A Spatial Analysis of "Most Weather Warned" Counties by Severe Weather Phenomena

in the

Contiguous United States

by

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A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Arts

Approved March 2019 by the
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ARIZONA STATE UNIVERSITY

May 2019

ABSTRACT

Severe weather affects many regions of the United States, and has potential to greatly impact many facets of society. This study provides a climatological spatial analysis by county of severe weather warnings issued by the National Weather Service (NWS) between January 1st, 1986 to December 31st, 2017 for the contiguous United States. The severe weather warnings were issued for county-based flash flood, severe thunderstorm, and tornado phenomena issued through the study period and region. Post 2002 severe weather warnings issued by storm warning area were included in this study in the form of county-based warnings simultaneously issued for each affected county. Past studies have researched severe weather warnings issued by the NWS, however these studies are limited in geographic representation, study period, and focused on population bias. A spatial analysis of severe weather warning occurrences by county identify that (a) highest occurrences of flash flood warnings are located in the desert Southwest and Texas, (b) severe thunderstorm warning occurrence is more frequent in Arizona, portions of the Midwest, the South, and the Mid and South Atlantic states, (c) the tornado activity regions of Tornado Alley and Dixie Alley (i.e. Colorado, Kansas, Oklahoma, Arkansas, Texas, Louisiana, Mississippi, Alabama, Tennessee, and Illinois) contained the highest occurrences of tornado warnings, and (d) the highest instances of aggregate warning occurrences are found in the desert Southwest, the Midwest, and the Southern regions of the United States. Generally, severe weather warning "hot spots" tend to be located in those same regions, with greater coverage. This study concludes with a comparison of local maxima and general hot spot regions to expected regions for each phenomenon.

Implications of this study are far reaching, including emergency management, and has potential to reduce risk of life.

ACKNOWLEDGMENTS

Firstly, I would like to thank my committee at Arizona State University and NOAA, consisting of Randall Cerveny, Robert Balling, Russel Vose, and Dan Krahenbuhl. I am extremely grateful for their assistance and time in completion of this thesis. I am especially grateful to my chair, Dr. Cerveny. Dr. Cerveny inspired me to pursue the subject of this thesis, greatly assisted me during writing, and has provided a pathway for my future career in the atmospheric sciences. I would also like to thank the staff and faculty in the School of Geographical Sciences and Urban Planning who provided assistance during my courses and provided an avenue to further explore my capabilities as an instructor.

Lastly, I would like to give a special thanks to my friends and family. To Steven, Katie, and Ryan who supported and encouraged me throughout my coursework and preparation of this thesis. And to my parents Don and Kris, and my brother Cody, all of whom were always there for me through my schooling and life, and encouraged me to pursue my dreams. Without the support of my family and friends, this thesis would never have been possible.

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CHAPTER 1

INTRODUCTION AND RESEARCH QUESTION

Introduction

With most discussions of severe weather in the United States, places like Kansas, Oklahoma, Texas, and Florida are often commonly mentioned. Research confirms that these regions are susceptible to certain types of severe weather, with the first two being contained in what is commonly referred to as the Tornado Alley, and the last two being in regions susceptible to hurricanes. But even though these places are susceptible to severe weather, the question remains as to where, and correspondingly who, experiences the highest occurrences of severe weather? Knowing who experiences the highest occurrences of severe weather provides benefits to emergency management agencies, to public interests, and private interests. For example, emergency managers can use this information to efficiently place equipment and supplies near these severe weather prone areas; people planning to move can find a town that is less prone to severe weather; and private companies, especially ones dealing in transport, can plan around these regions.

That question and related ones can potentially be addressed through the use of spatial analysis and Geographic Information Systems (GIS). Over the past several decades, GIS has evolved from being just a way of spatially visualizing data to analyzing data, and creating solutions for real-world problems (ESRI, https://www.esri.com/en-us/what-is-gis/overview). GIS, aided by modern computing power, is able to provide spatially accurate and fine data as well as use complex spatial analysis statistics in order to provide the spatial relationships between related and nonrelated datasets. This quality and aspect of GIS are perfect for addressing the spatial patterns and relationships of severe weather across the contiguous United States.

Research Questions

Consequently, given the importance of the overall question of location analysis of severe weather and the power of GIS and spatial analysis statistics, the aim of this study is to provide a spatial analysis of the record of severe weather warnings in the contiguous United States from the start of 1986 to the end of 2017. Specifically, the severe weather warnings addressed in the study are the flash flood, severe thunderstorm, and tornado warnings issued by the National Weather Service. These severe weather warnings are used to provide an answer to the who and where of severe weather occurrences. But since the original question is very limited in its scope, and to account for any influence on spatial variation, further analysis is completed using the aggregate of the severe weather warnings and the number of warnings adjusted for county population, county area, and county population density. To guide this study, the following research questions are asked:

(1) What is the spatial distribution of severe weather warnings for unadjusted and adjusted warning occurrences, and which regions contain maxima of these occurrences?

(2) Are there regions of high and low warning occurrences, and where are these regions located in the contiguous United States?

(3) In the established regions of high and low warning occurrences, do outliers exist and where are these outliers located?

Hypotheses

Given the three questions, I hypothesize the following:

(1) Flash flood warnings will be mostly located in the Southwest and along major river areas, with maxima located mostly in the Southwest; I expect severe thunderstorm warnings to be located in the Southwest, the South, and the Midwest with maxima mostly located in the Midwest; I expect tornado warnings to mostly be located in the Midwest, and the South, with maxima to be located in both regions; and lastly, I expect that the aggregate of warnings will mostly be in the South and Midwest with maxima likely in the Midwest.

(2) High occurrences of flash flood warnings will occur in the Southwest and low occurrences across the northern states of the United States; I expect that high occurrences of severe thunderstorm warnings occur over the Midwest and the South with low occurrences mostly over mountainous regions (e.g. Rocky Mountains); I expect that high occurrences of tornado warnings occur over the Midwest and the South with low warning occurrences mostly over non-flat regions, such as the western half of the United States; I expect that high occurrences of aggregate warnings will occur over the South, and the Midwest with the lowest occurrences over mountainous regions.

(3) I expect to find outliers (significant variations from the mean of the area), and for the outliers to be interspersed within regions of the high and low occurrences. I also expect outliers to be located where there are sharp gradients between high and low occurrence regions.

Thesis Outline

To validate the hypotheses, and to answer the research questions, this study will begin with relevant background information in the second chapter. This chapter will seek to define the severe weather warnings as well as provide a brief history of the organization that issues these warnings. Past research studies that utilize severe weather warnings and related products will be reviewed with an emphasis on the purpose of these studies and how this study relates.

The third chapter will describe the original dataset and the steps taken to transform that dataset into the one used during analysis. Potential biases and the analyses used will also be discussed in the third chapter.

The fourth chapter will provide the results from the analysis of the final dataset. This chapter is split into the three analyses that this study uses, with each analysis section discussing the spatial distributions of the severe weather warning occurrences and their adjusted values.

The final chapter will provide a brief closing summary of each section and discuss if the research questions have been answered and if the hypothesis is validated.

To begin addressing the issue of most frequent locations of severe weather occurrences, background on the nature of the data being used and previous research will be discussed in the next chapter.

CHAPTER 2

NATIONAL WEATHER SERVICE & PREVIOUS RESEARCH

Introduction

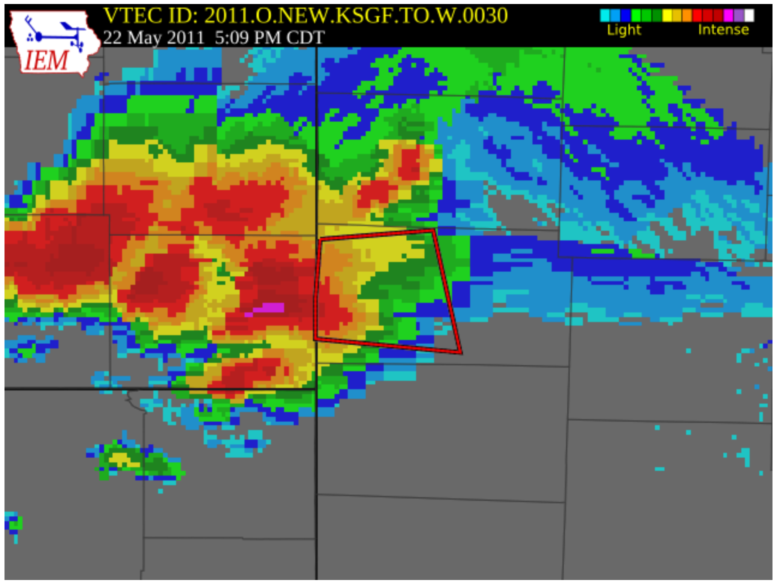
As discussed in the previous chapter, this thesis addresses the fundamental research question of where are the highest occurrences of severe weather in the contiguous United States. In order to answer that question, a good understanding of relevant concepts and previous studies is necessary. In this chapter, I review the methods that the U.S. National Weather Service (NWS) uses when determining a warning situation and the products issued concerning those situations, with particular emphasis on the role and recent use of the Doppler Radar WSR-88D system. In addition, I examine the differences of previous studies that include U.S. NWS waring data with the present study. In particular, I address the geo-spatial relationships of warnings detailed in Harrison and Karstens (2017) and how that relates to the present study. This information provides the past foundational basis for further work on development of a geospatial dataset of warnings from 1985 to present.

National Weather Service Warning Event Products

In the United States, the National Oceanic and Atmospheric Administration (NOAA) tasks the National Weather Service (NWS) as well as other government organizations with the monitoring and forecasting of daily atmospheric phenomena. Included in that monitoring and the forecasting, the NWS has the ability to issue event products that warn or advise the general population regarding specific types of weather that may have some impact on their lives.

Severe weather is one of the primary concerns of the NWS, as such activity proves to have a very significant impact on the lives and property throughout the United States (Folger 2013). Severe weather warning products are generally provided through newscasts on television or radio as well as on social media. When a warning event product is produced by a Weather Forecast Office (WFO), the warning phenomenon type as well as the specific geographic area affected are disseminated through a number of different mediums (Figures 2.1, 2.2, 2.3). Those mediums include mobile phones, radio, television, and other modes, though television still reigns as the most utilized source of a warning (Best 2017). Warning event products are sent to the public as well as NWS partners, though the NWS relies on their ability to understand the warning information as well as act accordingly (NWS Directive 10-1801).

The NWS produces many event products, each with a level of severity as well as the concerned atmospheric phenomena. The highest significant level that any one event product can attain is the "warning", which means that the atmospheric phenomena being alerted for is either likely occurring or imminent. Most warning events last for short durations, generally for only a few hours. Though many atmospheric phenomena can be warned for, only three specific types, flash floods, tornadoes, and severe thunderstorms, are examined in the course of this research as these categories have the most extensive data.

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BULLETIN - EAS ACTIVATION REQUESTED
TORNADO WARNING
NATIONAL WEATHER SERVICE SPRINGFIELD MO
509 PM CDT SUN MAY 22 2011

THE NATIONAL WEATHER SERVICE IN SPRINGFIELD HAS ISSUED A

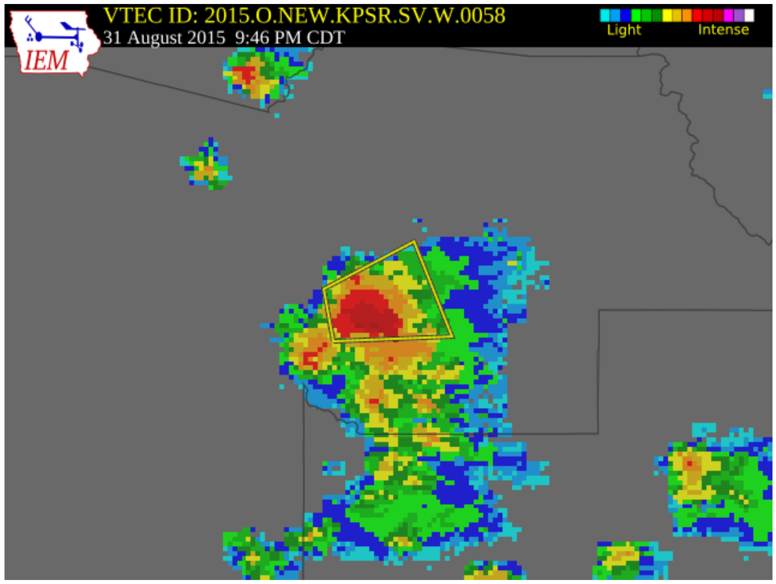
* TORNADO WARNING FOR...
  WESTERN JASPER COUNTY IN SOUTHWEST MISSOURI...

* UNTIL 600 PM CDT.

* AT 505 PM CDT...NATIONAL WEATHER SERVICE DOPPLER RADAR INDICATED A
  TORNADO 10 MILES WEST OF CARL JUNCTION...OR 6 MILES EAST OF
COLUMBUS...MOVING EAST AT 30 MPH. THIS STORM HAS A HISTORY OF
PRODUCING FUNNEL CLOUDS AND TENNIS BALL SIZE HAIL.

* LOCATIONS IMPACTED INCLUDE AIRPORT DRIVE...ALBA...ASBURY...ATLAS...
```

Figure 2.1: Tornado warning issued at 22:09 UTC for the Western Jasper County area. The top image (A) shows a map with a radar view of the approaching storm and the warning area surrounded in red. The bottom image (B) is the text bulletin that is issued with the warning, detailing the valid time of the warning, locations impacted, other severe weather threats (not shown), and precautionary/preparedness actions (not shown).

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076
WUUS55 KPSR 010246
SVRPSR
AZC013-010315-
/O.NEW.KPSR.SV.W.0058.150901T0246Z-150901T0315Z/

BULLETIN - IMMEDIATE BROADCAST REQUESTED
SEVERE THUNDERSTORM WARNING
NATIONAL WEATHER SERVICE PHOENIX AZ
746 PM MST MON AUG 31 2015

THE NATIONAL WEATHER SERVICE IN PHOENIX HAS ISSUED A

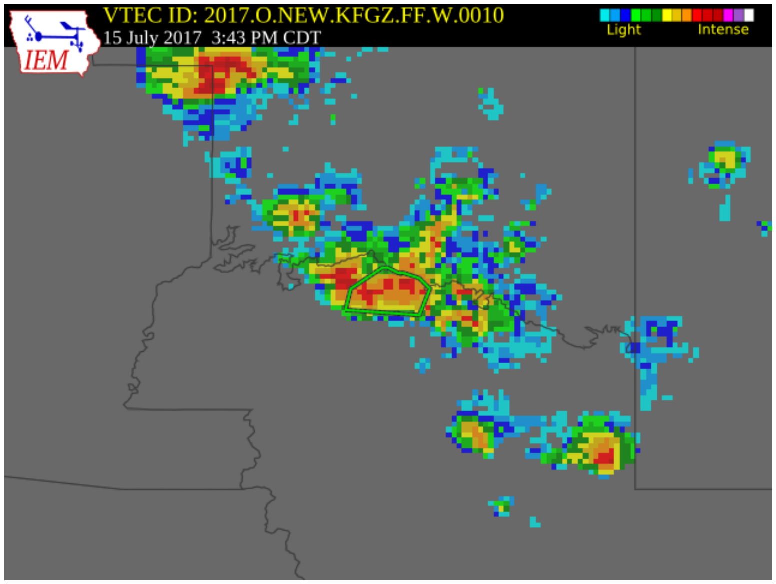
* SEVERE THUNDERSTORM WARNING FOR...
  NORTHEASTERN MARICOPA COUNTY IN SOUTH CENTRAL ARIZONA...

* UNTIL 815 PM MST

* AT 746 PM MST...DOPPLER RADAR INDICATED A SEVERE THUNDERSTORM
  CAPABLE OF PRODUCING DAMAGING WINDS IN EXCESS OF 60 MPH. THIS
  STORM WAS LOCATED OVER DOWNTOWN PHOENIX. THIS STORM WAS NEARLY
  STATIONARY.

* LOCATIONS IMPACTED INCLUDE...
  PHOENIX...TEMPE...PARADISE VALLEY...LAVEEN...PIESTEWA PEAK PARK...
```

Figure 2.2: Severe Thunderstorm warning issued at 2:46 UTC for the Northeastern Maricopa county area. The top image (A) shows a map with a radar view of the approaching storm and the warning area surrounded in yellow. The bottom image (B) is the text bulletin that is issued with the warning, detailing the valid time of the warning, locations impacted, other severe weather threats (not shown), and precautionary/preparedness actions (not shown).

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WGUS55 KFGZ 152043
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/O.NEW.KFGZ.FF.W.0010.170715T2043Z-170715T2345Z/
/00000.0.ER.000000T0000Z.000000T0000Z.000000T0000Z.OO/

BULLETIN - EAS ACTIVATION REQUESTED
Flash Flood Warning
National Weather Service Flagstaff AZ
143 PM MST SAT JUL 15 2017

The National Weather Service in Flagstaff has issued a

* Flash Flood Warning for...
  Gila County in east central Arizona...

* Until 445 PM MST

* At 142 PM MST, Doppler radar indicated thunderstorms producing
  heavy rain over the Highline Fire scar. Flash flooding within the
  scar and downstream is expected to begin shortly.

* Some locations that will experience flooding include...
  Whispering Pines, Bonita Creek Estates, Ellison Creek Estates, La
  Cienega Estates, Pyle Ranch.
```

Figure 2.3: Flash Flood warning issued at 20:43 UTC for an area north of Payson, AZ in Gila county. The top image (A) shows a map with a radar view of the storms within the vicinity and the warning area surrounded in green. The bottom image (B) is the text bulletin that is issued with the warning, detailing the valid time of the warning, locations impacted, and precautionary/preparedness actions (not shown).

Since the mid- 1990s, the issuance of warning event products is the responsibility of the 122 Weather Forecasting Offices (WFOs) that cover the United States and its territories (Friday 1994). These WFOs were created through the modernization and restructuring of the NWS, that started in the late 1980s, and replaced the previous two-tiered office system. Although there were two tiers of NWS offices with the first tier made up of 52 Weather Service Forecast Offices and the second made up of 204 Weather Services Offices, the first tier had warning responsibility for their proximate areas while the second tier had warning responsibility if a local weather radar was present (NRCNA, 2012).

The current structure of the NWS has given WFOs responsibility of monitoring and forecasting for their County Warning Areas (CWAs). A CWA consists of land areas that are generally determined by the existing county boundaries of the states, however the boundaries of a CWA can split counties into different WFOs as well as cross state boundaries (Figure 2.4). The responsibilities of a WFO are limited to the CWA, and therefore any event products issued by a WFO cannot cross CWA boundaries.

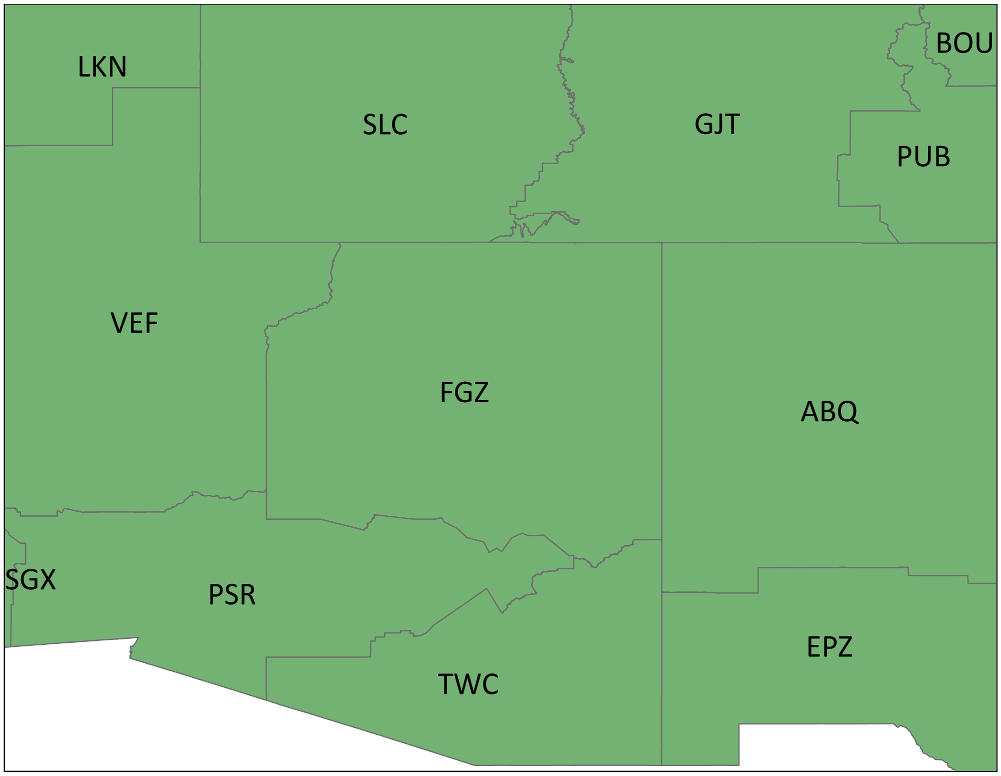


Figure 2.4 Example of WFO boundaries in the Southwest U.S. The three letter callsigns represent the location of a forecast office. For example, FGZ represents the Flagstaff, AZ office. PSR represents the Phoenix, AZ office. VEF represents the Las Vegas, NV office.

In order for a warning issuance of a flash flood, tornado, or severe thunderstorm the NWS has created specific criteria that must be satisfied. First, with regard to flash floods, the criteria that must be met for a flash flood warning to be issued include: (a) evidence suggesting a flash flood is occurring (including ground truth reports, radar evidence, instrument readings), or (b) a natural or man-made dam failure is occurring or imminent (NWS Directive 2017, 10-922). Out of the three possible phenomena above (flash floods, tornadoes and severe thunderstorms), only the flash flood warning does not have to rely directly on an occurring atmospheric phenomenon.

Second, with regard to tornado warnings, tornadoes are usually associated with severe thunderstorms, but also can be associated with tropical storm systems. For a tornado warning to be issued, either radar indication of rotation or ground truth reports of a developing or on the ground tornado are required (NWS Directive 2017, 10-511).

The third phenomenon of this study, severe thunderstorms, is known to produce conditions that can spawn tornadoes or flash flooding. For a severe thunderstorm warning to be issued, radar data, satellite data, or ground truth reports must indicate that wind gusts equal or greater than 58 miles per hour and/or hail size diameter of at least one inch are present (NWS Directive 2017, 10-511). Though severe thunderstorms may often contain dangerous lightning, lightning parameters (e.g., frequency, intensity, etc.) are not taken into account in determination of whether a thunderstorm reaches severe thunderstorm warning status.

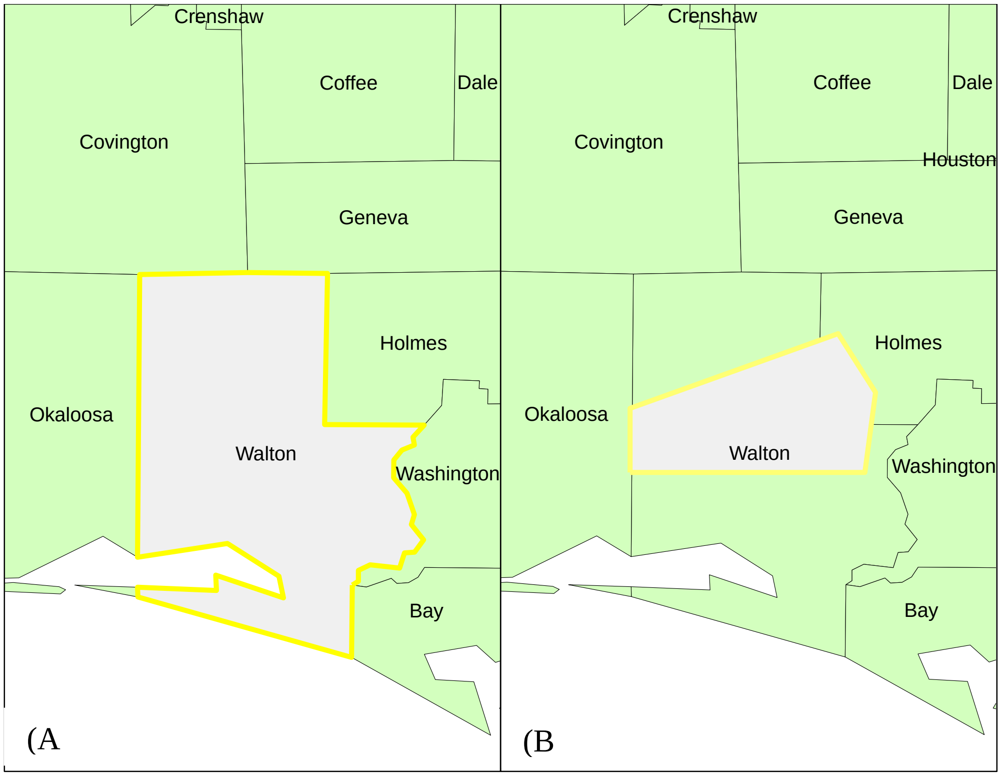


Figure 2.5: The image above shows the difference between a "county" warning and a "storm-based" warning. The left image (A) is a county warning for Walton county. The right image (B) is a storm-based warning that covers Walton and Holmes counties.

Before 2002, the NWS issued warnings for these weather phenomena encompassing the entire county or counties that was/were affected (Sutter and Erickson 2010). For example, a severe thunderstorm warning in Walton County (Figure 2.5A) was effective for the whole county, or counties, over which the storm was occurring. However, beginning in 2002 the NWS experimented with storm-based warning polygons, which are smaller in size compared to counties and more directly focused on the individual storms, and fully implemented the warning type in 2007. A comparison of the post-2002 storm-based warnings shows the warning area to be much smaller and localized (Figure 2.5 B) as compared to the whole county warning approach.

The degree to which above warning criteria have been met is heavily dependent upon an evidence-based process and reporting procedure that the NWS employs nationwide. Through programs such as the NWS Skywarn, storm spotters are trained to be able to identify atmospheric phenomena and report specific weather phenomenon to meteorologists at the local WFO (NWS Directive, 10-1708).

Other entities, such as law enforcement, emergency services personnel or members of the general public, can also contact the local WFO to report significant weather phenomena. These reports, called Local Storm Reports, can be used as grounds to issue warning event products, or even verify the issuance of a warning event product. Visual media, such as news broadcasts or videos and pictures from online social media sites, are also used as evidence for the issuance of a warning event product. One of the most-used tools at the disposal of a WFO for the detection of severe weather is the network of weather radar stations that cover the United States. This network of weather radars is used extensively in monitoring the intensity and movement of atmospheric phenomena as well as providing the grounds needed in order to issue warning event products.

NEXRAD network (WSR-88D)

One of the key data sources to accessing whether a weather phenomenon's severity with regard to issuance of a warning product is weather radar information. In the United States, a network consisting of more than 150 Weather Surveillance Radar – 1988 Doppler (WSR-88D) monitors the atmospheric conditions over most of the country is known as the NEXRAD network (Figure 2.6). This modern iteration of the radar coverage started with experimental operational use in 1990 in Norman, Oklahoma, and was completely installed by 1997 (Crum and Alberty 1993, Crum et al. 1998). At the time, the NEXRAD was a vast improvement over the radars installed before NEXRAD. The current NEXRAD network is still operational, though it has been continually improved and upgraded as technology and other data interpretation enhancements are created.

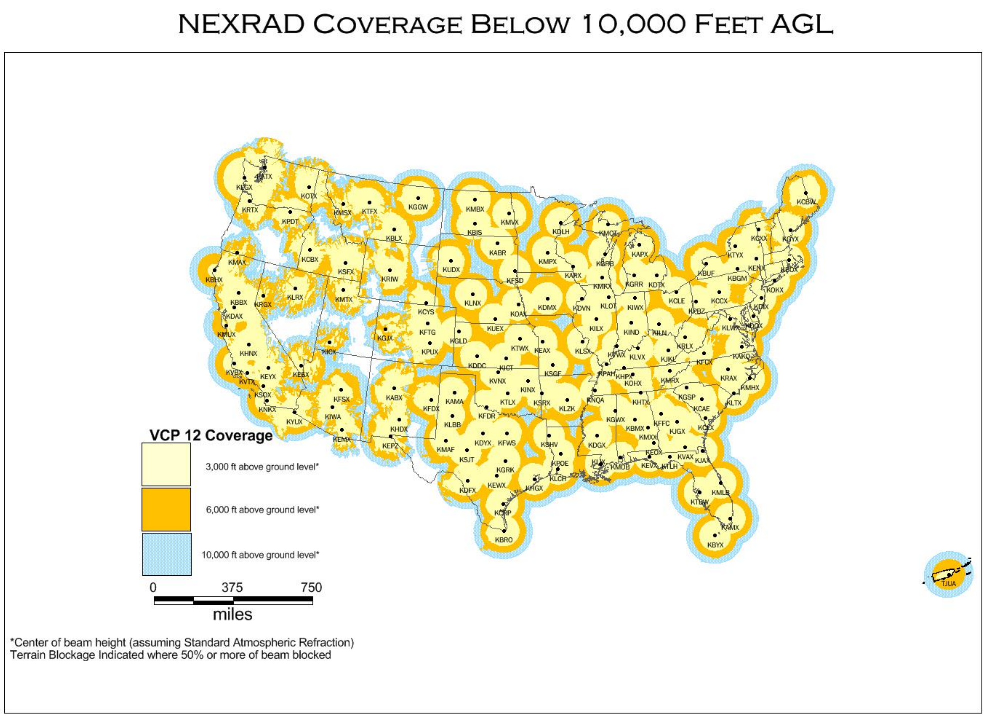


Figure 2.6: Map of the contiguous United States showing the coverage pattern of the NEXRAD Doppler Radar Network. Image from NOAA (https://www.roc.noaa.gove/WSR88D/Maps.aspx)

Through the NEXRAD network, the NWS can monitor the movement and intensity of atmospheric phenomena. The process in which monitoring occurs is that the radar emits an electromagnetic wavelength and measures the intensity of reflectivity of the materials in the atmosphere of the returned emitted signal. This return intensity is then processed through algorithms that provide meteorological values useful for decision-making by meteorologists.

Since the installation of the NEXRAD network, continual improvements were possible to the algorithms, technology, forecasting, and now-casting of weather phenomena. With the installation of the network, locations in the United States susceptible to tornadoes saw an increase in the probability of tornadoes being detected and an increase in the lead-times in tornado warnings (Bieringer and Ray 1996). Improved translation algorithms that were installed with the NEXRAD network positively influenced the warning performances and warning accuracy (Crum 1998).

Use of Weather Warning Data

Past research studies that utilize the severe weather warning products have focused on the relationships between population and the location of a severe weather warning. In a study by Hoium (1997), the Raleigh CWA was found to not have a relationship with population density. However, Dobur (2005) investigated the Atlanta-Peachtree CWA for how warning counts relate to large population densities. He determined that areas of higher populations experienced more warnings then those of lower populations, denoting a population bias of the WFO in that CWA.

In a research study that encompassed a larger area, White and Stallins (2017) examined verified and non-verified storm-based warnings across 36 CWAs. They concluded that a significant relationship existed between the number of verified warnings and areas of higher population. Barret (2012) also determined a higher number of warnings corresponded to areas of greater population across the contiguous United States.

Other studies utilizing the NWS warning dataset have focused on the impact of severe weather and their warnings on the human population. For example, Simmons and Sutter (2008) studied the fatality rates associated with the lead times on tornado warnings. Their findings indicated that tornado warnings have impacted the fatality rates in a positive way, however they did speculate that longer lead times may have a negative impact. Subsequently, Sutter and Erickson (2010) examined the relationship between tornado warning areas and the impact on person-hours and the related cost of these person hours. They found that whole county warnings have a significant impact on person-hours, however the storm-based warnings introduced in 2007 could potentially reduce this impact.

Few examples of studies social and economic research exist in the literature for severe weather warnings. Most other studies that are involved in severe weather use other products, such as radar imaging or text products, in their investigations. Paulikas (2014) discussed severe weather and its relationship with population centers but only used local storm reports in the analysis. In the other studies, severe weather warnings have been used for verification and decision tree analysis. For example, severe weather warnings have been used to verify how successful algorithms are when tested with real-time data, such as in Cintineo (2014). In Myers and Krzysztofowicz (2017), the severe weather warnings, as well as watches, were used to build stochastic models for initial warnings transitioning into an updated warning and watch being updated to a warning.

Finally, and most importantly with regard to the present study, Harrison and Karstens (2017) focused on climatological geo-spatial relationships of NWS warnings. Their study focused on the storm-based warnings issued for Severe Thunderstorms and

Tornadoes and the meta-data that are issued along with these types of warnings. Importantly, that study used the CWAs across the contiguous United States as the study boundaries and point of investigation, rather than the present study's use of county resolution (see chapter 3).

Harrison and Karstens (2017) results found uniformity of a mean warning direction, or mean direction of warned storms, averaging between 200° and 270° (South-Southwest and West respectively) in CWAs east of the Rocky Mountains (Figure 2.7). In their investigation of mean storm speed, there was a broad maximum with a mean of 34 knots in and around the Great Lakes and Ohio valley CWAs, with a uniform decrease in mean storm speed moving further from those CWAs (Figure 2.7). The authors noted that the uniformity in the geospatial relationship of these two variables amid the CWAs "supports the notion that storm-based warnings are representative of climatological severe storm motion in the United States" (Harrison and Karstens, 2017, 59). Conversely, the authors determined that the average size as well as average duration of a warning were greatly variable across the CWAs, and even explained that this may be due to CWA office policies or the short record in storm-based warnings.

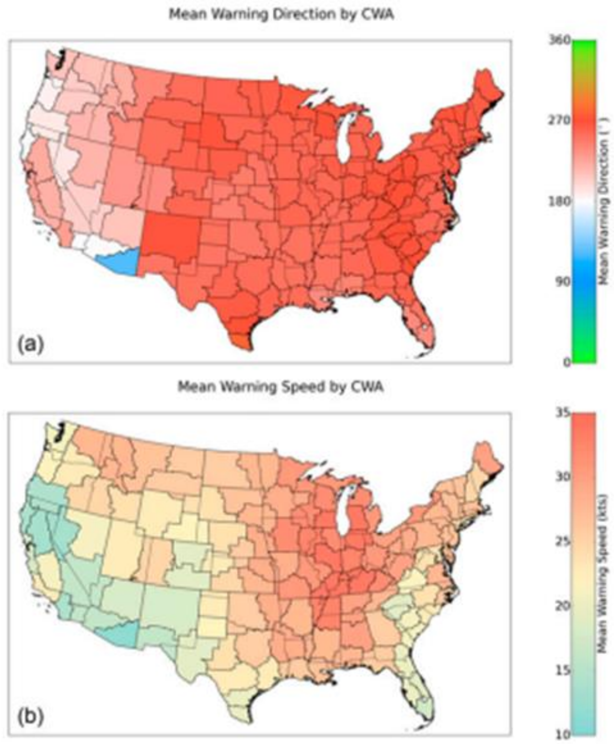


Figure 2.7: Image showing the Mean Warning Direction by CWA (TOP) and the Mean Warning Speed by CWA(BOTTOM). The top image (a) shows that most CWAs east of the Rocky Mountains have a mean warning direction between 200° and 270°. The bottom image (b) shows a maximum mean warning speed of 34 knots in and around the Great Lakes and Ohio valley CWAs. Images from Harrison and Karstens (2017, 53).

That study laid the foundations for the present study but it differs from the current study in several important ways. First, their warning coverage was focused on CWA boundaries, rather than by county boundaries. Second, they only examined severe weather warnings post-2007 as well as only the storm-based warnings. Third, their study only focused on the tornado and severe thunderstorm weather phenomenon.

Summary

In this chapter, I have reviewed relevant literature pertaining to NWS warnings. The responsibility of issuing severe weather warnings falls upon the network of 122 Weather Forecasting Offices (WFOs) across the United States and its territories. Each WFO is limited to a boundary known as a County Warning Area (CWA) and can only provide event products within that CWA boundary. When monitoring a weather system, the NWS relies heavily on the NEXRAD network to determine its severity.

To issue a flash flood, severe thunderstorm, or tornado warning, the NWS has created specific severity criteria that are homogeneous across the United States and its territories. The degree to which the severity criteria for a warning has been met is dependent upon an evidence-based process and reporting procedure that the NWS employs nationwide.

Past research studies that utilize severe weather warning products primarily focused on the relationships between population and the location of a severe weather warning. However, the recent study by Harrison and Karstens (2017) primarily focused on the climatological geospatial relationships of the NWS warnings. Using the warning data polygons, they determined that the mean storm direction and mean storm speed were fairly uniform across the U.S., whereas warning area and warning duration were greatly variable.

While that study laid the foundations for the present study, several important distinctions can be made. First, that study looked at the warnings by CWA, rather than by counties. Second, this study incorporates warnings since 1986 to 2017, whereas the other study only uses data starting in 2007. Lastly, only tornado and severe thunderstorm phenomena were incorporated into their study.

Given this knowledge, it appears possible to address who experiences the highest occurrences of severe weather in the contiguous United States using the NWS warning dataset. In the next chapter, I address the procedures that I have utilized to create a geospatial NWS warning dataset capable of addressing my research question.

CHAPTER 3

DATA SECTION

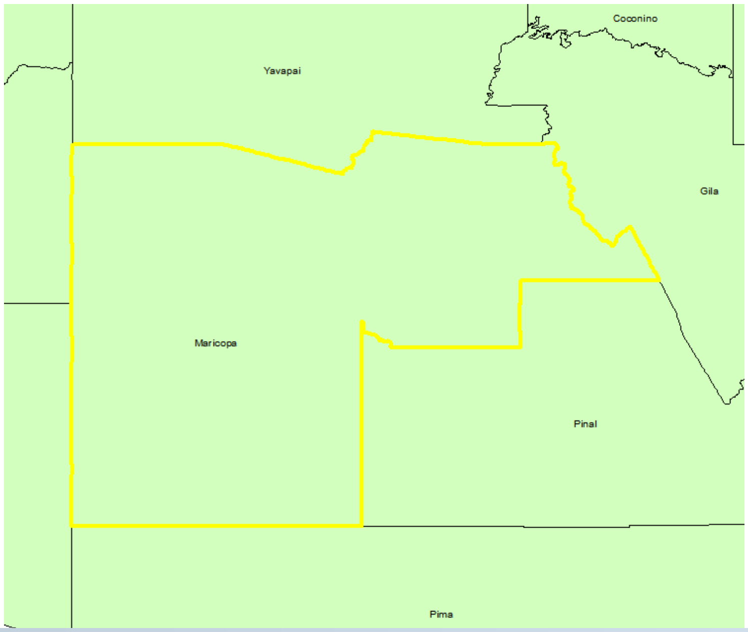
Introduction

In the previous chapter, the National Weather Service and its history were briefly covered, relevant severe weather warning products were defined, and past research studies were introduced in order to begin addressing where the highest occurrences of severe weather are located. In this chapter, I describe the data source for the severe weather warning dataset and its original data format. I next detail the processes undertaken in order to transform the original dataset into the final dataset and introduce inherent biases that may be present within the final dataset. Lastly, I will describe the final dataset and introduce the analysis procedures that will be used in the next chapter.

Data Source

The primary data used for this study are United States National Weather Service (NWS) warning data. The warning data are defined by (a) the duration of the issued warning, (b) the area that is affected, and (c) the type of severe weather phenomena that is occurring (Figures 3.1 a & b). The three severe weather phenomena (severe thunderstorm, tornado and flash flood) being studied in this study are part of four phenomena for which continual warnings have been issued since the beginning of the warning dataset in 1986. The excluded phenomenon, marine warnings, was not included in the analysis due to the unique limited nature of the geospatial warning area for which a marine warning could be issued. Although "watches" are available from the start of the dataset, only warnings are used in this research, as they are the specific weather products that require the specified atmospheric phenomena to be occurring or imminent.

(A)



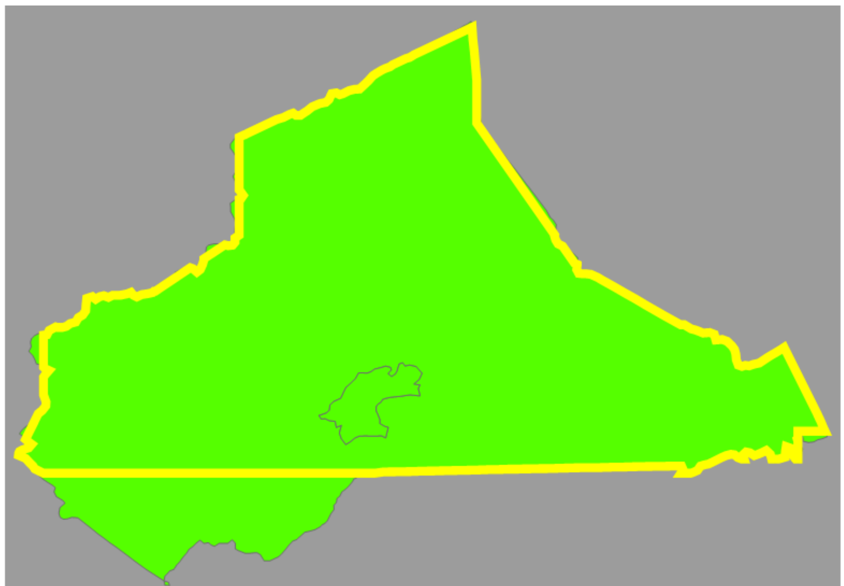
(B)

wwa_199001010000_199101010000

FID	Shape	WFO	ISSUED	EXPIRED	PHENOM	GTYPE	SIG	ETN	STATUS	NWS_UGC	AREA_KM2
1387	Polygon	PSR	199008120227	199008120330	SV	C	W	34		AZC013	23815.54
1387	Polygon	PSR	199008120227	199008120330	FF	C	W	40		AZC013	23815.54
1388	Polygon	PSR	199008120323	199008120430	SV	C	W	35		AZC013	23815.54
1388	Polygon	PSR	199008120323	199008120430	FF	C	W	41		AZC013	23815.54
1399	Polygon	PSR	199008141515	199008141900	FF	C	W	45		AZC013	23815.54

Figure 3.1 A & B: (A) Map showing the affected area of a warning surrounded in a yellow outline. (B) An attribute table showing the time frame of the warning (Issued and Expired columns showing the date and time of day) as well as the type of phenomena being warned (Phenom column).

Over the last thirty years of record, the manner of specifying affected areas for which warnings are issued has changed. From the beginning of the warning database, 1986, to the end of 2001 the area for which an issued warning covered was the specific county, or counties, where severe weather was present. Beginning in 2002, however, the NWS began to switch to a storm-based warning scheme where the area of an issued warning covered a non-political geographic area which included the area of the weather phenomenon, as well as an estimated area where the phenomenon may move. Although this warning area method has been in use since 2002, the warning database also still contains data for the affected county, or counties, under a storm-based warning (Figure 3.2).



FID	Shape *	OBJECTID	WFO	ISSUED	EXPIRED	PHENOM	GTYPE	SIG	STATUS	NWS_UGC	AREA_KM2	INIT_ISS	INIT_EXP
164061	Polygon	0	MRX	201712231404	201712231445	SV	P	W	NEW		974.068899	201712231404	201712231445
170361	Polygon	0	MRX	201712231404	201712231445	SV	C	W	CON	VAC720	19.493826	201712231404	201712231445
170362	Polygon	0	MRX	201712231404	201712231445	SV	C	W	CON	VAC195	1048.844116	201712231404	201712231445

Figure 3.2: The image shows an example of a storm-based warning outlined in yellow over Wise and City of Norton counties. The table shows that when the polygon-based warning was issued, the counties affected also were recorded with the same warning information.

The source of the warning data for this research was the Iowa Mesonet Severe Weather archive (https://mesonet.agron.iastate.edu/request/gis/watchwarn.phtml). The archive contains data from the NWS that is continually updated at the end of each day, starting from the beginning of 1986. In the database, warnings and watches for severe thunderstorm, flash flood, tornado, and marine warnings are available for all archived years, whereas beginning in 2005 other severe weather phenomena (Table 3.1) were receiving warnings. Due to the sheer size of the original warnings being archived, the Iowa Mesonet only provides a simplified version of the warnings when projected to a GIS program that shows the areas affected. This has no effect on the accuracy of the dataset.

Table 3.1: Table below shows the current categories of warnings in bold, while unhighlighted lettering are the warning phenomena.

Convective	**Coastal Flood**
Severe Thunderstorm	Coastal Flood
Special Marine	High Surf
Tornado	Lakeshore Flood
Tropical	**Marine**
Extreme Wind	Ashfall
Hurricane	Gale
Hurricane Wind	Hazardous Seas
Tropical Storm	Heavy Freezing Spray
Tropical Storm Wind	Hurricane Force Wind
Typhoon	Storm
	Tsunami
Winter	
Blizzard	**Non-Precipitation**
Ice Storm	Dust Storm
Lake Effect Snow	Excessive Heat
Wind Chill	Freeze
Winter Storm	Hard Freeze
	High Wind
Hydrology	
Flash Flood	**Fire Weather**
Flood	Red Flag
Other	
Airport Weather	

Data Format and Attributes

For this research and analysis, ESRI's ArcGIS program (https://www.esri.com/en-us/arcgis/about-arcgis/overview) was chosen due to its accessibility as well as to its multitude of functions, for example its ability to project GIS data and run spatial statistics on spatial data. The Iowa Mesonet severe weather archive records the warning data in several file formats that are compatible with GIS programs, such as Google Earth and ArcGIS. Specifically, for this research, the shapefile format that is compatible with ArcGIS was downloaded from the archive.

A shapefile format stores the location, shape, and attributes of a geographic feature, where a feature is defined as the representation of the real-world object that is being stored. In the case of weather warning data, each shapefile contains a set of polygons that represent the geographical location of the warnings as well as the nonspatial information associated with each polygon. Also, the polygons that are contained in the warning dataset either take the shape of the county or the area of a storm-based warning (Figure 3.3 a & b).

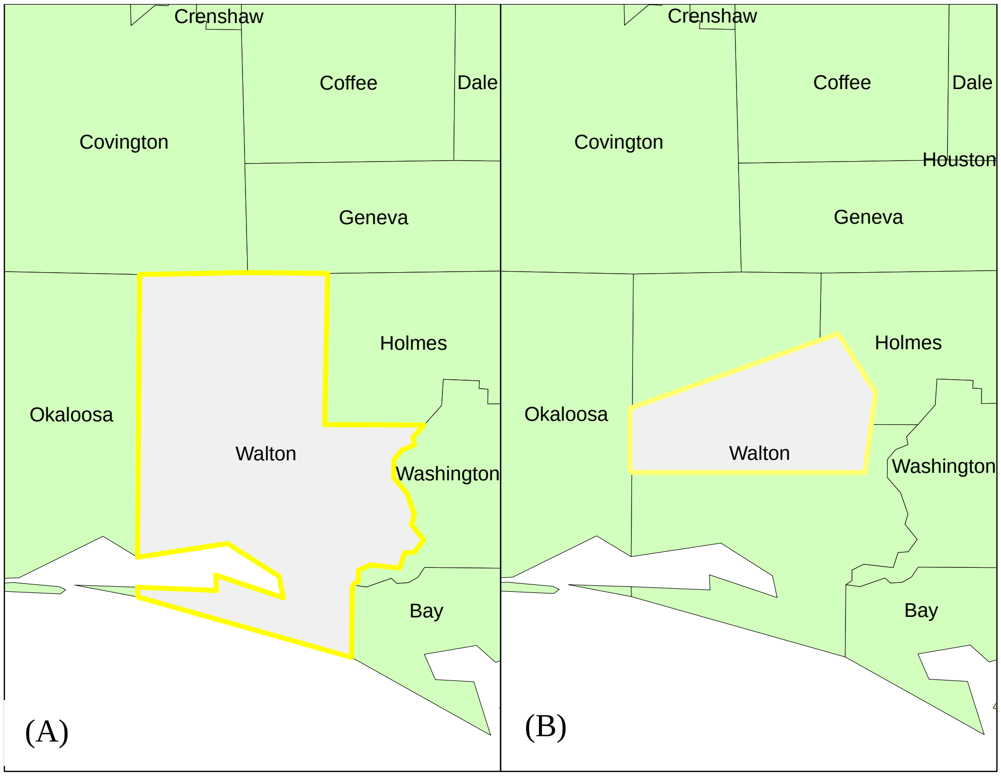


Figure 3.3: The image above shows the difference between a "county" warning and a "storm-based" warning. The left image (A) is a county warning for Walton county. The right image (B) is a storm-based warning that covers Walton and Holmes counties.

In addition to the shapefile polygon information, nonspatial information regarding a warning issued by the National Weather Service is contained within the attribute table of a shapefile (Figure 3.4). The attributes issued with each warning contain: (a) time information, such as the beginning time of a warning, (b) classifications, such as the type of polygon or severe weather phenomena, and (c) other identifying information, such as county identifier code. For each warning, the initial time of issuance and initial time of expiration are included. The last valid adjustment to the issuance and expiration times by the National Weather Service are also provided with each warning. If no adjustments are made, then no time data is available under that attribute for a warning. Characteristics of a warning include the type of phenomena issued, the significance of the phenomena, as well as geographical type of the polygon. For the purpose of this research, all significance attributes are denoted with a ‘w’, meaning “warning.” In addition, the geographical type of the polygons is denoted by a ‘c’, for county, or ‘p’, for storm-based area.

1986_2017

FID	Shape *	OBJECTID	WFO	ISSUED	EXPIRED	PHENOM	GTYPE	SIG	STATUS	NWS_UGC	AREA_KM2	INIT_ISS	INIT_EXP	Shape_Leng	Shape_Area	ETN
1703	Polygon	0	ILN	201711182057	201711190000	FF	C	W	EXP	INC041	556.601685	2017111820	2017111900	0	0	96
1703	Polygon	0	ILN	201711182057	201711190000	FF	C	W	EXP	INC177	1046.15576	2017111820	2017111900	0	0	96
1703	Polygon	0	ILN	201711182057	201711190000	FF	C	W	EXP	OHC037	1553.00451	2017111820	2017111900	0	0	96
1703	Polygon	0	ILN	201711182057	201711190000	FF	C	W	EXP	OHC135	1103.03479	2017111820	2017111900	0	0	96

Figure 3.4: The image above shows the attribute table of the warnings. The attributes from left to right are: FID, Shape, ObjectID, Weather forecasting office, Issued time, Expiration time, Phenomena type, Polygon Type (GType), Significance status (W=warning), Status (New, Expired, Continued), NWS_UGC, Area in Kilometer Squared, Initial Issued time, Initial Expiration time, Shape Length, Shape Area, and Event Tracking Number.

Additional identifying information of the event product includes: (a) the issuing weather forecasting office’s three letter identifier, such as the Phoenix AZ office being represented by ‘PSR’, and (b) the coded county identifier for the county that the warning is valid for, with the code being ssccc (ss = state/territory initials and ccc = three number code representing the county), as well as an event tracking number that is unique to a WFO, with the tracking number signifying what order the warning was issued (Figure 3.4). Other attribute information regarding a warning includes: (a) the calculated geographical size of a warning polygon, and (b) other GIS data attributes (Figure 3.4). The Iowa Mesonet stores these warning data in a simplified format. For example, warnings that cover neighboring counties normally have their boundaries match the boundaries of the counties. However, the boundaries of these warnings are not touching and in fact have an inaccurate open space between the borders. This means that any tools or statistic packages that are reliant on geographically accurate data may be skewed due to this simplified format.

Configuration of Shapefile Data to Geographic Constraints

In order to properly display and work with the warning data, more accurate geographical data were needed. Such geographical data include the boundaries of the counties of the contiguous United States. Due to the general geographic inaccuracies contained within the shapefiles of the warning data, the attribute data associated with the shapefiles for all years in the archive were moved to geographically accurate shapefiles. The steps for this conversion are detailed below.

In order to ensure that the warning attribute data were properly converted to the more accurate county shapefile, I used an identifier. Since ArcGIS can only use one column in the attribute data, I chose the NWS county identifier codes due to the uniqueness of each code. The NWS county identifier codes were not originally attached with the county shapefile that was chosen, so I created in Excel the NWS county codes based off the state initials and the 5-number identifier code that is used for every county in the United States. In a separate column, I wrote an excel formula that took the state initials for each county and amended the last three digits of the five-number identifier code for a county to the state initials. This new table of NWS county identifier codes was then loaded in the ArcGIS program where by a “join function” can be amended to the county shapefile’s attribute table. Population data were not initially provided with the county shapefile as well, so I obtained the latest census data through ESRI databases (US

Census) for each county. As was done with the NWS county identifier codes, I then loaded the population data into ArcGIS and through the join function amended the data to the county shapefile.

Before moving the data over to the geographically accurate shapefile, I decided to only include the county-based geographic information. Other methods were considered, such as using a grid across the contiguous United States. However, a grid-like structure for this analysis would have several disadvantages compared to using the county boundaries of the United States. First, half of the timeframe of the event product dataset was issued under the county geographic polygon, and under a gridded pattern could lead to biases being associated to the grid cells. Second, this analysis is also comparing number of warnings to population statistics. Latest census data are associated with a county level, and so trying to interpret populations into a gridded structure could lead to inaccuracies during analysis. Third, the geographic inaccuracy of the dataset due to storage methods can lead to inaccurate counts and analysis when associating the warnings to a grid like structure.

The geographic polygons contained in the warning data throughout the dataset are incompatible because both the counties and polygon warning areas are given. Though the polygon event areas could not be moved over, the county-based events that are issued alongside each event polygon were used and included in future analysis. After separating out only the county-based geographic polygons, event products that had a significance attribute representing ‘warning’ were selected and transformed into a new shapefile. Since the analysis of this paper is focused on warnings, all other event products were disregarded. This same process was also done for excluding all phenomena types that were not classified as severe thunderstorm, tornado, or flash flood.

Once all relevant event products were separated out of the original shapefiles, four new shapefiles were created. The four new shapefiles included (a) all relevant warnings within a given year, (b) all flash flood warnings within a given year, (c) all tornado warnings within a given year, and (d) all severe thunderstorm warnings within a given year (Figure 3.5).

Severe Thunderstorm for 1990

FID	Shape	WFO	ISSUED	EXPIRED	PHENOM	GTYPE	SIG	ETN	STATUS	NWS_UGC	AREA_KM2
1	Polygon	OUN	199001032310	199001032345	SV	C	W	1		OKC053	2583.03
2	Polygon	OUN	199001032323	199001040015	SV	C	W	2		OKC053	2583.03
3	Polygon	MOB	199001060303	199001060345	SV	C	W	1		ALC097	3297.41
6	Polygon	OUN	199001161747	199001161830	SV	C	W	3		OKC043	2616.85
7	Polygon	OUN	199001161756	199001161845	SV	C	W	4		OKC129	2967.32
8	Polygon	OUN	199001161823	199001161915	SV	C	W	5		OKC093	2483.09
9	Polygon	OUN	199001161903	199001162000	SV	C	W	6		OKC003	2258.81
10	Polygon	OUN	199001161953	199001162100	SV	C	W	7		OKC053	2583.03
11	Polygon	OUN	199001162111	199001162215	SV	C	W	8		OKC141	2276.38
12	Polygon	OUN	199001162111	199001162215	SV	C	W	8		OKC031	2817.22
13	Polygon	ICT	199001162144	199001162245	SV	C	W	1		KSC035	2952.47
14	Polygon	ICT	199001162144	199001162245	SV	C	W	1		KSC015	3761.19
16	Polygon	OUN	199001170019	199001170100	SV	C	W	9		OKC055	1680.06
17	Polygon	OUN	199001170019	199001170100	SV	C	W	9		OKC057	1409.46
18	Polygon	OUN	199001170045	199001170130	SV	C	W	10		OKC149	2633.69

1 (0 out of 11923 Selected)

Figure 3.5: Attribute table showing only county based severe thunderstorm warnings issued during the year 1990.

After each shapefile was created, I conducted a simple count function. The count function in ArcGIS identifies the number of times in which a variable in an attribute appears and extracts this information to a separate attribute table. For example, if the count function is performed on the phenomena attribute in the event product dataset, the output table contains the number of times that the flash flood, tornado, and severe thunderstorm variables appeared. For this analysis the count function was performed on the NWS county identifier code attribute so as to tally all the events within a given year for each county in the contiguous United States. The output attribute table with the NWS county identifier code tallies can then be amended to the geographically accurate county shapefile through the join function. Through this process, counts for each event product phenomena for each year can be displayed and further be used for analysis regarding county warnings. The shapefiles for each phenomena category are available for future research regarding other attributes, such as an analysis of time issuance.

Biases

Potential biases exist that could influence the analyses associated with the county boundaries. One such bias that occurs with use of warning data by the county boundaries involves the coverage boundaries of the weather forecasting offices issuing the event products. In early analysis of the warnings, clear boundary lines between states, or the separate weather forecasting offices are visible. This is consistent with White and Stallins (2017) analysis of total warning counts and its variability associated with CWA boundaries.

Second, the differing geographic sizes of the counties across the United States can lead to disparate differences in relative warning count. For example, Coconino county in Arizona is over twenty times the size of Dallas county in Texas but are close in total number of warnings (under a two-hundred count difference).

Third, variations in population densities between counties may play a role in warning activity (e.g., more densely populated counties experience more warnings). As discussed in Dobur (2005) and White and Stallins (2017), those counties with higher population densities, especially around major metropolitan areas, experienced a higher frequency of warnings than lower population density regions.

Final Dataset

The final dataset used to assist in answering this thesis' question is defined by 3108 rows by 16 columns. The rows are represented by the 3108 counties that comprise the contiguous United States. The columns are represented by (a) ArcGIS assigned values, (b) Identification information for each county, and (c) variables that will be used throughout the analysis.

The ArcGIS assigned values are the FID and the Shape. The FID is a unique identifier, known as the ObjectID, that ArcGIS assigns to each record, or in the case of this thesis each county (https://support.esri.com/en/other-resources/gis-dictionary/term/eff7ccdc-8f99-4ea4-ab39-d804d379a232). The Shape defines how each record is projected on to the map, or data frame. For this thesis, each record is defined by the 'polygon' Shape category.

The identifying information for each county is represented by several variables. First, the abbreviation of the state is given for each county. In this analysis, only the 48 contiguous United States are used. Second, the county name is given for each county. Third, the abbreviation of the County Warning Area (CWA) is listed for each county. In this column, it is possible to have multiple CWAs representing a county. Lastly, the National Weather Service Universal Geographic Code (NWS_UGC) is given for each county. The NWS_UGC is the NWS method for identifying each county. For example, the given NWS_UGC for Maricopa county in Arizona is AZC013.

The variables to be used in analysis are (a) warning counts, and (b) geographic and census data. First, the number of instances for each warning category are included. The warning categories span the years 1986 to 2017 and are defined as follows: total number of tornado warnings, total number of severe thunderstorm warnings, total number of flash flood warnings, and aggregate of the warning categories through the study period. Secondly, the geographic data and the census data are represented by the total square kilometer area of the warning area and 2010 population census for that warning area, respectively.

Analysis Procedures

In the following chapter (Results and Discussion), the analysis of the final dataset is separated into the following categories: (a) tornado warnings, (b) severe thunderstorm warnings, (c) flash flood warnings, and (d) sum total of the warnings. These categories are based on the warning count variables from the final dataset, which are the main focus of this thesis.

A series of analysis are performed on each category to answer the research question. The first analysis only examines the geospatial pattern of the base warning counts for each category. The second analysis examines the geospatial pattern of the warning counts when adjusted for county populations. The adjusted value for the second analysis reflects the per capita of each of the warning counts multiplied by one thousand. The third analysis examines the geospatial pattern of the warning counts when adjusted for county area sizes. The adjusted value for the third analysis reflects the number of warnings per square mile.

The fourth and final analysis use spatial statistic techniques that take into account the geospatial location of each record. These analyses, the Hot Spot analysis and the Cluster and Outlier analysis, are ran for the base, population adjusted, county area-adjusted, and population density adjusted counts for each category. The Hot Spot analysis calculates the Getis-Ord Gi* statistic for each county, where the Getis-Ord Gi* statistic (z-score) and the probability (p-value) define which counties are in a spatially high or low cluster. The Getis-Ord Gi* is given as:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \bar{X} \sum_{j=1}^{n} w_{i,j}}{S \sqrt{\frac{\left[n \sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j} \right)^2 \right]}{n-1}}} \quad (1)$$

$$\bar{X} = \frac{\sum_{j=1}^{n} x_j}{n} \quad (2)$$

$$S = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - \left(\bar{X}\right)^2} \quad (3)$$

where x_j is the count value for the county j, $w_{i,j}$ is the spatial weight between counties i and j, and n is equal to the total number of counties (Getis and Ord 1995). As denoted in the analysis name, the z-scores signify whether a county is contained in a hot spot or cold spot. Hot spots are represented by high statistically significant positive z-score values, while cold spots are represented by low statistically significant negative z-scores. The Cluster and Outlier analysis calculates the local Moran's I value, a z-score, and a p-value for each county, where the local Moran's I value indicates whether a county has similar values or dissimilar values to neighboring counties (Anselin 1995). The local Moran's I value is given as:

$$I_i = \frac{x_i - \bar{X}}{S_i^2} \sum_{j=1, j \neq i}^{n} w_{i,j}(x_j - \bar{X}) \quad (1)$$

$$S_i^2 = \frac{\sum_{j=1, j \neq i}^{n} (x_j - \bar{X})^2}{n - 1} \quad (2)$$

where x_i is the count value for a county I, $\bar{X}$ is the mean of the counts, $w_{i,j}$ is the spatial weight between counties I and j, and n is equal to the total number of counties (Anselin 1995). As denoted by its name, the Cluster and Outlier analysis uses the local Moran's I value to denote whether a county is within a cluster or is an outlier. When local Moran's I is a positive value, the county is within a cluster of similar count values. When local Moran's I is a negative value, the county is an outlier and has dissimilar values to neighboring counties. For a county's local Moran's I value to be statistically significant, the p-value must be small (Anselin 1995).

Summary

In this chapter, I have described relevant information of the creation of the final dataset and the statistical analyses used in the next chapter. The final dataset is based on three severe weather phenomena (flash flood, severe thunderstorm, and tornado) warnings issued by the National Weather Service between 1986 to 2017 for the contiguous United States. Due to its continuous nature, only county-based warnings from the Iowa Mesonet Severe Weather archive were used for the final dataset, so as to include severe weather warning data from before the year 2002. Considering that the Iowa Mesonet Severe Weather archive contained shapefile file formats of the severe weather warning data, the GIS program ArcGIS was chosen for its compatibility with the file format as well as its ability to analyze spatial data.

Since the original dataset was geographically inaccurate, a count of all the severe weather phenomena warnings for each county in the contiguous United States was performed. These counts were then transferred to a dataset that contained correct geopolitical boundaries of the counties as well as census population data based on the 2010 census. The following biases inherent to the severe weather warning data and the geopolitical boundaries of the counties were introduced: (1) coverage of weather forecasting boundaries being visible between county boundaries, (2) the geographic size disparity between counties, especially between the west coast and east of the Rocky Mountain range, and (3) variations in population densities between counties.

The final dataset consists of identifying information relevant to the 3108 counties in the contiguous United States. Each county is composed of the following variables: (1) unadjusted and adjusted warning counts for each phenomenon, (2) geographic size, and (3) census data. In the next chapter, the adjusted and unadjusted severe weather warning phenomenon are analyzed by their base geospatial pattern, a spatial statistic technique known as the Hot Spot Analysis, and the spatial statistic technique known as the Cluster and Outlier analysis.

Given the description and creation of the final dataset, the analysis on the dataset can be performed in order to address where the highest occurrences of severe weather occur. In the next chapter, I provide a discussion of the results that will be used to address the validity of my hypotheses.

CHAPTER 4

RESULTS AND DISCUSSION

Introduction

Following the synthesis of the National Weather Service warning data obtained from the Iowa State Mesonet archive to a count for each county in the contiguous United States, analysis can begin on the data to address which county receives the highest occurrences of severe weather. This chapter is segregated into four separate parts, where the first three sections provide the results from each analysis and the last section provides a summary of the findings. The first three sections are split into the base analysis, the hot spot analysis, and the outlier analysis respectively.

The base analysis examines the geographic relationship of the flash flood, severe thunderstorm, tornado, and aggregate warnings displayed as raw counts and as adjusted for county population, county area (square kilometers), and county population density (people/km^2). The hot spot analysis examines the geographic relationship of the warning counts by county using the Getis-Ord Gi* equation (discussed in section 3.7), or otherwise known as the Hot Spot Analysis function in ArcGIS. The third section examines the geographic relationship of warning counts by county using Anselin's Local Moran's I equation (discussed in section 3.7), or otherwise known as the Cluster and Outlier analysis in ArcGIS. In that section, the outlier values are overlaid the hot spot analysis results for the full analysis. The last section, the summary, extracts the important findings from the analyses of the warning values. Each geographic relationship analysis begins with the appropriate GIS figure, followed by a detailed explanation of the product.

Results and Discussion of Base Analysis

The base analysis consists of presenting the geographic relationship of the raw counts of the flash flood, severe thunderstorm, tornado, and aggregated warnings for counties across the contiguous United States from 1986 to 2017. These maps will display warnings per county population, per county area (square kilometers), and per county population density (people/km^2) and important and pertinent details of each map will be identified and discussed.

Flash Flood Warning Occurrence. The pattern of flash flood warning occurrence shows the highest occurrences in the desert Southwest, with a second local maxima covering central and coastal Texas (Fig. 4.2.1). Though not as high in occurrence, there is also an area of local maxima that covers Oklahoma, Arkansas, Missouri, Tennessee, Mississippi, and Alabama. A notable local high occurrence of Flash Flood warnings does cover portions of Pennsylvania, Maryland, and the Virginias.

One factor in highest occurrence of flash flood warning totals in the desert Southwest is the sizes of the counties. As noted in Section 3.4, a count is made whenever a flashflood warning occurs in a given county. Therefore, the large size of the desert Southwest counties, coupled with the propensity of this region to easily flood during intense periods of summer rainfall (Maddox et. al., 1980; Adams & Comrie 1997), likely accounts for this maximum. The local maxima of flash flood occurrence in the South and the Midwest are partially accounted for by the need to warn large population centers (e.g., the county containing Houston), and the occurrence of summer and tropical large rain events leading to flash floods (Saharia et. al., 2017; Smith & Smith, 2015). Lastly, the maximum occurring in the Northeast is likely the result of large population centers in this region coupled with topography concerns accenting flash flooding events (Lapenta et. al., 1995; Landel et. al., 1999).

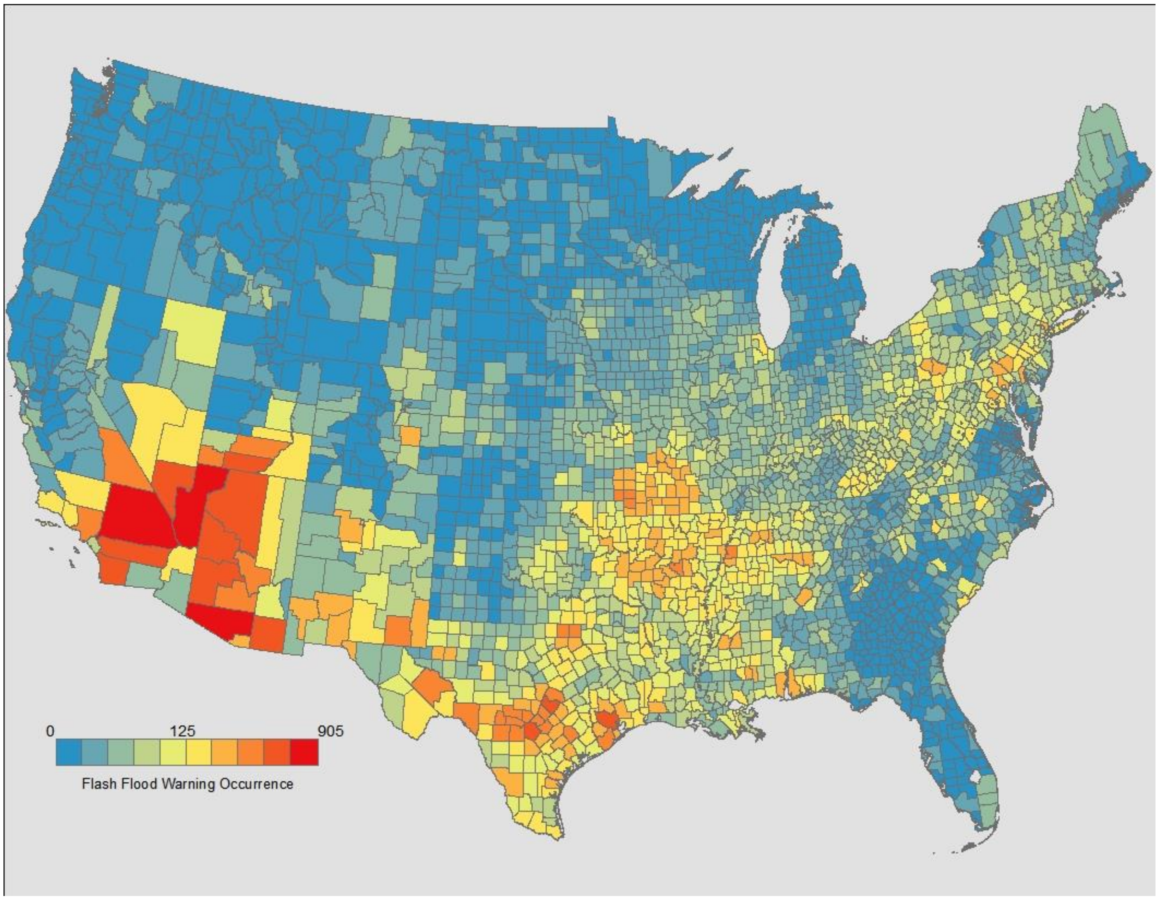


Figure 4.2.1: Map of the contiguous United States counties by Flash Flood warning occurrence for the period 1986 to 2017. Natural Breaks (Jenks) scaling shows the starting value to be 0, the middle value at 125, and the ending value at 905.

Flash Flood Warning Occurrence per Capita. As seen in **Figure 4.2.2**, the pattern of flash flood warning occurrence per 1000 people shows the highest values in Texas with local maxima in northeastern New Mexico and western Mississippi. Though not as high, other notable high value counties are located in Nevada, southern Utah, eastern Montana, south eastern Missouri, and along the border of Colorado and Kansas. Notable low warning occurrence per 1000 people regions can be found around the western United States and Florida.

One factor in the pattern of the highest values of flash flood warnings per capita is the location of the counties. As evident in the figure, and as will be discussed in later sections, the maxima regions have distinct boundaries as well as distinct geographies. For example, the political panhandle border of Texas is clearly visible. Though they do not make up one homogenous region, each area is significant as they each have certain physical geographies that become susceptible to flash flooding during high precipitation events (Saharia et. al., 2017; Smith & Smith, 2015). Another factor in these distinct maxima regions is the population sizes of the counties. In each of the local maxima regions, all the counties have populations that are below 10,000, with a majority of the counties having populations below 3,500. The low population sizes, coupled with each of these regions having the propensity for flash flooding, likely accounts for the pattern of distinct regions of the local maxima and the study area maxima.

The low flash flood occurrence per 1000 people regions are likely the result of (1) relatively low occurrences of flash flood warnings (e.g., western United States) and/or (2) higher populations (e.g., Florida).

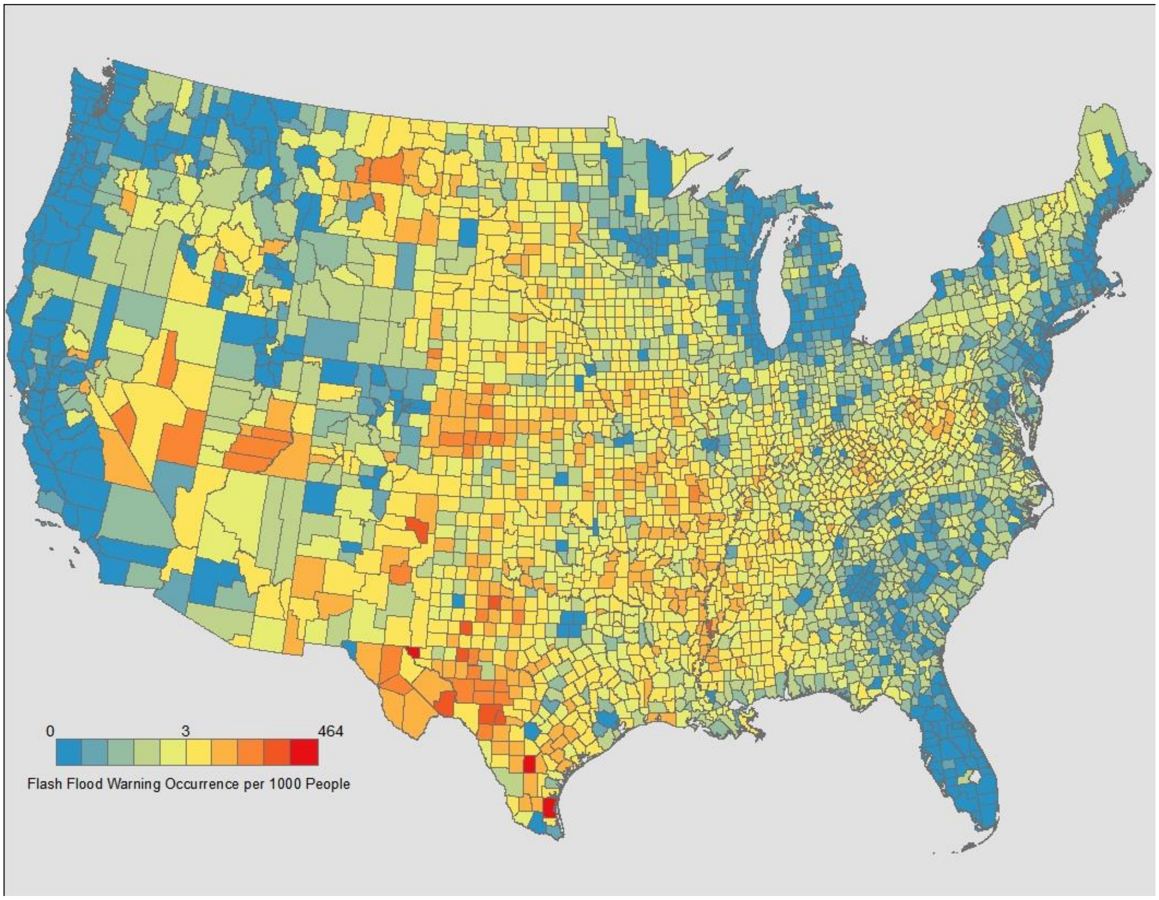


Figure 4.2.2: Map of the contiguous United States counties by Flash Flood warning occurrence per capita for the period 1986 to 2017. Geometrical Interval scaling shows the starting value to be 0, the middle value at 3, and the ending value at 464.

Flash Flood Warning Occurrence per Area. The pattern of flash flood warning occurrence per area (square kilometers) shows a relatively uniform pattern with the slightly highest values in Virginia with local maxima in New York, New Jersey, Maryland, Pennsylvania, Missouri, and New Mexico (Fig. 4.2.3). Though not as high in occurrence, local maxima occur in southwestern Missouri. central Texas, central Arkansas, eastern Kentucky, and western Tennessee. Notable low warning occurrence per area (square kilometers) regions can be found around the western and northern United States and Florida.

The size of the counties is obviously a factor in the pattern of the highest values of flash flood warning occurrence per area (square kilometers). As evident in the figure and the data, a majority of the smallest counties in the United States (e.g., those in Virginia) have the highest values, though the Flash Flood warning counts were variable. These counties have a mean Flash Flood warning count of 59 with a minimum of 7 warnings and a maximum of 179 warnings over the study period. Another factor in the pattern of flash flood warning occurrence is the location of the counties. In this figure, and is discussed throughout this chapter, the maxima are located within regions that are susceptible to flash flooding during high precipitation events (Saharia et. al., 2017; Smith & Smith, 2015; Landel et. al., 1999). Coupling the size of the counties with the susceptibility of some regions to flash flood, likely accounts for this pattern of flash flood warning occurrence per area (square kilometers).

The notable low flash flood warning occurrence per area (square kilometers) regions are likely the result of (1) relatively low occurrences of flash flooding (e.g., Florida) and/or (2) large county sizes (e.g., Desert Southwest).

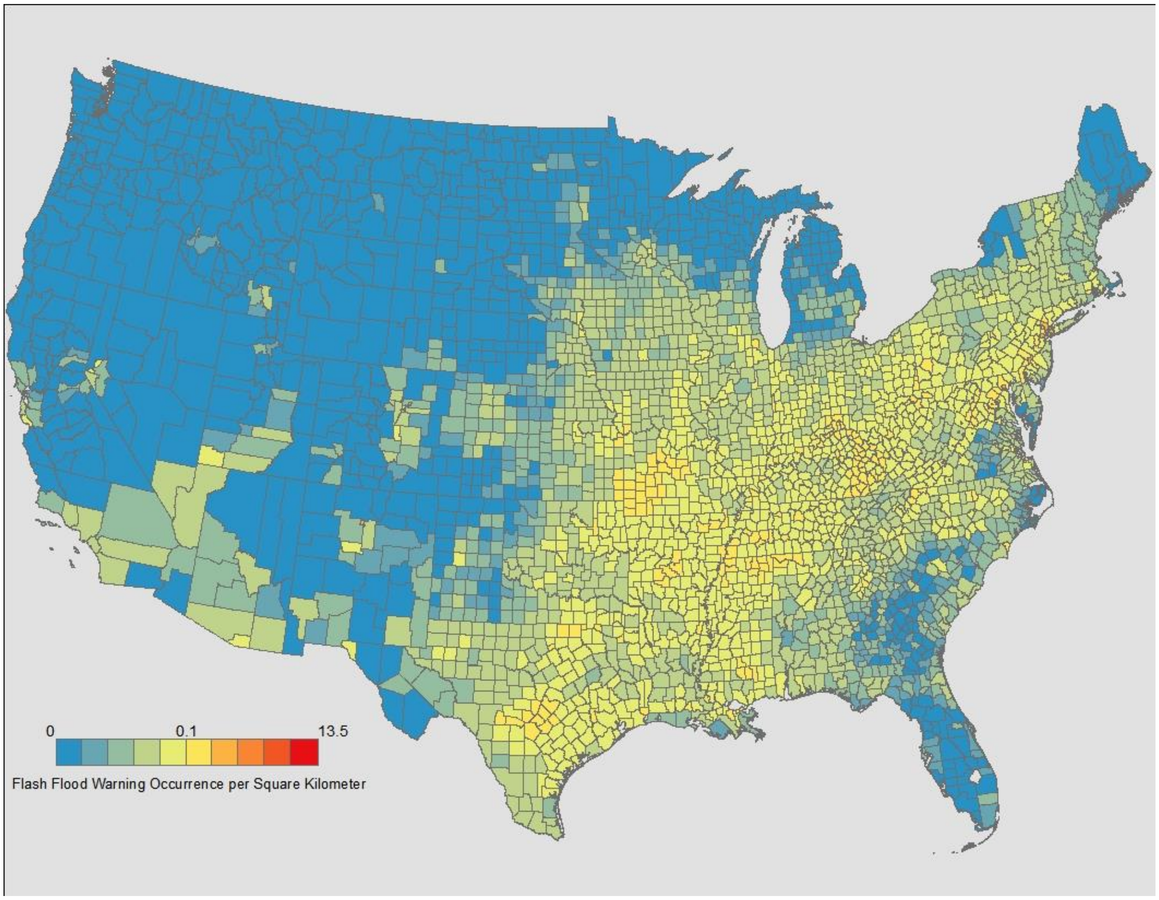


Figure 4.2.3: Map of the contiguous United States counties by Flash Flood warning occurrence per area (square kilometers) for the period 1986 to 2017. Geometrical Interval scaling shows the starting value to be 0, the middle value at 0.1, and the ending value at 13.5.

Flash Flood Warning Occurrence per Population Density. As seen in Figure 4.2.4, the pattern of flash flood warning occurrence per population density (people/km^2) shows several maxima across southern Texas, southern Utah, northeastern New Mexico, eastern Montana, and in southern Nevada. Though not as high, there are notable local maxima in California, Arizona, Idaho, Colorado, South Dakota, Nebraska, Kansas, Missouri, Arkansas, and Louisiana. Notable low flash flood warning occurrence per population density regions can be found in the Pacific Northwest and Florida.

One factor in the pattern of the highest values of flash flood warning occurrence per population density is the location of the counties. As evident in figure 4.2.4, and is discussed in section 4.2.2, the maxima have distinct boundaries and physical geographies from each other (e.g., the political boundary of western Texas). However, the significance of the physical geographies of each region allow for flash floods to occur during intense periods of precipitation (Saharia et. al., 2017; Smith & Smith, 2015; Maddox et. al., 1980). Another factor in the pattern is the population densities of the counties. In each of the maxima regions, all counties have a population density less than ten people per square kilometer, with many counties below one person per square kilometer. The low population densities, coupled with many of the region's propensity for flash flooding likely accounts for the pattern.

The notable low flash flood warning occurrence per population density pattern is likely the result of (1) relatively low population size, (2) relatively large county size, and/or (3) a high occurrence of flash flood warnings.

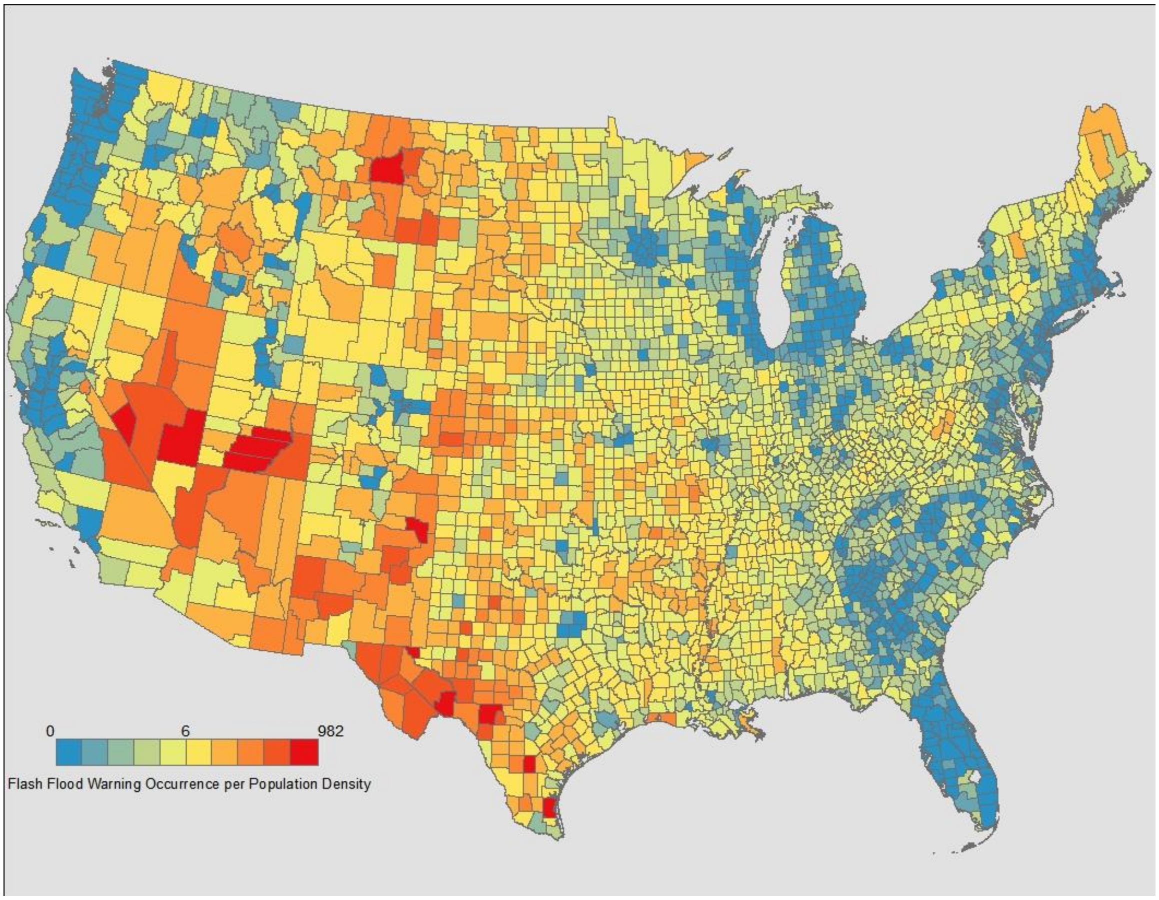


Figure 4.2.4: Map of the contiguous United States counties by Flash Flood warning occurrence per population density (people/km^2) for the period 1986 to 2017. Geometrical Interval scaling shows the starting value to be 0, the middle value at 6, and the ending value at 982.

Severe Thunderstorm Warning Occurrence. The pattern of severe thunderstorm warning occurrence shows the highest occurrences in Arizona, Texas, Colorado, Nebraska, South Dakota, Oklahoma, and Iowa (Fig 4.2.5). Though not as high in occurrence, there are also local maxima in North and South Carolina, Mississippi, Alabama, Louisiana, Kansas, Montana, Tennessee, Florida, Minnesota, Pennsylvania, Maryland, Virginia, Missouri, and Illinois.

A major factor in the highest occurrence of severe thunderstorm warning totals in the desert Southwest as well as in Nebraska, Montana, and Minnesota is the large size of the counties. As noted in section 3.4, a count is made whenever a severe thunderstorm warning occurs in a given county. Considering the areas of the highest count counties in Nebraska, Texas, Montana, and Minnesota equal that of several of the surrounding counties likely accounts for their higher occurrence of severe thunderstorm warnings. As for the desert Southwest, the large size of the counties coupled with the propensity of this area to have severe thunderstorms develop during the summer rainy season likely accounts for those maximum (Adams & Comrie, 1997). The highest occurrences and local maxima in the Midwest, South, and East Coast are best accounted for by the need to warn large population centers, and the occurrence of seasonal severe weather that frequently spawn severe thunderstorms (Brooks et. al., 2003; Owen, 1966; Schaefer et. al., 2004; Kelly et. al., 1985; Doswell, 1980; Weisman, 1990, Maddox, 1983).

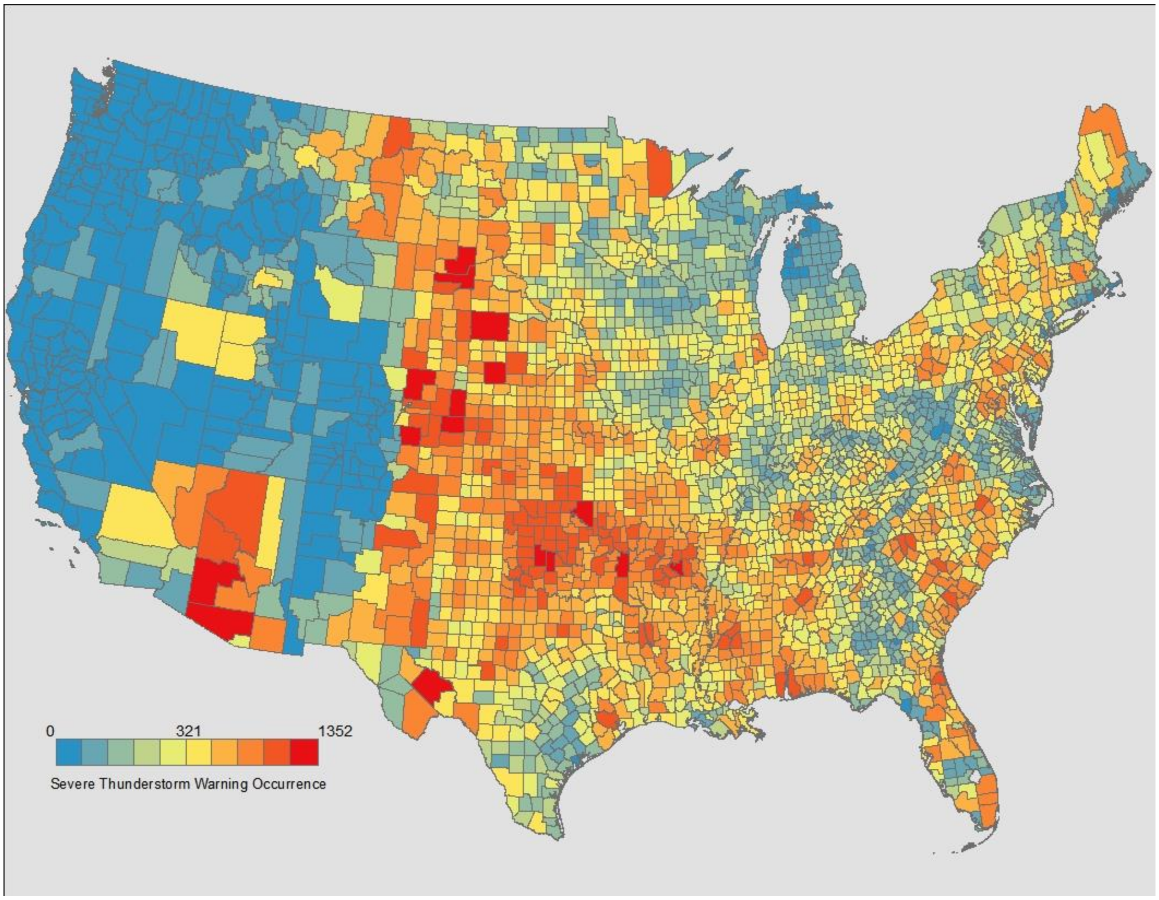


Figure 4.2.5: Map of the contiguous United States counties by Severe Thunderstorm warning occurrence for the period 1986 to 2017. Geometrical Interval scaling shows the starting value to be 0, the middle value at 321, and the ending value at 1352.

Severe Thunderstorm Warning Occurrence per Capita. As seen in Figure 4.2.6, the pattern of severe thunderstorm occurrence per 1000 people shows the highest values in Texas with local maxima in eastern Montana, Nebraska, New Mexico, western Mississippi, and along the Colorado and Kansas border. Notable low warning occurrence regions can be found around the western United States, Florida and the coastal Northeast.

The location of the counties is one factor in the pattern of the highest values of severe thunderstorm warning occurrence per 1000 people. As evident in the figure, and as will later be discussed in section 4.3.6, most high-occurrence counties are on the leeward side of the Rocky Mountain range. This location is significant due to a seasonal meteorological pattern in late spring and summer that starts with cooler air moving southward and changes in low-level flows (Doswell, 1980). Another factor in the leeward pattern is the population sizes of these counties. In this leeward pattern and in the general Great Plains region most counties have populations that are below 10,000, with many of the local maxima regions having populations below or at 5,000. The low population sizes, coupled with the propensity of this region to have severe weather form, likely accounts for the leeward pattern of the local and study area maxima.

The low-occurrence warning per population areas are likely the result of (1) relatively low occurrence of severe thunderstorms (e.g., Western United States) and/or (2) higher populations (e.g., coastal Northeast and Florida).

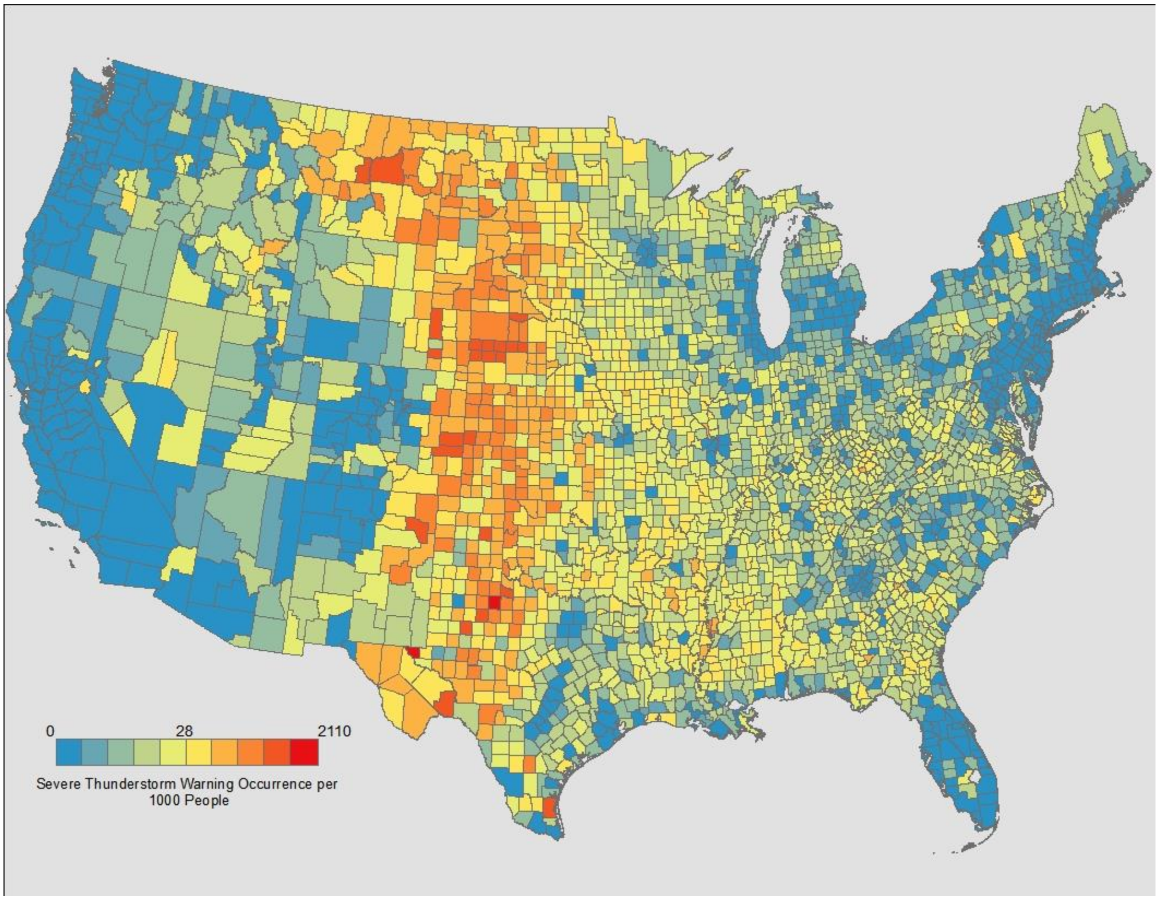


Figure 4.2.6: Map of the contiguous United States counties by Severe Thunderstorm warning occurrence per capita for the period 1986 to 2017. Geometrical Interval scaling shows the starting value to be 0, the middle value at 28, and the ending value at 2110.

Severe Thunderstorm Warning Occurrence per Area. As seen in Figure 4.2.7, the pattern of severe thunderstorm occurrence per area (square kilometers) shows a relatively uniform pattern with the highest values found in the Virginias and with local maxima in Colorado, between Missouri and Kansas, between Missouri and Illinois, the pan handle of West Virginia, Tennessee, Pennsylvania, New Jersey, and New York. Though not as high in occurrence, local maxima also occur in central Alabama, central Arkansas, Kentucky, eastern Nebraska, and along the border of Virginia and Maryland. Notable low warning occurrence per area (square kilometers) regions can be found in the western United States, Florida, and south Texas.

One factor in the pattern of highest values of severe thunderstorm warning occurrence per area (square kilometers), and is a reoccurring pattern in this category, is the size of the counties. As evident in the figure and the data, a majority of the smallest counties in the United States (e.g., those in Virginia) have the highest values, with a variable range of severe thunderstorm warning occurrences. The top valued counties have a mean severe thunderstorm warning occurrence of 168, with the minimum of 62 and a maximum of 371 warnings over the study period. Another factor in the pattern of the severe thunderstorm warning occurrence is the location of the counties. In this figure, and is discussed throughout the chapter, some of the maxima (e.g., those in Colorado, Missouri) and local maxima (e.g., central Alabama, Arkansas) are located in regions that experience seasonal severe weather that produce severe thunderstorms (Brooks et al, 2003; Kelly et. al., 1985; Maddox, 1983; Schaefer et. al., 2004). This production of severe thunderstorms coupled with small county sizes likely accounts for the pattern of severe thunderstorm warning occurrence per area (square kilometers).

The notable low severe thunderstorm warning occurrence per area (square kilometers) regions are likely the result of (1) the large county sizes (e.g., the desert Southwest, Texas) and/or (2) relatively low occurrences of severe thunderstorm warnings (e.g., Pacific Northwest).

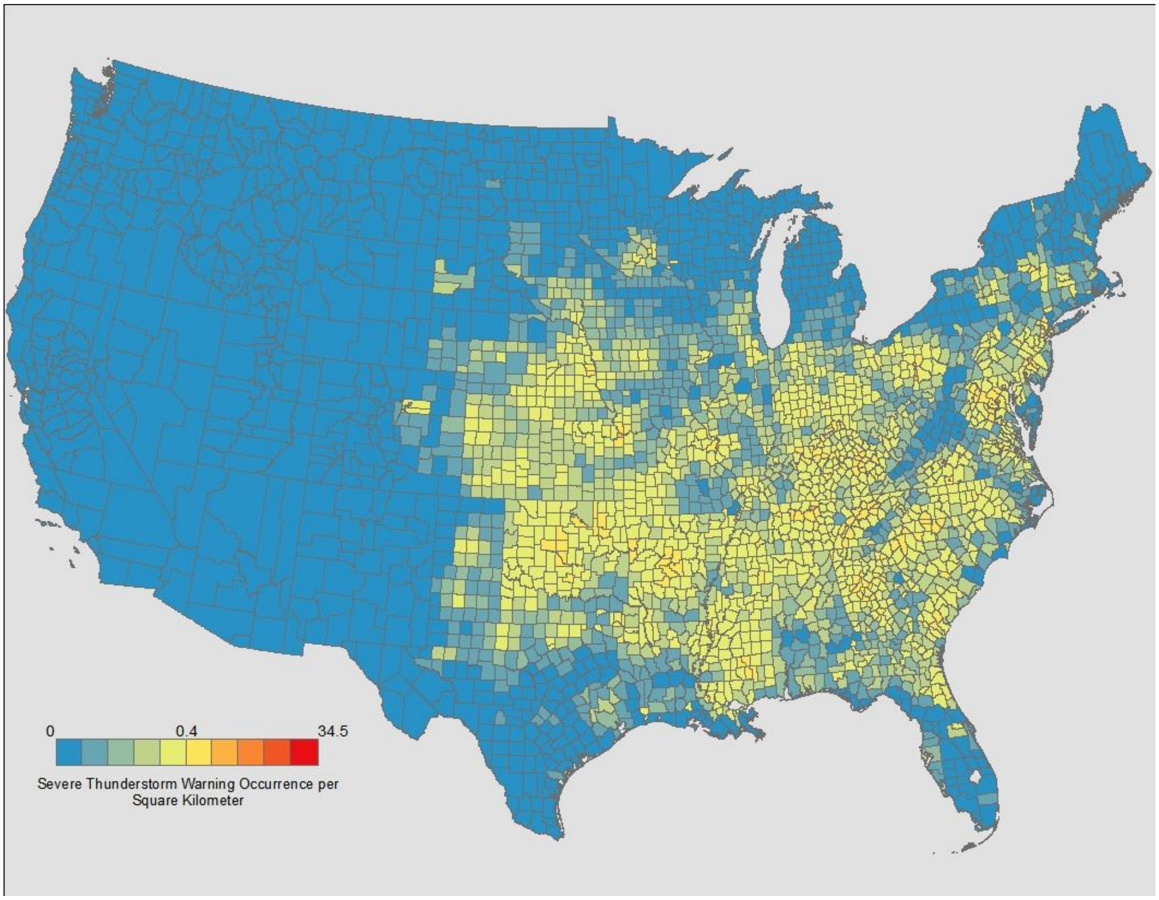


Figure 4.2.7: Map of the contiguous United States counties by Severe Thunderstorm warning occurrence per area (square kilometers) for the period 1986 to 2017. Geometrical Interval scaling shows the starting value to be 0, the middle value at 0.4, and the ending value at 34.5.

Severe Thunderstorm Warning Occurrence per Population Density. The pattern of severe thunderstorm warning occurrence per population density (people/km^2) shows several maxima in eastern Montana, northwestern South Dakota, northern Nebraska, eastern New Mexico, and across Texas (Fig 4.2.8). Though not as high, other maxima also occur in eastern Colorado, eastern Nevada, southern Idaho, western North Dakota, eastern Wyoming, and western Kansas. Other notable local maximums do occur in Oklahoma, Arkansas, Louisiana, Mississippi, Georgia, Michigan, Minnesota, New York, and North Carolina. Notable low severe thunderstorm occurrence per population density regions can be found in coastal Northeast and the West Coast.

The location of the counties one factor in the pattern of the highest values of severe thunderstorm warning occurrence per population density. As evident in the figure, and similar to the pattern in section 4.2.6, the counties with the highest-occurrence of severe thunderstorms per population density are mostly located on the leeward side of the Rocky Mountain range. This is likely attributed to the seasonal meteorological pattern in late spring and summer, and is aided by the position of the Rockies, that funnel cooler air south signaling the formation of severe weather systems (Doswell, 1980). Another factor in the pattern is the population densities of the counties. The counties with the highest warning occurrence per population density values have population densities below three people per square kilometer, with a majority being below one person per square kilometer. The low population densities coupled with the regions propensity for severe weather systems to form likely accounts for the pattern of severe thunderstorm warning occurrence per population density.

The notable low severe thunderstorm warning occurrence per population density values are likely attributed to (1) the high population density of the counties (e.g., coastal California and coastal Northeast) and/or (2) low severe thunderstorm warning occurrence (e.g., Pacific Northwest).

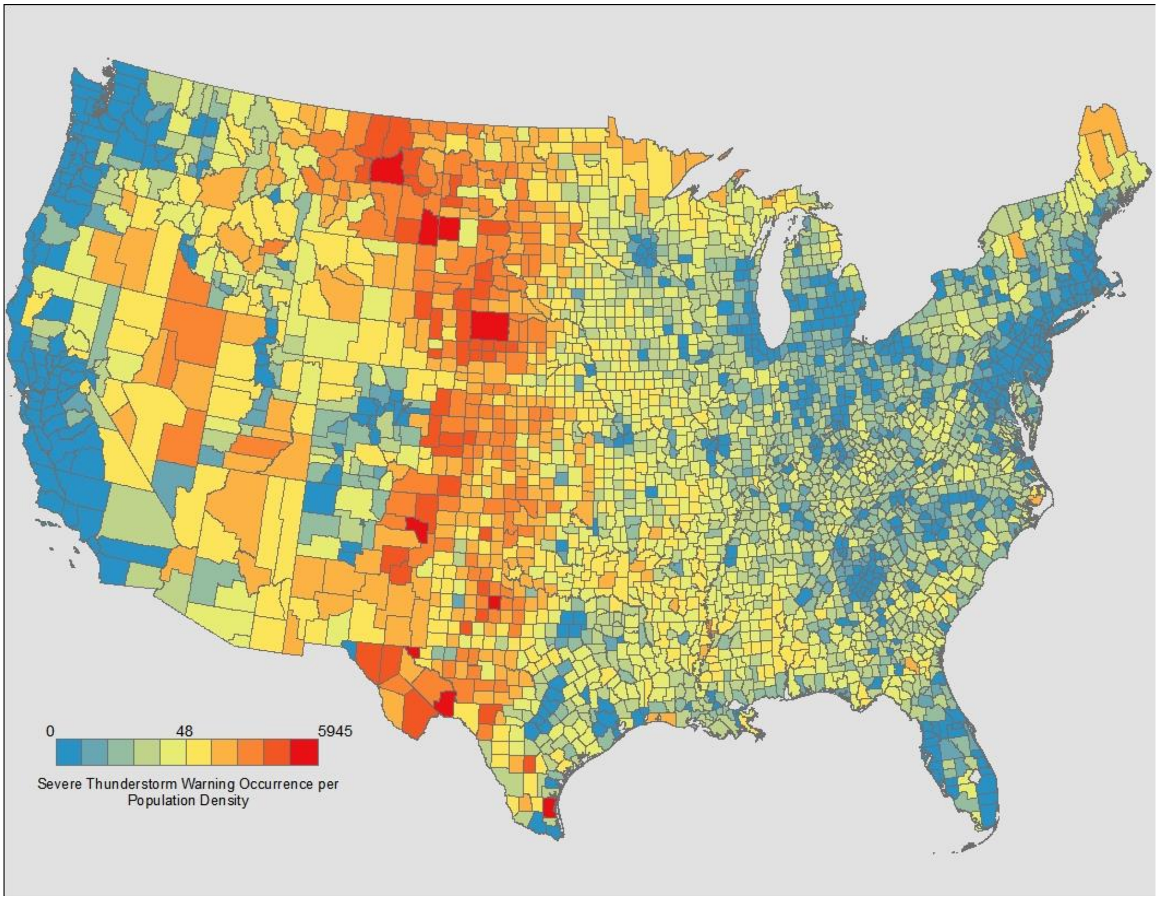


Figure 4.2.8: Map of the contiguous United States counties by Severe Thunderstorm warning occurrence per population density (people/km^2) for the period 1986 to 2017. Geometrical Interval scaling shows the starting value to be 0, the middle value at 48, and the ending value at 5945.

Tornado Warning Occurrence. As seen in Figure 4.2.9, the pattern of tornado warning occurrence shows the highest occurrences in northeastern Colorado, coastal Texas, northern Nebraska, southeastern Louisiana, southern and central Mississippi, and southern Alabama. Though not as high in occurrence, there are also areas of local maxima in western Texas, Oklahoma, coastal Florida, and northern Alabama. Notable local high occurrences of tornado warnings do occur in northern Arizona, North Dakota, Minnesota, central Illinois, Iowa, and Tennessee.

One factor in the study area maxima and local maxima of tornado warning totals across the Midwest and the South is the population size of the counties. Most of the counties with high occurrences of tornado warnings across the Midwest and the South also contain a significant portion of a local metropolitan area (e.g. Houston, Mobile, and Denver). Therefore, the large population sizes in these counties, coupled with each region's propensity for tornado formation mostly during the spring and summer months likely accounts for these maximums (Carbin et al. 2013; Coleman and Dixon 2014; Farney and Dixon 2015; Brady and Szoke, 1989; Broyles and Crosbie, 2004; Brooks et. al., 2003). The study area tornado maximum in Nebraska and the local tornado maxima in Arizona and Texas are best accounted for by the size of the counties. As noted in section 3.4, a count is made when a tornado warning occurs within or covers a portion of a county. Therefore, the size of the counties coupled with seasonal tornado development likely accounts for these maxima (Blanchard 2008; Broyles and Crosbie, 2004; Brooks et. al., 2003).

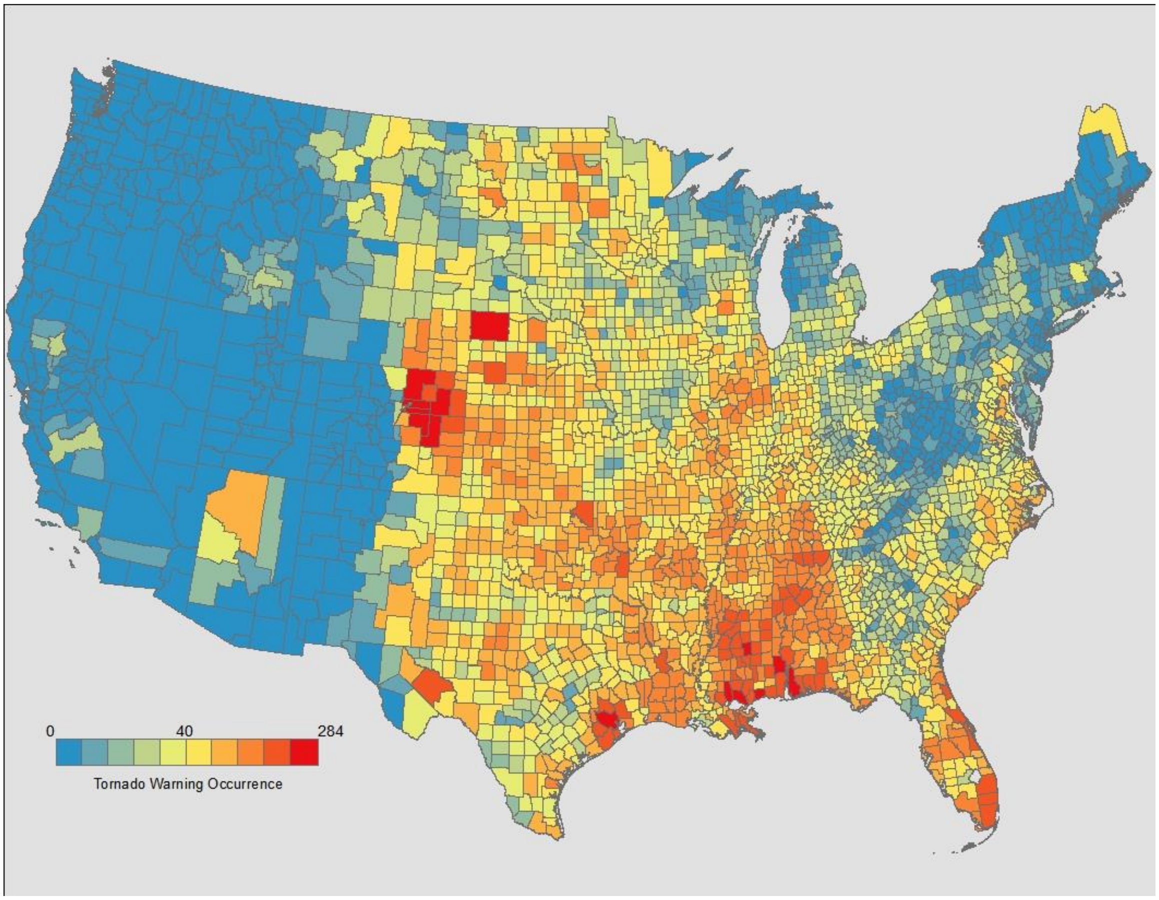


Figure 4.2.9: Map of the contiguous United States counties by Tornado warning occurrence for the period 1986 to 2017. Geometrical Interval scaling shows the starting value to be 0, the middle value at 40, and the ending value at 284.

Tornado Warning Occurrence per Capita. The pattern of tornado warning occurrence per 1000 people shows the highest occurrences in Texas and Nebraska, with local maxima in western Mississippi, along the border of Colorado and Kansas, and western Nebraska (Fig. 4.2.10). Notable local maxima values of tornado per capita also occur in Idaho, Montana, North Dakota, and central Kansas. There is a notable uniformity of tornado warning occurrence per 1000 people across the Midwest and the South. Notable low tornado warning occurrence per 1000 people regions can be found in the western United States and the coastal Northeast.

A likely factor in the tornado warning occurrence per 1000 people is the location of the counties. As evident in the figure, and is discussed throughout the chapter, the highest values can be found on the leeward side of the Rocky Mountain range, similar to the pattern found in section 4.2.6. This region along the Rocky Mountain range is conducive to meteorological patterns that spawn severe weather, including tornadoes (Brady and Szoke, 1989). Another factor contributing to the pattern is the population sizes of the counties. Those counties that have the highest tornado warning occurrence per 1000 people have populations that are well below 10,000 people, with the maximum being 8270 people, the minimum being 82, and the mean population size of 2031 people. The tornado warning occurrences amongst these counties are also highly variable, with the maximum warning occurrence at 275 (the second highest tornado count in the dataset over the study period), the minimum warning occurrence at 16, and the mean warning occurrence at 63. The low population sizes, coupled with the region's propensity to experience tornadoes, likely accounts for the pattern of tornado warning occurrence per 1000 people.

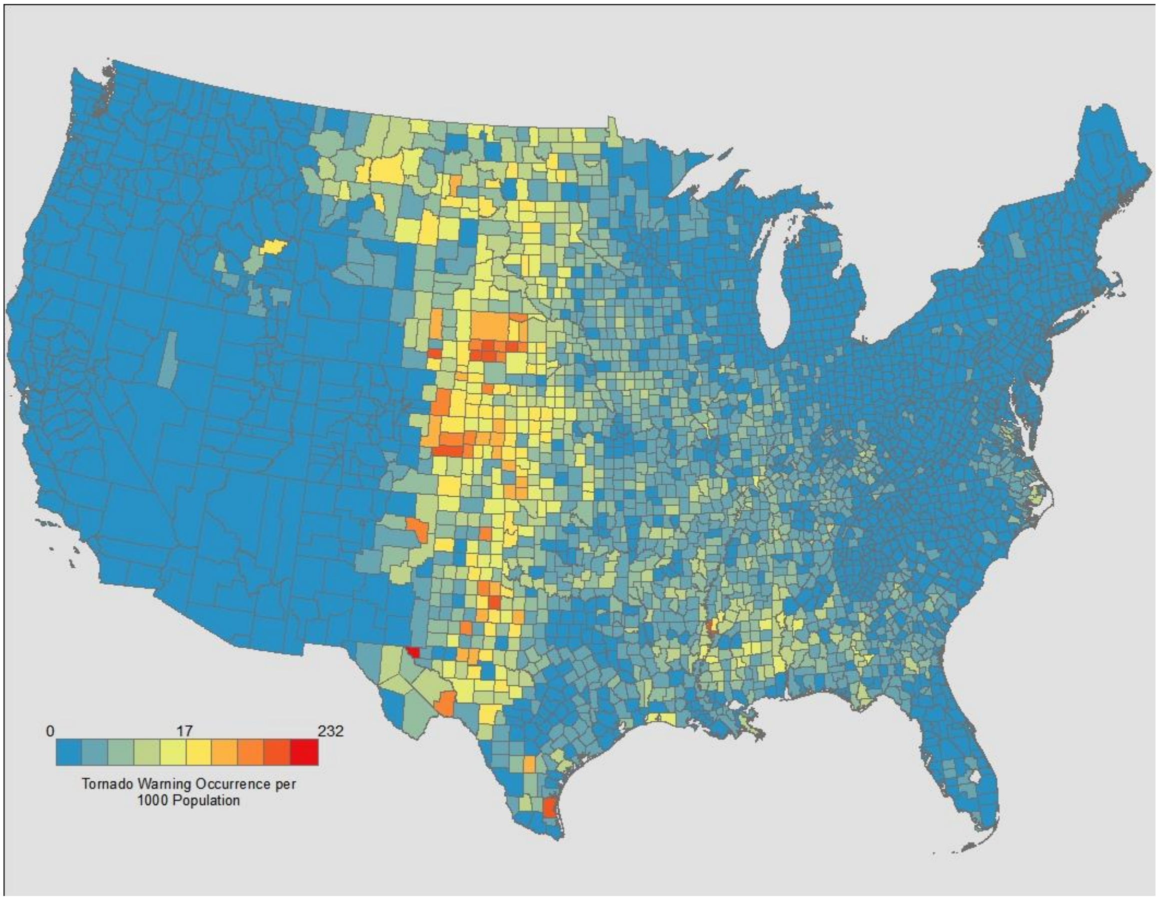


Figure 4.2.10: Map of the contiguous United States counties by Tornado warning occurrence per capita for the period 1986 to 2017. Natural Breaks (Jenks) scaling shows the starting value to be 0, the middle value at 17, and the ending value at 232.

Tornado Warning Occurrence per Area. As seen in Figure 4.2.11, the pattern of tornado warning occurrence per county area shows uniformity east of the Rocky Mountain range with the highest values in the city-counties of Virginia. Other local maxima of tornado warnings per county area occur in Colorado, Mississippi, northern Alabama, and central Tennessee. Though not as high in value, there are also local maxima in central Illinois, Kentucky, Texas, Georgia, North Carolina, central Minnesota, and along the border of Illinois and Missouri. Notable low tornado warning occurrence per area (square kilometers) regions cover the western United States and an area extending from the Appalachian Mountain range to the Northeast.

One factor in the pattern of the tornado warning occurrence per area (square kilometers) is the location of the counties. As evident in the figure, the counties that consist of the local maxima are located within regions that are susceptible to tornadoes during their respective seasonal severe weather patterns (Carbin et al 2013; Coleman & Dixon 2014; Farney and Dixon 2015). Another factor in the highest values of tornado warning occurrence per area (square kilometers) is obviously the size of the counties. As evident in the figure, a majority of the smallest counties in the United States (e.g., those in Virginia) have the highest values. However, counties with significantly higher areas (e.g. counties in Mississippi) than those in Virginia do fall into the top three value ranges, which is attributed to the higher occurrences of tornado warnings in those regions.

The notable low tornado warning occurrence per area (square kilometers) regions are likely the result of (1) relatively low occurrences of tornado warnings (coastal Northeast) and/or (2) large county sizes (e.g., western United States).

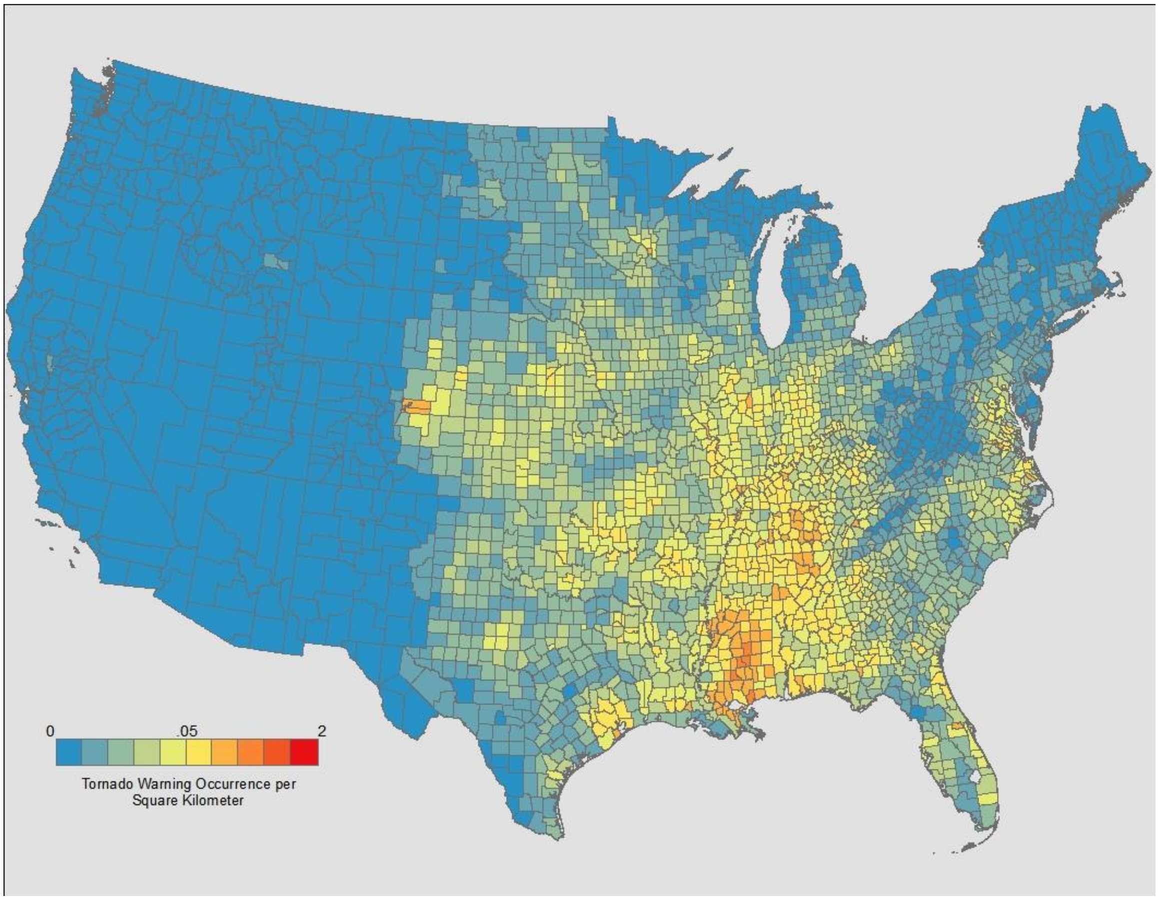


Figure 4.2.11: Map of the contiguous United States counties by Tornado warning occurrence per area (square kilometers) for the period 1986 to 2017. Natural Breaks (Jenks) scaling shows the starting value to be 0, the middle value at .05, and the ending value at 2.

Tornado Warning Occurrence per Population Density. The pattern of tornado warning occurrence per population density (people/km^2) shows maxima in eastern Montana, central and western Nebraska, eastern Colorado, northeastern New Mexico, and across Texas (Fig. 4.2.12). Though not as high, other local maxima occur in Idaho, northern Arizona, north central Nevada, North Dakota, western Kansas, western Mississippi, southern Louisiana, and eastern North Carolina. Notable low tornado warning occurrence per population density does occur across the coastal Northeast and coastal West.

One factor in the pattern of the highest values of tornado warning occurrence per population density is the location of the counties. As evident in figure 4.2.12, and similar to the pattern in section 4.2.10, a majority of the maxima counties are located on the leeward side of the Rocky Mountain range. As mentioned in previous sections, the significance of this region is that seasonal meteorological patterns, mostly during the spring and summer months, see competing air masses meet and subsequently form severe weather systems (Brady and Szoke, 1989). Another factor in the pattern is the population densities of the counties. In the regions where there are maxima and local maxima, the counties have population densities below five people per square kilometer, with the mean being less than one person per square kilometer. These lower population densities coupled with the propensity of the region to experience tornados likely explains the pattern of tornado warning occurrence per population density.

The notable low tornado warning occurrence per population density regions are likely the result of relatively low occurrences of tornadoes.

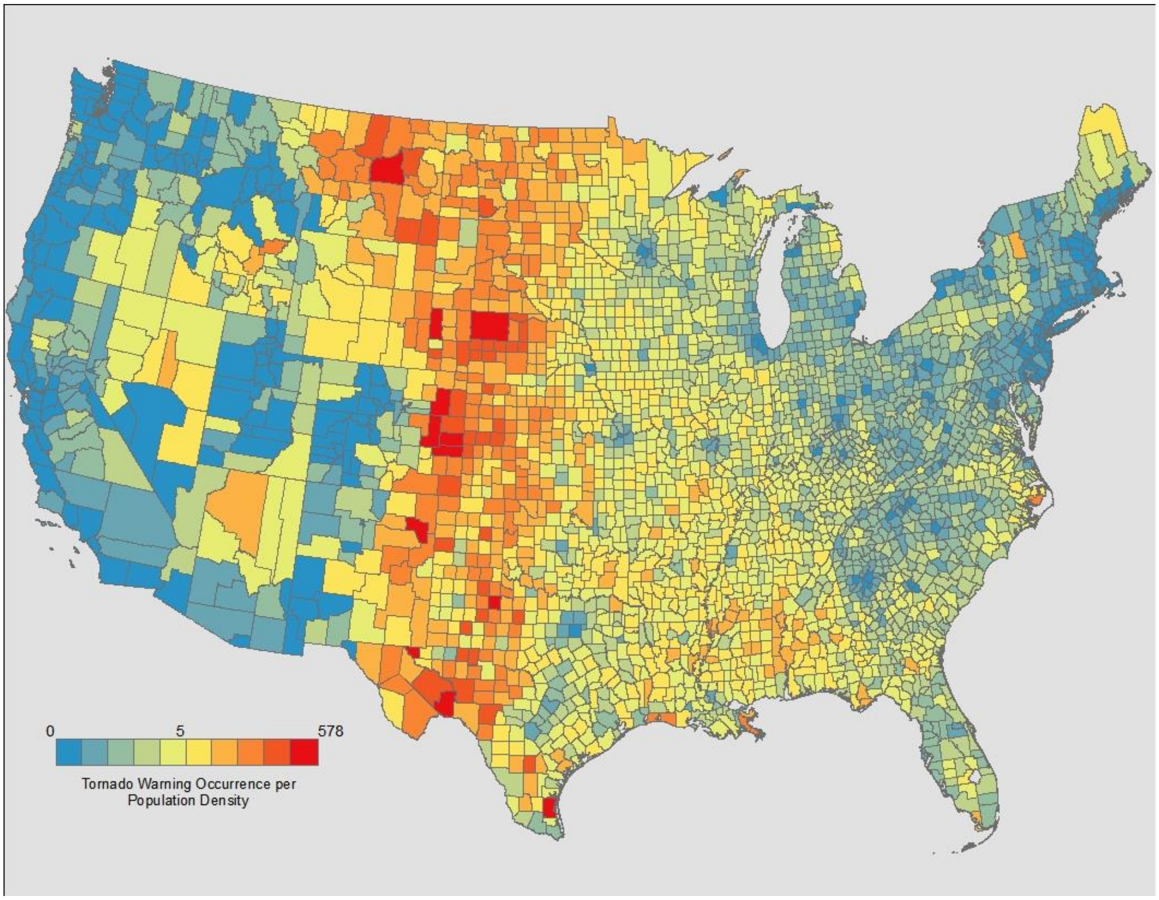


Figure 4.2.12: Map of the contiguous United States counties by Tornado warning occurrence per population density (people/km^2) for the period 1986 to 2017. Geometrical Interval scaling shows the starting value to be 0, the middle value at 5, and the ending value at 578.

Aggregated (flash flood, tornado and severe thunderstorm) Warning Occurrence. As seen in Figure 4.2.13, the pattern of aggregated (flash flood, tornado and severe thunderstorm) warning occurrence shows the highest occurrences in the desert Southwest, eastern and western Texas, western South Dakota, northeastern Colorado, north-central Nebraska, and northern Oklahoma, with local maxima in Oklahoma, Arkansas, Kansas, Mississippi, Alabama, Florida, New Mexico, California, Minnesota, North Carolina, and South Carolina. Other notable local high occurrences of total warnings also occur in Virginia, Maryland, Pennsylvania, and Missouri.

For the highest aggregated warning occurrence, many of the contributing factors that are present in this section are also found in the flash flood, severe thunderstorm, and tornado warning occurrence sections. One factor that attributes to the regions of maxima occurrence of total warnings is the location of the counties. In the Desert Southwest, these counties experience a seasonal change of winds, which allow for flooding during intense periods of rainfall as well as strong thunderstorms (Adams & Comrie, 1997; Maddox et. al., 1980). In the Midwest, South, and East Coast, seasonal weather patterns, especially in the early spring to summer months, allow for the formation of severe weather that have the ability to reach severe thunderstorm strength as well as create tornadic activity (Carbin et al. 2013; Coleman and Dixon 2014; Farney and Dixon 2015; Brady and Szoke, 1989; Broyles and Crosbie, 2004; Brooks et. al., 2003; Brooks et. al., 2003; Owen, 1966; Schaefer et. al., 2004; Kelly et. al., 1985; Doswell, 1980; Weisman, 1990, Maddox, 1983). Another factor in the high occurrence of total warnings is the size of the counties. Since a few of the maxima counties have areas larger than those in the vicinity, they have the ability to experience higher warning occurrences comparable to the sum of the surrounding counties.

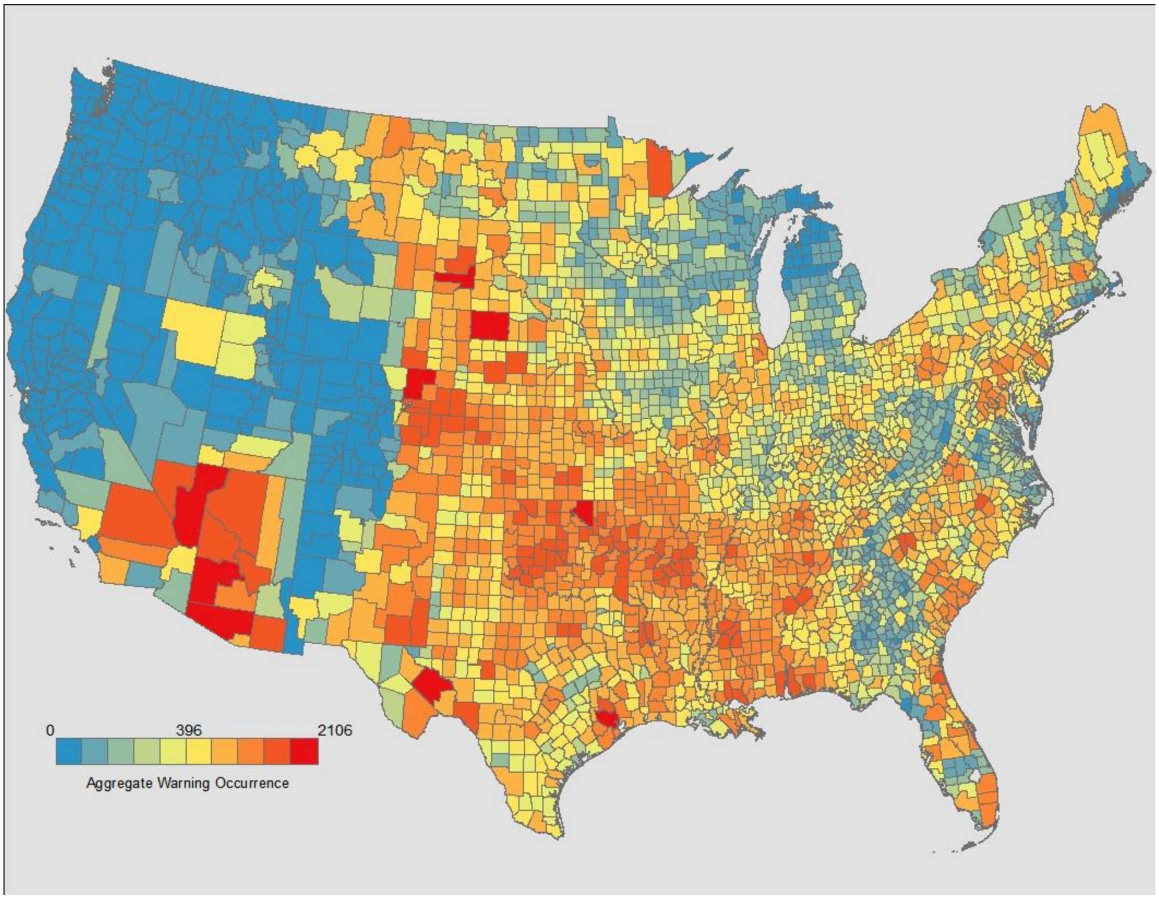


Figure 4.2.13: Map of the contiguous United States counties by aggregated (flash flood, tornado and severe thunderstorm) warning occurrence for the period 1986 to 2017. Geometrical Interval scaling shows the starting value to be 0, the middle value at 396, and the ending value at 2106.

Aggregated (flash flood, tornado and severe thunderstorm) Warning Occurrence per Capita. The pattern of aggregated (flash flood, tornado and severe thunderstorm) warning occurrence per 1000 people shows the highest values in Texas with local maxima in eastern Montana, central Nebraska, eastern Colorado, and eastern New Mexico (Fig. 4.2.14). Though not as high, other notable local maxima also occur in South Dakota, North Dakota, western Kansas, and western Mississippi. Notable low warning occurrence per 1000 people regions can be found in the coastal Northeast, Florida, and the West Coast.

One factor in the highest values of aggregated (flash flood, tornado and severe thunderstorm) warning occurrence per capita is the location of the counties. As evident in the figure, and as will later be discussed in section 4.3.14, the local maxima regions are located on the leeward side of the Rocky Mountains. Similar to sections 4.2.6 and 4.2.10, this region is susceptible to severe weather, both severe thunderstorms and tornadic activity, that occurs due to seasonal interactions of contrasting air masses (Doswell, 1980; Brady and Szoke, 1989). Another factor in the leeward pattern is the population sizes of the counties. In this pattern, the maxima counties have populations below 6,000 people with a majority of counties having populations below 2,000 people. The low population sizes, coupled with the propensity of this region to experience severe weather, likely accounts for the leeward pattern of local and study area maxima.

The low total warning occurrence per capita are likely the result of (1) relatively large populations and/or (2) the low occurrences of warnings (e.g., Northeast and West coasts).

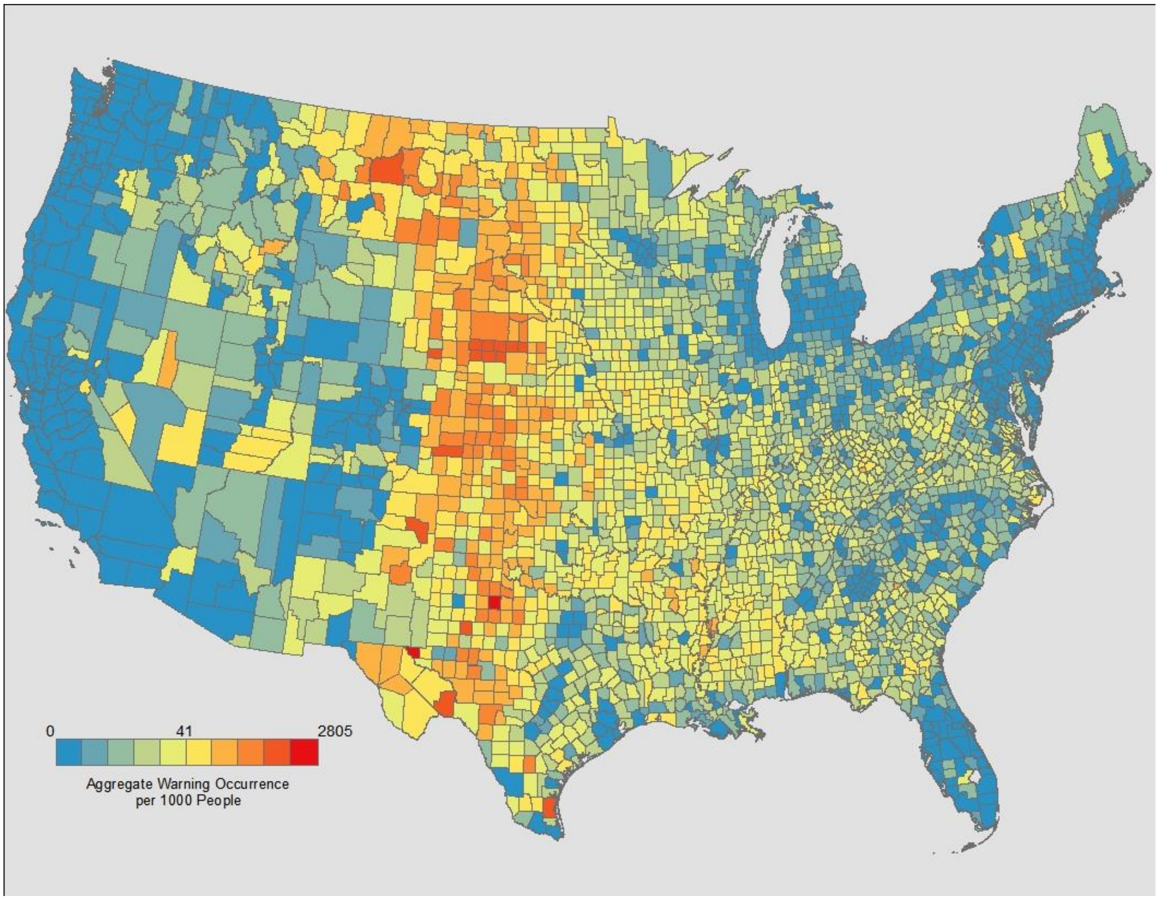


Figure 4.2.14: Map of the contiguous United States counties by aggregated (flash flood, tornado and severe thunderstorm) warning occurrence per capita for the period 1986 to 2017. Geometrical Interval scaling shows the starting value to be 0, the middle value at 41, and the ending value at 2805.

Aggregated (flash flood, tornado and severe thunderstorm) Warning Occurrence per Area. As seen in Figure 4.2.15, the pattern of aggregated (flash flood, tornado and severe thunderstorm) warnings per area (square kilometers) is relatively uniform east of the Rocky Mountain range with the highest values in Virginia with local maxima in southern New York, West Virginia, Pennsylvania, Maryland, Kansas, and Colorado. Though not as high in occurrence, local maxima occur in north-central New Mexico, central and northeastern Oklahoma, central Arkansas, southwestern Missouri, central Tennessee, central Mississippi, east-central Minnesota, eastern Kentucky, and north-central Georgia. Notable low warning occurrence per area (square kilometers) regions can be found in the western and northern United States as well as in Florida.

One factor in the pattern of the highest values of aggregate warning occurrence per area (square kilometers) is the size of the counties. As evident in the figure and the data, the smallest counties in the United States (e.g., Virginia) have the highest values, though total warnings do vary amongst the counties. These counties have a mean total warning count of 232 with a minimum of 94 warnings and a maximum of 493 warnings over the study period. Another factor in the overall pattern is the location of the counties with regard to seasonal meteorology. The local maxima, especially, are located within regions that are susceptible to seasonal weather patterns that spawn severe systems, mostly severe thunderstorm and tornadic activity (Carbin et al 2013; Coleman & Dixon 2014; Farney and Dixon 2015; Brooks et al, 2003; Kelly et. al., 1985; Maddox, 1983; Schaefer et. al., 2004). Coupling the small size of the counties east of the Rocky Mountain range with the propensity of these regions to experience severe weather likely accounts for the pattern of total warnings per area (square kilometers).

The notable low aggregate warning occurrence per area (square kilometers) regions are likely the result of (1) large county area (e.g. western United States) and/or (2) the low occurrence of severe weather (e.g. the coastal Northeast).

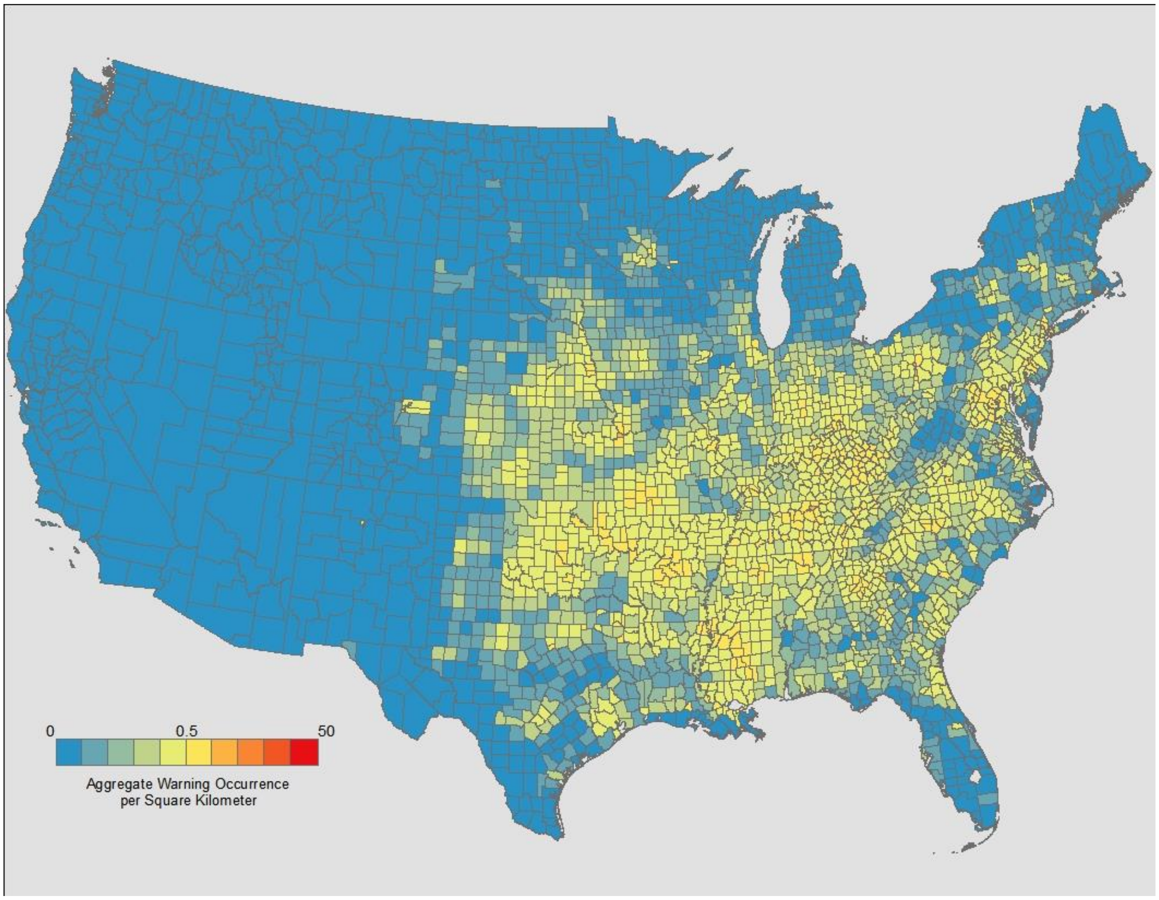


Figure 4.2.15: Map of the contiguous United States counties by aggregated (flash flood, tornado and severe thunderstorm) warning occurrence per area (square kilometers) for the period 1986 to 2017. Geometrical Interval scaling shows the starting value to be 0, the middle value at 0.5, and the ending value at 50.

Aggregated (flash flood, tornado and severe thunderstorm) Warning Occurrence per Population Density. The pattern of aggregated (flash flood, tornado and severe thunderstorm) warning occurrence per population density (people/km^2) shows maxima in eastern Montana, central Nebraska, eastern Colorado, eastern New Mexico, and across Texas with local maxima in central and eastern Nevada, central and western South Dakota, and western North Dakota (Fig. 4.2.16). Though not as high, there are also notable local maxima occur in southern Idaho, southern Utah, northern Arizona, western Oklahoma, and western Kansas. Notable low total warning occurrence per population density (people/km^2) regions can be found along the West Coast and the coastal Northeast.

One factor in the pattern of the highest values of aggregated warning occurrence per population density (people/km^2) is the location of the counties. As evident in the figure, there is a pattern of maxima and local maxima counties located on the leeward side of the Rocky Mountain range. As has been discussed in previous sections, this region is conducive to the formation of severe weather systems (Doswell, 1980; Brady and Szoke, 1989). Another factor in the pattern is the population densities of the counties. In each of the maxima counties, the population densities were under 3 people per square kilometer, with a majority of the counties below 1 person per square kilometer. Having a low population density coupled with a propensity to severe weather conditions likely accounts for the pattern.

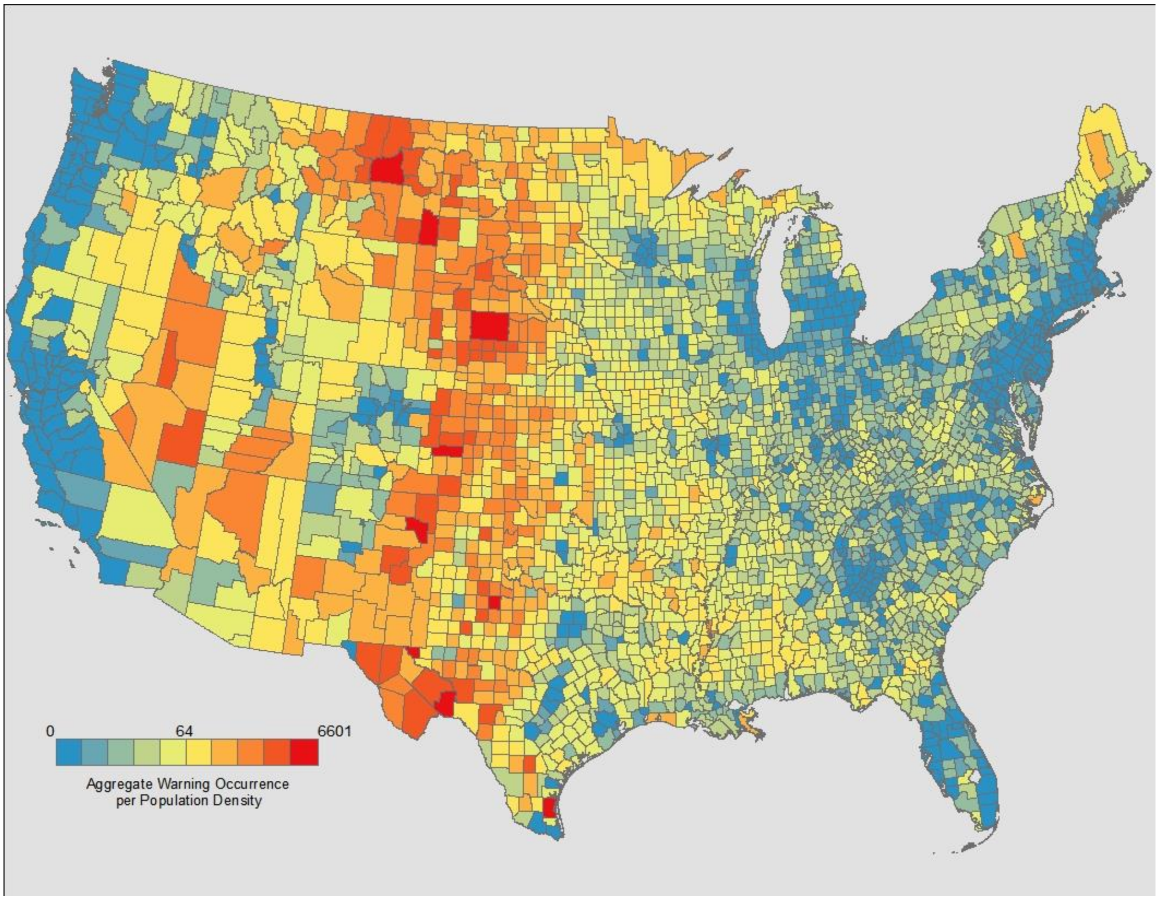


Figure 4.2.16: Map of the contiguous United States counties by aggregated (flash flood, tornado and severe thunderstorm) warning occurrence per population density (people/km^2) for the period 1986 to 2017. Geometrical Interval scaling shows the starting value to be 0, the middle value at 64, and the ending value at 6601.

Results and Discussion of Hot Spot Analysis

This section used the Hot Spot Analysis (Getis-Ord Gi*) function in ArcGIS, which is based on the equations discussed in section 3.7. The results from the hot spot analysis detail statistically high (hot) and low (cold) valued regions as they relate geographically. The GIS products will display the hot spot analysis results of the raw counts, population adjusted, area (square kilometers) adjusted, and population density (people/km^2) adjusted of the four warning categories (flash flood, severe thunderstorm, tornado, and aggregate). Important and pertinent details of each maps is identified and discussed below.

Flash Flood Warning Occurrence. As seen in Figure 4.3.1, the pattern of hot spots associated with flash flood warning occurrence has the highest occurrence in most of the desert Southwest extending along the southern international and coastal border in the South as well into the Midwest. Another hotspot region covers portions of Kentucky, Ohio, northern West Virginia, northern Virginia, Maryland, Pennsylvania, New Jersey, and southern New York. Notable cold spot areas cover areas in the Southeast United States, parts of coastal North Carolina and Virginia, and portions of northern California into the Pacific Northwest.

The flash flood warning occurrence hot spot analysis compliments the findings from section 4.2.1, where the maxima discussed earlier are contained within the boundaries of the 99% confidence interval. As evident in the figure, the region of 99% confidence level in Kentucky and Ohio were identified as part of the maxima region identified in the Northeast region. Further, the hot spot analysis identifies areas of transition between the higher and lower regions of flash flood warning occurrence. One such region extends across Alabama in the southern Gulf and Atlantic states, as well as a region that runs longitudinally between the hot spot region in the lower Northeastern states and the cold spot region in the Mid-Atlantic.

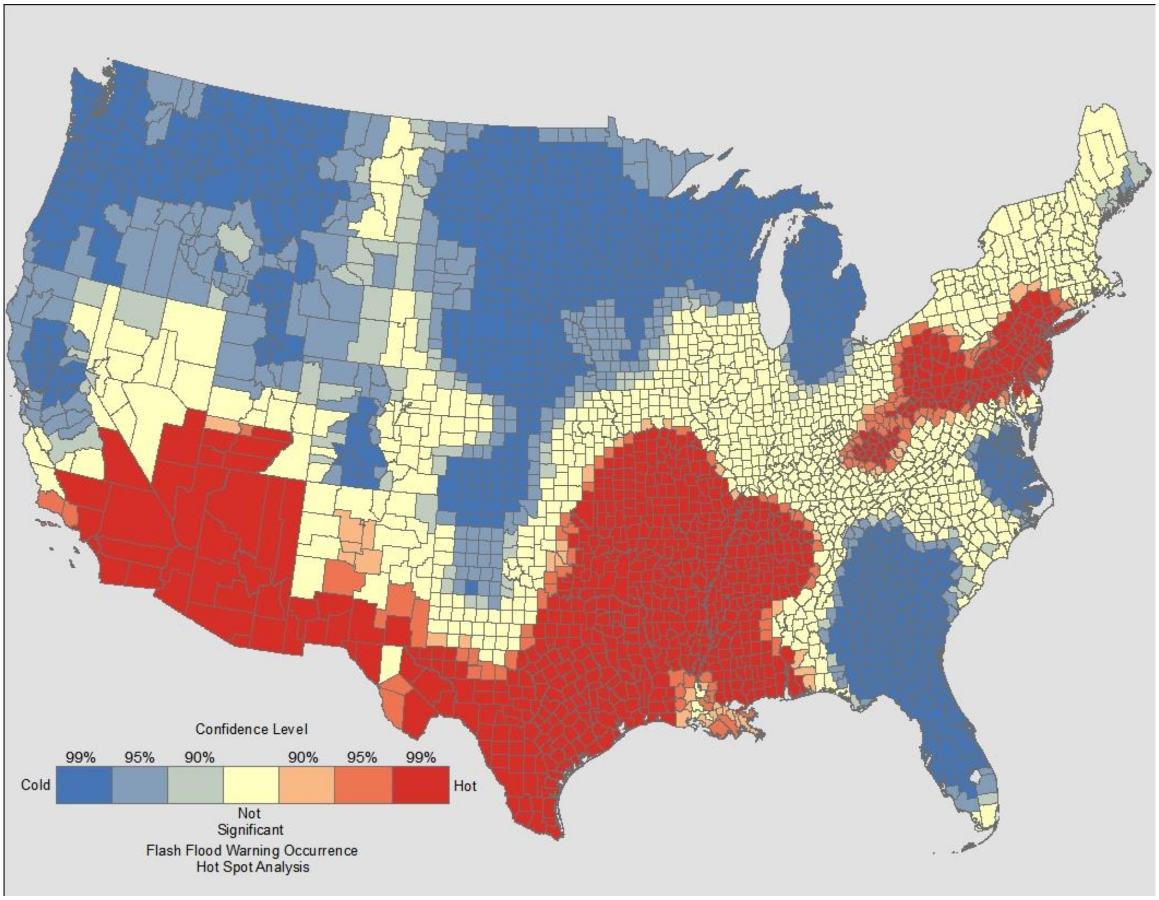


Figure 4.3.1: Map of the contiguous United States counties showing hot spot analysis findings for Flash Flood warning occurrence for the period 1986 to 2017. Scale shows confidence levels for high valued areas in a red shading and low valued areas in a blue shading. Statistically non-significant counties are shown in yellow.

Flash Flood Warning Occurrence per Capita. The hot spot pattern of flash flood warning occurrence per 1000 people shows many small hot spot pockets in Missouri, Arkansas, Louisiana, Mississippi, Montana, Nebraska, Kansas, Colorado, New Mexico, Nevada, Utah, and Arizona, with a large hot spot region that covers a large area of western Texas (Fig. 4.3.2). Two main cold spot regions can be identified in this analysis: (1) an area covering Michigan, Indiana, Ohio, and (2) an area that covers Georgia and extends through the Mid-Atlantic and ending in the coastal Northeast. In this analysis, no identified cold spot county has a 99% confidence level.

The hot spot analysis for flash flood warning occurrence per capita does offer support in confirming the local maxima discussed in section 4.2.2, with the exception of the lone county in Nevada. This exception, and will be discussed in later sections, is likely explained by the limitations of the hot spot analysis model when dealing with data that have significant differences in area. As evident in the figure, there are no significant transition areas between hot spot and cold spot regions.

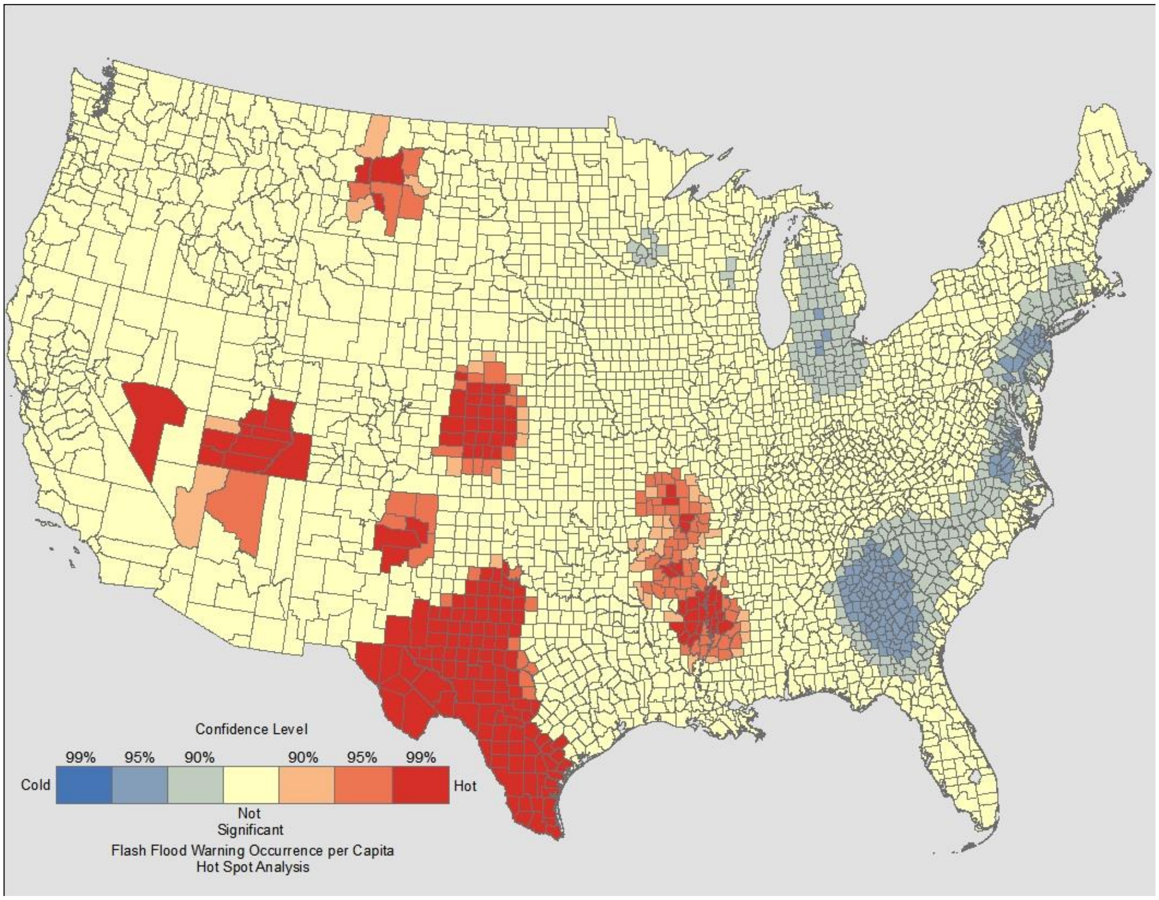


Figure 4.3.2: Map of the contiguous United States counties showing hot spot analysis findings for Flash Flood warning occurrence per capita for the period 1986 to 2017. Scale shows confidence levels for high valued areas in a red shading and low valued areas in a blue shading. Statistically non-significant counties are shown in yellow.

Flash Flood Warning Occurrence per Area. In initial runs of the hot spot analysis for flash flood warning occurrence per area (square kilometers), the statistical model was heavily influenced by the smallest counties (e.g the Virginias) and the output would only highlight these counties. In order to have a better model run, these counties were omitted, and the output from this run is used as Figure 4.3.3.

As seen in Figure 4.3.3, the hot spot pattern of flash flood warnings per area (square kilometers) show a hot spot region extending from the South, through the Midwest, and ending in the coastal Northeast. Notable cold spots cover much of Florida, Georgia, and South Carolina, as well as a large cold spot region covering most of the mountainous areas in the West extending to the western Midwest states.

The flash flood warning occurrence per area (square kilometers) hot spot analysis confirms with a 99% confidence level the regions of local maxima discussed in section 4.2.3, with the exception of the local maxima in New Mexico. This exception is likely the cause of the homogenizing of geographically close data points in the hot spot analysis, and will be further discussed in section 4.4.3. As evident in the figure, there are two transition areas between the hot spot regions and cold spot regions. The first region extends from the southwest to the northeast in the southeastern region of the United States, while the second region follows the leeward side of the Rocky Mountain range until northern Iowa where the area heads east towards the Great Lakes region.

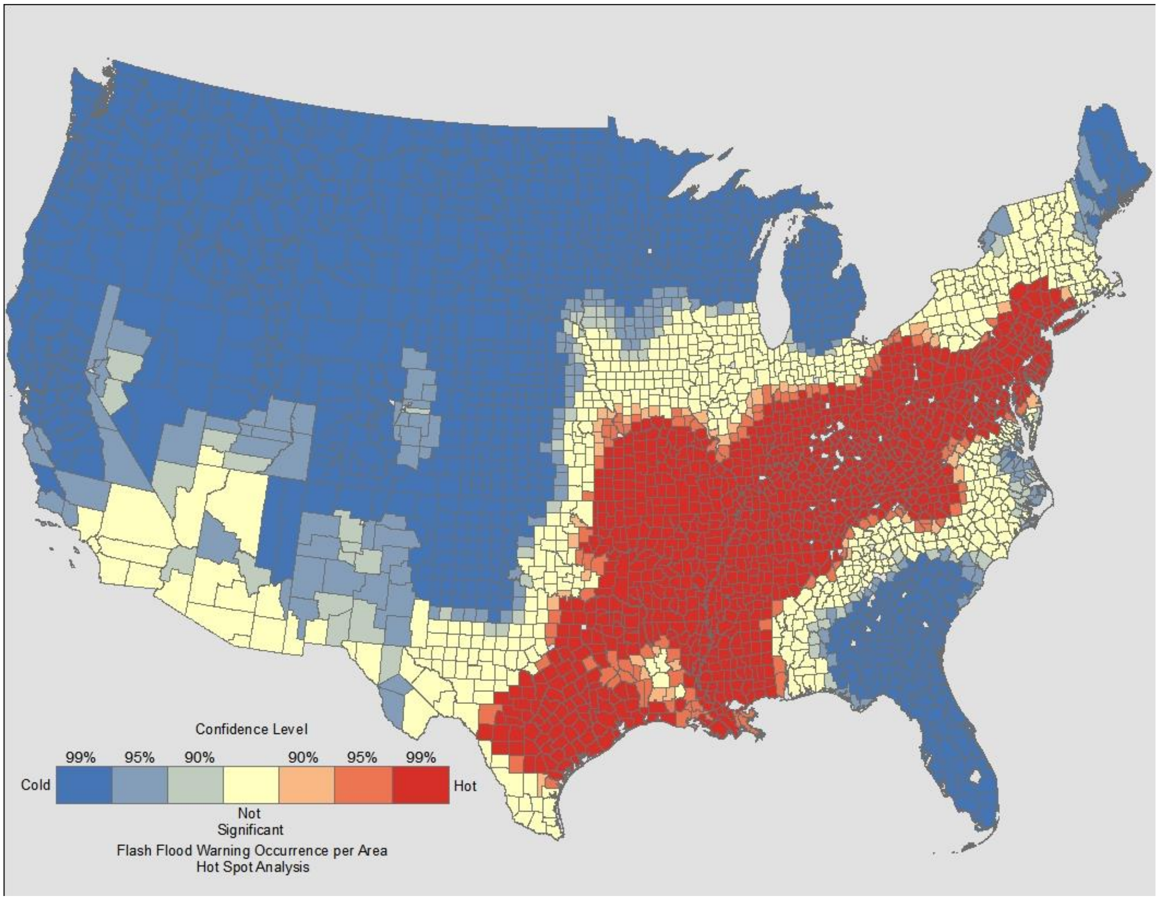


Figure 4.3.3: Map of the contiguous United States counties showing hot spot analysis findings for Flash Flood warning occurrence per area (square kilometers) for the period 1986 to 2017. Scale shows confidence levels for high valued areas in a red shading and low valued areas in a blue shading. Statistically non-significant counties are shown in yellow.

Flash Flood Warning Occurrence per Population Density. The pattern of hot spots associated with flash flood warning occurrence per population density (people/km^2) shows a large hot spot region that covers portions of California, Nevada, Utah, Arizona, New Mexico, and Texas (Fig. 4.3.4). Though not covering as large of an area, there are two additional hot spot regions with one covering an area along the Colorado/Kansas border and another covering most of eastern Montana. Two notable cold spot regions cover the coastal Mid-Atlantic and another covering portions of Georgia, the Carolinas, and Tennessee. In this analysis, no identified cold spot county has a 99% confidence level.

The flash flood warning occurrence per population density (people/km^2) hot spot analysis compliments the findings from section 4.2.4, where the maxima discussed earlier are mostly contained within the 99% confidence hot spot regions. As evident in figure 4.3.4, the region of 99% confidence level covering the Colorado/Kansas border were identified as a separate local hot spot region from the larger region to the west and south. This analysis of flash flood warning occurrence per population density did not produce any significant boundaries between hot spot and cold spot regions.

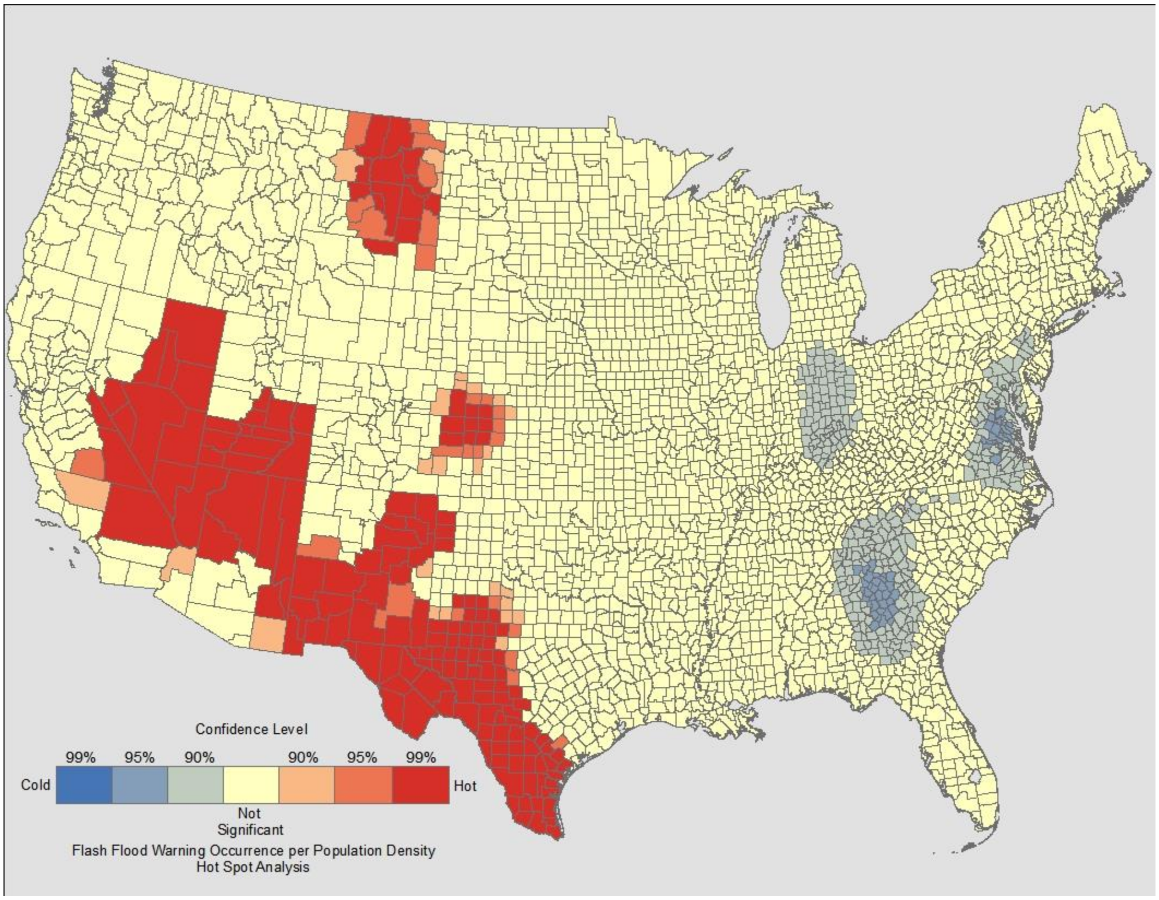


Figure 4.3.4: Map of the contiguous United States counties showing hot spot analysis findings for Flash Flood warning occurrence per population density (people/km^2) for the period 1986 to 2017. Scale shows confidence levels for high valued areas in a red shading and low valued areas in a blue shading. Statistically non-significant counties are shown in yellow.

Severe Thunderstorm Warning Occurrence. As seen in Figure 4.3.5, the hot spot pattern for severe thunderstorm warning occurrence shows three separate regions: 1) a region of highest confidence in Arizona, 2) a region of mixed confidence starting from the western edge of the Midwest and stretching down in to the southern states stopping in Alabama, and 3) a mixed confidence region that covers the Carolinas and follows the coastal counties south into Florida. There are several notable cold spot regions across the study area: 1) a mixed confidence area in southeast Texas, 2) a mixed confidence area that follows the eastern border of Iowa into southern Minnesota and eastward into Wisconsin and Michigan, 3) a mixed confidence that starts in southern Illinois and stretches eastward into the Virginias, Maryland, and northeastern North Carolina, and 4) a mixed confidence region covering most of Georgia.

The severe thunderstorm warning occurrence hot spot analysis supports the coverage of maxima that were discussed earlier in section 4.2.5 with 99% confidence levels. Though only three regions of hot spots were discussed, the hot spot analysis also identified with lower than 99% confidence the maxima in Pennsylvania as well as in Maryland. As evident in the figure above, there are many transition areas between the hot and cold spots. Notable transition areas are located in northern Arizona, an area extending along the Rocky Mountain range from southern New Mexico into central Wyoming, an area along the border of Georgia and Alabama, as well as a transition area along the border of South Carolina and Georgia.

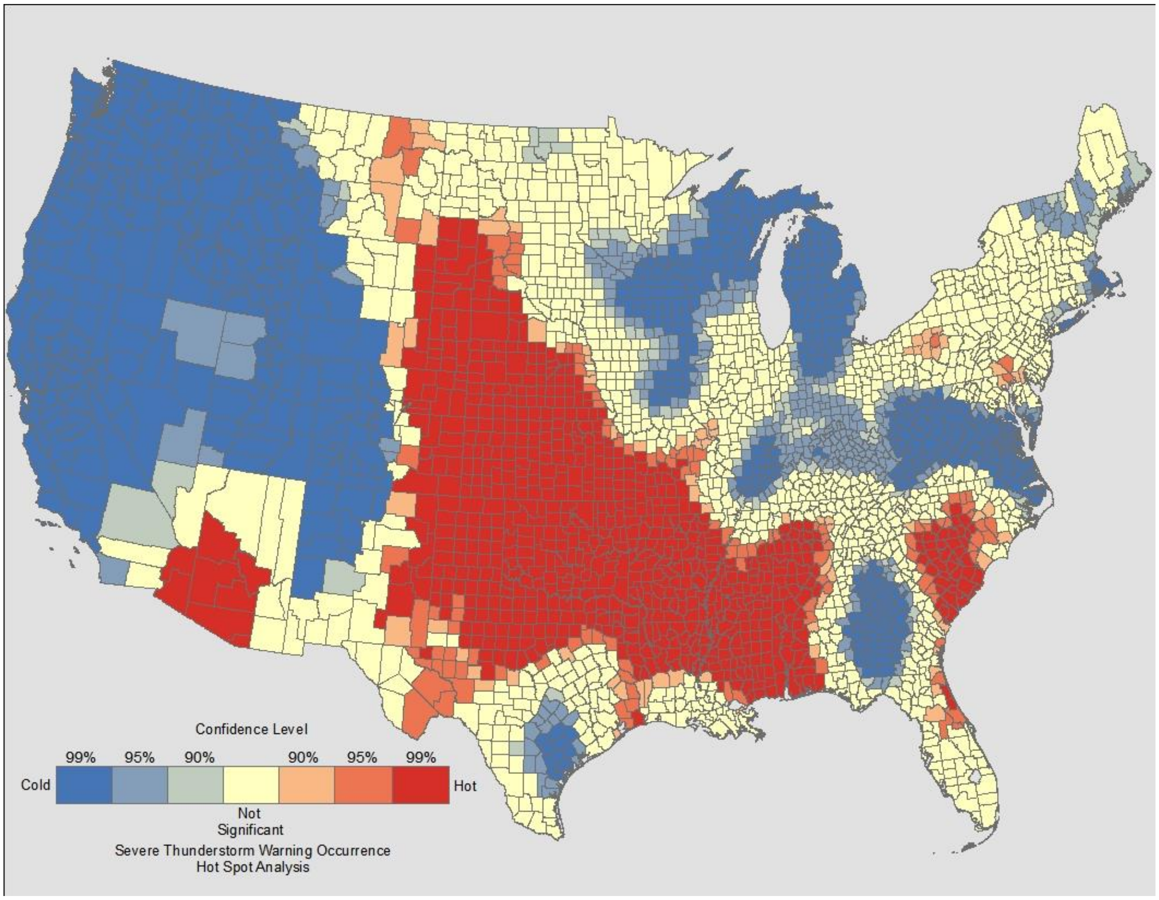


Figure 4.3.5: Map of the contiguous United States counties showing hot spot analysis findings for Severe Thunderstorm warning occurrence for the period 1986 to 2017. Scale shows confidence levels for high valued areas in a red shading and low valued areas in a blue shading. Statistically non-significant counties are shown in yellow.

Severe Thunderstorm Warning Occurrence per Capita. The pattern of hot spots associated with severe thunderstorm warning occurrence per 1000 people shows a hot spot region extending along the leeward side of the Rocky Mountain range into the Midwest from the southern international border to the northern international border (Fig. 4.3.6). Notable cold spot regions cover Indiana and Ohio, and another extending from northern Georgia and along the coastal Mid-Atlantic and Northeast. In this analysis, many of the cold spot regions are at or below the 95% confidence level, with the exception of several counties along the Pennsylvania and New Jersey border.

The severe thunderstorm warning occurrence per capita hot spot analysis significantly compliments the findings from section 4.2.6. The maxima discussed earlier are contained within the hot spot region of the leeward Rocky Mountains where geographical and meteorological conditions are conducive to severe weather formation. As evident in the figure, there are no significant transition areas between hot spot and cold spot regions.

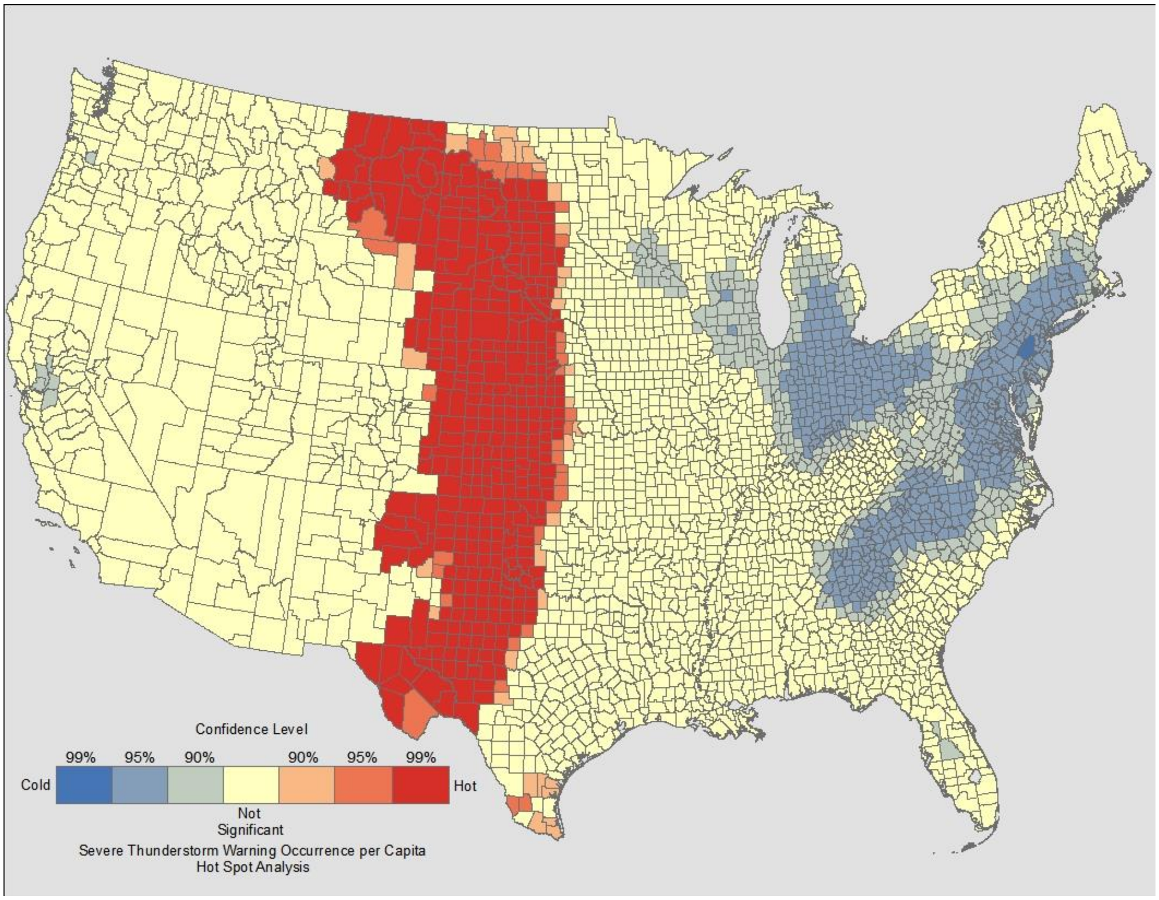


Figure 4.3.6: Map of the contiguous United States counties showing hot spot analysis findings for Severe Thunderstorm warning occurrence per capita for the period 1986 to 2017. Scale shows confidence levels for high valued areas in a red shading and low valued areas in a blue shading. Statistically non-significant counties are shown in yellow.

Severe Thunderstorm Warning Occurrence per Area. In initial runs of the hot spot analysis for severe thunderstorm warning occurrence per area (square kilometers), the statistical model was heavily influenced by the smallest counties (e.g., Virginia) and the output would only highlight these counties. In order to have a better model run, these counties were omitted, and the output from this run is used as Figure 4.3.7.

The pattern of hot spots associated with severe thunderstorm warning occurrence per area (square kilometers) shows a large region covering most of the Midwestern, Southern, and Mid-Atlantic states (Fig. 4.3.7). Notable cold spot regions cover a large area consisting of the West, southern Texas, and Northern states, a region covering southern Florida, and a region covering the northern North East states.

The severe thunderstorm warning occurrence per area (square kilometers) hot spot analysis better delineates the region of uniform values that were mentioned in section 4.2.7. Though local maxima were identified in the previous section, the analysis provides a 99% confidence level for most of the region that it covers. This may likely be due to the homogenizing effects of the hot spot analysis. As evident in the figure, there is a large transition region that wraps from the south, along the western edge, and along the northern edge of the hot spot region.

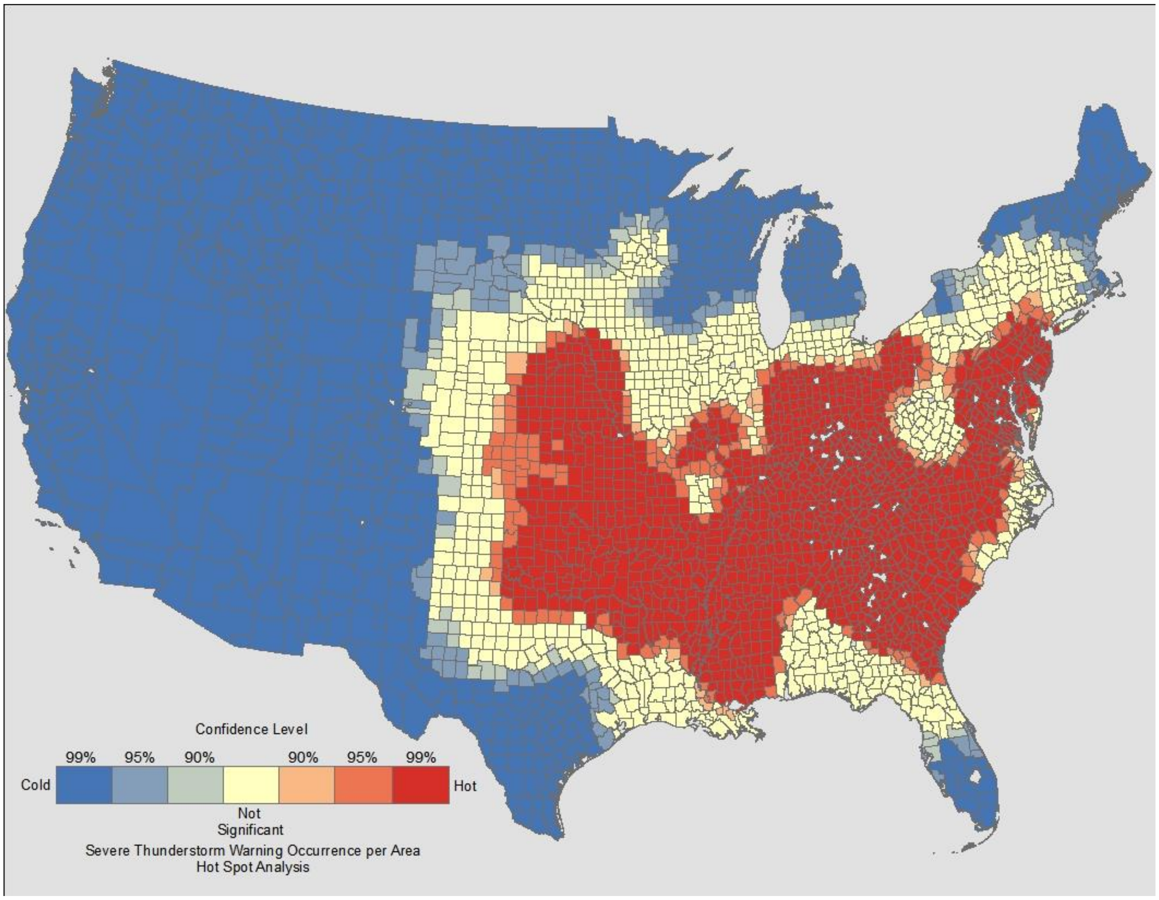


Figure 4.3.7: Map of the contiguous United States counties showing hot spot analysis findings for Severe Thunderstorm warning occurrence per area (square kilometers) for the period 1986 to 2017. Scale shows confidence levels for high valued areas in a red shading and low valued areas in a blue shading. Statistically non-significant counties are shown in yellow.

Severe Thunderstorm Warning Occurrence per Population Density. As seen in Figure 4.3.8, the pattern of hot spots associated with severe thunderstorm warning occurrence per population density (people/km^2) shows a region extending along the leeward side of the Rocky Mountain range into the Midwest from the southern international border to the northern international border, with a smaller hot spot region covering the southern tip of Texas. Though there is not a 99% confidence level, the hot spot analysis did identify a hot spot region in Nevada. There is a cold spot region that covers portions of the Midwest, the South, the Mid-Atlantic, and the Northeast. In this analysis, nearly all counties identified in a cold spot region were at or below the 95% confidence level, with the exception of a small county in Virginia.

The severe thunderstorm warning occurrence per population density hot spot analysis compliments the findings from section 4.2.8, where the maxima region discussed earlier are contained within the 99% confidence level hot spot region. As evident in the figure, the maxima in southern Texas were identified as a separate hot spot region. In this analysis, there is no significant transition area between hot spot region and cold spot regions.

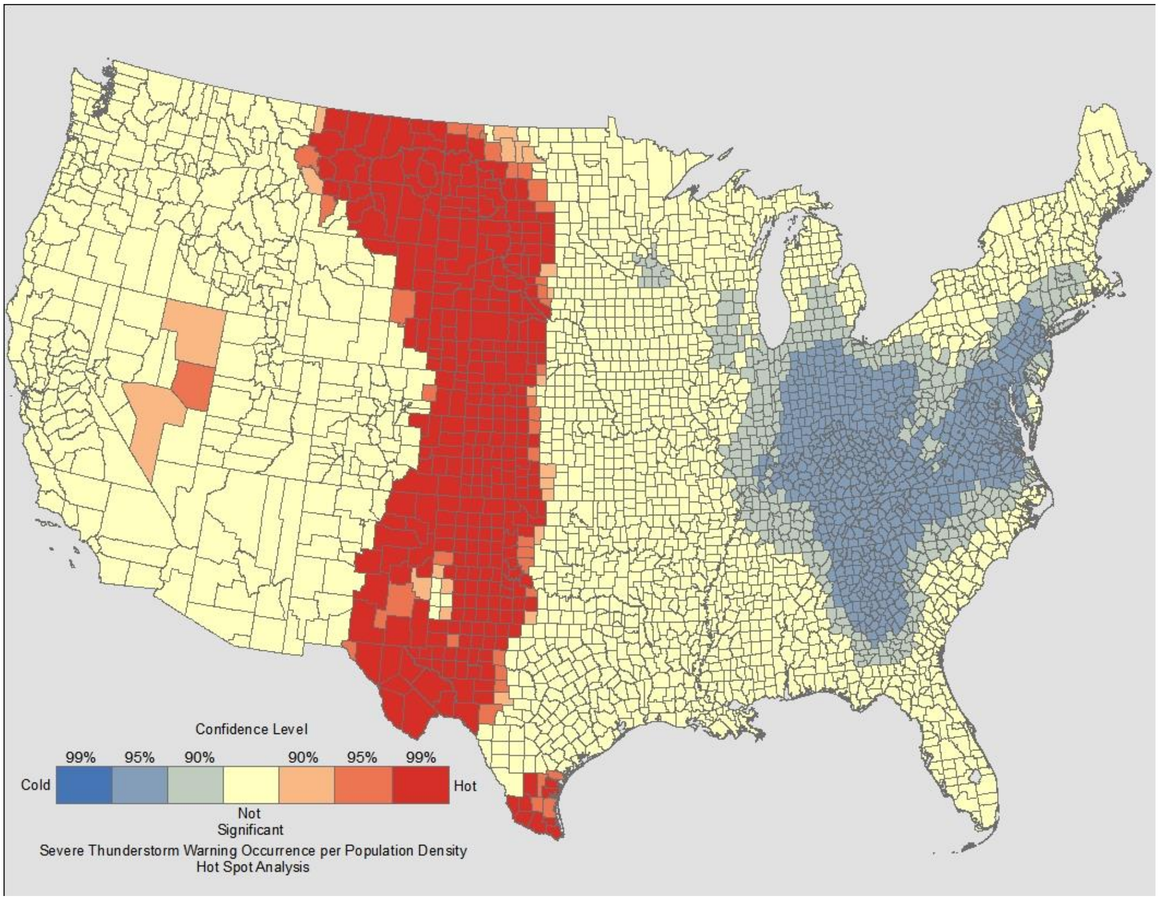


Figure 4.3.8: Map of the contiguous United States counties showing hot spot analysis findings for Severe Thunderstorm warning occurrence per population density (people/km^2) for the period 1986 to 2017. Scale shows confidence levels for high valued areas in a red shading and low valued areas in a blue shading. Statistically non-significant counties are shown in yellow.

Tornado Warning Occurrence. The pattern of hot spots associated with tornado warning occurrence shows a large region that covers portions of the Midwest, the South, and an extension into central Texas, with another hotspot region that covers most of the Florida peninsula (Fig. 4.3.9). Though the confidence level is below 99%, there is a notable hotspot region covering a small area of coastal North Carolina. Notable cold spot regions cover most of the western states with another region that extends from Georgia, through the Mid-Atlantic and covering the entire Northeast.

The tornado warning occurrence hot spot analysis compliments the findings from section 4.2.9 for the most part, where most maxima and local maxima discussed earlier are contained within their respective 99% confidence level hot spot. The exceptions to this would be local maxima in Arizona, western Texas, and Iowa. As evident in the figure, the hot spot analysis identified a hot spot region in central Texas, but did not include the western Texas maxima. The hot spot analysis identifies areas of transition between hot spot and cold spot regions. One such transition is located mostly in Colorado, where 99% confidence level cold spot counties and hot spot counties are adjacent to each other. Another area of transition is in the South, where the transition area follows the border between Georgia and Alabama.

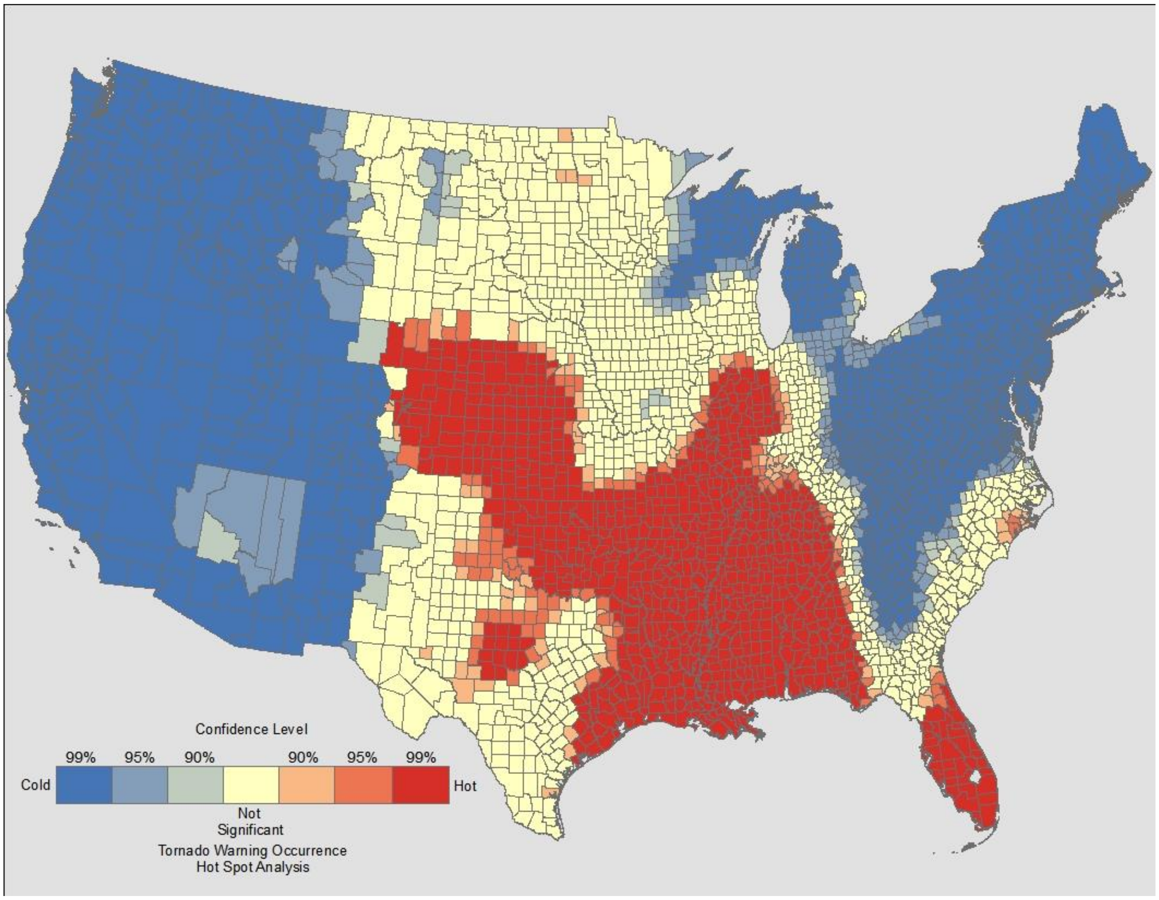


Figure 4.3.9: Map of the contiguous United States counties showing hot spot analysis findings for Tornado warning occurrence for the period 1986 to 2017. Scale shows confidence levels for high valued areas in a red shading and low valued areas in a blue shading. Statistically non-significant counties are shown in yellow.

Tornado Warning Occurrence per Capita. As seen in Figure 4.3.10, the pattern of hot spots associated with tornado warning occurrence per 1000 people shows a large hot spot region along the leeward side of the Rocky Mountains from the southern international border to the northern border. There are also other, much smaller hot spot regions that cover the southern tip of Texas and another area over western Mississippi. A notable cold spot region covers the Mid-Atlantic and Northeastern states.

The tornado warning occurrence per capita hot spot analysis does well in identifying the areas with maxima and local maxima discussed in section 4.2.10, where these regions are covered with a 99% confidence level hot spot. Though there is a high confidence cold spot region that covers the mountainous Appalachian region, there is only a slight signal in the Rocky Mountain even with the large hot spot region to its east. In this analysis, there were no notable transition areas between hot spot regions and cold spot regions.

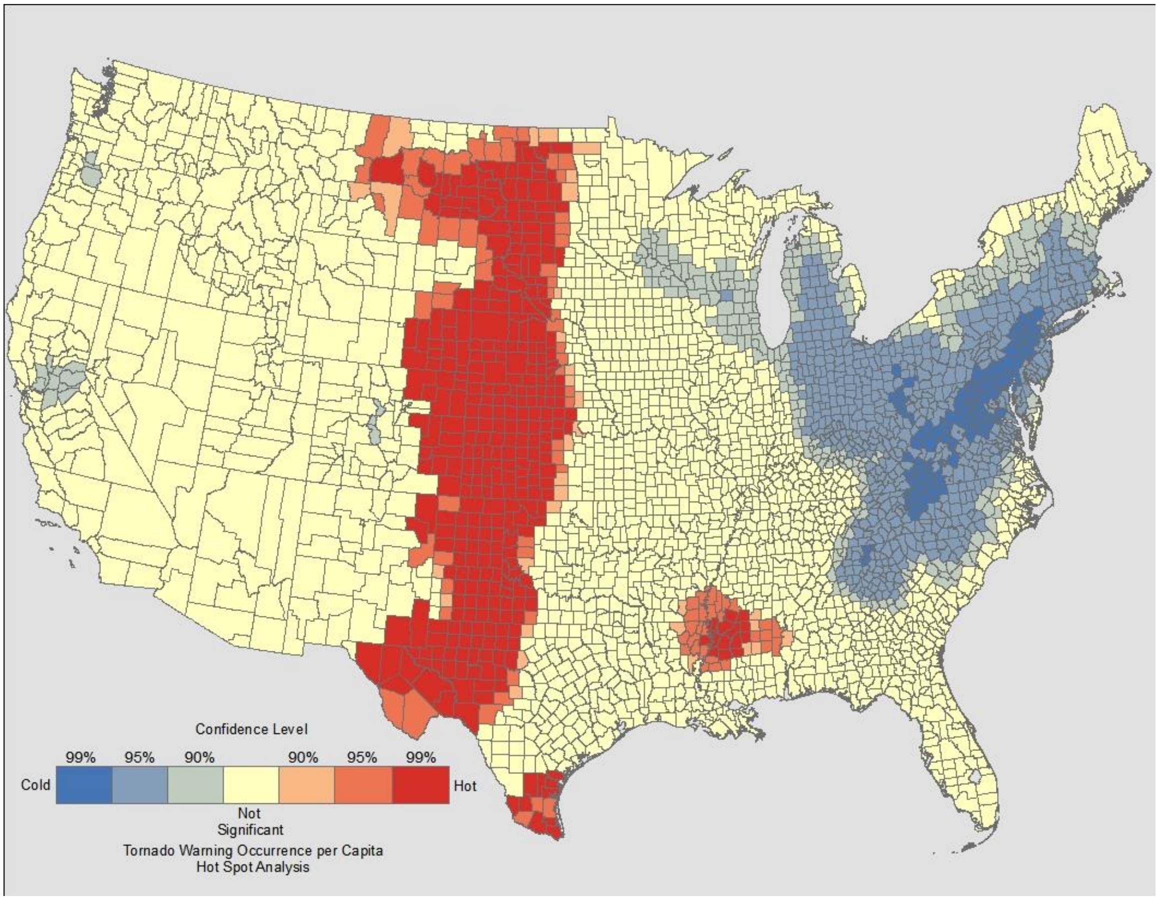


Figure 4.3.10: Map of the contiguous United States counties showing hot spot analysis findings for Tornado warning occurrence per capita for the period 1986 to 2017. Scale shows confidence levels for high valued areas in a red shading and low valued areas in a blue shading. Statistically non-significant counties are shown in yellow.

Tornado Warning Occurrence per Area. In initial runs of the hot spot analysis for tornado warning occurrence per area (square kilometers), the statistical model was heavily influence by the smallest counties (e.g., Virginia) and the output would only highlight these counties. In order to have a better model run, these counties were omitted, and the output from this run is used as Figure 4.3.11.

The hot spot pattern associated with tornado warning occurrence per area (square kilometers) shows a large region that covers portions of the South and the Midwest (Fig. 4.3.11). Smaller hot spot regions cover portions of northeastern Colorado, and area covering eastern Nebraska and central Kansas, and an area that covers coastal North Carolina and Virginia. Notable cold spot regions cover a large area in the western United States, an area that covers the Great Lake states, as well as an area that covers most of the Northeast.

The tornado warning occurrence per area (square kilometers) hot spot analysis compliments the findings from section 4.2.11, where regions of maxima identified are covered by a 99% confidence level hot spot. Though not identified as local maxima in section 4.2.11, the hot spot analysis did identify a 99% confidence level hot spot region covering eastern Nebraska, as well as a portion of coastal Virginia. The hot spot analysis did identify several transition areas between hot spot and cold spot regions. One such region exists between the large hot spot region in the Midwest and the cold spot region in the Northeast. In this same area, there is transition area between the Northeast cold spot and the coastal Mid-Atlantic hot spot. Though much smaller, there is a transition area in southern Texas as well as in Colorado.

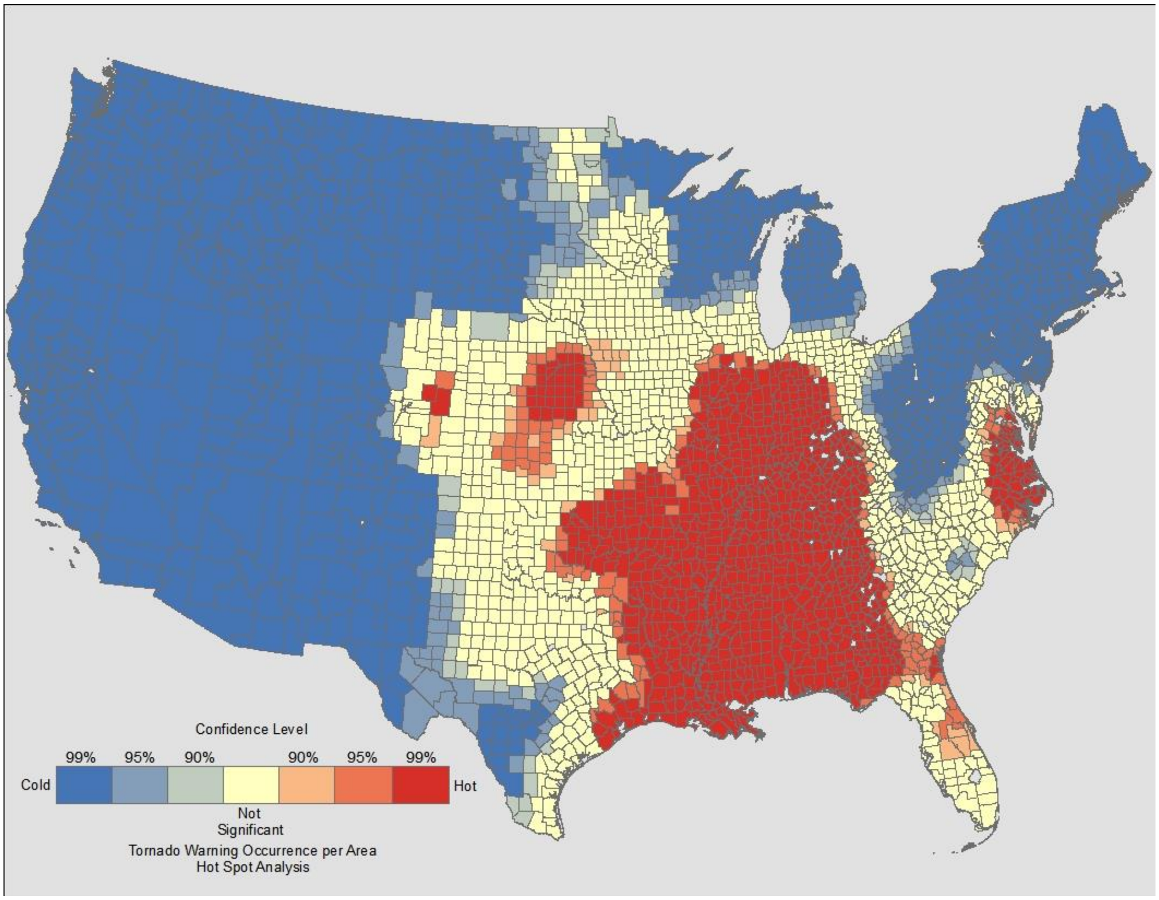


Figure 4.3.11: Map of the contiguous United States counties showing hot spot analysis findings for Tornado warning occurrence per area (square kilometers) for the period 1986 to 2017. Scale shows confidence levels for high valued areas in a red shading and low valued areas in a blue shading. Statistically non-significant counties are shown in yellow.

Tornado Warning Occurrence per Population Density. As seen in Figure 4.3.12, the pattern of hot spots associated with tornado warning occurrence per population density (people/km^2) shows a large hot spot region along the leeward side of the Rocky Mountain range from the southern international border to the northern border with a smaller hot spot region that covers the southern tip of Texas. A notable cold spot region covers portions of the South, the Midwest, the Mid-Atlantic, and the Northeastern United States. In this analysis, there was no county identified with a 99% confidence level cold spot.

The tornado warning occurrence per population density (people/km^2) hot spot analysis mostly agrees with the findings from section 4.2.12, where the maxima and local maxima identified along the leeward side of the Rocky Mountain range are covered by a 99% confidence level hot spot. However, local maxima identified outside of the hot spot regions (e.g., western Mississippi) were not identified in the analysis. As evident in the figure, the hot spot analysis did not show any transition areas between hot spot and cold spot regions.

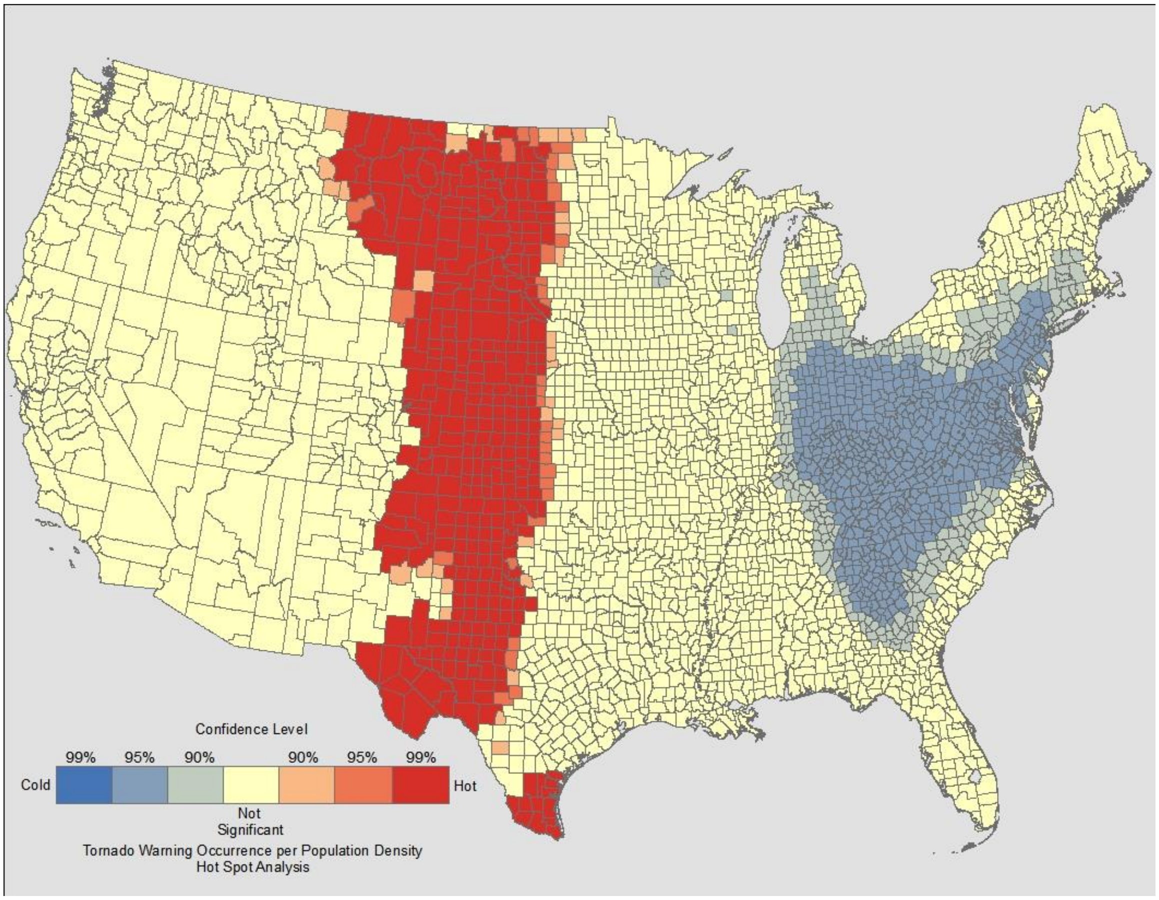


Figure 4.3.12: Map of the contiguous United States counties showing hot spot analysis findings for Tornado warning occurrence per population density (people/km^2) for the period 1986 to 2017. Scale shows confidence levels for high valued areas in a red shading and low valued areas in a blue shading. Statistically non-significant counties are shown in yellow.

Aggregated (flash flood, tornado and severe thunderstorm) Warning Occurrence. As seen in Figure 4.3.13, the pattern of hot spots associated with the aggregated (flash flood, tornado and severe thunderstorm) warning occurrence shows the largest region extending from the leeward side of the Rocky Mountain range, across the Midwest, and in the South. Other hot spot regions cover an area over most of Arizona and another small region across the state of South Carolina. Notable cold spot regions cover a large portion of the western United States, an area that covers a majority of Georgia, an area that covers a large portion of the Great Lake states, and an area that extends from West Virginia to coastal Virginia.

The total warning occurrence hot spot analysis agrees with the findings from section 4.2.13, where a majority of the maxima discussed earlier are contained within a 99% confidence level hot spot. However, as evident in the figure, local maxima in Maryland, Pennsylvania, and Florida were either not strongly identified or not identified at all by the analysis. The hot spot analysis does identify transition areas between hot spot and cold spot regions. One such region extends between the central areas of New Mexico, Colorado, and Wyoming where the hot spot region and cold spot region are adjacent to each other in Colorado. Another transition area is identified in Arizona, where the western cold spot region wraps around the Arizona hot spot. Lastly, there is a transition area along the border of Alabama and Georgia as well as between the border of South Carolina and Georgia.

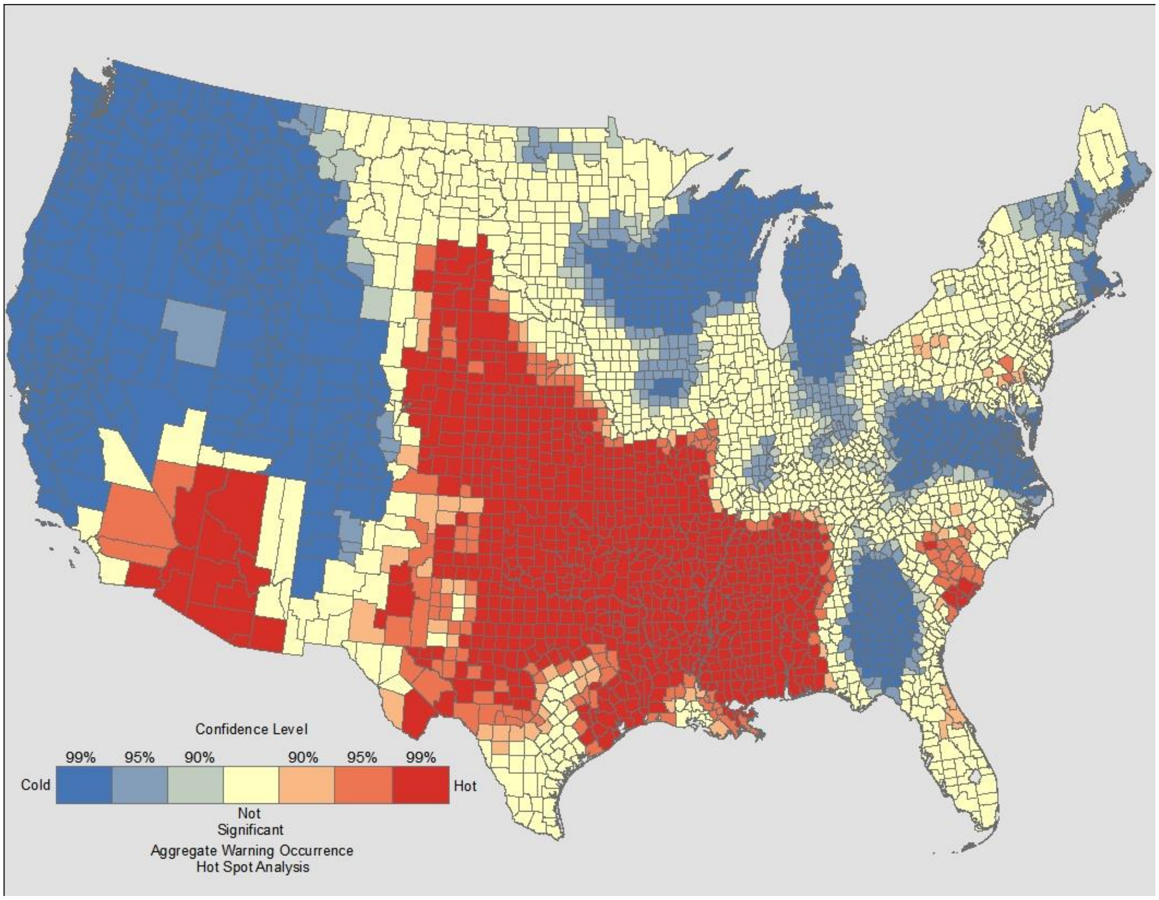


Figure 4.3.13: Map of the contiguous United States counties showing hot spot analysis findings for Aggregated (flash flood, tornado and severe thunderstorm) warning occurrence for the period 1986 to 2017. Scale shows confidence levels for high valued areas in a red shading and low valued areas in a blue shading. Statistically non-significant counties are shown in yellow.

Aggregated (flash flood, tornado and severe thunderstorm) Warning Occurrence per Capita. The hot spot pattern associated with aggregated (flash flood, tornado and severe thunderstorm) warning occurrence per 1000 people shows a large region that covers counties on the leeward side of the Rocky Mountain range from the southern international border to the northern border (Fig. 4.3.14). There is also a smaller hot spot region that covers the southern tip of Texas. Notable cold spot regions cover an area extending from northern Georgia, through the Mid-Atlantic to the coastal Northeast and another region covering portions of Wisconsin, Indiana, and Ohio.

The aggregated (flash flood, tornado and severe thunderstorm) warning occurrence per capita hot spot analysis agrees with the findings from section 4.2.14, where the maxima and local maxima identified are contained within a 99% confidence level hot spot. However, the notable local maxima identified in western Mississippi was not identified at any hot spot confidence level. As evident in the figure, there are no significant transition areas between hot spot regions and cold spot regions.

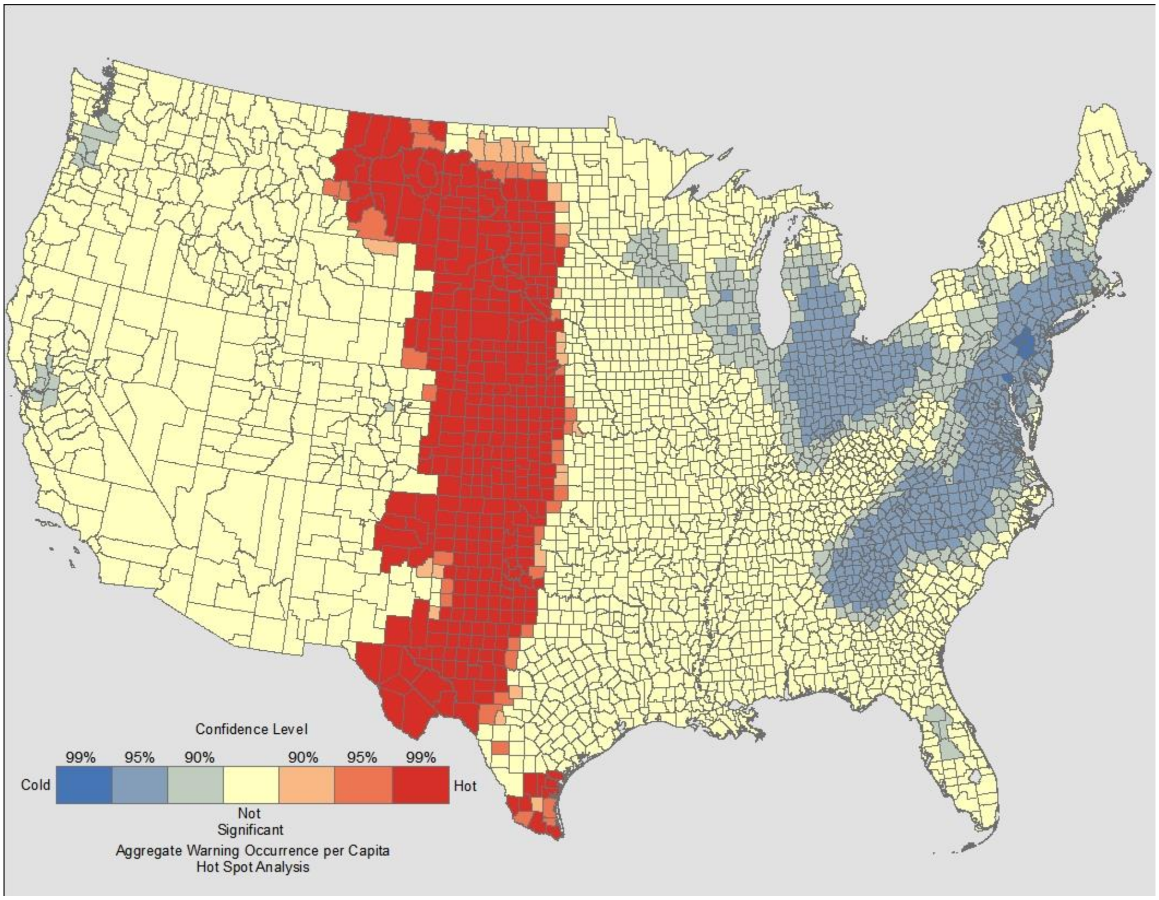


Figure 4.3.14: Map of the contiguous United States counties showing hot spot analysis findings for Aggregated (flash flood, tornado and severe thunderstorm) warning occurrence per capita for the period 1986 to 2017. Scale shows confidence levels for high valued areas in a red shading and low valued areas in a blue shading. Statistically non-significant counties are shown in yellow.

Aggregated (flash flood, tornado and severe thunderstorm) Warning Occurrence per Area. In initial runs of the hot spot analysis for aggregated warning occurrence per area (square kilometers), the statistical model was heavily influenced by the smallest counties (e.g., Virginia) and the output would only highlight these counties. In order to have a better model run, these counties were omitted, and the output from this run is used as Figure 4.3.15.

As seen in Figure 4.3.15, the pattern of hot spots associated with aggregated (flash flood, tornado and severe thunderstorm) warning occurrence per area (square kilometers) shows a similar pattern to the severe thunderstorm warning occurrence per area (square kilometers), where Midwestern, Southern, and Mid-Atlantic states are contained within the hot spot region. Notable cold spot regions cover areas in the Northeast, southern Florida, and the largest region covering the western United States into portions of the northern most Midwestern states.

The total warning occurrence per area (Square kilometers) hot spot analysis compliments the findings from section 4.2.15, where many of the local maxima identified are contained within a 99% confidence level hot spot. However, other local maxima identified (e.g., Minnesota) were not identified at any hot spot confidence level, with some being contained within a cold spot region. The hot spot analysis did identify two areas of transition between hot spot and cold spot regions. The first transition area occurs between the large cold spot region covering the western United States and the hot spot region covering the Midwest, where the area follows the leeward side of the Rocky Mountain range and extends east across Nebraska, Iowa, Wisconsin, and Michigan. The other transition area occurs between the cold spot region in the extreme northeastern states and the hot spot region in the lower northeastern states.

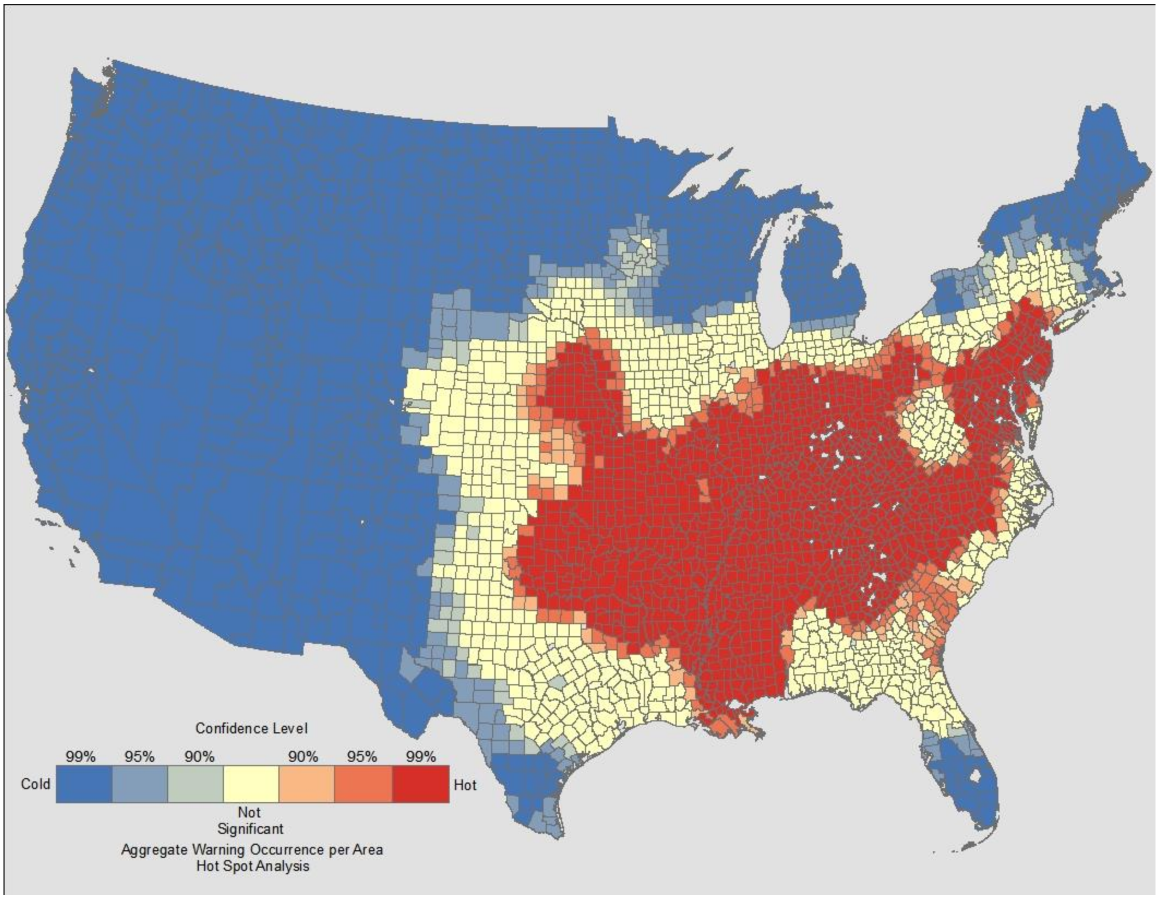


Figure 4.3.15: Map of the contiguous United States counties showing hot spot analysis findings for aggregated (flash flood, tornado and severe thunderstorm) warning occurrence per area (square kilometers) for the period 1986 to 2017. Scale shows confidence levels for high valued areas in a red shading and low valued areas in a blue shading. Statistically non-significant counties are shown in yellow.

Aggregated (flash flood, tornado and severe thunderstorm) Warning Occurrence per Population Density. The pattern of hot spot associated with aggregated (flash flood, tornado and severe thunderstorm) warning occurrence per population density (people/km^2) shows a large region that follows the leeward side of the Rocky Mountain range from the southern international border to the northern border (Fig. 4.3.16). Other hot spot regions cover an area of the southern tip of Texas, and another sparse region covering portions of Nevada, Utah, and Arizona. A notable cold spot region covers portions of the South, the Mid-Atlantic, and the coastal Northeast.

The aggregated (flash flood, tornado and severe thunderstorm) warning occurrence per population density (people/km^2) hot spot analysis agrees with the findings from section 4.2.16, where the maxima and local maxima discussed are contained under a hot spot region. However, several counties were identified as hot spot regions during the analysis, though those counties have significantly lower values than adjacent counties (e.g., south eastern Utah). As evident in the figure no significant transition area between hot spot and cold spot regions was identified.

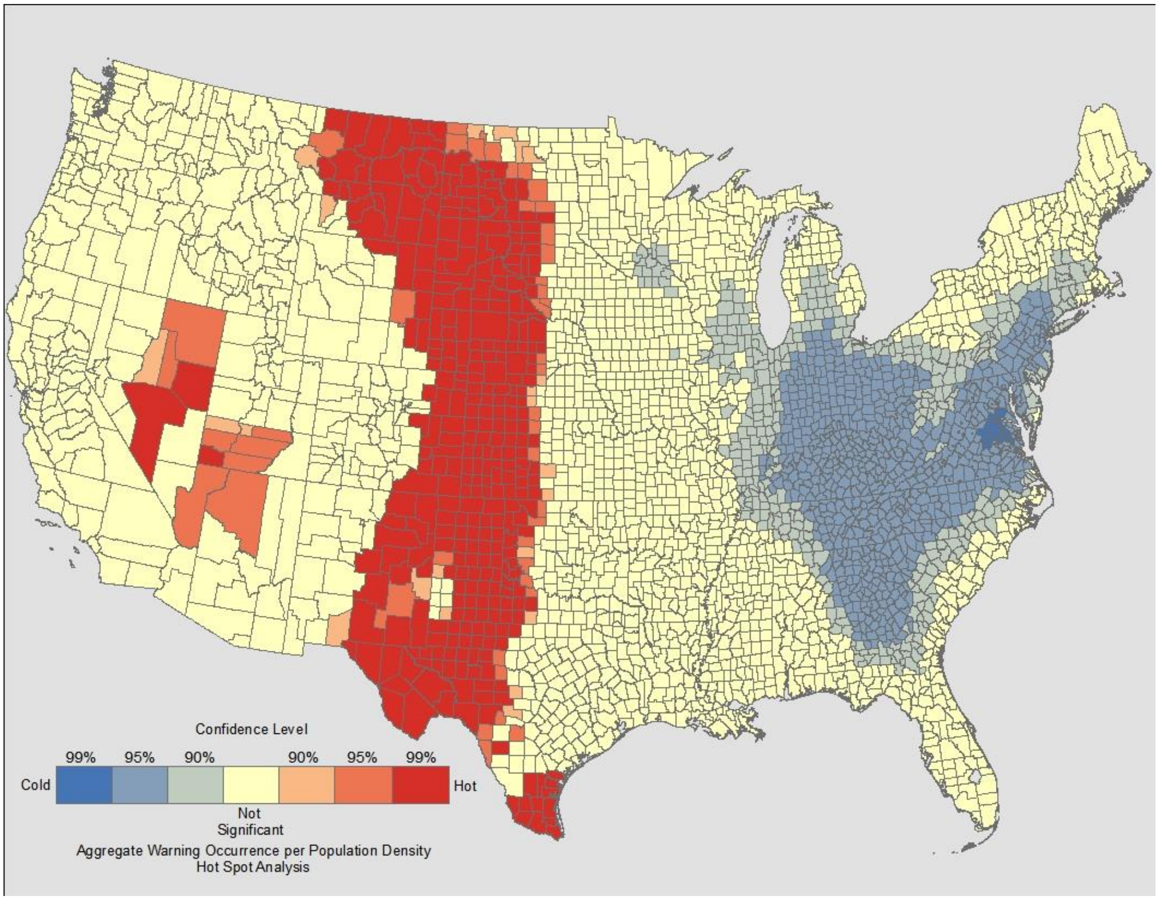


Figure 4.3.16: Map of the contiguous United States counties showing hot spot analysis findings for aggregated (flash flood, tornado and severe thunderstorm) warning occurrence per population density (people/km^2) for the period 1986 to 2017. Scale shows confidence levels for high valued areas in a red shading and low valued areas in a blue shading. Statistically non-significant counties are shown in yellow.

Results and Discussion of Outlier Analysis

Outlier analysis results are found using the Cluster and Outlier Analysis (Anselin 1995 Local Moran's I) function in ArcGIS, which is based on the equations discussed in section 3.7. The outlier portion of the analysis highlights whether a county is a high value or low value outlier in relation to geographically neighboring counties. The GIS products will display the outlier results of the raw counts, population adjusted, area (square kilometers) adjusted, and population density (people/km^2) adjusted of the four warning categories (flash flood, severe thunderstorm, tornado, and aggregate). From the function output, the outlier results then overlay the results from the corresponding hot spot analysis. Important and pertinent details of this is identified and discussed below and in the Appendix.

Flash Flood Warning Occurrence. The cluster and outlier analysis performed on the flash flood warning occurrence found 100 counties to be outliers, where 38 counties were identified as high value outliers and 62 counties as low value outliers. As seen in Figure 4.4.1, the outliers were mapped against the cold and hot spots identified in section 4.3.1. The figure identifies several high value outliers interacting with cold spots in Iowa, South Dakota, Colorado, Georgia, and South Carolina. Several low value outliers interacting with hot spots are identified in Utah, Arizona, Texas, Oklahoma, Kansas, Missouri, Louisiana, and Mississippi. As evident in the figure, there are several small clusters of outlier groups, with low value outlier clusters in Texas and New York, as well as high value clusters in Illinois, North Carolina, and Colorado.

A majority of outliers identified are located either in non-significant regions or on the peripheries of the hot spot or cold spot regions, which are expected as these are boundaries between a higher valued area and a lower valued area. There are significant low value outliers contained within a hot spot region in Texas, Louisiana, and Missouri. Significant high value outliers contained fully within a cold spot are found in Georgia, Iowa, and South Dakota. These instances show variability exists between counties in these hot and cold spot regions. The variability itself may be explained by several factors, such as population sizes, county area, or other external factors affecting the warnings themselves that are not covered in the scope of this thesis. Further, the flash flood warning occurrence cluster and outlier analysis is used to identify local maxima. The analysis did not identify local maxima discussed in section 4.2.1. High value outliers did, however, identify local maxima regions in Colorado, Illinois, and in the Carolinas.

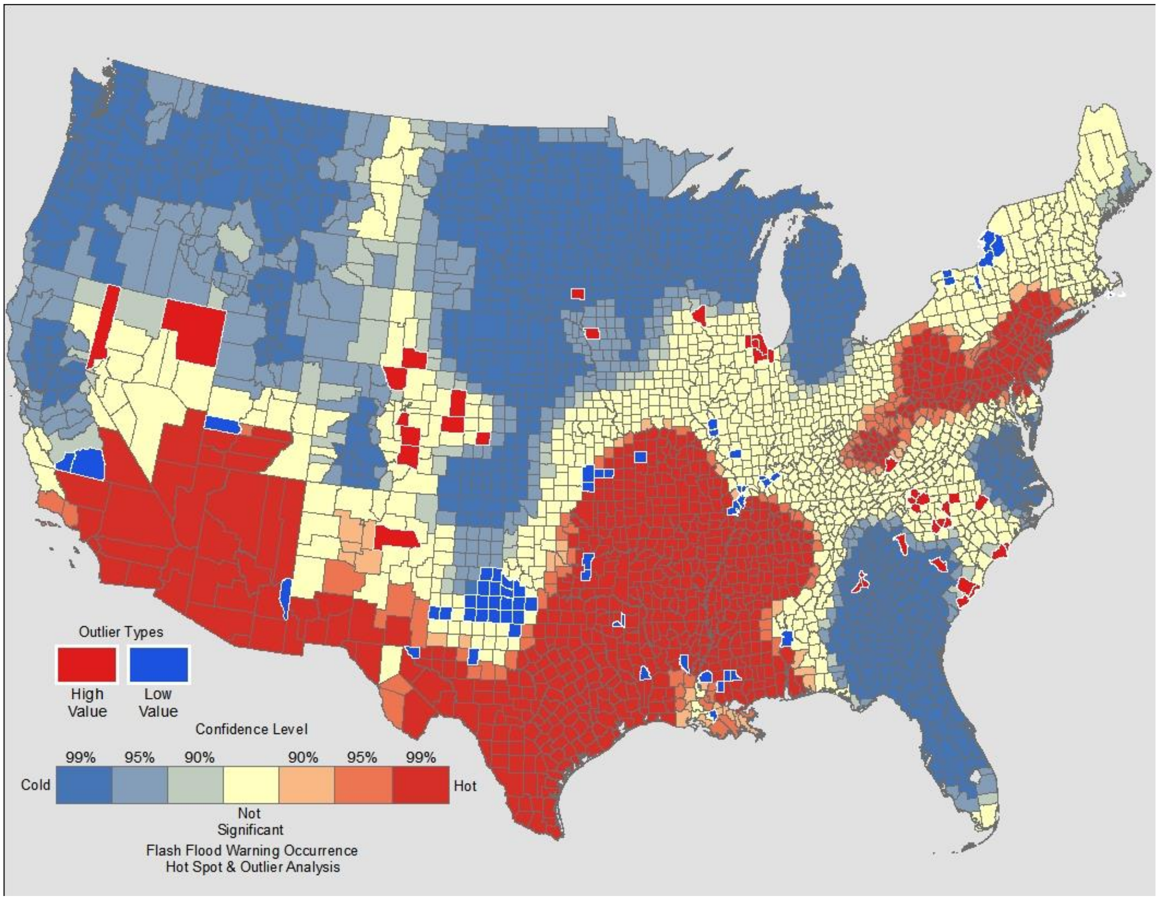


Figure 4.4.1: Map of the contiguous United States counties showing high value and low value outliers in relation to findings from the flash flood warning occurrence hot spot analysis for the period 1986 to 2017. The high value outliers are denoted by a brighter red shading with a white border, and the low value outliers are denoted by a brighter blue shading with a white border. Refer to figure 4.3.1 for explanation of hot spot analysis symbology.

Severe Thunderstorm Warning Occurrence. The cluster an outlier analysis performed on the severe thunderstorm warning occurrence found 786 counties to be outliers, where 124 of the counties are high value outliers and the other 662 are low value outliers. As seen in figure 4.4.2, the outliers were mapped against the cold and hot spots that were identified in section 4.3.5. The figure identifies several high value outliers interacting with cold spots in the desert Southwest, Montana, the Virginias, Maryland, Massachusetts, and Maine. Low value outlies interacting with hot spot regions are identified in New Mexico, Arizona, Colorado, Wyoming, Texas, Kansas, Nebraska, Louisiana, Mississippi, Alabama, and Tennessee. As evident in the figure, a majority of low value outliers consist of clusters found along the Rocky Mountain range, southern Texas, Georgia, and two separate clusters in the northern areas of the Midwest. Several regions of high value outlier clusters are also identified in the desert Southwest, the Mid-Atlantic states, and in the Northeast states. The clustering of outliers in the Northeast do show that a higher valued region may exist, however they may also be influenced by the lower valued regions identified to the south and west.

As evident in figure 4.4.2, the cluster and outlier analysis identified many outlier counties actually within corresponding hot/cold spot regions from section 4.3.5 as well as outliers on the periphery of the hot/cold spot regions. High value outliers not in the previous areas were identified within cold spots in Nevada, Utah, and West Virginia. In contrast, many low value outliers were identified to be contained within hot spot regions in Colorado, Texas, Kansas, Arkansas, and Mississippi. The low value outliers do show some variability in warning occurrence across the largest hot spot. As these outliers are not contained within the clusters described earlier, they may be the result of factors relating to population sizes, or other influences that would affect warning occurrences. The cluster and outlier analysis did identify previously discussed maxima from section 4.2.5, more specifically the maxima in Arizona, North Carolina, Montana, Virginia, and Pennsylvania. Maxima not discussed previously were also identified by the cluster and outlier analysis in the New York, Maine, and Massachusetts.

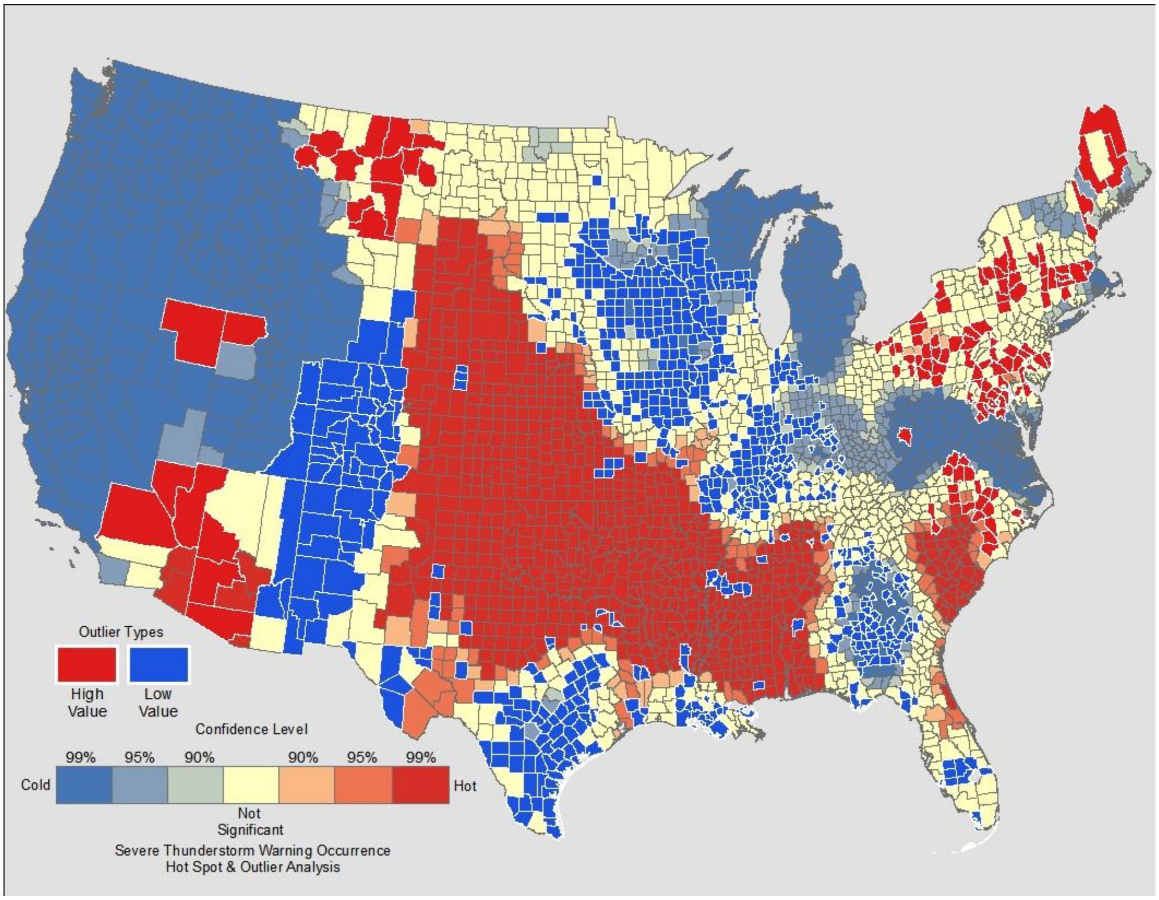


Figure 4.4.2: Map of the contiguous United States counties showing high value and low value outliers in relation to findings from the severe thunderstorm warning occurrence hot spot analysis for the period 1986 to 2017. The high value outliers are denoted by a brighter red shading with a white border, and the low value outliers are denoted by a brighter blue shading with a white border. Refer to figure 4.3.5 for explanation of hot spot analysis symbology.

Tornado Warning Occurrence. The cluster and outlier analysis performed on the tornado warning occurrence found 530 counties to be outliers, where 33 counties were identified as high value outliers and 497 counties were identified as low value outliers. As seen in figure 4.4.3, the outliers were mapped against the findings from the hot spot analysis in section 4.3.9. The figure identifies areas in Arizona, the Great Lakes region, and the Mid-Atlantic region where high value outliers are interacting with cold spots. Cold value outliers interact with hot spot regions in Colorado, Kansas, Nebraska, Texas, Louisiana, Arkansas, Missouri, Tennessee, Kentucky, Illinois, Indiana, Georgia, and Florida. As evident in the figure, there are several clusters of both high and low value outliers. There are high value outlier clusters in North Carolina and another cluster in Maryland and Virginia, while clustering of low value outliers is found in Georgia, North Carolina, Tennessee, Iowa, Missouri, Kansas Texas, New Mexico, and Colorado.

As evident in the figure, a majority of outliers identified are located outside of the opposing hot and cold spots. There are significant low value outliers contained within the hot spots in Florida, Texas, Louisiana, Arkansas, Missouri, and Nebraska. Significant high value outliers contained within a cold spot are identified in Arizona, Wisconsin, Ohio, Virginia, Maryland, and Pennsylvania. Identification of the high and low value outliers in the respective hot and cold spot regions demonstrate variability of tornado warning occurrence. The variability of these outliers may be explained by population centers, county area, or other external factors (e.g., topographical features, proximity to radar) that are not examined in this research. Further, the tornado warning occurrence cluster and outlier analysis did identify the local maxima in northern Arizona. High value outliers did identify other local maxima not identified in previous sections in North Carolina, Virginia, Maryland, and Pennsylvania.

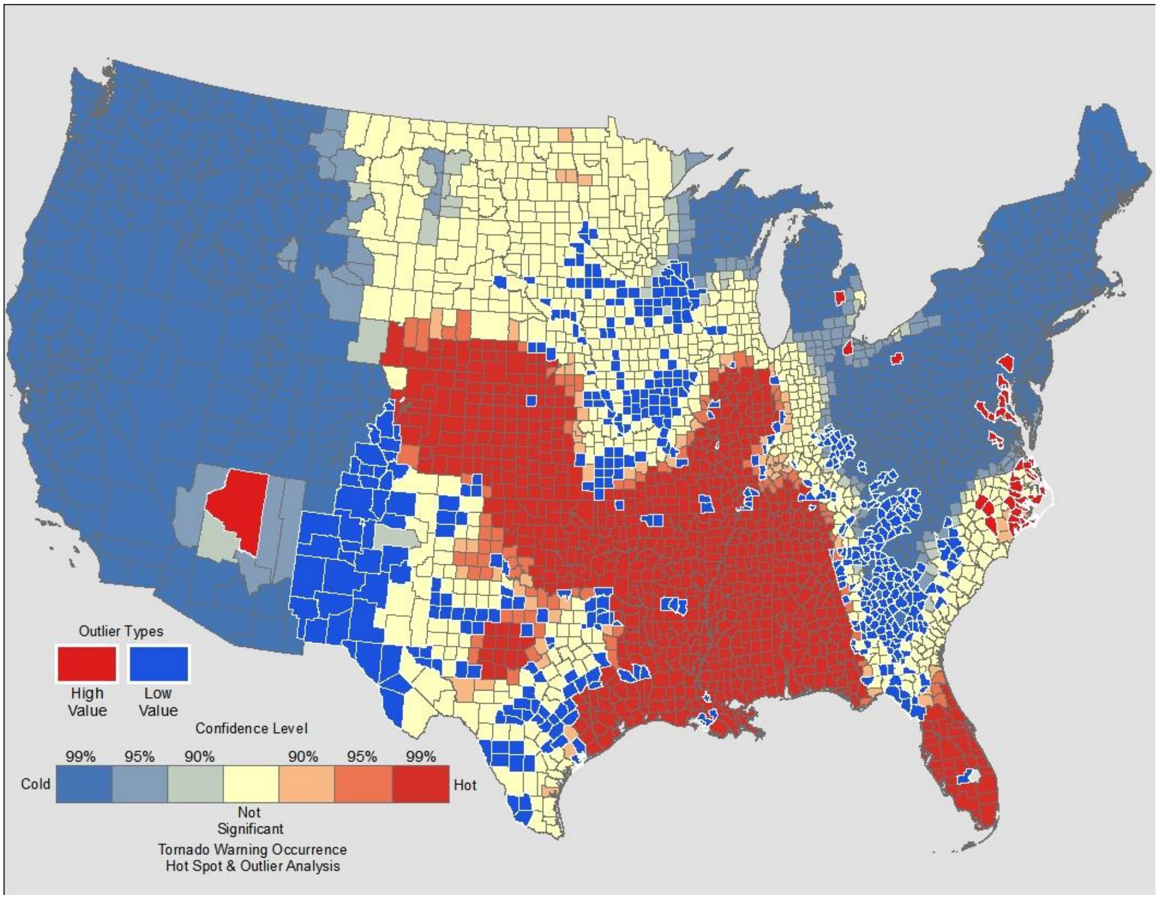


Figure 4.4.3: Map of the contiguous United States counties showing high value and low value outliers in relation to findings from the tornado warning occurrence hot spot analysis for the period 1986 to 2017. The high value outliers are denoted by a brighter red shading with a white border, and the low value outliers are denoted by a brighter blue shading with a white border. Refer to figure 4.3.9 for explanation of hot spot analysis symbology.

Aggregated (flash flood, severe thunderstorm and tornado) Warning Occurrence. The cluster and outlier analysis performed on the aggregated (flash flood, severe thunderstorm and tornado) warning occurrence found 722 counties to be outliers, where 120 counties were identified as high value outliers and 602 counties were identified as low value outliers. As seen in figure 4.4.13, the outliers were mapped against the cold and hot spots identified in section 4.3.13. The figure shows that many of the low value outliers not only occur over cold spot regions (e.g., Georgia, western Colorado), but also interact with the hot spot regions. In the Southwest, high value outliers are observed over a hot spot region, however most high value outliers occur away from other hot spot regions (e.g., Mid-Atlantic and Northeast) and only several are interacting with a cold spot region (e.g., Montana, Virginia, Maryland). As evident in the figure, several clusters are identifiable between the low and high value outliers. There are three large low value outlier clusters located in New Mexico and Colorado, another in upper Midwest, and a cluster covering Georgia, while smaller clusters occur in Texas, Florida, and Illinois. Though not as large, there are three cluster groups of high value outliers located in the Southwest, Montana, and in Mid-Atlantic and Northeast states.

As mentioned above, many outliers fall within matching hot/cold spot regions or occur on the peripheries of these regions. There are a few significant high value outliers contained within a cold spot region in Nevada, Virginia, and Maine. Significant low value outliers occurring within hot spots are located in Texas, Kansas, Colorado, Nebraska, and Mississippi. Contrasting outliers for the hot and cold spots show some variability may exist within those regions. The variability in these regions may be explained by county population sizes, or that the variability could be due to other external factors that affect warning occurrence. Further, the total warning occurrence cluster and outlier analysis did identify the maxima in the Southwest, Minnesota, North Carolina, Pennsylvania, Maryland, and Virginia. Other local maxima identified in this analysis are located in eastern Montana, Wyoming, Ohio, and New York.

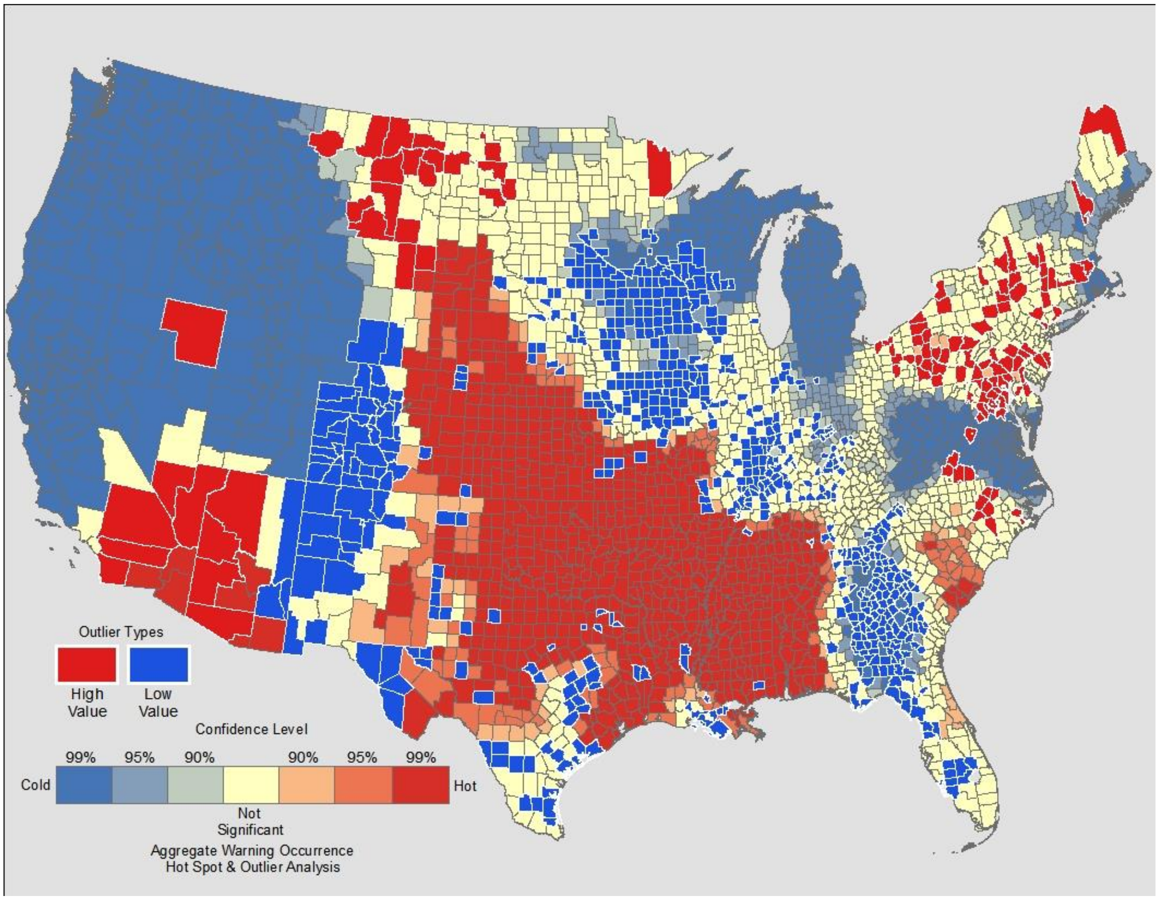


Figure 4.4.4: Map of the contiguous United States counties showing high value and low value outliers in relation to findings from the aggregated (flash flood, severe thunderstorm and tornado) warning occurrence hot spot analysis for the period 1986 to 2017. The high value outliers are denoted by a brighter red shading with a white border, and the low value outliers are denoted by a brighter blue shading with a white border. Refer to figure 4.3.13 for explanation of hot spot analysis symbology.

Adjusted Warning Categories. The outlier analysis results for the per county population, per county area, and per population density of the flash food, severe thunderstorm, tornado, and aggregate warnings can be found in the appendix section under **A.1** through **A.12**. The results from the majority of the outlier analysis under the adjusted values exhibited similar patterns as well as similar concerns to low value outlier locations.

When examining the severe thunderstorm, tornado, and aggregated warnings adjusted for county population, the low value outliers were found to be mostly located on either side of the hot spot region that extends along the leeward side of the Rocky Mountain range in each warning type. Low value outliers are mostly expected on the boundary of a hot spot, as the boundaries would be considered transition zones from higher valued areas into relatively lower valued areas. However, several low value outliers for each warning type were located within the hot spot regions, showing that some variability exists amongst the high value areas. This variability may be explained by some of the low value outlier counties having much higher populations than their neighbors, considerably lower warning counts, or other external factors affecting the warnings themselves (e.g., proximity to radar). Though the flash flood warning category did not exhibit the same pattern for the population adjusted value, the same pattern of where low value outliers is located in relation to the hot spots is exhibited, as well as the same issues regarding the variability within the hot spots.

Adjusted for county area, the flash flood, severe thunderstorm, tornado, and aggregated warning categories exhibited the same general pattern, where the hot spot is centrally located within the southern and central regions of the United States and the low value outliers are mostly located on the periphery of the hot spots. Like the population adjusted warning categories, the low value outliers are expected to be in the periphery as this is a transition zone. However, each warning category exhibited low value outliers within the hot spot regions, showing some variability within. This variability may be the result of the low value outlier counties being larger in area (this is directly visible in the appendix figures), the warning frequency for each warning category being lower than their neighbors, or other external factors that are out of scope for this thesis.

Lastly, population density adjusted severe thunderstorm, tornado, and aggregated warning low value outliers follow the same pattern as the population adjusted results; low value outliers were observed along the periphery of the hot spot region that extends along the leeward side of the Rocky Mountain range. As with the other categories, variability is represented by the low value outliers that fall within the hot spot regions for each warning category. In this instance, the variability in regards to population density may be the result of the population sizes or area coverage in the low value outlier counties having significantly differing values to their neighbors, or that other external factors are present.

Summary

In order to address the question of where, and consequently who, experiences the highest occurrences of severe weather in the contiguous United States, this chapter has presented the results from three analyses (i.e. base, hot spot and outlier). The base analysis examined the raw counts of flash flood warnings, severe thunderstorm warnings, tornado warnings, and an aggregate of the three warnings as well as the warnings adjusted for county population, county area (square kilometers), and county population density (people/km^2). The hot spot analysis examined the geographical relationship of the warning counts and their adjusted values, detailing regions of hot (high) and cold (low) spots across the contiguous United States. The outlier analysis provided an overlay of the counties identified as high value and low value outliers for each adjusted and non-adjusted warning counts that was compared to the results from the hot spot analysis. Across all the analyses, the most important results in regards to flash flood warning values include:

(1) Flash flood warning occurrence maxima are identified across the Southwest as well as in Texas. These maxima regions are likely the result of an inherent susceptibility to flash flooding during their respective rainy seasons (Maddox et. al., 1980; Adams & Comrie, 1997; Saharia et. al., 2017),

(2) Along with the flash flood warning occurrence signal across the Southwest and Texas, a signal of higher flash flood warning occurrences is identified across parts of the Midwest, South, and the Northeast states. The cause of this higher occurrence may be attributed to local topographies and other physical geographies that support flash flood events (LaPenta et. al., 1994; Saharia et. al., 2017; Landel et. al., 1999, Smith & Smith, 2015),

(3) Southern and western Texas was identified as higher value flash flood warning per capita region, however there are several low value outlier counties within this region,

(4) When county warnings are computed as per area (square kilometers), there is a corridor of flash flood warning occurrences that extends across parts of the Midwest, the South, the Mid-Atlantic, and Northeastern states. This pattern may be attributed to these regions containing a majority of the smallest counties by area coupled with a

susceptibility to flash flooding in each region (LaPenta et. al., 1994; Saharia et. al., 2017; Landel et. al., 1999; Smith & Smith, 2015), and,

(5) Along with a high valued corridor of flash flood warnings per population density (people/km^2) extending from Nevada to Texas, a smaller region in eastern Montana was identified. This region was likely identified because of several counties in eastern Montana containing much lower population densities, and subsequently higher warnings per population density, than their neighbors.

In regards to severe thunderstorm warning values, the most important findings include the following:

(1) Maxima of severe thunderstorm warning occurrences are identified in Arizona, parts of the Midwest, the South, and the Mid to South Atlantic states. These maxima are likely the result of seasonal weather patterns that produce severe weather as well as the need to warn large population centers (Adams & Comrie, 1997; Brooks et. al., 2003; Rhea, 1964; Schaefer et. al., 2004; Kelly et. al., 1985),

(2) Significantly noticeable regions of lower severe thunderstorm warning occurrences were identified in Georgia and Virginia. These regions of minima may likely be due to infrequent severe weather patterns as well as other factors that are not discussed in this paper,

(3) The effect of the Rocky Mountain range (elevated topography) and lower populations on the leeward side of the mountain range is evident when examining severe thunderstorm warnings per capita values, as the main region of higher values extends from north to south along the leeward side of the mountain range,

(4) Severe thunderstorm warnings per area (square kilometers) exhibits a uniform pattern of higher values across portions of the Midwest, the South, the Mid and South Atlantic, and Northeast states. This pattern is likely attributed to these regions containing a majority of the smallest counties by area coupled with each region's susceptibility to severe weather patterns (Kelly et. al., 1985; Brooks et. al., 2003; Koch & Ray, 1997; Weisman, 1990), and,

(5) Severe thunderstorm warnings per population density (people/km^2) reflect the same pattern as identified by the severe thunderstorm per capita, where the higher valued region extends north to south across the leeward side of the Rocky Mountain range indicating the effects of the topography and lower populations.

Through the course of analysis, results in regards to tornado warning value includes:

(1) A large region of higher tornado warning occurrences is identified, covering the states of Colorado, Kansas, Oklahoma, Arkansas, Texas, Louisiana, Mississippi, Alabama, Tennessee, and Illinois, encompassing the areas commonly referred to as Tornado Alley and the Dixie Alley (Carbin et al. 2013; Coleman and Dixon 2014; Farney and Dixon 2015; Brady and Szoke, 1989),

(2) Across this region, the maxima were identified as being on the very western edge (the front range of the Rockies) as well as the southern edge (the Gulf states) corresponding to the primary regions of Tornado Alley and Dixie Alley,

(3) Topographical barriers (e.g., the Rocky Mountains) as well as geopolitical boundaries (e.g., Alabama and Georgia) could be identified through the base analyses,

likely owing to topographical barriers limiting storm development and other factors not discussed in the course of this thesis (i.e. difference in weather forecasting offices),

(4) The peninsula of Florida is identified as high tornado warning occurrence region. This likely due to the high potential for tornado formation during summer convection and tropical cyclones (Hagemeyer, 1997; Hagemeyer, 1998),

(5) Tornado warnings per capita values exhibit the same pattern as seen with severe thunderstorm warnings per capita, where a region of high values is identified along the leeward side of the Rocky Mountain range, indicating that population is not a major factor in tornado warnings,

(6) A small region of high tornado warnings per capita values is identified in west-central Mississippi, which is likely due to a combination of lower populations in these counties and higher occurrences of tornado warnings (Broyles and Crosbie, 2004; Coleman and Dixon, 2014),

(7) Regions of high tornado warnings per area (square kilometers) value were identified mainly across the South into northern Illinois and Indiana, with smaller pockets located across Colorado, Nebraska, North Carolina, and Virginia, likely because of these regions containing smaller counties than their neighbors coupled with a susceptibility to tornado formation (Broyles and Crosbie, 2004), and,

(8) The higher tornado warnings per population density (people/km^2) values cover the same region as found in the analyses of the tornado warnings per capita, where the region covered extends along the leeward side of the Rocky Mountains. This is likely due to the influence of the lower populated counties in this region coupled with the propensity of tornado formation.

The aggregation of flash flood, severe thunderstorm, and tornado warnings produced the following important results through the three analyses performed on the values:

(1) The maxima of the aggregated warning counts identify three regions of the United States, the desert Southwest, the Midwest, and the South, as experiencing higher warning occurrences, likely due to these regions susceptibility to severe weather formations (Adams & Comrie, 1997; Maddox et. al., 1980 Carbin et al. 2013; Coleman and Dixon 2014; Farney and Dixon 2015; Brady and Szoke, 1989; Broyles and Crosbie, 2004; Brooks et. al., 2003; Brooks et. al., 2003; Owen, 1966; Schaefer et. al., 2004; Kelly et. al., 1985; Doswell, 1980; Weisman, 1990, Maddox, 1983),

(2) The aggregate counts of the warnings highlight areas of topographic barriers (e.g., the Rocky Mountains) and geopolitical boundaries (e.g., Texas and New Mexico) with steep gradients between values,

(3) The aggregate warnings per capita values follow the same pattern identified in severe thunderstorm and tornado warnings adjusted per capita, where a region of high values is identified along the leeward side of the Rocky Mountain range,

(4) A uniform pattern of high aggregate warnings per area (square kilometer) values is identified across the Midwest, the South, the Mid-Atlantic, and the Northeast states, which is likely due to the influence of these regions containing much smaller counties than other regions (i.e. the western United States), and,

(5) Similar to aggregate warnings per capita values, the higher aggregate warnings per population density (people/km^2) values cover a region along the leeward side of the Rocky Mountains.

Across the warning categories and analyses, the following patterns and concerns are identified:

(1) The severe thunderstorm and tornado warning hot spot regions cover similar areas where they start at the leeward of the Rocky Mountains, and while heading east the northern border of this region moves further south until reaching Georgia, showing that the region of tornado warnings in the eastern United States does not vary much from that of severe thunderstorms,

(2) Across all warning values Georgia is consistently a lower valued region compared to surrounding states which are higher valued. This occurrence may possibly due to infrequent severe weather patterns or other factors not discussed in this paper,

(3) The Northeast states tend to have a higher quantity of high value outliers for severe thunderstorm and tornado warnings compared to other regions, likely due to this region being more densely populated coupled with the need to warn these populations,

(4) The only region consistently under a hot spot, and subsequently the most susceptible to, for the flash flood, severe thunderstorm, and tornado warning occurrences covers Tennessee, Arkansas, Mississippi, and Alabama,

(5) The large size of counties in the western half of the United States provide difficulty in comparing warning occurrences per area, and,

(6) The lower population densities and populations along the leeward side of the Rocky Mountains provide difficulty when making comparisons with the South when examining severe thunderstorm and tornado warnings.

These findings from the base, hot spot, and outlier analyses provide the foundation from which I can address whether the hypotheses to who receives the highest occurrences of severe weather in the contiguous United States can be accepted. In the next chapter, I summarize this thesis with specific regard to my hypothesis and present the overall significance and importance of this thesis.

CHAPTER 5

SUMMARY

Justification of Research

Severe weather is a common occurrence across many parts of the United States, so much so that certain regions in the South and the Midwest have become synonymous with the type of severe weather that occurs. But even though previous research has confirmed the severity and type of the severe weather in these regions, the question remains for where the highest occurrences of severe weather occur. In order to address this problem, I developed the following research questions:

(1) What is the spatial distribution of severe weather warnings for unadjusted and adjusted warning occurrences, and which regions contain maxima of these occurrences?

(2) Are there regions of high and low warning occurrences, and where are these regions located in the contiguous United States?

(3) In the established regions of high and low warning occurrences, do outliers exist and where are these outliers located?

For this research, I had initially formulated three hypotheses:

(1) Flash flood warnings will be mostly located in the Southwest and along major river areas, with maxima located mostly in the Southwest; I expect severe thunderstorm warnings to be located in the Southwest, the South, and the Midwest with maxima mostly located in the Midwest; I expect tornado warnings to mostly be located in the Midwest, and the South, with maxima to be located in both regions; and lastly, I expect that the aggregate of warnings will mostly be in the South and Midwest with maxima likely in the Midwest.

(2) High occurrences of flash flood warnings will occur in the Southwest and low occurrences across the northern states of the United States; I expect that high occurrences of severe thunderstorm warnings occur over the Midwest and the South with low occurrences mostly over mountainous regions (e.g. Rocky Mountains); I expect that high occurrences of tornado warnings occur over the Midwest and the South with low warning occurrences mostly over non-flat regions, such as the western half of the United States; I expect that high occurrences of aggregate warnings will occur over the South and the Midwest with the lowest occurrences over mountainous regions.

(3) I expect to find outliers (significant variations from the mean of the area), and for the outliers to be interspersed within regions of the high and low occurrences. I also expect outliers to be located where there are sharp gradients between high and low occurrence regions.

Having this knowledge of the most likely regions to experience severe weather can be beneficial by guiding decision making in several different sectors of the United States. For instance, emergency management personnel could find the information valuable in planning equipment and supply placement; transportation agencies may use the information to optimize transportation routes when reducing risks; and the general public can find the information useful when deciding to move to some place in the country.

The question of where and related inquiries can potentially be answered through the use of spatial analysis methods commonly found in Geographic Information Systems (GIS). Through the past few decades, GIS has been utilized to project and discover spatial relationships between many types of data, or more aptly show the where of the data (ESRI, https://www.esri.com/en-us/what-is-gis/overview). Having this quality and the ability to incorporate methods off spatial analysis statistics, makes GIS a great tool for discovering the location of severe weather occurrences. But, in order for GIS to be used responsibly, the type of data being analyzed first needs to be understood.

Background

In order to address the hypothesis of spatial variation in severe weather warnings issued by the National Weather Service (NWS) between 1986 and 2017, I reviewed relevant literature regarding NWS warnings in Chapter 2. I discussed that weather warnings are produced by the 122 NWS Warning Forecast Offices (WFO) in order to warn the population of impending or already occurring severe weather. Each WFO is assigned a boundary known as a County Warning Area (CWA) and only provides event products within that CWA boundary. When monitoring a weather system, the NWS employs several methods to determine its severity, including using trained storm spotters, but will heavily rely on evidence from the NEXRAD network.

In order to necessitate a flash flood, severe thunderstorm, or tornado warning, the NWS has developed a specific severity criterion that is the same for every WFO. Whether the criteria for a severe event has been met is dependent upon the reporting procedure and evidence-based process that WFOs employ.

Previous research studies explored the relationship of population and severe weather warnings. Several studies focused on the relationship of population densities and warning bias, while others further examined the social and economic aspects of warnings on the human population. Very few studies utilize the actual warning data, instead using related products such as radar imaging, text products, and local storm reports. Similar to the current study, Harrison and Karstens (2017) utilized storm-based severe thunderstorm and tornado warnings as well as meta data, that is issued alongside these types of warnings, and focused on climatological geo-spatial relationships. Though similar, their study differs from the current in several aspects: (1) the geo-spatial relationship was focused on county warning area (CWA) boundaries, instead of county boundaries; (2) only severe weather warnings post-2007 were utilized in their study; and (3) their study only focused on severe thunderstorm and tornado weather phenomenon.

Data

As discussed in Chapter 3, data used in the analysis of this study are United States National Weather Service flash flood, severe thunderstorm, and tornado warning data for the continuous United States issued between the beginning of 1986 through the end of 2017. The primary data were obtained from the Iowa Mesonet Severe Weather archive in a file format compatible with Esri's ArcGIS program. Attributes associated with each warning in the obtained datasets included spatial and non-spatial information, for example: issuance time of the warning, associated weather forecasting office, type of warning area (county vs storm-based area), and type of phenomena. For the purpose of this study, only the county area types were used, as they were recorded through the entire study period and accounted for those storm-based area warnings that were excluded.

From this dataset, a simple count function was performed on the uniquely coded county identifier attributes for each warning phenomena, as to count the number of warnings in the study period for each county. In the final dataset, the base counts for each warning phenomena were then adjusted for the population, area, and population density of their corresponding counties. Several analyses were performed on the final dataset of warning data. The first analysis consisted of examining the geospatial pattern of the adjusted and non-adjusted warning counts. The second analysis used a function based on the Getis-Ord Gi* statistic, in which regions of high valued and low valued clustering is identified. The last analysis is based on the Moran's I value, in which counties that are outliers to neighboring counties are identified and compared to results from the second analysis.

Several potential biases were identified in the creation of the final dataset. These biases included: (1) boundaries between weather forecast offices being identified, (2) difference in area coverage between counties, and (3) variations in population densities.

Results

Results from the analyses (as detailed in Chapter 4) provided several overlying patterns to the warning data when inspected by county basis, as well as confirm biases that were noticed when the final dataset was created. Inspecting the maxima for the base warning phenomena produced the following results:

(1) The highest occurrences of flash flood warnings are identified in the desert Southwest and Texas,

(2) severe thunderstorm warning occurrence is highest in Arizona, portions of the Midwest, the South, and the Mid-Atlantic states,

(3) the highest occurrences of tornado warnings conformed to the Tornado Alley and Dixie Alley regions of tornado activity (i.e. Colorado, Kansas, Oklahoma, Arkansas, Texas, Louisiana, Mississippi, Alabama, Tennessee, and Illinois), and,

(4) the highest instances of the aggregate warning occurrence are found in the desert Southwest, the Midwest, and in the Southern regions of the United States.

Through the hot spot analysis, several generalized areas not immediately noticeable in the base analysis were found. For flash flooding, though maxima were generally located near the southern United States border, the hot spot analysis highlighted a high occurrence region extending northward along the Mississippi River. Though the severe thunderstorm and tornado warning occurrences cover similar regions, the hot spot analysis pointed out regions of divergence between them:

(1) the tornado warning hot spot infiltrated further north into Illinois than the severe thunderstorm hot spot, and,

(2) the tornado warning hot spot retreated away from northern Texas where the severe thunderstorm hot spot covers. The hot spot analysis also highlights regions of topographical barriers (Rocky Mountain range and portions of the Appalachian range) as well as a peculiar region of low warning occurrences covering the state of Georgia.

Several biases inherent to the final dataset and the weather warnings were found during the course of this study. The first bias relates to the geopolitical boundaries of the contiguous United States. Several instances of noticeable boundaries between County Warning Areas as well as state borders was evident in the base analysis of the severe warnings. These were most evident in the Texas and Oklahoma region as well as in the Alabama and Georgia region. The second bias presents itself in the form of county populations. In the base and hot spot analysis for the severe thunderstorm and tornado warning occurrence adjusted for population, the region that contains maxima as well as the hot spots is on the leeward side of the Rocky Mountain range. Located on the leeward side of the Rocky Mountain range is a region of counties that have lower populations compared to the rest of the contiguous United States. The last bias in the final dataset is the geographic size of the counties. For every warning phenomena category adjusted for population size, the maxima and hot spot regions are located in the eastern half of the country. This is very likely due to the concentration of small counties east of the Rocky Mountain range.

Given the results from my analyses, I can now address the validity or non-validity of my hypotheses.

The first hypothesis was partially validated, in that results from the base analysis provided several differences in regards to the flash flood maxima, the severe thunderstorm maxima, as well as the aggregate maxima. Though flash flood maxima were found in the Southwest, several maxima were also identified in the state of Texas. The severe thunderstorm warnings did prove to be mostly located in the regions specified in the first hypothesis, however, maxima were identified in the Southwest and the South. Lastly, aggregate warning maxima were not only found in the South and Midwest, but the Southwest also had several counties in which maxima were identified.

With regard to the second hypothesis, the flash flood warning coverage, the severe thunderstorm warning coverage, as well as the aggregate warning coverage from the hot spot analysis highlighted areas not mentioned.

Additionally, I found that with regard to coverage of high flash flood warning occurrence, the hot spot analysis identified areas in Texas and along the Mississippi River, and in the Northeast United States. The severe thunderstorm warning occurrence coverage not only showed high occurrence over the Midwest and South, but a region covering the Southwest as well as the Mid-Atlantic were identified. Lastly, the coverage of aggregate warning occurrence identified a region of high occurrence over the Southwest.

The results of the outlier analysis did validate part of the third hypothesis. Across the severe weather warning occurrences, both high and low value outliers were found in and around regions of high and low value occurrence, with groups of outliers being identified between spatially close high and low occurrence regions. However, most outlier values were located on the periphery of the opposite level of occurrence coverage, highlighting that the outlier values were not as interspersed as hypothesized.

Significance

This study has provided a severe weather climatology for the contiguous United States based on severe weather warnings issued by the National Weather Service between 1986 and 2017. Small regions within the Southwestern, the Southern, and the Midwestern U.S. experience the highest occurrences of severe weather based on the severe weather warnings. These results suggest the possibility of sub regions of severe weather activity existing within the larger areas that severe weather is likely to occur (e.g. Tornado Alley). For research and NWS meteorologists, this provides both an opportunity to study the dynamic meteorological conditions behind the higher occurrences of severe weather as well as testing grounds for developing new warning technology and methods. These results can also be translated to emergency management agencies, where equipment and supplies can be strategically placed within or near these areas of historically high warning occurrence. In essence, the knowledge of the location of the most and least warned regions for severe weather across the contiguous United States can positively impact the preservation of infrastructure and more importantly, life.

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APPENDIX A

ADJUSTED WARNING VALUES OUTLIER ANALYSIS

A.1 Flash Flood Warning Occurrence per Capita

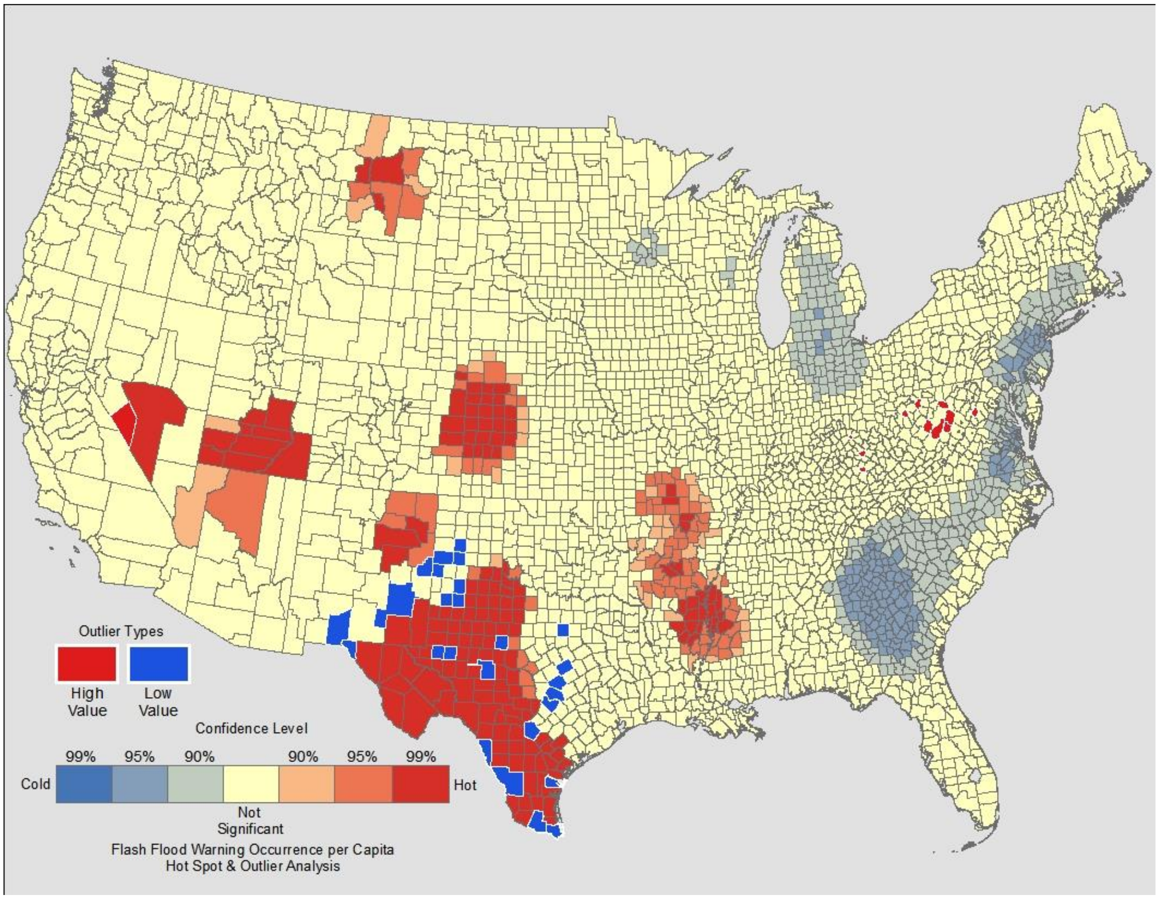

Figure A.1: Map of the contiguous United States counties showing high value and low value outliers in relation to findings from the flash flood warning occurrence per capita hot spot analysis for the period 1986 to 2017. The high value outliers are denoted by a brighter red shading with a white border, and the low value outliers are denoted by a brighter blue shading with a white border. Refer to figure 4.3.2 for explanation of hot spot analysis symbology.

A.2 Flash Flood Warning Occurrence per Area

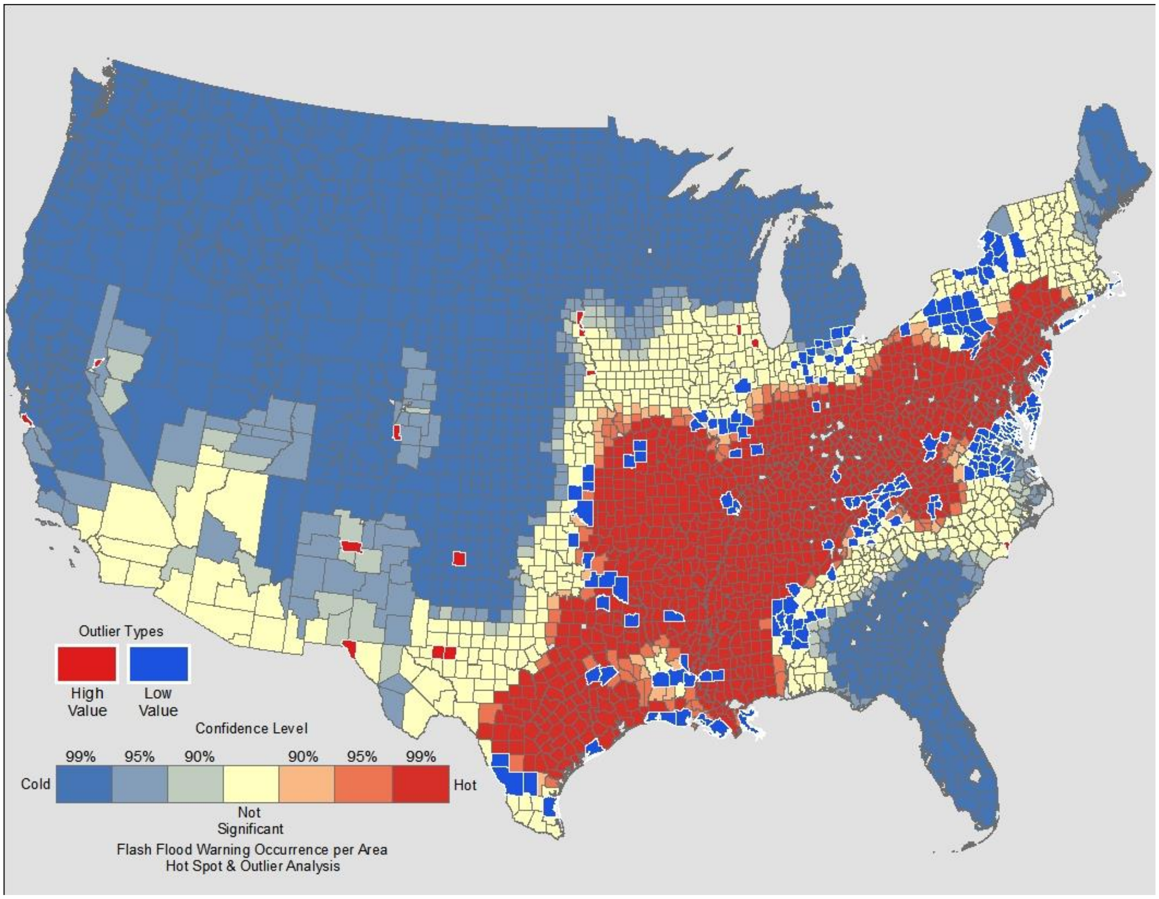

Figure A.2: Map of the contiguous United States counties showing high value and low value outliers in relation to findings from the flash flood warning occurrence per area (square kilometers) hot spot analysis for the period 1986 to 2017. The high value outliers are denoted by a brighter red shading with a white border, and the low value outliers are denoted by a brighter blue shading with a white border. Refer to figure 4.3.3 for explanation of hot spot analysis symbology.

A.3 Flash Flood Warning Occurrence per Population Density

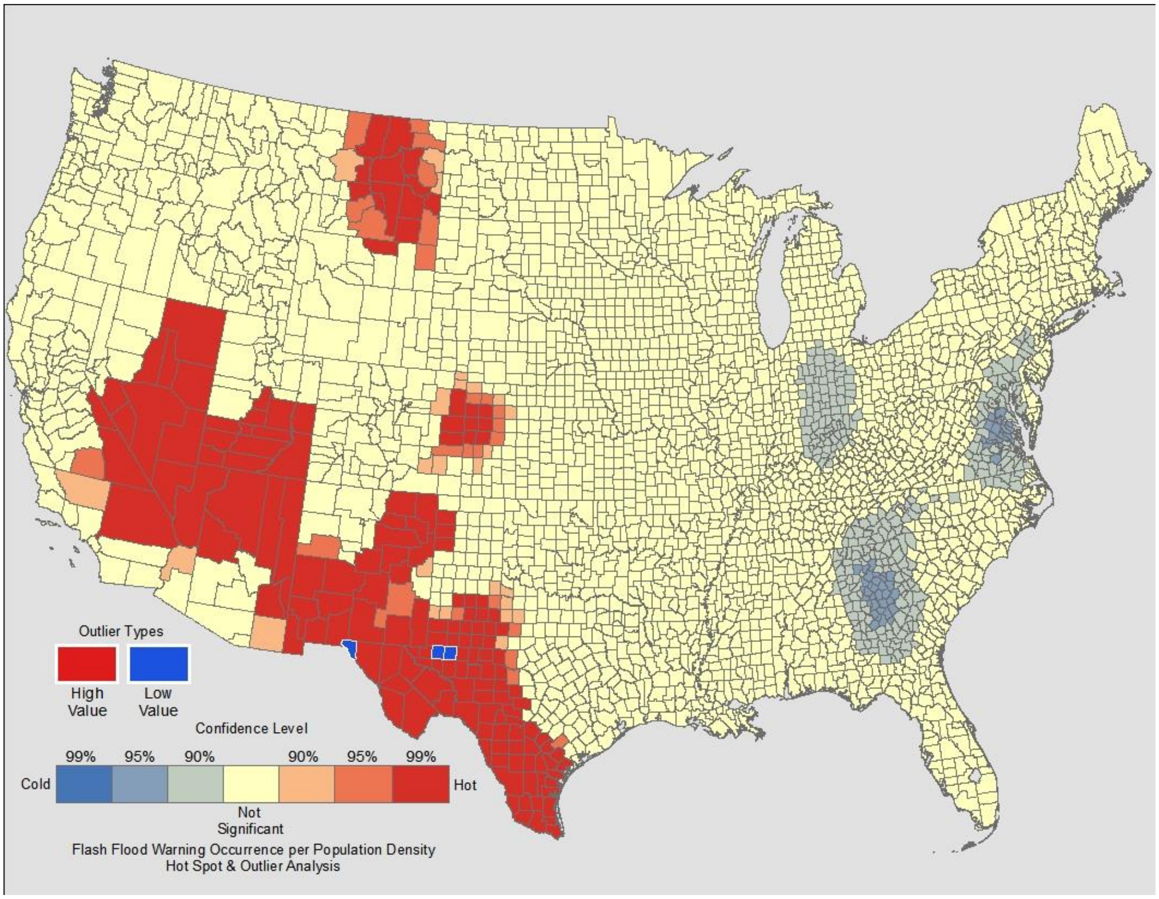

Figure A.3: Map of the contiguous United States counties showing high value and low value outliers in relation to findings from the flash flood warning occurrence per population density (people/km^2) hot spot analysis for the period 1986 to 2017. The high value outliers are denoted by a brighter red shading with a white border, and the low value outliers are denoted by a brighter blue shading with a white border. Refer to figure 4.3.4 for explanation of hot spot analysis symbology.

A.4 Severe Thunderstorm Warning Occurrence per Capita

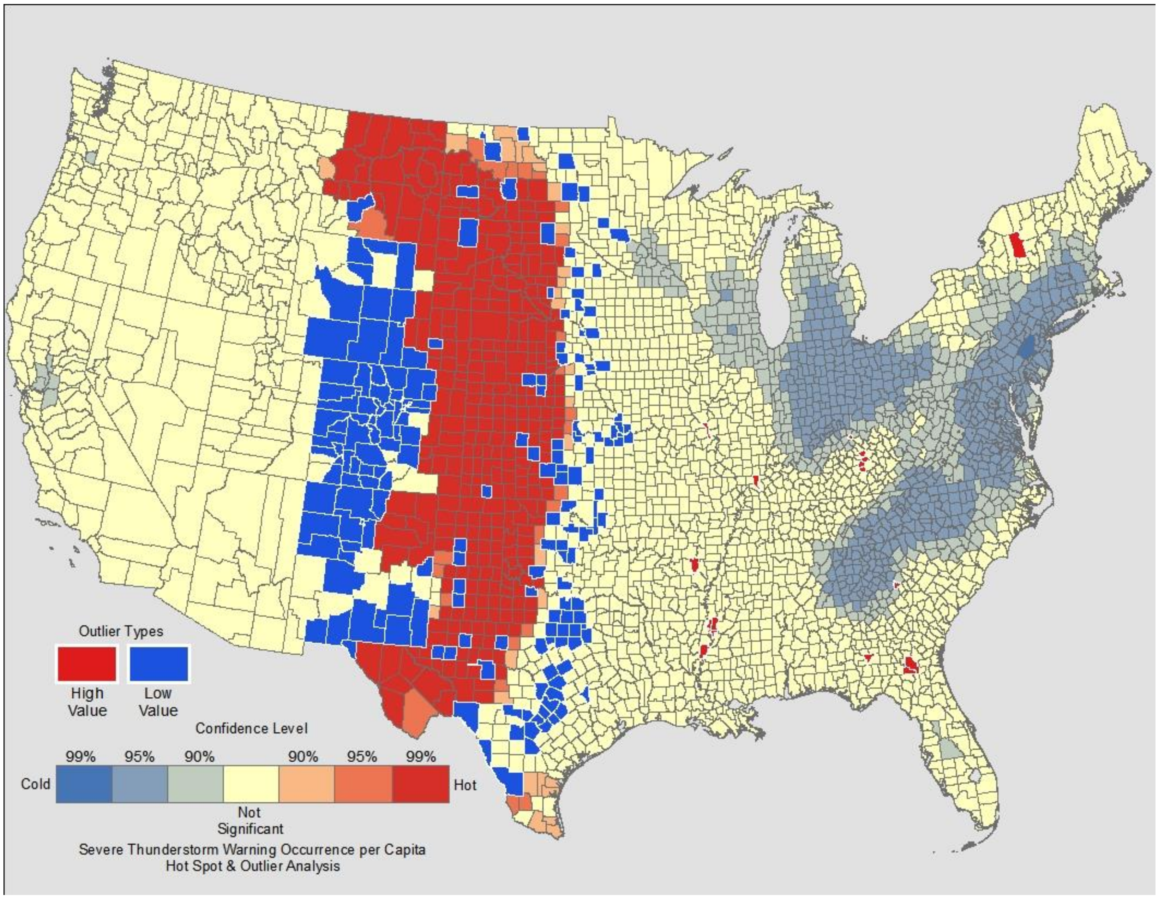

Figure A.4: Map of the contiguous United States counties showing high value and low value outliers in relation to findings from the severe thunderstorm warning occurrence per capita hot spot analysis for the period 1986 to 2017. The high value outliers are denoted by a brighter red shading with a white border, and the low value outliers are denoted by a brighter blue shading with a white border. Refer to figure 4.3.6 for explanation of hot spot analysis symbology.

A.5 Severe Thunderstorm Warning Occurrence per Area

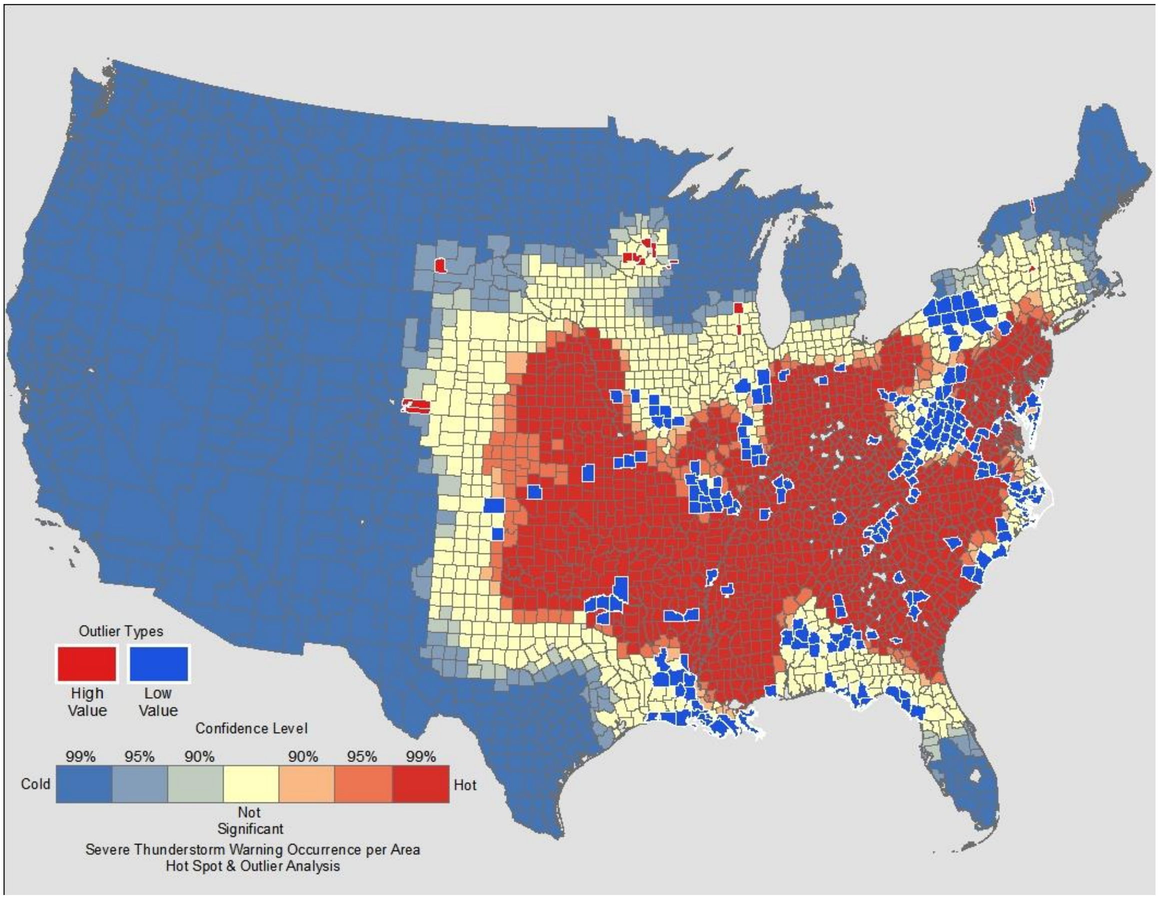

Figure A.5: Map of the contiguous United States counties showing high value and low value outliers in relation to findings from the severe thunderstorm warning occurrence per area (square kilometers) hot spot analysis for the period 1986 to 2017. The high value outliers are denoted by a brighter red shading with a white border, and the low value outliers are denoted by a brighter blue shading with a white border. Refer to figure 4.3.7 for explanation of hot spot analysis symbology.

A.6 Severe Thunderstorm Warning Occurrence per Population Density

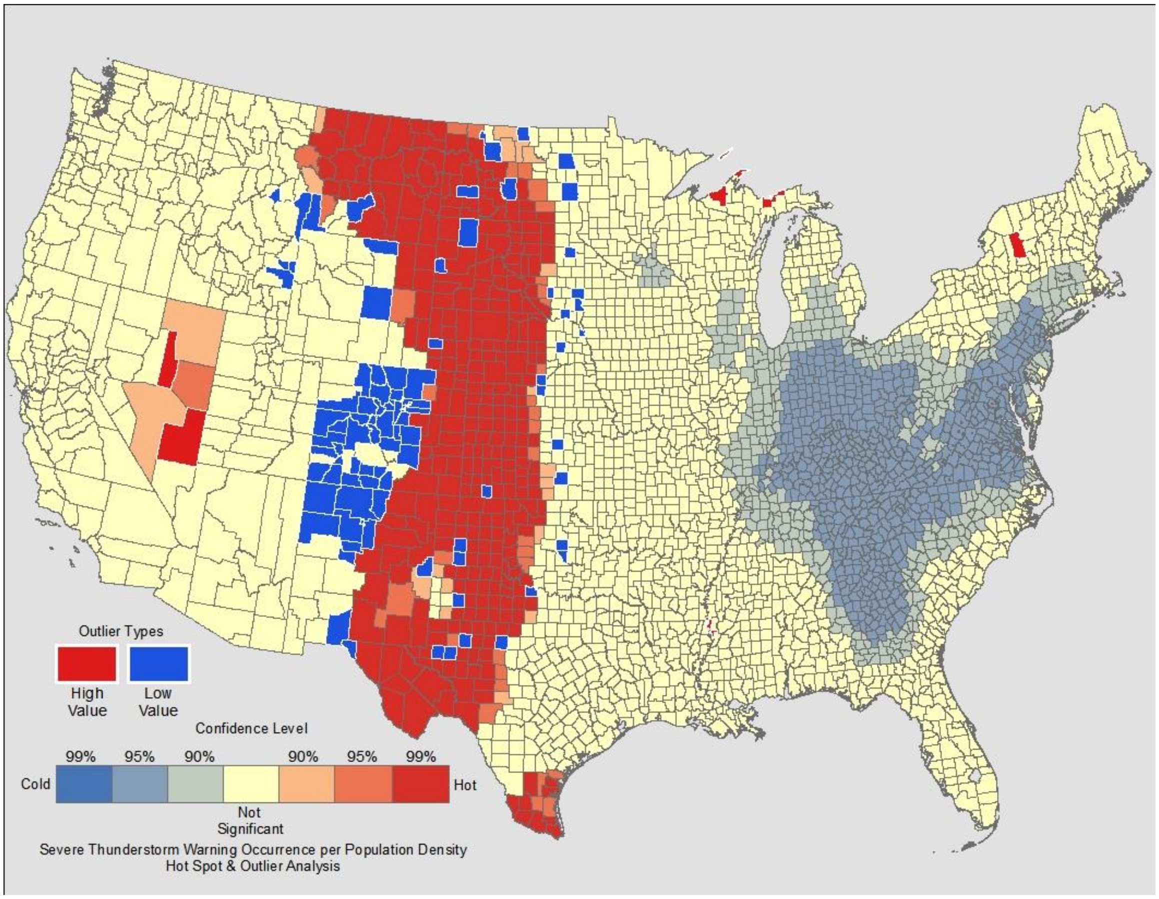

Figure A.6: Map of the contiguous United States counties showing high value and low value outliers in relation to findings from the severe thunderstorm warning occurrence per population density (people/km^2) hot spot analysis for the period 1986 to 2017. The high value outliers are denoted by a brighter red shading with a white border, and the low value outliers are denoted by a brighter blue shading with a white border. Refer to figure 4.3.8 for explanation of hot spot analysis symbology.

A.7 Tornado Warning Occurrence per Capita

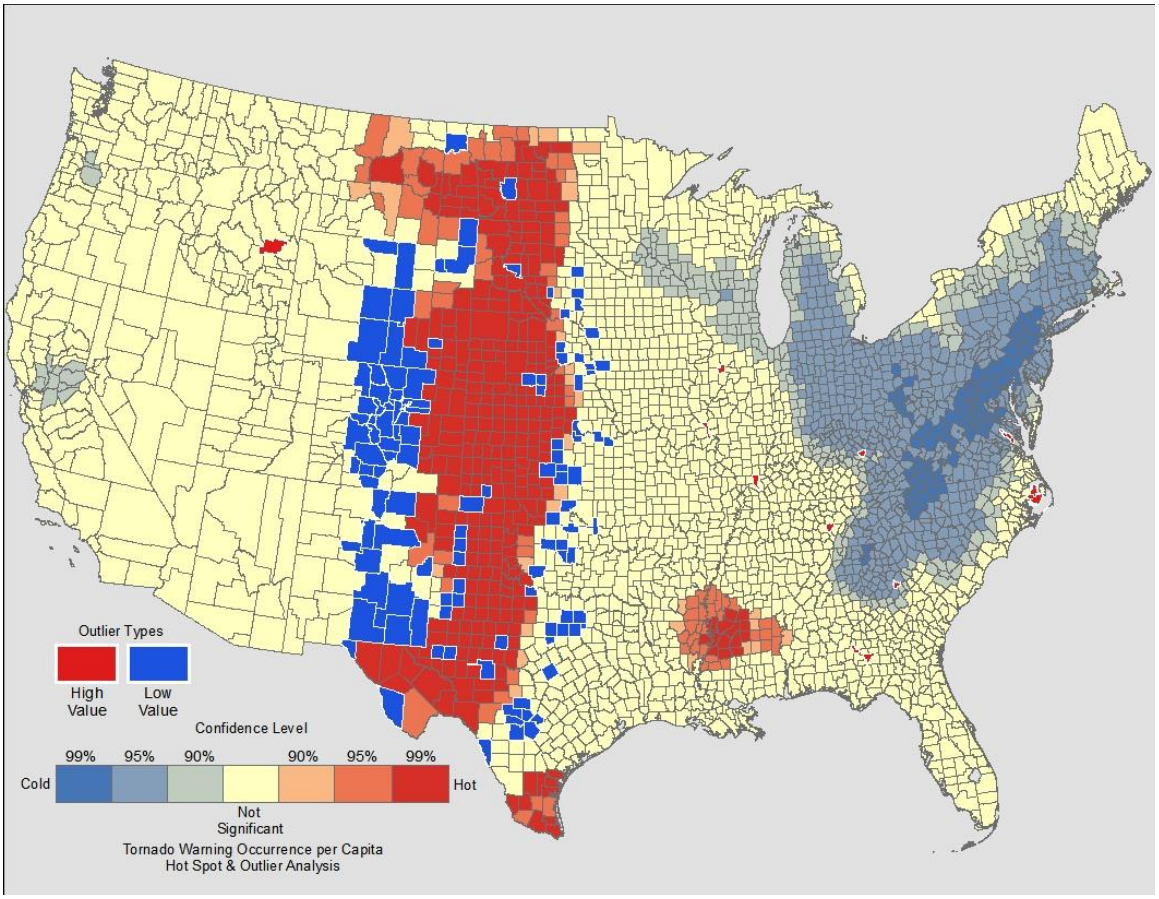

Figure A.7: Map of the contiguous United States counties showing high value and low value outliers in relation to findings from the tornado warning occurrence per capita hot spot analysis for the period 1986 to 2017. The high value outliers are denoted by a brighter red shading with a white border, and the low value outliers are denoted by a brighter blue shading with a white border. Refer to figure 4.3.10 for explanation of hot spot analysis symbology.

A.8 Tornado Warning Occurrence per Area

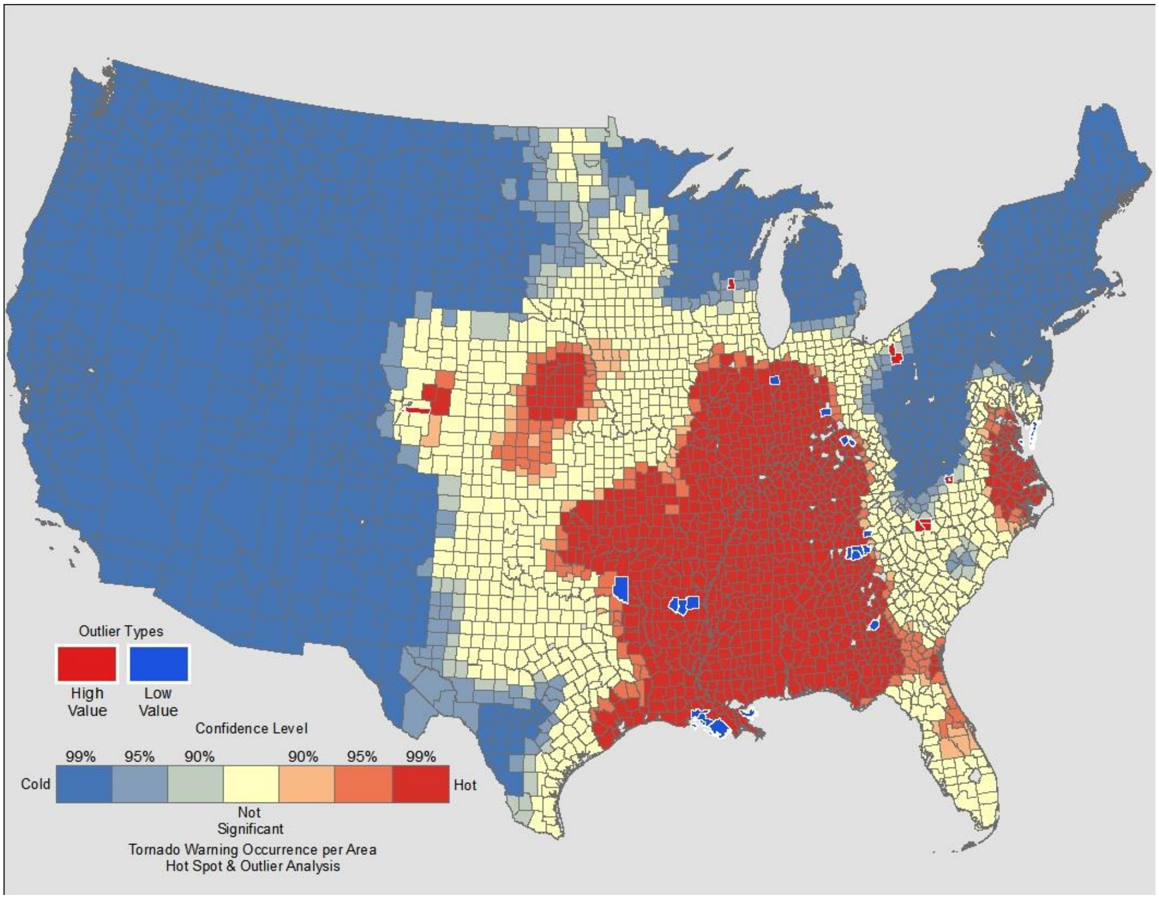

Figure A.8: Map of the contiguous United States counties showing high value and low value outliers in relation to findings from the tornado warning occurrence per area (square kilometers) hot spot analysis for the period 1986 to 2017. The high value outliers are denoted by a brighter red shading with a white border, and the low value outliers are denoted by a brighter blue shading with a white border. Refer to figure 4.3.11 for explanation of hot spot analysis symbology.

A.9 Tornado Warning Occurrence per Population Density

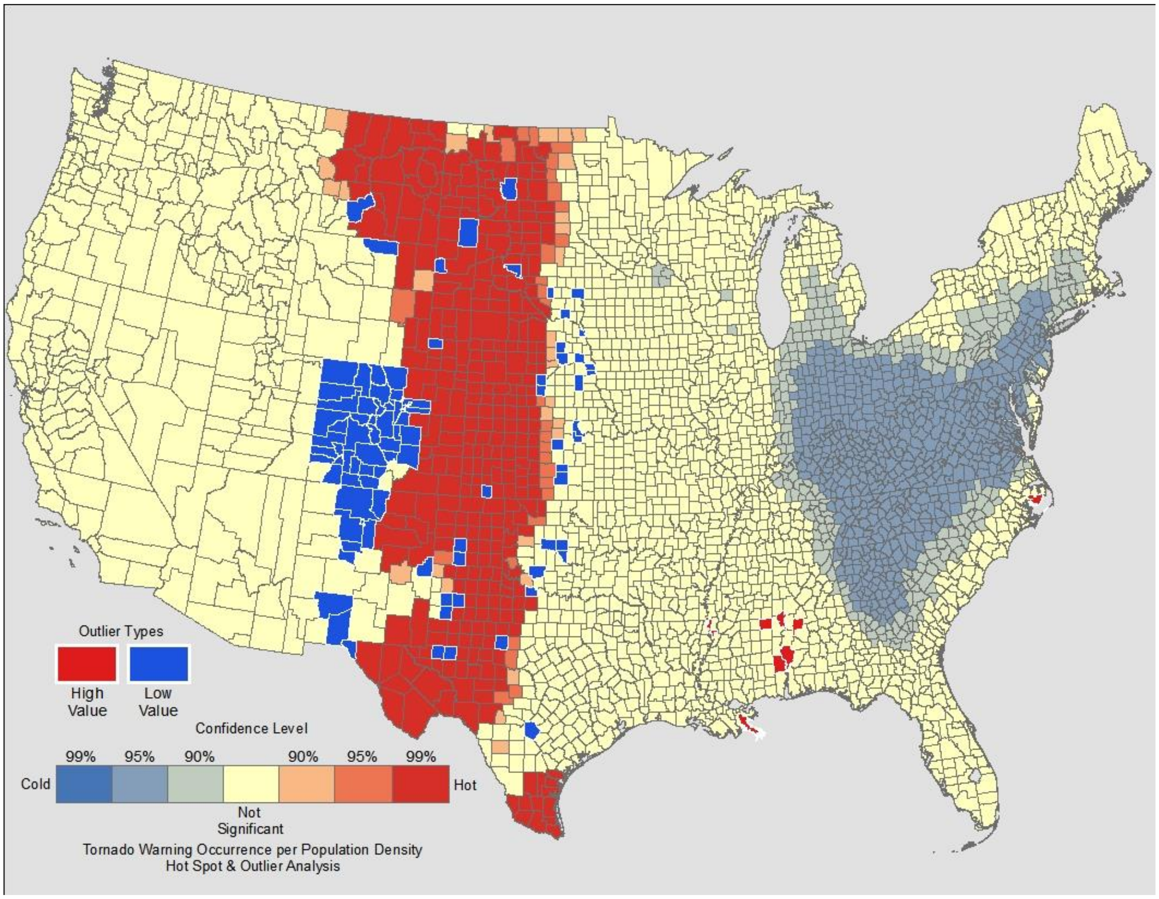

Figure A.9: Map of the contiguous United States counties showing high value and low value outliers in relation to findings from the tornado warning occurrence per population density (people/km^2) hot spot analysis for the period 1986 to 2017. The high value outliers are denoted by a brighter red shading with a white border, and the low value outliers are denoted by a brighter blue shading with a white border. Refer to figure 4.3.12 for explanation of hot spot analysis symbology.

A.10 Aggregated (flash flood, severe thunderstorm and tornado) Warning Occurrence per Capita

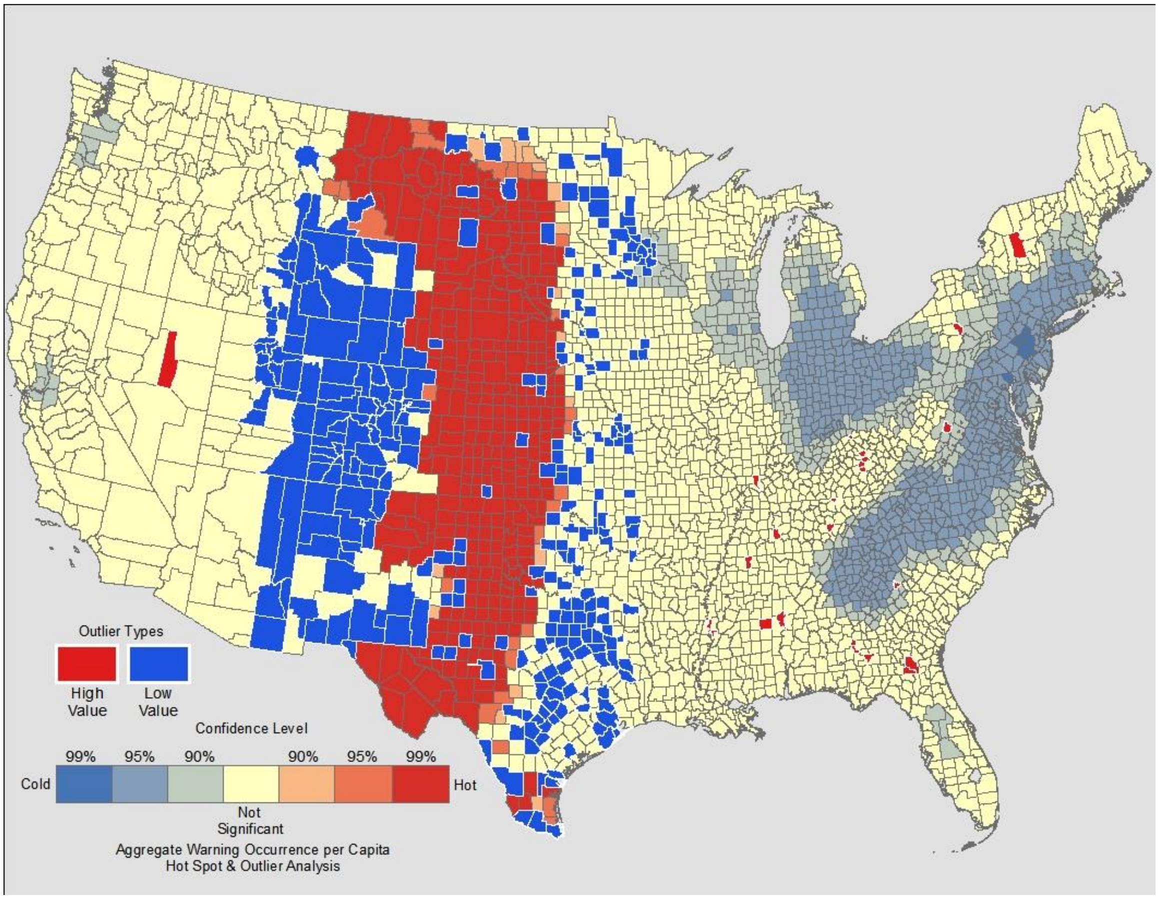

Figure A.10: Map of the contiguous United States counties showing high value and low value outliers in relation to findings from the aggregated (flash flood, severe thunderstorm and tornado) warning occurrence per capita hot spot analysis for the period 1986 to 2017. The high value outliers are denoted by a brighter red shading with a white border, and the low value outliers are denoted by a brighter blue shading with a white border. Refer to figure 4.3.14 for explanation of hot spot analysis symbology.

A.11 Aggregated (flash flood, severe thunderstorm and tornado) Warning Occurrence per Area

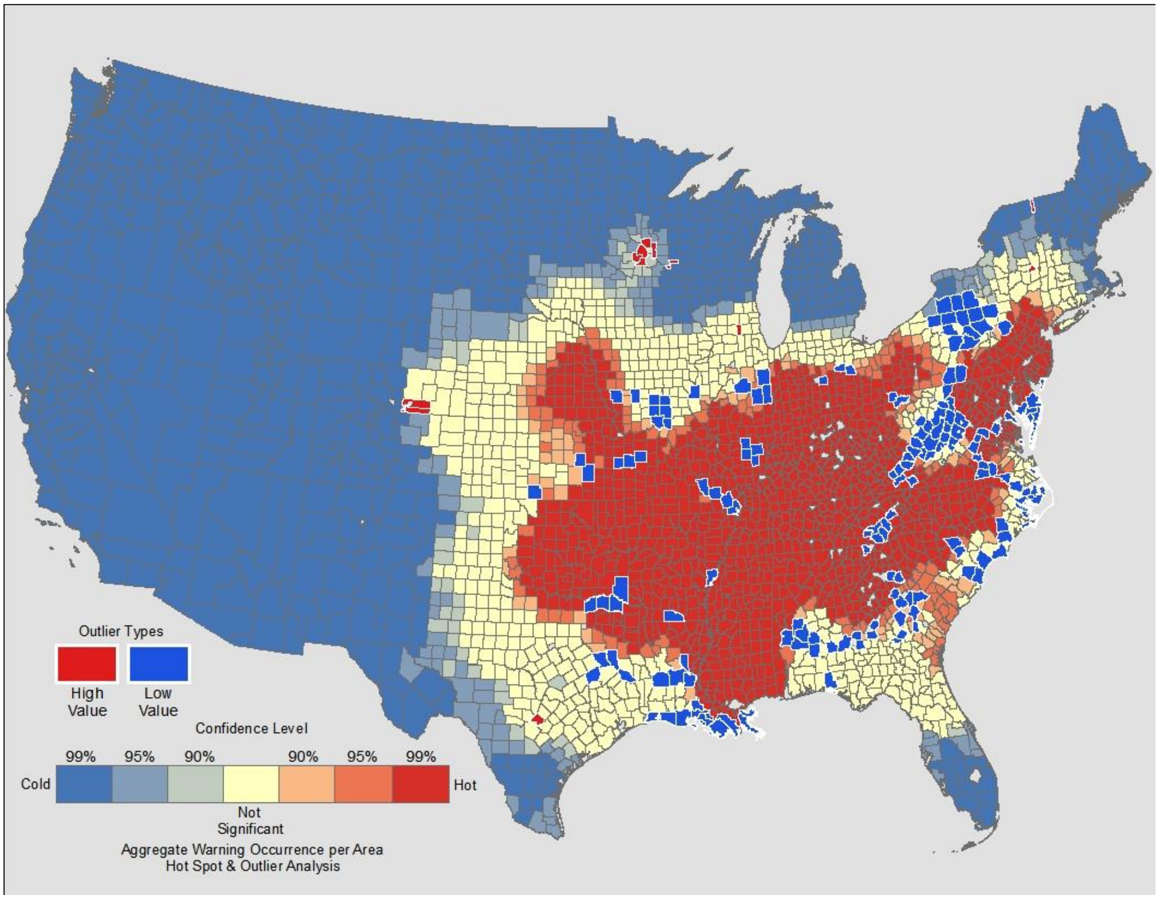

Figure A.11: Map of the contiguous United States counties showing high value and low value outliers in relation to findings from the aggregated (flash flood, severe thunderstorm and tornado) warning occurrence per area (square kilometer) hot spot analysis for the period 1986 to 2017. The high value outliers are denoted by a brighter red shading with a white border, and the low value outliers are denoted by a brighter blue shading with a white border. Refer to figure 4.3.15 for explanation of hot spot analysis symbology.

A.12 Aggregated (flash flood, severe thunderstorm and tornado) Warning Occurrence per Population Density

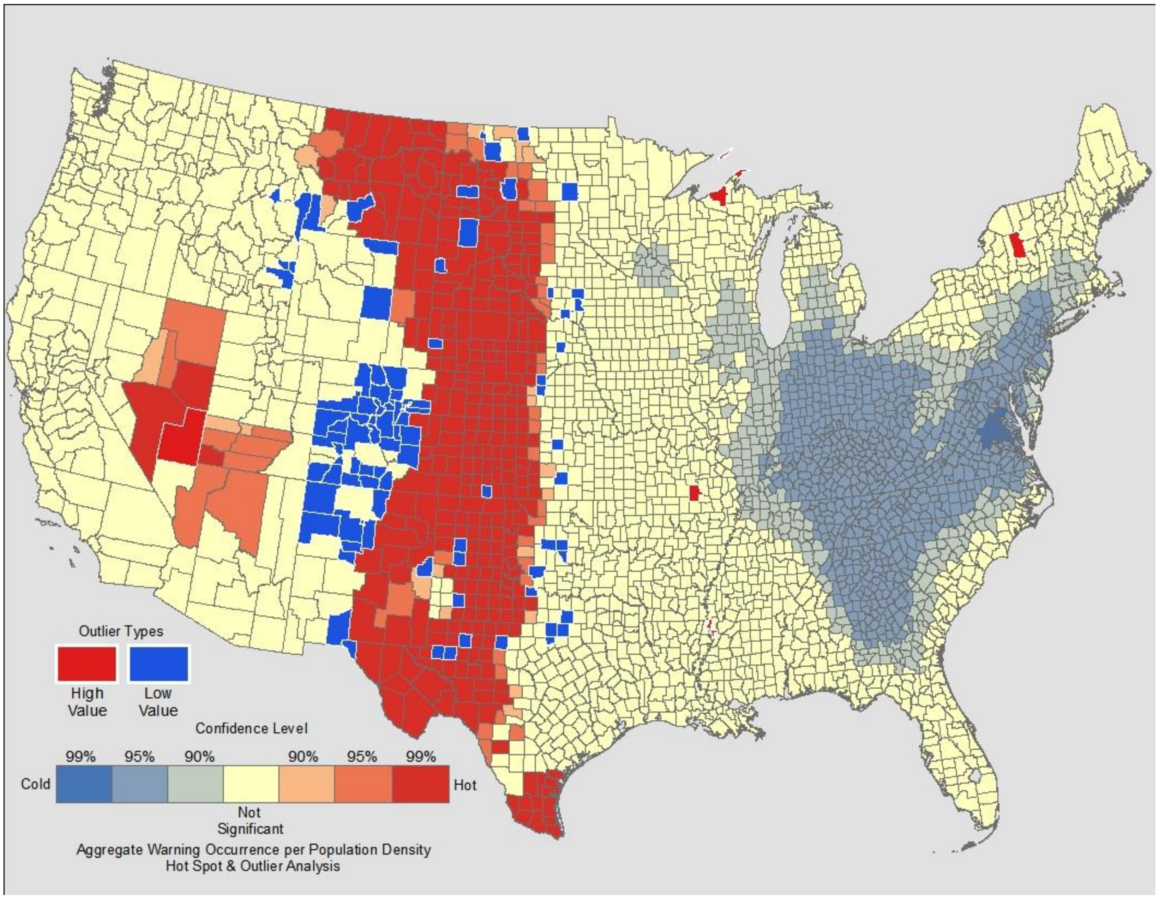

Figure A.12: Map of the contiguous United States counties showing high value and low value outliers in relation to findings from the aggregated (flash flood, severe thunderstorm and tornado) warning occurrence per population density (people/km^2) hot spot analysis for the period 1986 to 2017. The high value outliers are denoted by a brighter red shading with a white border, and the low value outliers are denoted by a brighter blue shading with a white border. Refer to figure 4.3.16 for explanation of hot spot analysis symbology.