows a nearly perfect linear relationship. Indeed, the regression R^2 is .91; an even stronger linear relationship, however, exists between the number of tornadoes per tract and the size of the tract, which recalls the fact that census tracts become smaller as the population density within them becomes larger. Thus, the tracts most likely to report a tornado due to their numbers are so small they might not have actually experienced one. These facts were used to take into account these two variables, with their extremely high R^2, to predict what tornado counts might be like in those tracts currently reporting none, given perfect conditions

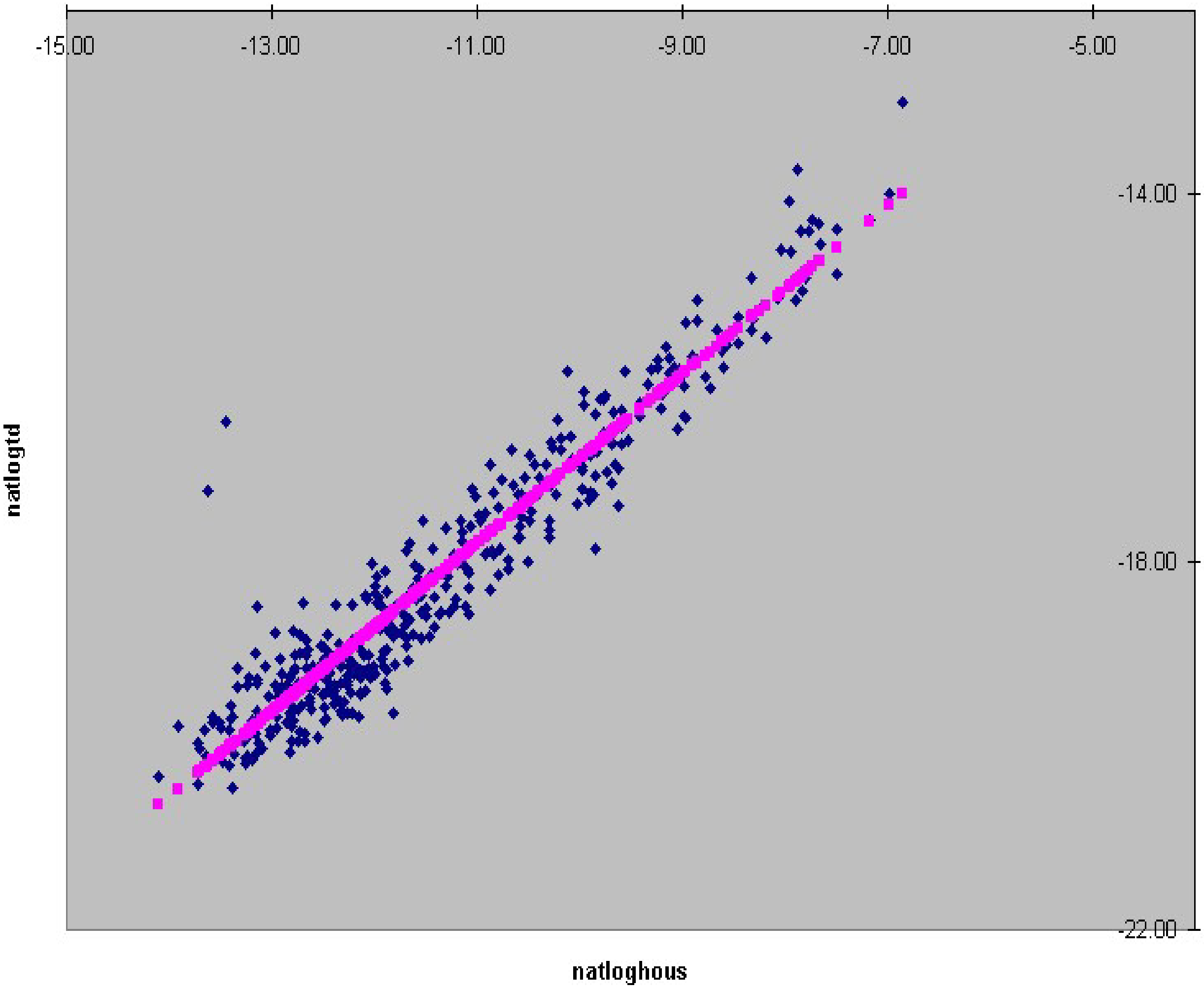

Figure 1: Scatterplot of touchdowns per square mile and houses per square mile.

(good line of sight, the right surface conditions) simply by size of tract and houses per areal unit; the predicted values were done for each variable rather than together. The number of houses per square mile predicted an additional 269 tornadoes, while area size predicted 210. Figure 2 presents the distribution of tornado touchdowns per census tract; the same map with predicted tornadoes is shown in Figure 3; the distribution using area was similar in appearance. I was unable to find a regression equation that predicted well the high end of the distribution; that is to

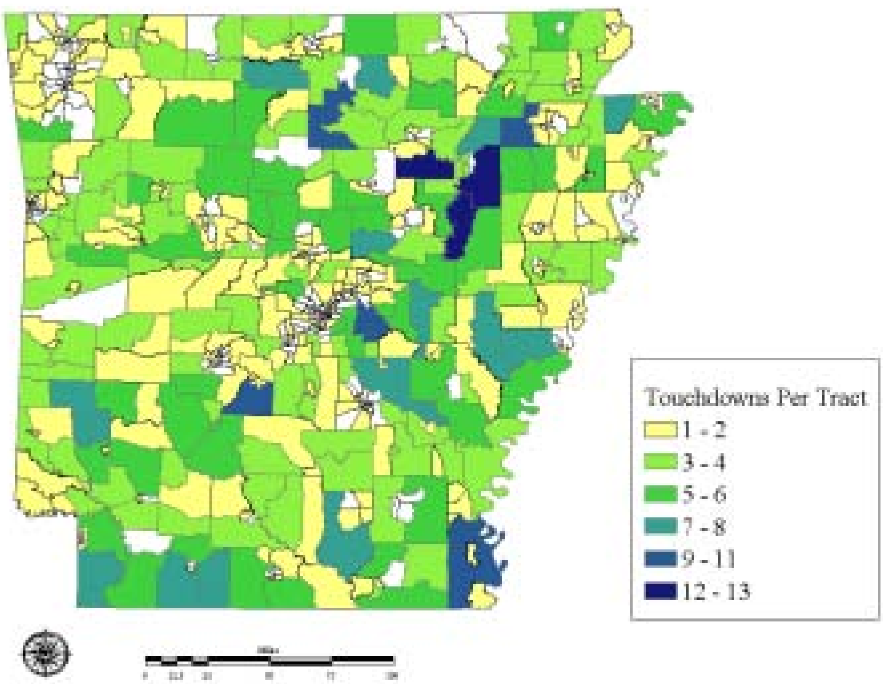

Figure 2: Census tracts by touchdown per square mile; white areas indicate tracts experiencing no touchdowns.

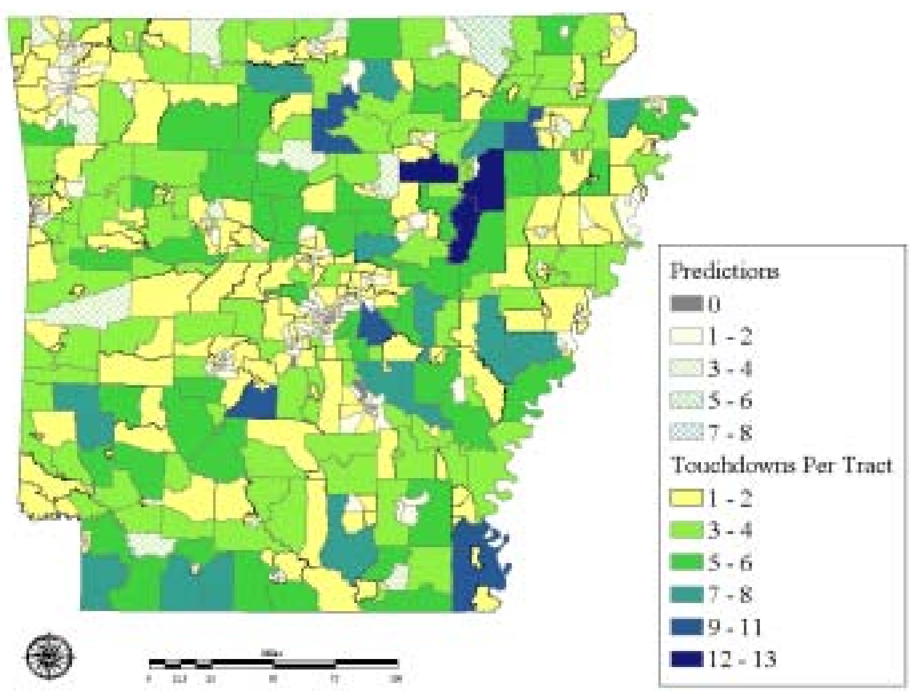

Figure 3: Census blocks with predicted touchdowns added.

say, when the equation did a good job of predicting low and moderate numbers of tornadoes in any tract, it did not do well predicting larger numbers. The above method might predict an additional two or three tornadoes over some of the tracts which previously have recorded none; the reasoning behind this possibility is that tornadoes in some areas are not seen even when people are near, due to poor line of sight. Another method of prediction will be necessary to capture the tornadoes uncounted due to a lack of human settlement.

Variables in the Model

Soils. The findings from the soil study are shown in Table 1; the chi-square statistic (228; $p < .0001$) is the strongest of all those tested, and thus the soil layer will receive the largest weighting (5). While no real characteristic stood out in the soils found to have extraordinarily high or low numbers of tornadoes per areal unit, there was a tendency for those with more than expected tornadoes to be sandy with more silty-loam, while those with fewer tornadoes were well-drained. Moisture content is the finding most likely to have an effect on tornadogenesis, so this would be in keeping with the literature. The table shows only those soil units with 10 or more tornadoes present or absent; one of the units missing tornadoes is water, as has been suggested by some authors (Gibson and VonderHaar, 1990) due to its relative coolness and consequent sinking air.

Land Use/Land Cover. The findings on land use/land cover (hereafter LULC) are shown in Table 1. Both spring and fall LULCs showed two categories with expected values different enough to affect the significance of the chi-square statistic: urbanness and forest. I have included only the larger spring breakdown in the table. Again we are faced with the reporting issue; is population the sole reason for the increased numbers? The 40 extra urban tornadoes are almost all missing from forested areas of the state, which could lend support to the notion that areas

Table 1: Soil Units and Observed v. Expected Tornado Touchdowns				
Soil Assoc Name*	Touchdown Frequency	Expected Proportion	Expected Frequency	Difference
Leadvale-Taft-Cane	73	0.030	33	+40
Linker-Mtnberg-Enders	73	0.039	43	+30
Smithdale-Savannah-Sacul	63	0.041	44	+19
Foley-Jackport-Crowley	49	0.031	34	+15
Rilla-Hebert-Perry	37	0.020	22	+15
Dundee-Sharkey-Bosket	40	0.025	27	+13
Amagon-Dundee-Sharkey	26	0.014	16	+10
Clarksville-Nixa-Captina	22	0.011	12	+10
Guyton-Amy-Ouachita	33	.041	45	-12
Enders-Linker-Mtnberg	9	.021	23	-14
Gepp-Doniphan-Agnos	21	.034	37	-16
Sharkey-Alligator-Tunica	26	.039	43	-17
Clarksville-Noark-Nixa	30	.046	50	-20
Carnasaw-Clebit-Sherless	73	.089	97	-24
Enders-Nella-Mtnberg	54	.084	91	-37

$\Pi^2 = 228$; $p < 0.000000001$

*Includes only those soil groups where difference between observed and expected was 10 or greater.

Table 2: Classified Spring Land Use/Land Cover and Observed/Expected Touchdowns					
Class	Code	Touchdown Frequency	Expected Proportion	Expected Frequency	Difference
1	Urban	45	.020	5	+40
2	Bare/Fallow	47	.19	48	-1
3	Water	5	.03	8	-3
4	Forest	92	.53	135	-43
5	Crop	10	.02	6	+4
6	Pasture	54	.20	51	+3
Totals		253	1	253	
$\Pi^2 = 328$; $p < 0.001$					

consisting primarily of forest do not have enough change in plant species to instigate tornado touchdowns, but also might reflect a lack of line of sight and reduced reporting. It is impossible to know for certain which is more likely; model construction might aid in interpretation.

There were 65 census tracts that experienced tornadoes in the fall; the average variety within these tracts was 5 land use/land cover classifications; the same held true for the 559 tracts that had no tornadoes. Thirty-nine of the tracts with tornadoes were predominantly forest (60 percent) and 13 (20 percent) were predominantly pasture. Of those with no tornadoes, 41 percent of each tract was forest, but 28 percent was urban; recall that only 2 percent of the land area of the state is urban. These findings would seem to contradict the notion that forested areas would not be conducive to tornado formation as well as complicating sighting of tornadoes. If we use the same expected proportions as we used above, which reflect percentages of land area, we should have more tornado-free tracts that are forest and more that are urban.; this lends further credence to the idea that at least in the fall, far more tornadoes occur in tracts that are predominantly forested than elsewhere, and than would be expected. The most interesting thing about the visualization of fall tornadoes (Figure 4) and land use is the line of census tracts with

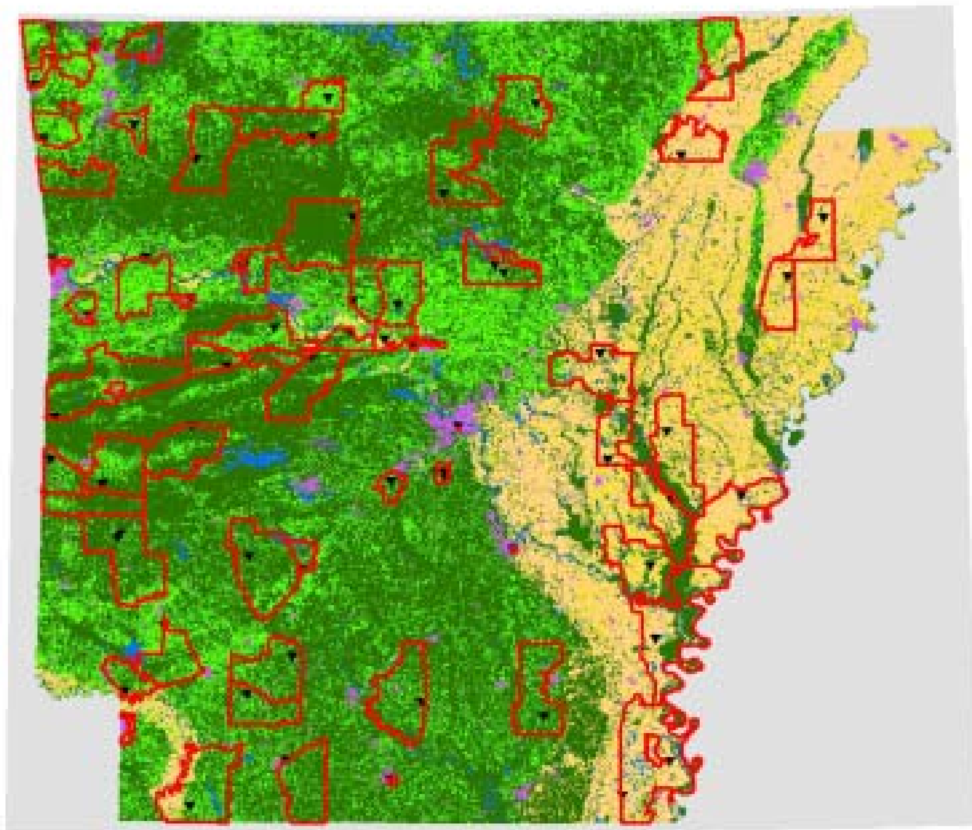

Figure 4: Census tracts with Fall Touchdowns and Fall LULC.

tornadoes following the forested river valley through the most heavily agricultural and flattest region of the state, the southeastern half. Few tornadoes take place very far from a major river.

Turning to spring, the urban trend continues, with almost the entire number that are expected in forest actually being in urban landscape…but *not* in central cities, as Figure 5 rather surprisingly depicts. This leads back to the discussion of surface roughness, or perhaps other tornado-inhibiting factors associated with urban landscapes, and calls again into question the notion that population is the sole reason for differences in the distribution of tornado reports. While not in the scope of this paper, this is a finding that begs further study.

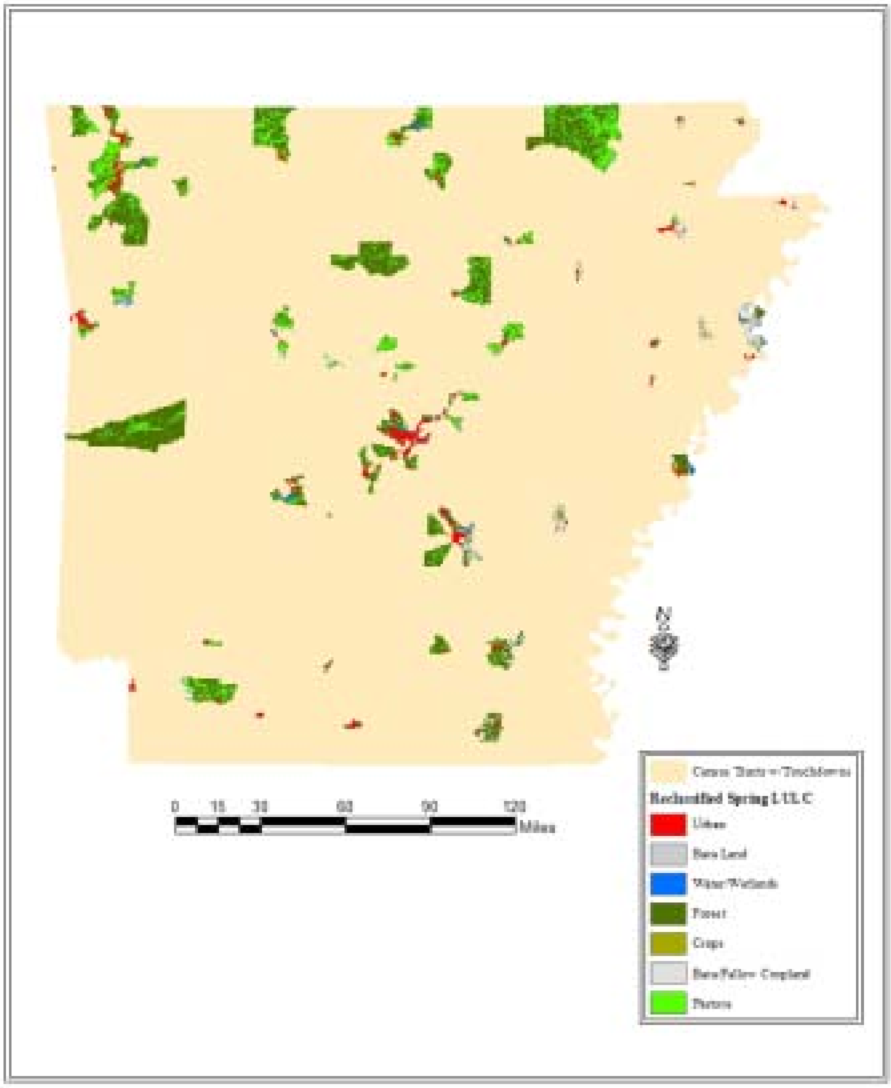

Figure 5: Anomalous Urban Census Tracts without Tornado Touchdowns.

Thus, our spring LULC layer, with its large numbers of tornadoes and very strong chi-square statistic ($p < .00001$), will be weighted by four, and include urban areas in a high-likelihood model, and exclude forest from the second model.

Topography. Elevation, slope, and aspect were all derived from the NED and categorized using Jenks' optimization or, for aspect, 45 degree quadrants. The results are presented in Tables 3, 4, and 5, in the order of the strength of their chi-square statistic. Fall and spring tornadoes exhibited nearly the same distribution, so, for the sake of brevity, spring figures were used for model construction due to its large N (253 tornadoes).

Table 3: Elevation by Class and Observed/Expected Touchdowns

Elevation Class (meters)	Expected Proportion	Touchdown Frequency	Expected Frequency	Difference
1-83	0.4294	113	109	4
83-155	0.2090	75	53	22
155-250	0.1501	31	38	-7
250-351	0.0926	10	23	-13
351-483	0.0839	20	21	-1
483-837	0.0351	4	9	-5
TOTALS	1	253	259	
$\Pi^2 = 21$ $p = 0.00007$				

Table 4: Aspect by Class and Observed/Expected Touchdowns

Aspect	Expected Proportion	Touchdown Frequency	Expected Frequency	Difference
North (0-22.5˚)	0.04	25	11	14
NE	0.09	27	23	4
East	0.09	23	22	1
SE	0.11	26	27	-1
South	0.14	29	35	-6
SW	0.10	20	25	-5
West	0.09	30	22	8
NW	0.09	25	23	2
North (337.5-360˚)	0.04	7	11	-4
Flat	0.21	41	53	-12
TOTALS	1	253	253	
$\Pi^2 = 27$ $p = 0.001$				

Table 5: Slope by Class and Observed/Expected Touchdowns				
Slope (degrees)	Expected Proportion	Touchdown Frequency	Expected Frequency	Difference
0-1.247	0.48	125	121	4
1.247-3.742	0.24	81	62	19
3.742-6.985	0.13	27	32	-5
6.985-10.477	0.07	9	18	-9
10.477-14.469	0.04	6	11	-5
14.469-19.209	0.02	5	6	-1
19.209-25.445	0.01	0	3	-3
25.445-63.862	0.00	0	1	-1
TOTALS	1	253	253	
Π^2= 17 p = 0.01				

Again, if elevation was equal to 2 (83-155 meters), aspect was north, and slope equaled 2 (1.247-3.742 degrees), the cells were included in the High Likelihood Model; if the cells were equal to anything other than elevation class 4 (250-351 meters), flat in aspect, or between 6.985 and 10.477 degree slope, they were included in the Exclusion model. Elevation was weighted three times; aspect two, and slope 1.

Testing the model. The High Likelihood model was a failure in that over a third of the spring tornadoes in the state were in the "No Criteria" class, and progressively fewer in the more likely categories, with none in the top class. This is not unexpected, as the most important LULC factor was urbanness, and urban areas encompass only 2 percent of the state's area.

The Exclusion model (see Figure 6, reclassified into 5 categories) was extremely successful, and the results for all tornadoes are shown in Table 6. Not only did the largest number of spring tornadoes fall into the top category, but the bottom categories were all far lower than would be expected given the size of the area they encompass. The chi-square statistic is extremely significant. This pattern is repeated in the full tornado data (Table 6), with either far fewer than expected or no tornadoes in the lower categories, and many more in the top categories.

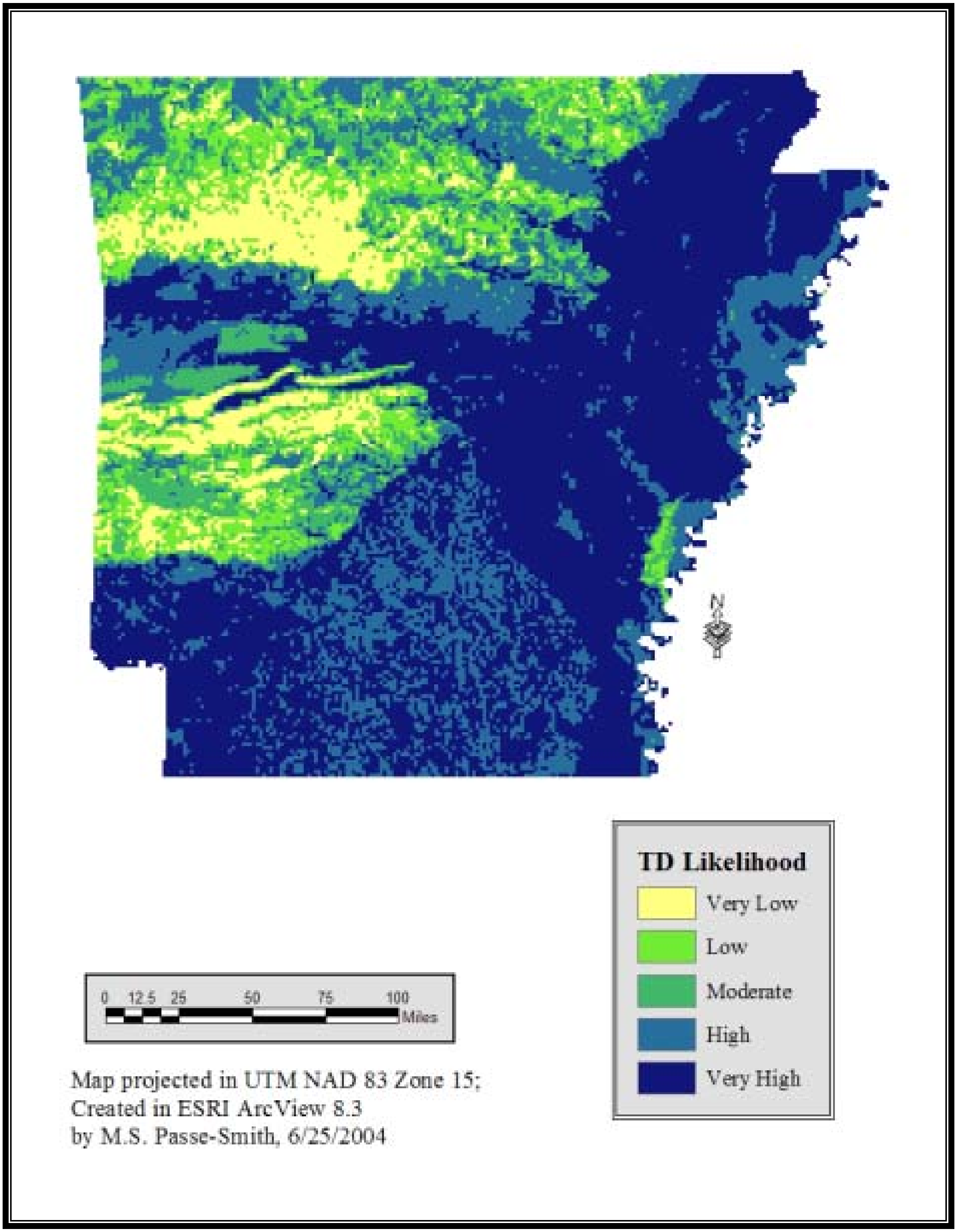

Figure 6: The Exclusion Model.

Table 6: Distribution of Total Tornadoes in the Exclusion Model Categories				
Category (Least to Most Likely)	Expected Proportion	Observed Frequency	Expected Frequency	Difference
1	0.0007	2	1	1
2	0.1322	71	146	-75
3	0.0396	28	44	-16
4	0.0027	1	3	-2
5	0.0124	7	14	-7
6	0.0346	24	38	-14
7	0.0838	65	93	-28
8	0.0404	40	45	-5
9	0.0531	45	59	-14
10	0.0582	57	64	-7
11	0.1831	177	203	-26
12	0.0387	62	43	19
13	0.1101	162	122	40
14	0.0108	21	12	9
15	0.1992	345	221	124
$\Pi^2 = 172$; $p < 0.00001$				

The model was vectorized and the vectors with a code of 5 (high risk of tornadoes) were assessed by selecting them from census tracts which had experienced no tornadoes. There were 114 tracts (out of 232) which had experienced no tornadoes yet had high-risk segments, according to the model. Areas with no tornadoes and the right conditions are prevalent in the Arkansas River Valley (see Figure 7); in the Little Rock, Fort Smith, and Pine Bluff metro areas, and scattered throughout the forested areas of Southern Arkansas. These areas should be studied to determine what makes them resistant to tornadoes, or why tornadoes are not being counted.

Future Studies

Waterways. Some of the findings displayed a marked tendency for tornadoes to touch down in or near river valleys. This could be a function of horizontal wind fields, elevation, increased humidity, vegetation change, or some combination of these factors. The Rydell and

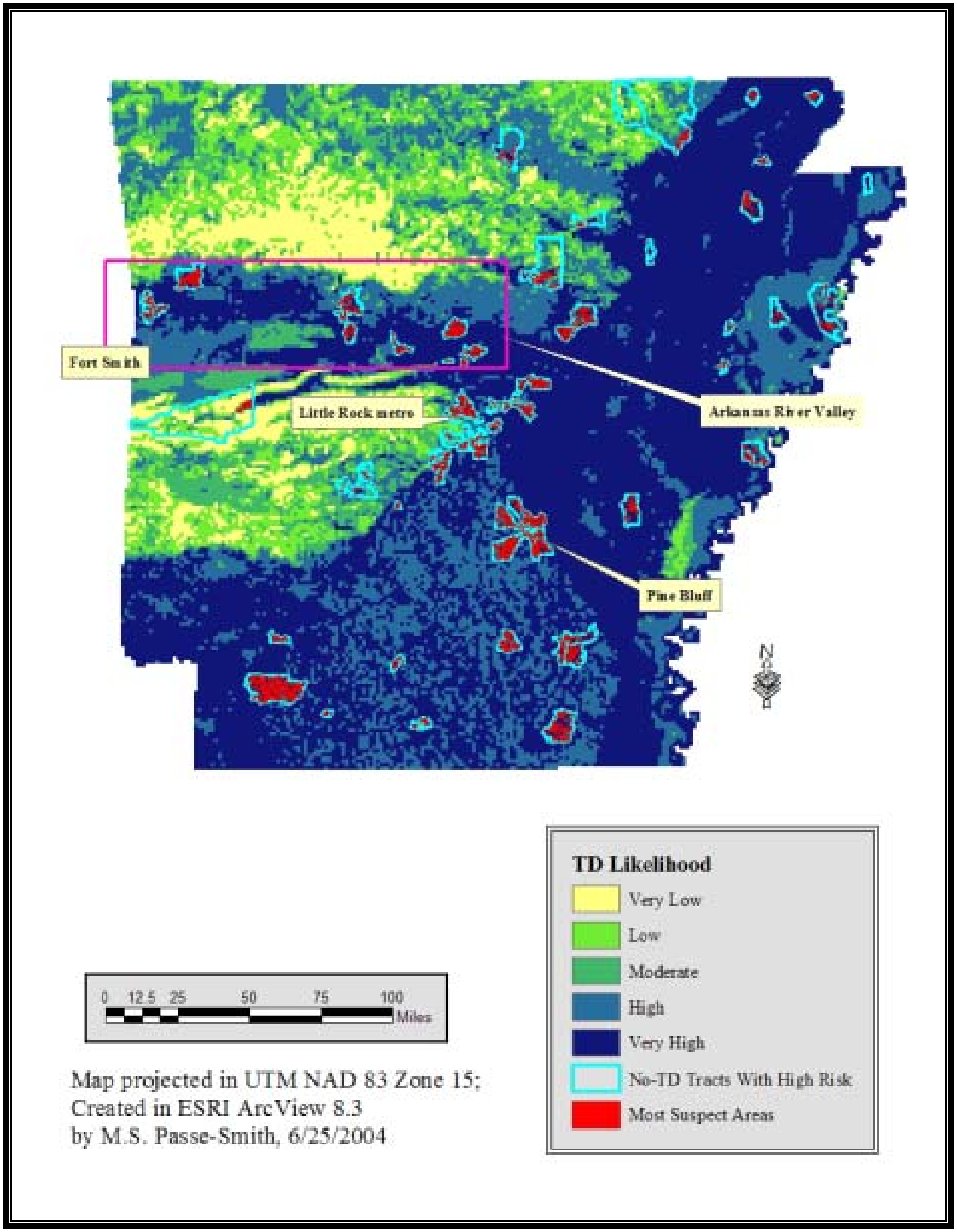

Figure 7: Areas conducive to tornadoes with no recorded touchdowns, and reference points.

Kloesel (2003) study above, as well as others find “funneling of wind by the river valleys may be an important factor in creating preferred regions for severe weather” (Cacciola *et al*., 2000). A study of the possible interactions between prevailing wind flow, storm tracks, and increases in storm-relative helicity would be an interesting pursuit given the above findings.

Urban Anomalies. Another question left unanswered was why so many urban areas were without any touchdowns despite the overwhelming correlation between population and reports. A look at the prevailing wind around each urban area and its relation to the placement of urban low-tornado anomalies and possible nearby maxima should be done.

Model Findings. Finally, the areas singled out above need to be studied at a large-scale level to determine a) how many tornadoes might be occurring in areas devoid of population, and b) as above, why the Little Rock, Fort Smith, and Pine Bluff areas seem conducive but suffer no touchdowns. While these areas have experienced tornadoes crossing through them, they seemingly have a strong negative effect on tornadogenesis.

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