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Evaluation of a Social Vulnerability Index for Utility in Tornado Event Mortality Prediction

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Abstract

Evaluation of a Social Vulnerability Index for Utility in Tornado Event Mortality Prediction
By Erica Elaine Adams

Social vulnerability describes a community's resilience to hazards based on its socio-economic and demographic characteristics, in contrast to the physical vulnerability of its natural and built environment. The Centers for Disease Control and Prevention (CDC) released a Social Vulnerability Index (SVI) in 2009 using 14 socio-demographic variables to rank census tracts across the United States. These 14 variables fall into four main themes: socioeconomic status, household composition, minority status and language, and housing and transportation. The intended purpose of the SVI is to aid state and local governments in planning for all stages of disaster management: mitigation, preparedness, response, and recovery.

The SVI is undergoing evaluation for its utility in both predicting human outcomes and planning for disaster-specific scenarios. In support of that effort, this study seeks to determine whether areas of high social vulnerability, as characterized by the SVI, experienced higher rates of mortality during the April 2011 Tornado Outbreak in the southeastern United States.

Poisson regression was used to model the interaction between tornado presence and the overall SVI on mortality (adjusting for strength of tornadoes) in census tracts of four states affected by the 2011 tornado outbreak. The analysis was repeated for each of the four individual social themes in the SVI. Resulting rate ratios were generally imprecise across all models. Models containing interactions were not were not found to explain additional variance.

Overall, these analyses do not support the hypothesis that SVI modifies the association between presence of tornadoes and mortality in the April 2011 tornado outbreak. However, estimated rate ratios exhibited wide confidence intervals, which is likely due to the extreme nature of the case study event and a low number of data points. Future studies should consider lagged health outcomes, recovery times, and mitigation strategy performance as these indicators may be more likely to accurately assess the SVI's utility as a tool for mitigation, planning, and recovery.

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1. Extended Literature Review

1.1 Social Vulnerability in Disaster Management

Hazard and disaster vulnerability research and practice have, historically, focused on physical and infrastructural factors, rather than the more difficult to quantify social components (Cutter, Boruff, & Shirley, 2003). Vulnerability is described as "the potential for loss" or the extent to which people and places may be affected as a result of a particular hazard, and is an important factor in measuring risk (Cutter, 1996; B. E. Flanagan, Gregory, Hallisey, Heitgerd, & Lewis, 2011). Only in recent decades have policy makers, disaster management personnel, and public health practitioners began to recognize *social vulnerability* as a relevant factor in disaster management (Cutter et al., 2003; B. E. Flanagan et al., 2011; Flax, Jackson, & Stein, 2002). Social vulnerability refers to a community's resilience to hazards – that is, potential disasters - based on its socio-economic and demographic characteristics, in contrast to vulnerability based solely on its physical and built environment (Cutter et al., 2003; B. E. Flanagan et al., 2011). Social determinants of health including factors such as age, gender, income, social networks, neighborhood characteristics, access to health care, etc. are those commonly used in assessing the social vulnerability of a population (Cutter et al., 2003; B. E. Flanagan et al., 2011). The extant literature indicates that the socially vulnerable are not only more likely to be adversely affected by disaster, but less able to take precautions before hazards arise nor recover sufficiently in the aftermath (Cutter et al., 2003; B. E. Flanagan et al., 2011; Juntunen, 2005; Morrow, 1999). These vulnerable communities often require more social and economic support during post-disaster response and recovery, thus it may be more financially and ethically sound to consider social vulnerability during the mitigation and preparedness phases of emergency management as well.

To varying degrees, disaster management researchers and practitioners across the field now incorporate social determinants of vulnerability in hazard mitigation as part of their work (Cutter & Finch, 2008). Research suggests, however, that the various tools and resources that have been developed are not being used consistently (Wolkin et al., 2015). At a global scale, both the United Nations and Inter-American Development Bank simply cite social determinants in their various reports on risk reduction and management strategies (Inter-American Development Bank, 2006; International Strategy for Disaster Reduction, 2004; United Nations Development Programme, 2004). On the other hand at a local scale, the Community Vulnerability Assessment Tool (CVAT) assesses community vulnerability and risk using both social determinants and built environment factors to prioritize mitigation measures (Flax et al., 2002).

Attempts to quantify and operationalize social vulnerability in disaster management are inconsistent, employing varying methods, and characterizing vulnerability at a range of geographic scales. Attempts to model social vulnerability have been most numerous in research and planning surrounding hurricane mitigation and recovery (C. Burton & Cutter, 2008; C. G. Burton, 2010; Finch, Emrich, & Cutter, 2010; Myers, Slack, & Singelmann, 2008; Rygel, O'sullivan, & Yarnal, 2006; Wu, Yarnal, & Fisher, 2002), however some have attempted to quantify it beyond a disaster-specific scale. Montz and Evans (2001) tested several methods of modeling overall social vulnerability to disasters; this, however did not result in an index or other planning tool (Montz & Evans, 2001). Cutter et al., (2003) were among the first to quantify social vulnerability in the form of a Social Vulnerability Index (SOVI), using factor analysis and an additive model to measure the interaction of social and biophysical components to estimate place vulnerability at county level in the U.S (Cutter et al., 2003). The Australian government modeled social vulnerability in Australia as part of an overall disaster risk assessment using decision tree analysis and simulated estimates (Dwyer, Zoppou, Nielsen, Day, & Roberts, 2004). The Geospatial Research, Analysis, and Services Program (GRASP) at the Center for Disease Control and Prevention (CDC) created a Social Vulnerability Index (SVI) for the entire U.S. Using 14 socio-demographic variables, the SVI is the first published index to quantify social vulnerability nationally at census tract level. With the understanding that potential hazards vary geographically, the index ranks social vulnerability of tracts on a generic basis. However, the application is open to customization by the user for a given stressor (B. E. Flanagan et al., 2011).

The varying nature of resources, tools, and methods for quantifying social vulnerability renders comparisons and assessment of respective validity difficult. Further evaluation and validation of these products is critical for effective use in emergency management decision-making, yet little to date has been completed. Tate (2013) uses uncertainty analysis to compare various social vulnerability index construction methods and asserts that these models exhibit a high magnitude of uncertainty, statistical bias, and increased imprecision in the areas of highest vulnerability. A lack of consensus in the field related to indicator selection and weighting scheme during model construction are likely key drivers in this (Tate, 2013). Further evaluation of current social vulnerability measures is necessary as their use increases across sectors of emergency management. Sufficient knowledge of the strengths and limitations of these measures is critical for effective decision-making, especially as applied to various disaster types. This study looks specifically at whether the association between mortality and tornadoes varies according to the CDC SVI, in support of a larger validation effort for the index.

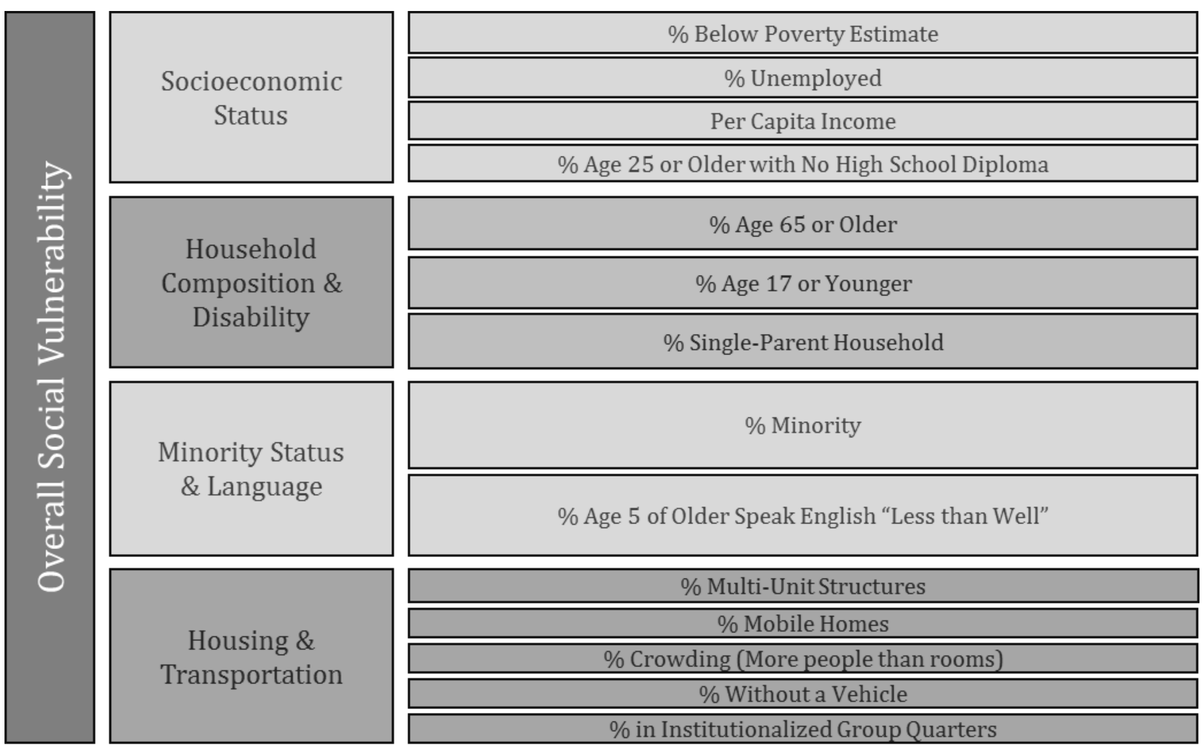
1.2 CDC Social Vulnerability Index

CDC's SVI ranks the social vulnerability of communities to external stressors such as natural or technological disasters and disease outbreaks based on socio-economic and demographic characteristics of communities. (B. E. Flanagan et al., 2011). The origins of the SVI are in a 2006 congressional mandate calling for federal agencies to implement procedures to assist state and local emergency planners in their efforts to mitigate potential disasters. The SVI was released in 2009 using 2000 census data and updated in 2012 with both 2010 US census data and 2006 – 2010 American Community Survey (ACS) data. The 2010 index ranks census tracts on each of 14 variables, further provides an aggregated ranking of the variables collected into the four themes shown in Figure 1.1, and finally, yields an overall ranking of the variables. The justification for the selection of these census variables is described in detail in Flanagan et al., 2011. The variables were chosen from among indicators commonly cited in the relevant literature (Cutter et al., 2003; Morrow, 1999; Tierney, 2006) as social determinants of risk for disaster events. Individual variables were normalized for each tract and ordered from zero (lowest vulnerability = 0.0) to one (highest vulnerability =1.0), with the exception of per capita income, necessarily reversed as high income equates with low vulnerability and vice versa. Percentile ranks were calculated using the following formula:

Percentile Rank = (Rank-1) / (N-1)

The percentile ranks of each tract's variables were then grouped and summed within one of four themes to arrive at a percentile rank of census tracts for each theme. Finally, the individual percentile rankings were summed and ordered to produce an overall SVI ranking (B. Flanagan & Hallisey, 2013; B. E. Flanagan et al., 2011).

Figure 1.1 Census variables included in the composite Social Vulnerability Score



Data from the CDC's Social Vulnerability Index is now publicly available at www.svi.cdc.gov. Users can download a dataset containing data from each step of analysis: values and percentile rankings for each of the 14 census variables, the four themes, and the overall SVI scores. Documentation and publications related to the index, as well as an interactive mapping application for data visualization are also accessible from the website (ATSDR, 2014). The index has become more widely used by public health and emergency management offices at the state and local level since its release in 2009. Within a few months of publication, the article describing the index (Flanagan et al., 2011) had been downloaded over 1000 times (B. Flanagan, personal communication, October 13, 2015). Since 2009, the publication has been cited over 40 times and is now the 3rd most downloaded article from the Journal of Homeland Security and Emergency Management (researchgate.net, accessed April 9, 2016). These statistics alone speak to its potential influence and impact in the emergency management community. North Carolina, Vermont, New Hampshire, and Georgia have since incorporated the SVI into their overall emergency planning procedures, while other states and municipalities have referenced it for more specific considerations such as potential disease outbreaks and emergency management budgeting (B. Flanagan, personal communication, October 13, 2015).

1.3 Validation of the SVI

As the SVI is becoming more widely utilized, GRASP is conducting a psychometric evaluation on the validity of the SVI to ensure that it is a valuable measure of social vulnerability. This evaluation has several components including estimating the degree to which the SVI accurately measures social vulnerability, its comparability to other theoretically similar constructs, and its reliability in predicting performance with regard to various hazards. The last of these will be evaluated in this thesis using statistical analyses to estimate predictive capacity of the SVI for individual hazards at various stages of disaster management. This study supports that effort by using statistical analyses to determine if the SVI modifies the association of mortality and tornadoes. More broadly, the analysis may suggest whether the SVI could be useful for decision-making regarding mitigation and preparedness in tornado-related disaster management.

The aim of psychometric evaluation is to assess the validity and reliability of measurement tools, such as composite indices like the SVI (DeVon et al., 2007). Reid et al., (2012) use an event-specific approach to evaluate a heat vulnerability index (HVI), investigating whether the mortality and morbidity associated with a set of heat events varied according to their HVI. They regress health outcomes against extreme heat days, HVI, and the interaction of the two variables, to determine if the health outcomes vary according to the HVI (Reid et al., 2012). As this approach was found to be useful in validating the HVI, a similar event-specific approach will be used to evaluate the CDC SVI. The April 2011 Tornado Outbreak in the southeast US was selected as the case study event for the evaluation.

1.4 Mortality and Tornadoes

Existing literature (Ashley, Krmenec, & Schwantes, 2008; Boruff et al., 2003; CDC, 2012; Cutter et al., 2003; Paul & Stimers, 2012; K. Simmons & Sutter, 2014) identifies known risk factors for morbidity and mortality from tornadoes as proximity to a high magnitude (EF4 or EF5 scale) tornado path, advanced age (≥ 65), inaccessibility of a safe room, sheltering in mobile homes, existence of tree cover, and night-time tornado events. Considering these factors, the southeastern U.S. is considered especially vulnerable to tornado impacts due to its frequency of high magnitude tornadoes and high concentration of mobile homes (Ashley, 2007; Boruff et al., 2003; CDC, 2012). Paul and Stimers (2012) provide further discussion on risk factors for fatality related to the natural phenomenon of tornado events themselves (as opposed to human mitigation intervention) including magnitude, frequency, timing, path, and season of occurrence. Overall, fatalities resulting from tornadoes have decreased in the past fifty years, likely due to advances in forecasting and warning systems (Ashley, 2007; Cutter et al., 2003; Paul & Stimers, 2012). Still, tornadoes often form very quickly. Many early warning systems provide no more than a 5 minute advisory for an impending tornado, leaving little time to find adequate cover, a circumstance especially difficult for the socially vulnerable in the event of an EF4 or EF5 magnitude tornado (Cutter et al., 2003; Paul & Stimers, 2014). However, even strong permanent structures are not always protective against EF4 and EF5 tornadoes, which can make them more deadly, regardless of social determinants (Paul & Stimers, 2014; K. Simmons & Sutter, 2012a). The leading cause of death from tornadoes is traumatic injury, often occurring in the course of inadequate sheltering (CDC, 2012).

1.5 Case Study: April 2011 Tornado Outbreak

The year 2011 was exceptionally deadly for tornado events in the United States, as there were over 550 deaths related to tornadoes (CDC, 2012; K. Simmons & Sutter, 2014). From April 25-28, 2011, an enormous storm system generated 351 tornadoes, including 27 that were deadly, and 15 of which registered as EF4 or EF5.

With 338 fatalities over 5 states, the storm system was the third-deadliest tornado event in the history of the U.S.

The American Red Cross completed data collection on fatalities associated with the event. Their sources included media reports, funeral homes, coroners, emergency managers, and interviews with next-of-kin. The fatality case definition for the Red Cross included any death attributed directly (i.e. trauma) or indirectly (i.e. smoke or carbon monoxide asphyxiation, cardiovascular events, etc.). However, 94.1% (N=318) of deaths were considered directly related to exposure (CDC, 2012). The leading cause of death was multi-system trauma at 95.6% (N=324), and 90% (N=306) of addresses associated with decedents were within a 5 mile radius of a tornado (CDC, 2012). Of the total deaths, 94.3% (N=319) were on the date of the exposure and 81% (N=274) were caused by EF4 or EF5 magnitude tornadoes (CDC, 2012). EF4 and EF5 tornadoes traveled an average distance of 66 miles on the ground crossing multiple counties, with wind velocities greater than 50mph (NOAA, 2011, 2012; Prevatt, Van De Lindt, & Graettinger, 2011).

Further research surrounding the April 2011 event is limited; however, existing studies suggest that the outbreak was an exceptional event, both meteorologically and with regard to risk and impact. Chaney et al. (2012) look at factors related to housing that contributed to lethality in the April 2011 outbreak (Chaney, Weaver, Youngblood, & Pitts, 2012). In their book, *Deadly Season: Analysis of the 2011 Tornado Outbreaks* (2012), Simmons and Sutter explore tornado fatalities from the 2011 tornado season and provide perspective. In chapter 2, they address the April 2011 tornado outbreak and conclude that excess deaths related to the event were due more to the violent nature of the tornadoes than other risk factors. Furthermore, the authors assert that this event was not characteristic of typical tornado event patterns in this region with regard to magnitude, timing and season of occurrence, thus it is difficult to determine the degree to which the region's elevated vulnerability played a role (K. Simmons & Sutter, 2012b). Knupp et al. (2014) provide a meteorological overview of the event as a preliminary analysis on the event. The authors conclude that the diverse and exceptional nature of this outbreak warrants additional research (Knupp et al., 2014).

Beyond the April outbreak, 2011 was an extreme year for tornadoes as a whole, resulting in 553 tornado-related fatalities, the most in one year since 1925 (K. Simmons & Sutter, 2012a; K. Simmons & Sutter, 2014). In 2012, Simmons and Sutter published an article highlighting future research that will be necessary to prevent such high death tolls in the future. They explain that the major tornado events of the year were well anticipated and proper warning was provided, concluding that mortality was not a result of poor early warning systems. Simmons and Sutter note, however, that appropriate safe rooms for such high magnitude events are costly and homes in this region did not have adequate shelter for the enormity of the event. They propose moving to an evacuation-based system for large-scale tornado events and call for further research on geographic locations of high and low tornado risk, based on persistent tornado tracks (K. Simmons & Sutter, 2012a).

Simmons and Sutter (2014) explore whether the unusually high death toll in 2011 was due to the strength and number of tornadoes or what they call 'societal vulnerability,' which for the purposes of this thesis is synonymous with social vulnerability. They applied regression analysis to fatalities from 1950 to 2010 to produce out-of-sample fatality projections for the 2011 events, comparing models that included socio-demographic variables to models without. Factors related to number, strength, and path of tornadoes were stronger predictors of the high death toll of 2011 than societal factors. Simmons and Sutter ultimately emphasize that extreme weather drove the high death toll in 2011, as opposed to societal factors. However, they also assert that these results do not imply that social vulnerability played no role. The analysis revealed that lethality varies regionally and these variations reflect patterns of social vulnerability. The authors conclude by noting that future research should "focus on addressing existing societal vulnerabilities" (K. Simmons & Sutter, 2014).

1.6 Evaluation of the CDC Social Vulnerability Index.

Understanding the geography of social vulnerability may play a key role in minimizing fatalities and other negative impacts of tornadoes in the future. The aim of this research is to use a tornado event as a case study to estimate the extent to which populations in census tracts with higher social vulnerability, as indicated by the CDC SVI, experienced higher mortality than census tracts with lower social vulnerability. Findings may support the validation of the SVI as it relates to tornados, as well as add to the body of literature surrounding the April 2011 tornado outbreak by clarifying the role of social vulnerability in the 2011 tornado event.

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Chapter 2: Manuscript

Introduction

Social vulnerability refers to a community's resilience to hazards based on its socio-economic and demographic characteristics, in contrast to vulnerability based solely on physical and built environment (Cutter, Boruff, & Shirley, 2003; Flanagan, Gregory, Hallisey, Heitgerd, & Lewis, 2011). In recent decades, policy makers, disaster management personnel, and public health practitioners have recognized the utility of characterizing and quantifying *social vulnerability* for disaster management. To varying degrees, practitioners across the field now incorporate social determinants of vulnerability into their work (Cutter et al., 2003; Dwyer, Zoppou, Nielsen, Day, & Roberts, 2004; Flanagan et al., 2011; Flax, Jackson, & Stein, 2002; Inter-American Development Bank, 2006; International Strategy for Disaster Reduction, 2004; Montz & Evans, 2001; Mustafa, Ahmed, Saroch, & Bell, 2011; United Nations Development Programme, 2004). Research suggests however that the various proposed resources, tools, and methods of quantification lack consistency, evaluation, reliability, and specifically that social vulnerability index construction methodology needs further validation in pursuit of consensus across the field. (Tate, 2013; Wolkin et al., 2015).

In 2011, the Geospatial Research, Analysis, and Services Program (GRASP) at the Center for Disease Control and Prevention (CDC) released a Social Vulnerability Index (SVI) for the entire U.S. at the census tract level using 14 U.S. Census and American Community Survey based socio-demographic variables. This index was designed to be used broadly across disaster management and is growing in utilization by state and local governments. GRASP is in the process of evaluating the validity of the index in its measurement of social vulnerability as it relates to disaster management. This evaluation has several components including estimating the degree to which the SVI accurately measures social vulnerability, its comparability to other theoretically similar constructs, and its reliability in predicting performance with regard to various hazards. In support of the last of those components, the study presented here uses statistical analyses and a case study event to estimate the extent to which the SVI modifies the association of mortality and tornadoes. More broadly, the analysis may suggest whether the SVI could be useful for decision-making regarding mitigation, recovery and preparedness in tornado-related disaster management.

Existing literature (Ashley, Krmenec, & Schwantes, 2008; Boruff et al., 2003; CDC, 2012; Cutter et al., 2003; Paul & Stimers, 2012; K. Simmons & Sutter, 2014) identifies known risk factors for morbidity and mortality from tornadoes as proximity to a high magnitude (EF4 or EF5 scale) tornado path, advanced age (≥ 65), inaccessibility of a safe room, sheltering in mobile homes, existence of tree cover, and night-time tornado events. There is also considerable evidence for increased mortality associated with exposure to a tornado among specific social sub-groups, including minorities, the elderly, and those with lower economic status.

This research examines a case study tornado event (here described as the April 2011 Tornado Outbreak) to analyze the effect of the SVI on the association between mortality and tornadoes. On the days of April 25-28, 2011, an enormous storm system generated 351 tornadoes, including 27 that were deadly, and 15 of which registered as EF4 or EF5. With the American Red Cross reporting 338 fatalities over 5 states, the storm system was the third-deadliest tornado event in the U.S. Existing studies, though limited, suggest that the outbreak of tornadoes was an exceptional event both meteorologically as well as with regard to its risk and impact due to the extreme and violent natures of the storm. (Chaney et al., 2012; Knupp et al., 2014; K. Simmons & Sutter, 2012).

Data and Methods

In this study we estimate associations between CDC's Social Vulnerability Index and daily mortality counts in census tracts that were affected by the April 2011 tornado outbreak under the following hypothesis: the SVI modifies the association between tornadoes and mortality in the April 2011 tornado outbreak. The tornado event affected census tracts in five states: Arkansas, Mississippi, Alabama, Tennessee, and Georgia. Of the five states, all but Tennessee elected to participate in the study. Datasets of mortality counts by either census tract or ZIP code (depending on the format of individual state surveillance systems) were assembled for the other four states. These datasets contain the census tract-specific (or ZIP code-specific) overall mortalities (as opposed to direct event-specific fatalities) on the date of the tornado event as well as the mortalities on the same day of the week from the prior week (baseline mortality). For all mortality data provided by ZIP code (Arkansas and Alabama), HUD-USPS crosswalk files were used to convert mortality from ZIP codes to census tracts. HUD-USPS crosswalk files were created by the U.S. Department of Housing and Urban Development (HUD) to provide a data allocation method between disparate geographic units that is based on residential addresses rather than area or population (DHUD, 2015). This conversion produces non-integer mortality estimations at baseline and on the date of the event for each census tract. The estimations were rounded to the nearest whole integer values to be used as inputs in a Poisson regression analysis. All spatial analysis and geographic data manipulation were completed in ArcGIS 10.2.2. Further data cleaning and statistical analysis were performed using SAS 9.4.

Tornado tracks for the April 25-28 storm were obtained from the National Weather Service (NWS) (NOAA, 2016). The study area was defined as any census tract in the four participating states that was intersected by an NWS –designated tornado track. Overall 368 census tracts were included in the study. Table 2.1 summarizes collected mortality data by tornado magnitude.

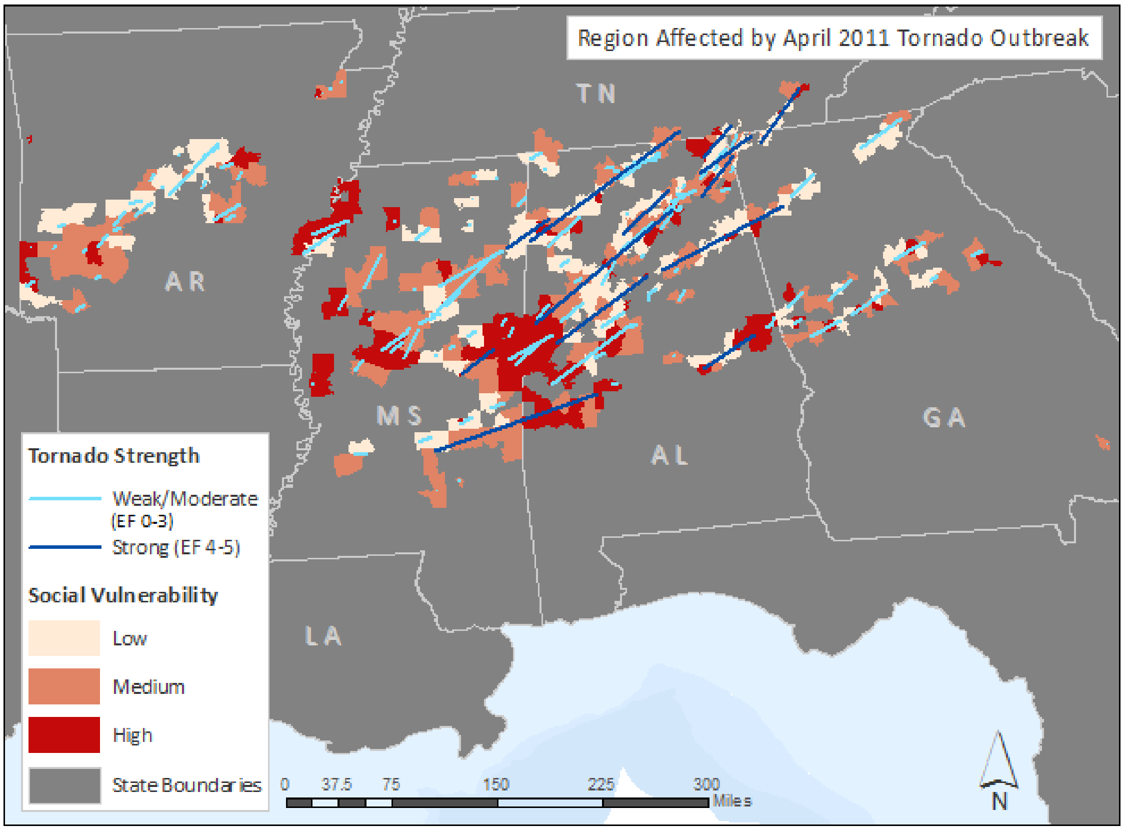
Table 2.1 Daily Mortality by Tornado Magnitude (EF Scale)

Magnitude	# Census Tracts	Maximum Deaths in a Census Tract	Total deaths (n)	Mortality Rate*
No tornado (baseline date)	368	1	15	0.86
0	23	1	2	1.82
1	73	5	14	4.44
2	53	1	12	4.67
3	71	4	24	7.10
4	110	7	47	8.88
5	38	18	68	33.88
Total (Tornado Date)	368		167	9.53

*per 100,000

The NWS uses the Enhanced Fujita scale to assign magnitude to tornados. The scale is based on wind speed (miles per hour) and runs from 0 to 5, with 5 being the most severe. Where wind speed data is unavailable, levels of damage are used to determine tornado magnitude. Spatial joins were used to associate tornado magnitude with each affected census tract. There were four instances where more than one tornado occurred in a census tract. In these cases, the highest tornado magnitude value was assigned. Figure 2.1 displays the study area with tornado tracts and census tracts symbolized by their respective SVI scores.

Figure 2.1 Study Area with Census Tracts displayed by Social Vulnerability with Tornado Tracts Overlay



The development of the Social Vulnerability Index is described in detail in Flanagan et al. (2011). Briefly, the 2010 version of the SVI is derived from summed percentile rankings of 14 census and American Community Survey variables, characterized in Table 2.2, at the census tract level. These variables represent social and demographic characteristics from four themes: socioeconomic status, household composition, minority status and language, and housing and transportation. SVI scores range from 0 to 1, with 1 representing the highest level of social vulnerability (Flanagan et al., 2011).

Table 2.2 Social Vulnerability Index Themes and Variables

SVI Theme	Variables Included
1. Socioeconomic Status	% Below Poverty Level
	% Unemployed
	Per Capita Income
	% Age 25 or Older with No High School Diploma
2. Household Composition & Disability	% Age 65 or Older
	%Age 17 or Younger
	% Single Parent Household
3. Minority Status & Language	% Minority
	% Age 5 or Older Speak English "Less than Well"
4. Housing & Transportation	% Multi-Unit Structures
	% Mobile Homes
	% Crowding (More people than rooms)
	% Without a Vehicle
	% In Institutionalized Group Quarters

Several models, shown in Table 2.3, were constructed using Poisson regression analysis (See Appendix for SAS code). First, the relationship between mortality and the social vulnerability index was estimated (Model 1). In Model 2, the relationship of daily mortality counts against SVI score and tornado presence (date), while controlling for tornado magnitude was estimated. The natural log of the census tract population was used as the offset. A third model was constructed containing the same independent variables and an additional SVI and tornado presence interaction term (Model 3). Deviances from the full and reduced model were compared to evaluate whether areas of higher social vulnerability experienced significantly higher mortality.

Table 2.3 Poisson Regression Analysis Model Formulations

Model	Formula
1	Logit(mortality) = $\alpha + \beta_1$(SVI) + ε
2	Logit(mortality) = $\alpha + \beta_1$(SVI)+ β_2(Presence) + ε
3	Logit(mortality) = $\alpha + \beta_1$(SVI) + β_2(Presence) + β_3(Presence*SVI) + ε
4	Logit(mortality) = $\alpha + \beta_1$(SVI) + β_2(Weak) + β_3(Strong) + ε
5	Logit(mortality) = $\alpha + \beta_1$(SVI) + β_2(Weak) + β_3(Strong) + β_4(Weak*SVI) + β_5(Strong *SVI) + ε
6, 8, 10, 12	Logit(mortality) = $\alpha + \beta_1$(SVI Theme X) + β_2(Weak) + β_3(Strong) + ε
7,9,11,13	Logit(mortality) = $\alpha + \beta_1$(SVI Theme X) + β_2(Weak) + β_3(Strong) + β_4(Weak *SVI) + β_5(Strong *SVI) + ε

Because existing literature suggests that as tornado severity increases, vulnerability tends to equalize across social and demographic factors and the case study event was notably extreme, the above analysis was repeated with tornado presence dichotomized to weak (EF magnitude 0-3) and strong (EF Magnitude 4-5). Weak and strong designations were determined based on previous literature designations (Paul & Stimers, 2014; K. Simmons & Sutter, 2012a). This analysis was completed in an attempt to parse out the potential modification of mortality due to SVI in separate contexts of weak and strong tornadoes. Further secondary analyses investigated the utility of specific parts of the SVI by repeating the Poisson regression analysis with each of the four theme themes' percentile ranking scores individually, using the dichotomized tornado presence variables (models 6 -13).

Results

Unadjusted, there was a significant association between mortality and tornadoes in the April 2011 tornado outbreak (RR: 8.0, 4.1– 15.4). Table 2.4 displays estimated rate ratios and confidence intervals from adjusted models for mortality at social vulnerability levels of 0.2, 0.4, 0.6, and 0.8 respectively relative to the lowest social vulnerability level (SVI = 0). No significant association was exhibited between mortality in the event and the SVI alone (Model 1). A strong association between mortality and tornados is present in all adjusted models. Specifically, when adjusting for strength of tornado, mortality increases substantially in census tracts with strong tornados.

Table 2.4 Mortality Rate Ratios and 95% confidence intervals for presence vs. absence of tornados and model Deviance for Overall SVI Analysis

Models for Overall SVI Analysis	Rate Ratios at SVI Levels SVI=0.2	SVI=0.4	SVI=0.6	SVI=0.8	Deviance Statistic
Model 1	**1**	**1.1**	**1.2**	**1.2**	
	(0.8, 1.3)	(0.7, 1.7)	(0.6, 2.2)	(0.5, 2.9)	
Model 2 (Reduced)	**11.7**	**12.2**	**12.8**	**13.4**	694.5
	(5.0, 27.1)	(5, 30)	(4.8, 34.1)	(4.5, 39.7)	
Model 3 (Full)	**15.9**	**12.4**	**9.7**	**7.5**	693.1
	(4.3, 58.9)	(5, 30.7)	(4.1, 22.9)	(2.2, 25.3)	
	Deviance Goodness of Fit Test (X^2 Dist., 1 *df*):				**1.4**
Model 4 (Reduced)					643.1
Weak Tornado Strength	**6.4**	**7**	**7.6**	**8.2**	
	(2.8, 14.7)	(2.9, 16.7)	(2.9, 19.4)	(2.9, 23.2)	
Strong Tornado Strength	**20.2**	**21.9**	**23.8**	**25.9**	
	(9.2, 44.3)	(9.5, 50.8)	(9.5, 59.8)	(9.3, 71.9)	
Model 5 (Full)					642.1
Weak Tornado Strength	**8**	**6.5**	**5.3**	**4.3**	
	(2.2, 29)	(2.7, 15.9)	(2.2, 12.4)	(1.3, 14.3)	
Strong Tornado Strength	**25.2**	**20.4**	**16.6**	**13.4**	
	(7.5, 84.5)	(8.8, 47.3)	(7.4, 37.1)	(4.3, 42.1)	
	Deviance Goodness of Fit Test (X^2 Dist., 2 *df*):				**1**

In models adjusting for SVI without interactions (Models 2 and 4), rate of mortality slightly increases with social vulnerability, an expected trend, However rate ratios are extremely imprecise in both parameterizations of the tornado association (presence alone and presence dichotomized by strength). Models adjusting for the interaction of SVI and tornados (Models 3 and 5) showed a decreasing trend of mortality as SVI increases in both parameterizations of the tornado association, however it cannot necessarily be inferred that tracts with lower social vulnerability, as characterized by the SVI, actually have higher mortality rates during these events as baseline mortality may be higher in high SVI tracts lending to lower rate ratios. Furthermore, rate ratios were extremely imprecise unilaterally. When comparing full and reduced models using a deviance goodness of fit test, interactions were not found to explain additional variance in the models for either parameterization of the tornado association. Thus, these analyses do not support the hypothesis that SVI modifies the association between tornadoes and mortality in the April 2011 tornado outbreak.

Results of the secondary analysis, shown in Table 2.5, indicate similar trends to the results from the models that included overall SVI: imprecise increases in mortality with increasing social vulnerability in reduced models, and imprecise decreases in mortality with increasing social vulnerability in full models. The only notable exception to this trend is exhibited in the set of models analyzing SVI Theme 3 (Minority Status/Language), which show increases in mortality with increasing social vulnerability, although precision is still weak. Furthermore, when comparing the full and reduce model deviance statistics, the SVI Theme 3 full model was significant at X^2.100.

Table 2.5 Mortality Rate Ratios and 95% confidence intervals for presence vs. absence of tornados and model Deviance for SVI by Theme Adjusting for Tornado Strength

Models for Analysis by SVI Theme	Rate Ratios at SVI Levels				Deviance Statistic
	SVI=0.2	**SVI=0.4**	**SVI=0.6**	**SVI=0.8**	
Model 6 - SVI Theme 1 (Reduced)					645
Weak Tornado Strength	**6.0**	**6.1**	**6.2**	**6.3**	
	(2.6, 14.0)	(2.5, 15.1)	(2.3, 16.9)	(2.1, 19.3)	
Strong Tornado Strength	**18.7**	**19.0**	**19.3**	**19.6**	
	(8.4, 41.6)	(8.0, 45.4)	(7.3, 51.2)	(6.5, 59.2)	
Model 7 - SVI Theme 1 (Full)					640.7
Weak Tornado Strength	**7.3**	**6.2**	**5.3**	**4.6**	
	(2.1, 25.8)	(2.6, 14.8)	(2.2, 12.8)	(1.2, 16.7)	
Strong Tornado Strength	**29.5**	**19.9**	**13.4**	**9.0**	
	(9.1, 95.9)	(8.9, 44.5)	(5.7, 31.6)	(2.5, 32.6)	
	Deviance Goodness of Fit Test (X^2 Dist., 2 *df*):				**4.3**
Model 8 - SVI Theme 2 (Reduced)					639.3
Weak Tornado Strength	**5.2**	**4.5**	**3.9**	**3.4**	
	(2.2, 12.0)	(1.9, 10.9)	(1.5, 10.2)	(1.2, 9.8)	
Strong Tornado Strength	**16**	**13.9**	**12.1**	**10.6**	
	(7.3, 35.1)	(6.0, 32.1)	(4.9, 30.2)	(3.8, 29.1)	
Model 9 - SVI Theme 2 (Full)					637.3
Weak Tornado Strength	**7.5**	**5.4**	**4.0**	**2.9**	
	(2.8, 19.8)	(2.4, 12.5)	(1.3, 11.9)	(0.6, 14.0)	
Strong Tornado Strength	**21.5**	**17.7**	**14.6**	**12.0**	
	(8.5, 54.4)	(8.2, 38.0)	(5.5, 38.5)	(3.0, 48.4)	
	Deviance Goodness of Fit Test (X^2 Dist., 2 *df*):				**2**
Model 10 - SVI Theme 3 (Reduced)					643.7
Weak Tornado Strength	**6.3**	**6.7**	**7.2**	**7.7**	
	(2.7, 14.5)	(2.8, 16.1)	(2.8, 18.3)	(2.8, 21.1)	
Strong Tornado Strength	**19.8**	**21.2**	**22.6**	**24.1**	
	(9.0, 43.6)	(9.2, 48.8)	(9.1, 55.9)	(8.9, 65.3)	
Model 11 - SVI Theme 3 (Full)					638
Weak Tornado Strength	**14.4**	**9**	**5.7**	**3.5**	
	(2.8, 72.7)	(2.9, 27.5)	(2.4, 13.1)	(1.3, 9.6)	
Strong Tornado Strength	**46.9**	**28.5**	**17.3**	**10.5**	
	(10.0, 220.7)	(9.8, 82.9)	(7.8, 38.1)	(4.2, 26.4)	
	Deviance Goodness of Fit Test (X^2 Dist., 2 *df*):				**5.7***
Model 12 - SVI Theme 4 (Reduced)					644.6
Weak Tornado Strength	**6.2**	**6.4**	**6.7**	**7**	
	(2.7, 14.2)	(2.7, 15.5)	(2.6, 17.4)	(2.5, 19.9)	
Strong Tornado Strength	**19.3**	**20.1**	**21**	**21.8**	
	(8.7, 42.5)	(8.6, 46.9)	(8.3, 53.1)	(7.8, 61.3)	
Model 13 - SVI Theme 4 (Full)					642.5
Weak Tornado Strength	**8.4**	**6.5**	**5**	**3.8**	
	(2.5, 28.8)	(2.7, 15.5)	(2.1, 12.0)	(1.1, 13.1)	
Strong Tornado Strength	**27.4**	**20.2**	**14.9**	**11**	
	(8.6, 87.5)	(8.9, 46.0)	(6.5, 34.1)	(3.4, 35.6)	
	Deviance Goodness of Fit Test (X^2 Dist., 2 *df*):				**2.1**

*Significant at X^2 0.10

Discussion

The objective of this study was to investigate whether people living in more socially vulnerable census tracts, as characterized by the SVI, experienced higher mortality during the April 20ll tornado outbreak. The results presented do not provide evidence to suggest that the low SVI tracts have lower mortality rates than high overall SVI tracts during the tornado events. Higher baseline mortality in high SVI tracts may have resulted in smaller rate ratios in high SVI tracts, and a limited number of data points resulted in imprecise rate ratios across all SVI levels. Finally, a large number of deaths were due to high magnitude tornadoes, which can be devastating regardless of social vulnerability. Due to these factors, it is difficult to make any strong inferences about the role of the SVI in modifying the association between tornado presence and mortality.

The increased mortality associated with strong tornadoes supports assertions in the literature that mortality related to this event was more likely due to the extreme nature of the event than other factors (Knupp et al., 2014; K. Simmons & Sutter, 2012b). Furthermore, these results may support implications in the literature related to the diminishing return of social or societal vulnerability as a predictor for outcomes as tornado events increase in strength (Paul & Stimers, 2014; K. Simmons & Sutter, 2012a). The event under consideration in this study was extreme, with most mortality associated with EF4 and EF5 tornadoes as shown in Table 2.1. Perhaps repeating this study with a less extreme set of tornado events and/or over a period of events where higher mortality counts could be accumulated would provide stronger evidence as to whether the relationship between tornadoes and mortality is actually modified by the SVI or one of its themes.

Based on the literature's implications regarding housing type as a major risk factor in tornado events, model 13 (Theme 4: Housing and Transportation) would seem a more likely candidate to be significant with interactions, as opposed to model 11 (Theme 3: Minority/Language Status) in the secondary theme-based analysis. However, when comparing full and reduced models containing SVI Theme 4 using a deviance goodness of fit test, interactions were not found to explain additional variance, while the SVI Theme 3 full model was significant at $X^2_{.100}$. One could hypothesize that, similar to the overall SVI analysis, this is due to the extreme nature of the event, in that most deaths were related to EF4 or EF5 tornadoes, at which point housing and/or transportation context could likely become irrelevant. Or perhaps language barriers associated with tornado warning systems in more vulnerable tracts prevented people in vulnerable census tracts from responding. This mild association warrants further examination in context of both the SVI and tornado preparedness intervention research.

The SVI was created using a percentile ranking methodology based on 14 variables to provide a broad estimation of social vulnerability in disaster situations. There are other ways of developing a vulnerability index such as factor analysis or risk mapping that could include different variables and thus result in slightly different rankings. Furthermore, there are a large number of variables composited in this index. The literature suggests several social and demographic characteristics are risk factors during tornadoes, lending to the hypothesis that the SVI would modify the association between mortality and tornadoes. However, it is possible that the importance of those few variables were lost in the large number of equally-weighted variables comprising the SVI. A disaster-specific social vulnerability index for tornadoes would likely contain an altered and more limited set of variables, specific to risk factors associated with tornadoes, such as age, income, housing type, etc. (Ashley, Krmenec, & Schwantes, 2008; Boruff et al., 2003; CDC, 2012; Paul & Stimers, 2012), as opposed to the all-encompassing set of variables included in the broader SVI evaluated here. Thus, the social vulnerability represented by this SVI is not necessarily specifically descriptive of tornado-related social vulnerability. Although, this is a limitation in this study, all CDC's SVI data are publicly available, including preliminary and intermediate data, and thus could easily be reconstructed to be more disaster-specific. The SVI was intentionally created using the easily reproducible percentile ranking method for that the user could choose to construct more specific indices as they may see fit. This study however only analyzes the SVI as a whole and broken into its four main themes.

There were several limitations in this study which may have introduced selection bias, confounding, or measurement error. Selection bias may have been introduced in defining the study area. All census tracts that intersected a tornado track, as delineated by the NWS, were included in the study. Mortality, however, is recorded by residence in all participating states. It is likely that some tornado-related fatalities were recorded in census tracts buffering the selected study region, if residents of that tract were killed while visiting a tornado-intersected tract during the event. This is likely one of the reasons for the reduced number of mortalities in this study as compared to the number fatalities recorded by the American Red Cross in the event. Furthermore, approximately 10% of actual tornado-related fatalities associated with this tornado event were in Tennessee who declined to participate and unavailable for the study. Furthermore, the study was limited by the low number of data points greater than zero. These limitations likely contributed to the wide confidence intervals associated with output estimates. The inclusion of mortality data from Tennessee and census tracts adjacent to the study area may have increased precision in this study. There are no clear threats to the validity of this study due to confounding.

Finally, measurement error was introduced into the dataset in the conversion of mortality from ZIP code to census tract scale during data preparation. The SVI is quantified at the census tract level, however two states (Alabama and Arkansas) were only able to provide data at ZIP code level. The process of converting spatial data from one jurisdictional type to another, called "crosswalking" calculates percentage of overlapping areas by number of residences and sums them to assign a value to the output jurisdiction type. This process results in non-integer values that estimates the likelihood of an event occurring there rather than providing a true count. These estimations were rounded to the nearest integer for use in the Poisson regression analysis, potentially inflating or deflating mortality counts and rate ratios in census tracts, and introducing measurement error to the study.

Considering the extreme nature of this event and the imprecision in the results of this study, it is difficult to draw broad conclusions about the SVI's utility in emergency management as it relates to predicting tornado mortality. Future SVI evaluation efforts related to predicting tornado mortality may consider focusing on non-extreme events (< EF4) as these may provide a more realistic view of social vulnerability's role in health outcomes during these disasters. Furthermore, future research should consider evaluating the SVI with a different endpoint. Literature suggests that despite the magnitude of a tornado event, the socially vulnerable are more likely to have poor health outcomes and slower recovery in the aftermath (Cutter et al., 2003; B. E. Flanagan et al., 2011; Juntunen, 2005; Morrow, 1999). An index such as the SVI would likely be much more beneficial to preparedness and recovery stages of disaster management than impact prediction. Studies looking at lagged health outcomes, recovery time, and mitigation strategy success may be beneficial to determining the utility of the SVI for planning, preparedness, and recovery phases of the disaster cycle.

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Appendix

The following SAS code was used to model associations between mortality and tornadoes in this study. Substantial data cleaning and processing was done prior to constructing these models, however only the models themselves are presented here.

Model 1:

```
**Association between SVI and mortality;
PROC GENMOD data=h.thesis6;
	model mort_rnd =  svi / dist=poisson link=log offset=ln_pop pscale;
	estimate 'RR for tornado with SVI=.2' svi .2/exp;
	estimate 'RR for tornado with SVI=.4' svi .4/exp;
	estimate 'RR for tornado with SVI=.6' svi .6/exp;
	estimate 'RR for tornado with SVI=.8' svi .8/exp;
run;
```

Model 2:

```
**REDUCED: Association between presence and mortality adjusting for SVI;
PROC GENMOD data=h.thesis6;
	model mort_rnd = presence svi / dist=poisson link=log offset=ln_pop pscale;
	estimate 'RR for tornado with SVI=.2' presence 1 svi .2/exp;
	estimate 'RR for tornado with SVI=.4' presence 1 svi .4/exp;
	estimate 'RR for tornado with SVI=.6' presence 1 svi .6/exp;
	estimate 'RR for tornado with SVI=.8' presence 1 svi .8/exp;
run;
```

Model 3:

```
**FULL: Association between presence and mortality adjusting for SVI and its
interaction with tornado presence;
PROC GENMOD data=h.thesis6;
	model mort_rnd = presence svi presence*svi / dist=poisson link=log
		offset=ln_pop pscale;
	estimate 'RR for tornado with SVI=.2' presence 1 presence*svi .2/exp;
	estimate 'RR for tornado with SVI=.4' presence 1 presence*svi .4/exp;
	estimate 'RR for tornado with SVI=.6' presence 1 presence*svi .6/exp;
	estimate 'RR for tornado with SVI=.8' presence 1 presence*svi .8/exp;
run;
```

Model 4:

```
**REDUCED: Association between dichotomized presence and mortality adjusting
for SVI;
PROC GENMOD data=h.thesis6;
	model mort_rnd = weak_torn strong_torn svi / dist=poisson link=log
		offset=ln_pop pscale;
	estimate 'RR for weak tornado with SVI=.2' weak_torn 1 svi .2/exp;
	estimate 'RR for weak tornado with SVI=.4' weak_torn 1 svi .4/exp;
	estimate 'RR for weak tornado with SVI=.6' weak_torn 1 svi .6/exp;
	estimate 'RR for weak tornado with SVI=.8' weak_torn 1 svi .8/exp;
	estimate 'RR for strong tornado with SVI=.2' strong_torn 1 svi .2/exp;
	estimate 'RR for strong tornado with SVI=.4' strong_torn 1 svi .4/exp;
	estimate 'RR for strong tornado with SVI=.6' strong_torn 1 svi .6/exp;
	estimate 'RR for strong tornado with SVI=.8' strong_torn 1 svi .8/exp;
run;
```

Model 5:

```
**FULL: Association between dichotomized presence and mortality adjusting for SVI
and its interaction with tornado presence;
PROC GENMOD data=h.thesis6;
	model mort_rnd =  weak_torn strong_torn svi weak_torn*svi strong_torn*svi
		/ dist=poisson link=log offset=ln_pop pscale;
	estimate 'RR for weak tornado with SVI=.2' weak_torn 1 weak_torn*svi
		.2/exp;
	estimate 'RR for weak tornado with SVI=.4' weak_torn 1 weak_torn*svi
		.4/exp;
	estimate 'RR for weak tornado with SVI=.6' weak_torn 1 weak_torn*svi
		.6/exp;
	estimate 'RR for weak tornado with SVI=.8' weak_torn 1 weak_torn*svi
		.8/exp;
	estimate 'RR for strong tornado with SVI=.2' strong_torn 1 strong_torn*svi
		.2/exp;
	estimate 'RR for strong tornado with SVI=.4' strong_torn 1 strong_torn*svi
		.4/exp;
	estimate 'RR for strong tornado with SVI=.6' strong_torn 1 strong_torn*svi
		.6/exp;
	estimate 'RR for strong tornado with SVI=.8' strong_torn 1 strong_torn*svi
		.8/exp;
	contrast 'LR Test for SVI interaction' weak_torn*svi 1, strong_torn*svi 1;
run;
```

Models 6, 8, 10, 12: *These models all resembled the following with the exception that associated SVI themes for each model were substituted for SVI# variables.*

```
**REDUCED: Association between dichotomized presence and mortality adjusting
for SVI theme 1;
PROC GENMOD data=h.thesis6;
	model mort_rnd = weak_torn strong_torn svi_1 / dist=poisson link=log
offset=ln_pop pscale;
	estimate 'RR for weak tornado with SVI=.2' weak_torn 1 svi_1 .2/exp;
	estimate 'RR for weak tornado with SVI=.4' weak_torn 1 svi_1 .4/exp;
	estimate 'RR for weak tornado with SVI=.6' weak_torn 1 svi_1 .6/exp;
	estimate 'RR for weak tornado with SVI=.8' weak_torn 1 svi_1 .8/exp;
	estimate 'RR for strong tornado with SVI=.2' strong_torn 1 svi_1 .2/exp;
	estimate 'RR for strong tornado with SVI=.4' strong_torn 1 svi_1 .4/exp;
	estimate 'RR for strong tornado with SVI=.6' strong_torn 1 svi_1 .6/exp;
	estimate 'RR for strong tornado with SVI=.8' strong_torn 1 svi_1 .8/exp;
run;
```

Models 7, 9, 11, 13: *These models all resembled the following with the exception that associated SVI themes for each model were substituted for SVI# variables.*

```
**FULL: Association between dichotomized presence and mortality adjusting for SVI
theme 1 and its interaction with tornado presence;
PROC GENMOD data=h.thesis6;
	model mort_rnd =  weak_torn strong_torn svi_1 weak_torn*svi_1
		strong_torn*svi_1 / dist=poisson link=log offset=ln_pop pscale;
	estimate 'RR for weak tornado with SVI=.2' weak_torn 1 weak_torn*svi_1
		.2/exp;
	estimate 'RR for weak tornado with SVI=.4' weak_torn 1 weak_torn*svi_1
		.4/exp;
	estimate 'RR for weak tornado with SVI=.6' weak_torn 1 weak_torn*svi_1
		.6/exp;
	estimate 'RR for weak tornado with SVI=.8' weak_torn 1 weak_torn*svi_1
		.8/exp;
	estimate 'RR for strong tornado with SVI=.2' strong_torn 1 strong_torn*svi_1
		.2/exp;
	estimate 'RR for strong tornado with SVI=.4' strong_torn 1 strong_torn*svi_1
		.4/exp;
	estimate 'RR for strong tornado with SVI=.6' strong_torn 1 strong_torn*svi_1
		.6/exp;
	estimate 'RR for strong tornado with SVI=.8' strong_torn 1 strong_torn*svi_1
		.8/exp;
	contrast 'LR Test for SVI interaction' weak_torn*svi_1 1, strong_torn*svi_1 1;
run;
```