# 5B.5 ESTIMATING POTENTIAL SEVERE WEATHER SOCIETAL IMPACTS USING PROBABILISTIC FORECASTS ISSUED BY THE NWS STORM PREDICTION CENTER

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## 1. INTRODUCTION

In addition to expressing the relative uncertainty of high impact weather forecasts through the use of probabilities, community efforts are also focused on effectively communicating the uncertainty to the public and describing the potential impacts to society. Collectively, these efforts are sometimes described as "completing the forecast" (NRC, 2006). The Storm Prediction Center (SPC) has been issuing a variety of its severe weather forecasts in probabilistic format since 2000. These forecasts include information on the individual severe weather hazards (tornado, severe wind, large hail) and their expected intensity and areal coverage. The SPC is beginning an initial effort to estimate potential severe weather societal impacts based on a combination of probabilistic forecasts and high resolution population data. For equal severe weather threat, events that occur over densely populated areas of the country are likely to have greater societal impact than events over less populated areas. The effort is focused on the study of historic severe weather hazard forecasts with modern high resolution population density grids to examine quantitative information on the estimated and observed societal impact. Future work will also be needed to examine the optimal communication of this type of information to interested partners in the weather enterprise and ultimately to the general public.

This manuscript examines SPC severe weather forecasts from 1994-2008 and uses high resolution population density information derived from the 2000 United States Census to help estimate the potential impact of the severe weather events on society. Use of population density thresholds for dense urban, urban and rural allows additional dimensions of the potential threat to be quantified. Specifically, the potential for catastrophic impacts due to a tornado in a dense urban area can be estimated through the combination of information on the threshold areal coverage and the forecast probability for tornadoes and strong tornadoes.

After a brief discussion of the data and methodology, the manuscript describes a few initial results. First, key patterns in United States population density and their relationship to tornado occurrence are discussed. Next, the relationship between tornadoes, EF2+ tornadoes and killer tornadoes as a function of population density is explored. The climatology of SPC high risk categorical severe weather forecasts is combined with population density to illustrate the large scale relationship between the hazard forecasts population. Finally, the relationship between tornado hazard forecasts, population density and the potential impact on population (and society) are illustrated by comparison of three scenarios.

## 2. DATA SET PREPARATION AND ANALYSIS

High-resolution gridded population data was obtained from the Socioeconomic Data and Applications Center (SEDAC) at Columbia University. The SEDAC data was generated from the 2000 U.S. Census and mapped to a 30 arc second grid (slightly less than 1 km grid length). The gridded population counts were converted to population density by dividing the population by the area of each grid box. The population density associated with each tornado was obtained by creating a 0.02 degree buffer around each tornado track (from NWS Storm Data) and accumulating all of the population density grid points that fell within the resulting polygon. The resolution of the tornado tracks in Storm Data is limited to a start point and end point for each event, so this approach will only yield an imprecise estimate of the population density along the tornado path. All SPC severe weather forecasts, both probabilistic and categorical, were obtained from the SPC archive database. The forecasts are archived as latitude-longitude strings that define the polygons as originally drawn by the operational forecaster. For some diagnostics, SPC forecasts and the population density grid were both transformed to a 10 km grid for computational ease.

## 3. RESULTS

The fundamental patterns of population over the United Sates are apparent in the high resolution population density grids for the United States (Fig. 1). The concentration of populations in major cities and along both the eastern and western coastal regions, the sparse population of the rural intermountain and high plains regions, and the general gradient in population from west to east between the Rocky Mountains and the East Coast are all evident. Additional patterns also emerge, such as the concentration of population along interstate highways interconnecting major cities and the more uniform area of dense population extending from the Northeast to the Great Lakes States and southward to the Mid South across to the Piedmont (compare Fig.

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1 and 2). At very high resolution, state and U.S. highways, terrain features and river valleys are also evident. Examination of population densities greater than 10 km$^{-2}$ focuses on towns, suburbs and cities where severe weather events including tornadoes are most likely to cause extensive damage and injuries (Fig. 2). The interplay between the well known maximum of tornado hazard in the Great Plains (Brooks et. al, 2003) with the widespread population densities greater than 10 people km$^{-2}$ of the East is fundamental to the tornado impact on societal structure.

A simple overlay of observed tornado tracks (1999-2008) and population density, reveals the basic character of this interplay (Fig. 3). Visual observation of the distribution of killer tornados relative to EF0-EF2 or EF2+ tornadoes suggests that killer tornadoes tend to occur in areas with more dense populations. A similar shift of killer tornado activity relative to the total tornado population was found for a longer tornado sample (1950-2004) by Ashley et al. (2007). In this study, direct analysis of EF0-EF2, EF2+ and killer tornadoes as a function of population density helps quantify the shift of killer tornadoes towards areas of greater population density (Fig. 4). The peak normalized tornado count occurs at much lower population density (2.2 people km$^{-2}$) than the peak for killer tornadoes (5.0 people km$^{-2}$). Although the result that killer tornadoes are more common when the event occurs in greater population is expected, the result confirms the importance of population density in estimating the likely societal impact of individual tornadoes, tornado outbreaks, or even probabilistic tornado forecasts.

If we further normalize the probability distributions for various "events" as a function of the logarithm of population density, values greater than 1 will indicate that the distribution for that event is more likely than overall mean for United States (Fig. 5). The analysis suggests that few tornadoes occur in the lowest population density areas of the US, mostly in the western US, with the maxima in occurrence at approximately 2 people km$^{-2}$ and 500 people km$^{-2}$. Strong (EF2+) tornadoes occur in approximately the same regions of the population density space as any tornado, but the low population maximum in the distribution of killer tornadoes is shifted to significantly higher values (~5-6 people km $^{-2}$). This is indicative of the combination of meteorological and demographic factors required to produce killer tornadoes. In the low population density regions of the west, there are few tornadoes, and as a result, few fatalities. The extremely high population density regions are relatively small and dominated by the Northeast Megapolitan Area along the East Coast (Lang and Dhavale, 2005), where tornadoes are rare and, again, few fatalities occur. The population growth rate in the I-35 Corridor Megapolitan Area from Kansas City through Oklahoma City, Dallas Forth Worth to San Antonio is more than double that of the Northeast Area (Lang and Dhavale, 2005). This will result in expanded areas of dense population near the climatological maximum in EF2+ tornadoes (Brooks et. al., 2003) and significantly alter this tornado-population relationship in the future.

In addition to exploration of the relationship between tornadoes and population, this study also seeks to explore the relationship between *forecasts* of tornado hazards and the impacts produced by the resulting observed weather. The Storm Prediction Center (SPC) has been issuing categorical severe weather forecasts since 1955 and individual probabilistic forecasts for tornado, hail and wind hazards since 2000. The probabilistic tornado forecasts also include, when the forecaster believes appropriate, an area with expected coverage of EF2+ tornadoes greater than 10 percent (within 40 km of a point). Examination of tornado forecasts from 2000-2008 indicate that the EF2+ areas verified overall with a coverage of 7.7 percent, a slight over forecast of these rare but important strong tornadoes.

Given the longer record of categorical severe weather outlooks, our initial exploration of the relationship between forecast severe weather and population focuses on outlooks with Moderate or High categorical areas. These categories are generally reserved for forecast areas where major severe episodes are expected. Although forecast hail and wind hazards can also cause issuance of a Moderate Risk, when tornadoes are the forecast focus there is a greater than 10 percent probability of EF2+ tornadoes for at least a portion of the outlook area. The maximum frequency of SPC Day 1 Moderate Risk Convective Outlooks for the period 1994-2008 over the Great Plains and extending eastward toward the Southeast (Fig. 6) corresponds closely to the maximum climatological tornado and EF2+ tornado frequency found in Brooks et al. (2003) and Ashley et al. (2007). Simple multiplication of the gridded frequency of Moderate Risk outlooks (Fig. 6) and the gridded population density (Fig. 1) on a 10 km x 10 km grid,further illustrates the spatial character of the relationship (Fig. 7). As illustrated for the entire domain and observed tornadoes in Figs. 4 and 5, the climatological forecast tornado risk to population (Fig. 7) is shifted toward areas in the Great Plains extending eastward toward the Southeast.

Future studies will focus more on the use of explicit SPC tornado forecast probabilities in addition to the categorical outlooks that are available for a longer time record. High Risk categorical outlook areas are almost always associated with tornado hazard probabilities of 30 percent for EF0-EF5 Tornadoes and greater than 10 percent for EF2+ tornadoes. During the period from 2000-2008, the EF2+ area within these high risk forecasts verified with 16 percent EF2+ coverage. The verification results suggest that there is forecast skill in distinguishing between more sparse and more widespread EF2+ tornado coverage in SPC Tornado Outlooks.

To illustrate the potential societal impact forecast implications based on the location where the High Risk tornado forecast is located, three example areas of similar size will be compared (Fig. 8). The forecast High Risk areas for 5 May 2007 and the 5 February 2008 "Super Tuesday" events were of similar areal size, but the former was located over the Great plains, while the latter was located over the lower Mississippi River Valley (Fig. 8). A hypothetical area was also created by moving the 5 February 2008 forecast area toward the area impacted by the 30 May 1985 "Ohio-Pennsylvania Outbreak". The total population, area with population density greater than 10 people km$^{-2}$ (generally dense rural or towns), and area with population density greater than 100 people km$^{-2}$ (generally town center or suburb) are calculated for each tornado forecast area (Fig. 8).

The likely population-impact implied by the different forecast areas is dramatic. The Great Plains forecast area contains 354,000 people, whereas the hypothetical risk area contains almost ten million people. A similar contrast exists in areal coverage for both the population density thresholds examined, assuming equal forecast tornado probabilities, as the probability of a tornado impacting population densities over 10 people km$^{-2}$ is 13 times larger than the Great Plains area for the Super Tuesday forecast, and over 40 times larger for the hypothetical Ohio-Pennsylvania example. Similarly, the probability of a tornado impacting population densities over 100 people km$^{-2}$ is almost 25 times larger for the hypothetical Ohio-Pennsylvania example compared to the Great Plains. Although the observed tornado distribution for each forecast played a key role in the observed impacts, there were only 1 fatality and 23 injuries during the Great Plains event, whereas 59 fatalities and 425 injuries were reported during the Super Tuesday Outbreak. The 1985 Pennsylvania-Ohio Outbreak resulted in 76 fatalities and 876 injuries. Given the current skill in tornado forecasts and the spatial variability in the distribution of population, it is likely that some predictive skill in the likely magnitude of societal impact is already present in current severe weather forecasts.

## 4. SUMMARY AND FUTURE WORK

Initial explorations into the relationship between severe weather forecasts, observations, population density and basic societal impact in the form of fatalities were performed. It was found that the peak normalized tornado count occurs at much lower population density (2.2 people km$^{-2}$) than the peak for killer tornadoes (5.0 people km$^{-2}$). Additional normalized analysis suggests that few tornadoes occur in the lowest population density areas of the US, mostly in the western US, with the maxima in occurrence at approximately 2 people km$^{-2}$ and 500 people km$^{-2}$. Strong (EF2+) tornadoes occur in approximately the same regions of the population density space as any tornado, but the low population maximum in the distribution of killer tornadoes is shifted to significantly higher values (~5-6 people km $^{-2}$). This is indicative of the combination of meteorological and demographic factors required to produce killer tornadoes. Exploration of three separate high tornado risk areas, of similar size but over different locations, revealed dramatic changes in the likely population-impact simply due to differences in population density.

Although the result that killer tornadoes are more common when the event occurs in greater population is expected, the result confirms the importance of population density in estimating the likely societal impact of individual tornadoes, tornado outbreaks, or even probabilistic tornado forecasts. One facet of future study is to examine the combination of severe hazard probability and population density as an integral measure of the likely societal impact on a given day. Damage, injury and fatality data for historic severe weather events will be used to examine the statistical effectiveness of the societal impact estimates from the forecast sample. Additional work will focus on developing a spatial model of the tornado population to explore additional issues including the distribution of mobile homes, the timing of convection (nocturnal, fast-moving winter), and estimation of the likelihood of a large death (catastrophic) event.

## 5. REFERENCES

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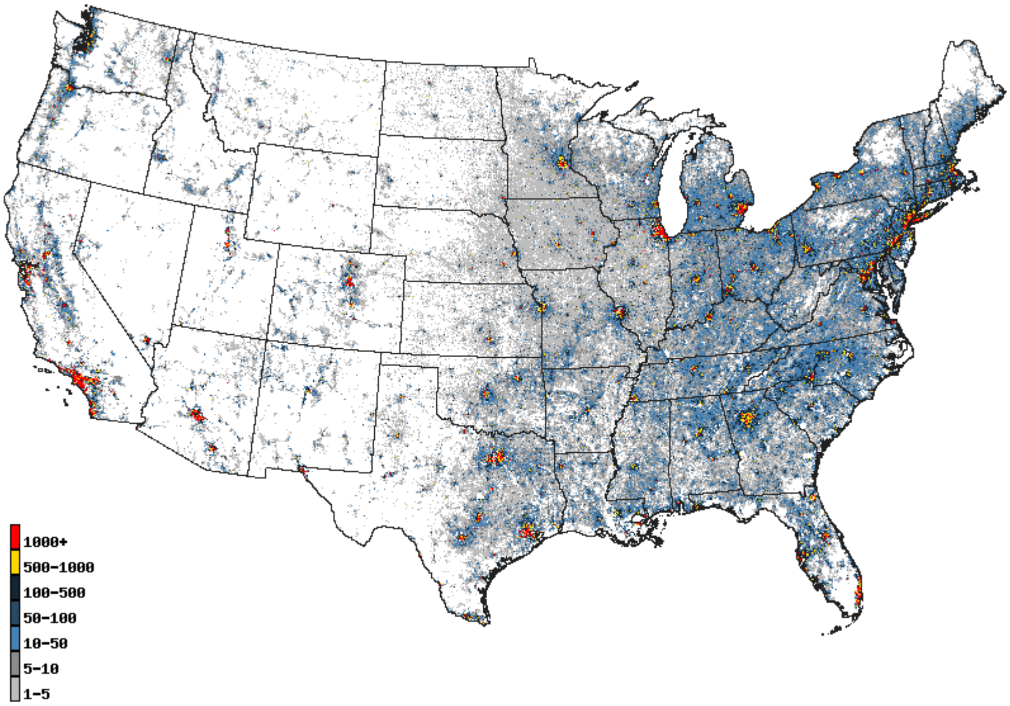


**Figure 1.** Plot of population density for the United States. The legend at the lower left indicates the color of plotted population density ranges (people km$^{-2}$ ).

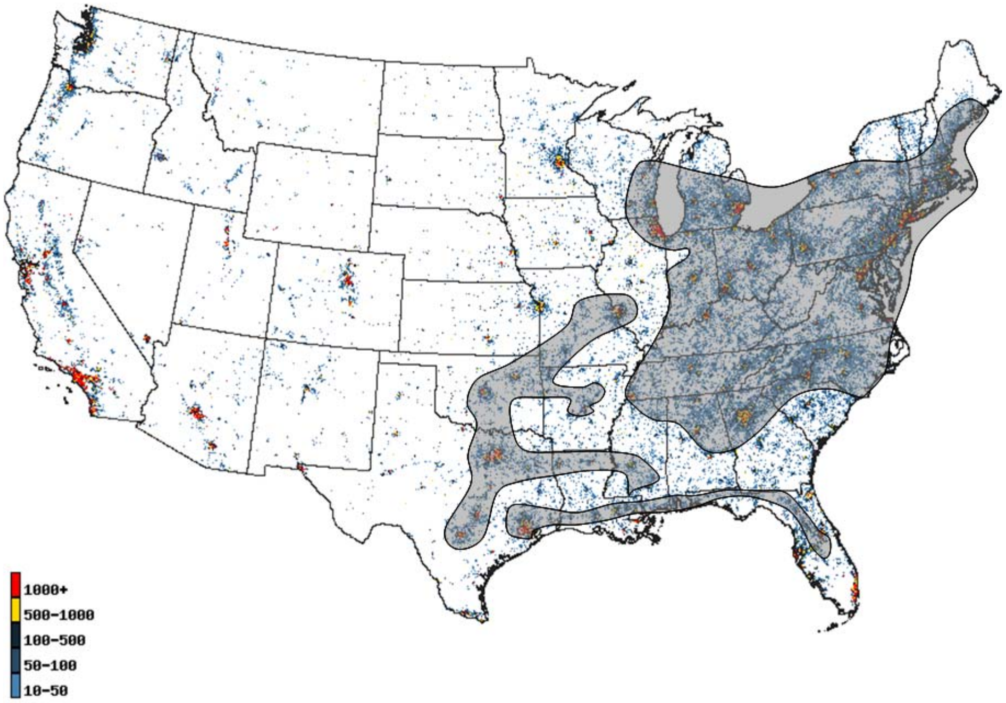


**Figure 2.** Plot of population density for the United States for values above 10 people km$^{-2}$ . The legend at the lower left indicates the color of plotted population density ranges. The shading highlights patterns of higher population density evident in figure 1.

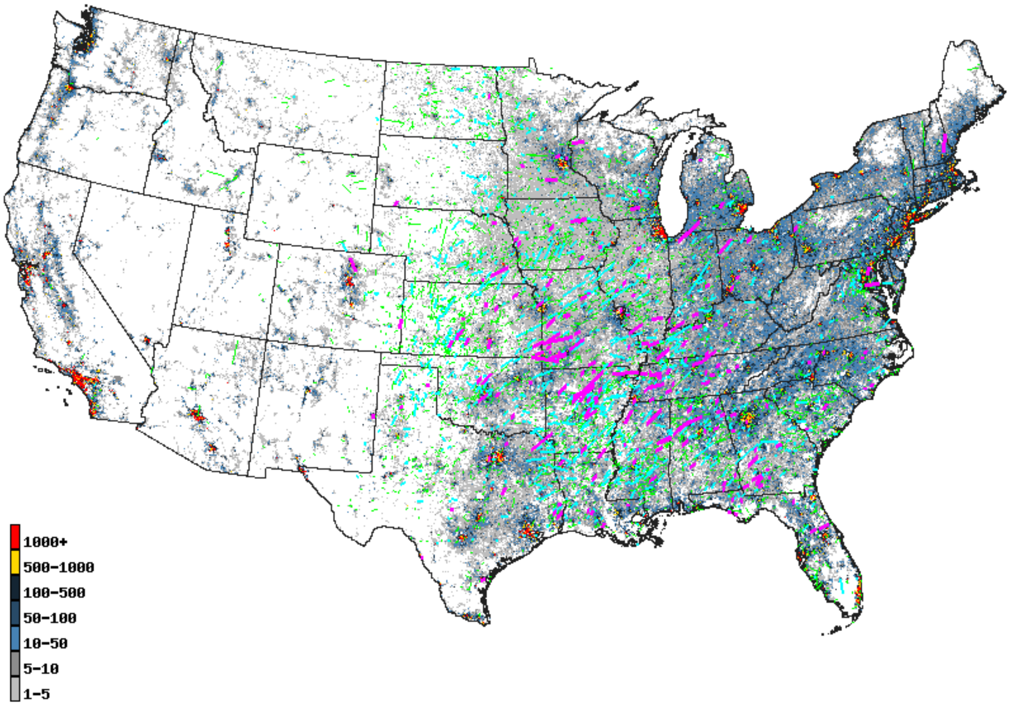


**Figure 3.** Plot of tornado tracks by EF scale (green: EF0-EF1; cyan: EF2-EF5; Magenta: killer tornadoes) for the years 1999-2008 and population density (people km$^{-2)}$ ) for the United States (as in Figure 1).

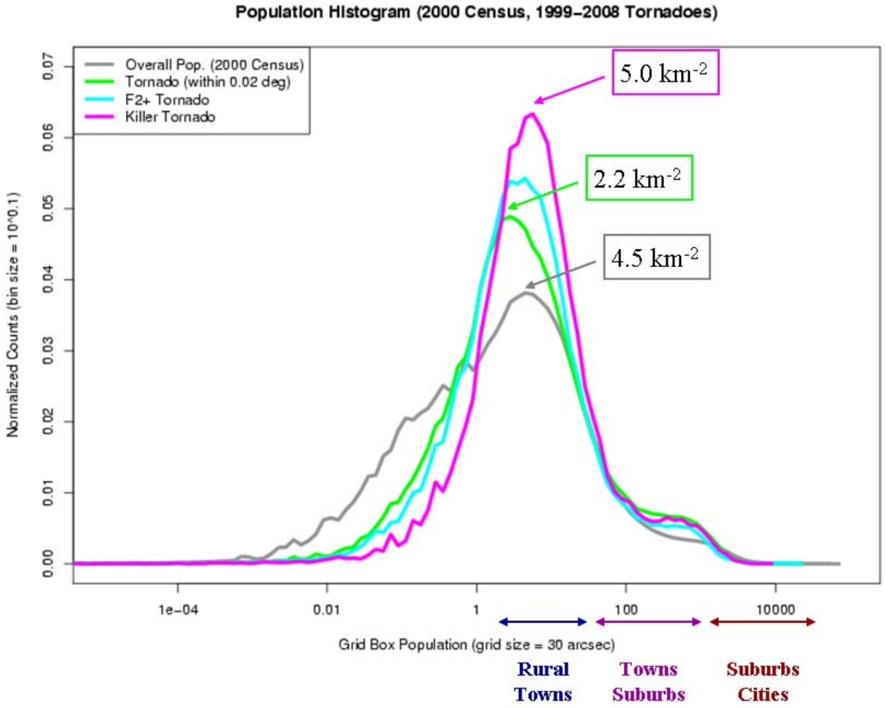


**Figure 4.** Graph of normalized tornado and population counts as a function of population density (people km$^{-2)}$ for overall population (gray), tornadoes (within 0.02 deg.) (green), EF2+ tornadoes (cyan) and killer tornadoes (magenta).

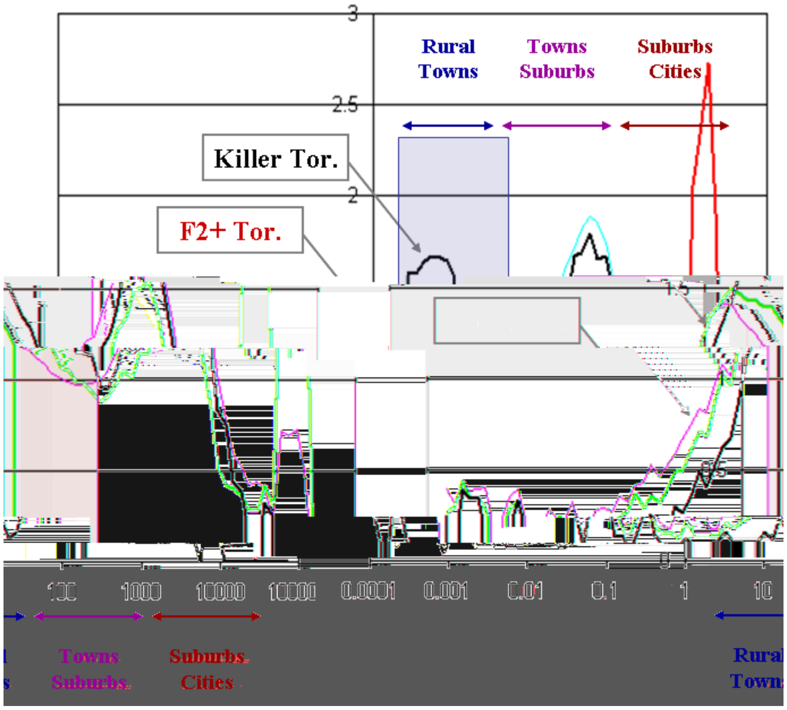


**Figure 5.** Normalized probability distributions for various "events" as a function of the logarithm of population density (people km$^{-2)}$. Values greater than 1 indicate that distribution for that event is more likely than overall mean for US. Shaded vertical bar indicates population densities for which killer tornadoes are most likely to occur, relative to all tornadoes. Cyan line is distribution for all tornadoes, red-F2 or greater tornadoes, black-killer tornadoes.

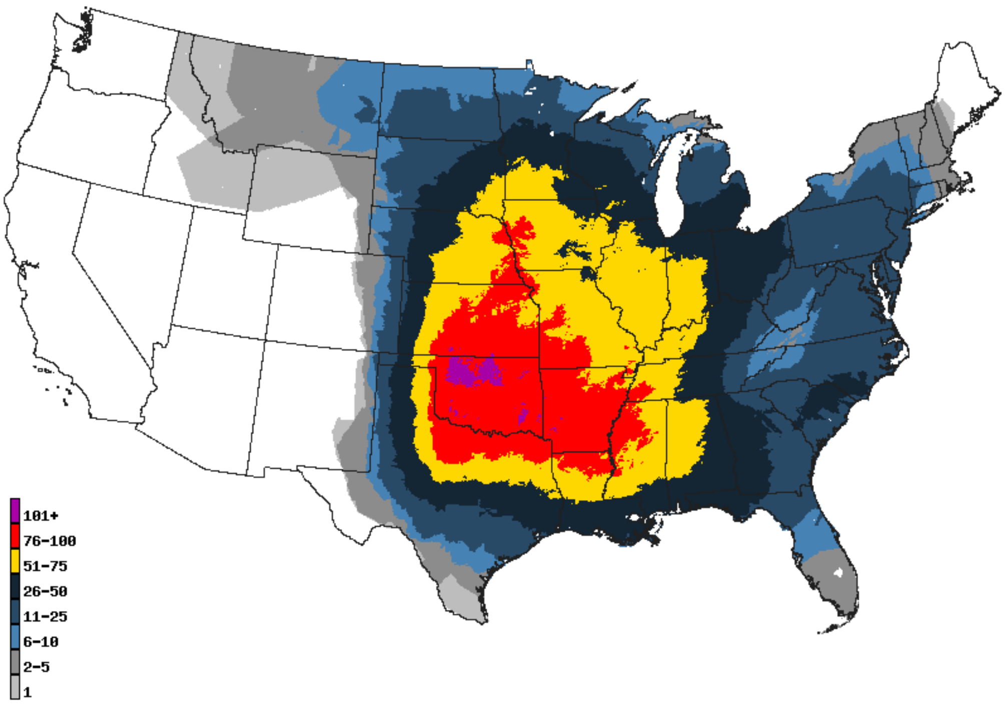


**Figure 6.** Count of SPC 1630 UTC Day 1 Categorical Forecasts of Moderate or High Risk by grid box (10 km x 10 km) for the period 1994-2008.

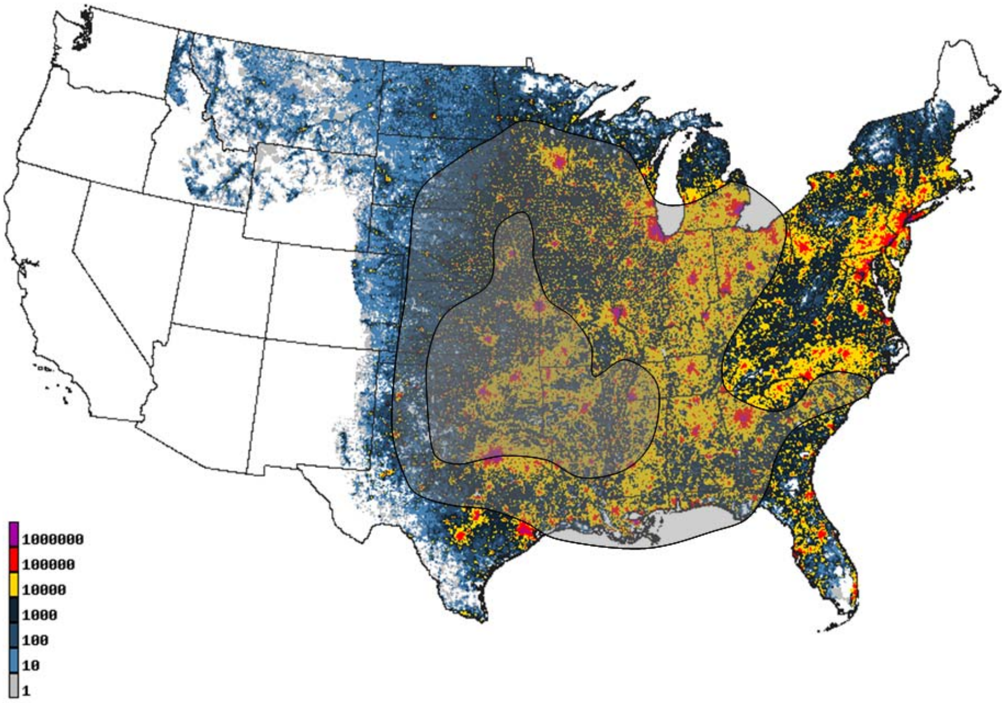
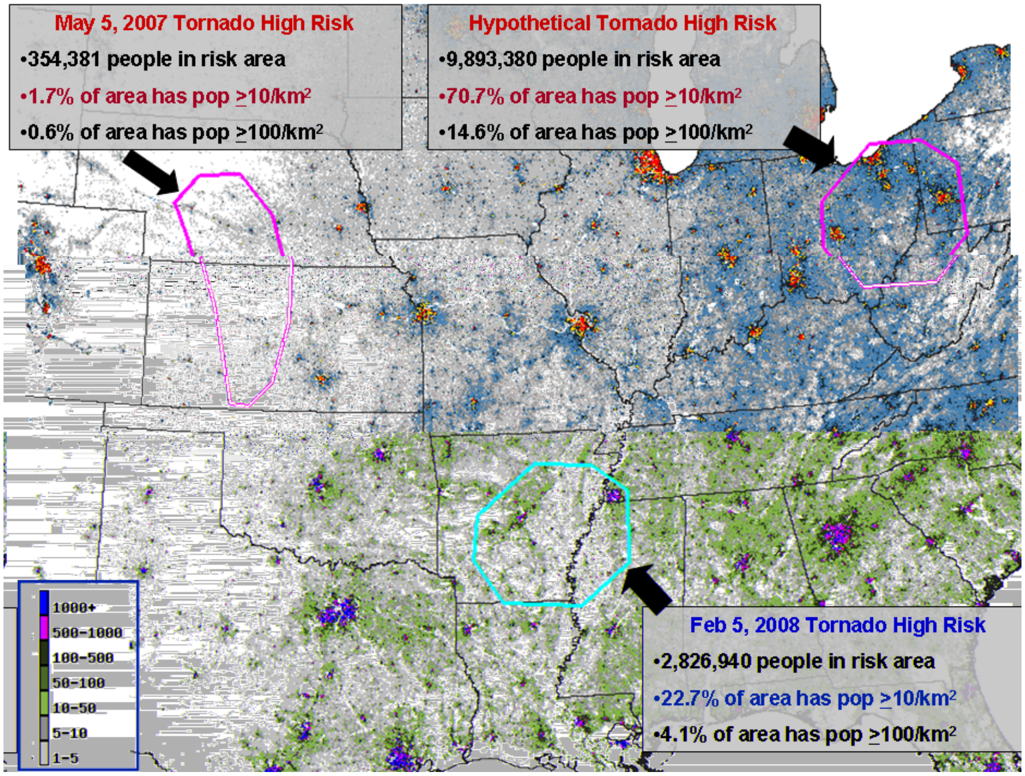


**Figure 7.** Plot of the product of count of SPC 1630 UTC Day 1 Categorical Forecasts of Moderate or High Risk for the period 1994-2008 and Census 2000 based population density for 10 km x 10 km grid boxes. The SPC categorical forecast count for Moderate or High Risk (Fig. 6) is shaded.


**May 5, 2007 Tornado High Risk**

- •354,381 people in risk area
- •1.7% of area has pop $\geq$10/km$^2$
- •0.6% of area has pop $\geq$100/km$^2$

**Hypothetical Tornado High Risk**

- •9,893,380 people in risk area
- •70.7% of area has pop $\geq$10/km$^2$
- •14.6% of area has pop $\geq$100/km$^2$

**Feb 5, 2008 Tornado High Risk**

- •2,826,940 people in risk area
- •22.7% of area has pop $\geq$10/km$^2$
- •4.1% of area has pop $\geq$100/km$^2$

**Figure 8.** Forecast High Risk areas for 5 May 2007 and the 5 February 2008 “Super Tuesday” events and a hypothetical area with the 5 February 2008 forecast area replicated over the area impacted by the 30 May 1985 “Ohio-Pennsylvania Outbreak”. Population characteristics for each area are annotated.