A Comparative Analysis of Severe Weather Warnings in the Continental United States

Journal: *Weather and Forecasting*

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Abstract

The National Weather Service (NWS) issues many thousands of warnings each year, and these warnings vary spatially and temporally. This study served to quantify severe thunderstorm and tornado warning differences from 2005-2012 for the 116 NWS offices in the conterminous U.S. This was investigated by looking at regional differences, as well as changes occurring with the switch from county-based warnings to storm-based warnings on October 1, 2007. It was found that length and lead time of warnings were variable per region, and the change in lead time from county-based to storm-based warnings was negligible for most Weather Forecast Offices. The switch from county-based to storm-based warnings impacted the size of warnings most particularly in the Western Region of the NWS. Measures of forecast quality such as Probability of Detection and Success Ratio improved for most offices with the transition from county-based to storm-based warnings. The scope of this work did not include any societal aspects of warnings, such as whether the warning is received by the emergency managers and/or the public, but this is an important factor in warning success that is not considered here.

I. Introduction and Background

In the United States, the National Weather Service (NWS) is in charge of issuing warnings and advisories for the entire country. It achieves this by splitting the contiguous U.S. into 4 NWS Regions and 116 different county warning areas (CWAs), each with their own Weather Forecast Office (WFO). Warnings issued by these offices are the primary way information is communicated to the public during life-threatening severe weather events. Fig. 1, obtained from the NWS, shows the boundaries associated with each WFO. It should be noted that this map includes the names of six offices not in the contiguous U.S.: Anchorage, AK (AFC), Fairbanks, AK (AFG), Guam (GUM), Honolulu, HI (HFO), Juneau, AK (AJK), and San Juan, PR (SJU); these offices were not studied in this project. Fig. 2, again from the NWS, is a map that displays outlines of the NWS Regions.

From their inception, WFOs issued warnings by county. These county-based warnings (CBWs) meant that the entire county was included in the warning, not just the part anticipated to be in the direct path of the storm. This changed in October of 2007, when the NWS began issuing storm-based warnings (SBWs). Unlike CBWs, a SBW can warn particular sections of a county while leaving the rest of the county unwarned. Besides improving the specificity of warnings so that fewer people are warned for each warning, the NWS stated that the switch to SBWs "will improve NWS warning accuracy and quality" (National Weather Service 2008). To date, the authors are unaware of any research that has been published regarding the results of the switch or the validity of the above statement.

This paper explores specific characteristics of warnings issued by different WFOs, as well as the changes the shift to SBWs made in the issuance of warnings, by looking at forecast quality statistics, the size and shape of warnings, and warning lengths and lead times. These results are compared by NWS Region and differences between offices are examined. Inconsistencies between regions or offices are particularly interesting to study, because while each office follows certain criteria that qualify a storm as severe or tornadic, the size and shape of warnings, and when and for how long the warnings are issued, are decisions left to the local WFO and the forecaster.

II. Data and Methodology

To accomplish the goals of this project, data from January 1, 2005 to December 31, 2012 was collected from Iowa State University Department of Agronomy's IEM Cow (an online database that contains information regarding NWS warning size, duration, and verification information). Comma Separated Variable (CSV) files for each WFO during this time period were obtained from the Iowa Environmental Mesonet to use in Microsoft Excel 2010 and in Python scripts for data analysis of size and related parameters, length, and lead time of warnings. Forecast quality statistics were created using the IEM Cow website (http://mesonet.agron.iastate.edu/cow/) and Microsoft Excel 2010.

Lead time data was created only for warnings that had local storm reports (LSRs) associated with them. In other words, a warning that did not verify (did not have an LSR) was not included in the lead time analysis, rather than being counted as a zero lead time. Additionally, LSRs without warnings were excluded rather than being counted as a zero or negative (if a warning were to be issued after a severe event was reported) lead time.

To simplify forecast verification, a 2x2 contingency table was used that groups events into four categories based on whether or not the event was forecasted and whether or not the event actually happened. It is important to note that with this table, it is impossible to determine the value of D (Brooks 2004). This difficulty is due to the fact that one cannot accurately assess the number of correct forecasts made for events that do not exist.

Table 1: Contingency Table from Roebber 2009

2x2 Contingency Table		**Event Observed**	
		Yes	**No**
Event Forecasted	**Yes**	A	B
	No	C	D

From this table, five statistics can be determined that help measure the strength of a forecast: Probability of Detection (POD, equation 1), False Alarm Ratio (FAR, equation 2), Bias (equation 3), Critical Success Index (CSI, equation 4), and Success Ratio (SR, equation 5) (Roebber 2009). Using these statistics, one can gauge the forecast performances for different WFOs. For example, a forecast office that averaged high forecast strength would have a high POD, a low FAR, a high CSI, and a high SR. It is also possible to see how forecast strength changed over time with these statistics. A WFO that decided to start issuing more warnings would have an increase in POD, but there would also likely be an increase in FAR (Brooks 2004). Thus there is a delicate balance between trying to increase a forecast's POD while at the same time decreasing its FAR. This analysis focuses on POD, FAR, and SR.

$$POD = \frac{A}{A + C} \ (1)$$

$$FAR = \frac{B}{A + B} \ (2)$$

$$Bias = \frac{A + B}{A + C} \ (3)$$

$$CSI = \frac{A}{A + B + C} \ (4)$$

$$SR = 1 - FAR \ (5)$$

One data issue to be aware of is that the LSR data for Springfield, MO (SGF) was corrupt on both the IEM Cow website and the CSV file obtained. Thus, lead time statistics, as well as forecast quality statistics from the CBW era, cannot be produced for SGF. There were also approximately ~25 warnings from IEM Cow that had errors in length of warnings, some with unreasonably long times (a couple days, a week, or even a month) or with warnings that ended before they began. These warnings were deleted and statistics were calculated from the warnings with reasonable times.

III. Results and Implications

A. Number of Warnings Issued

The average number of warnings an office issues in a given year is an important statistic because it gives insight into the local climate as well as office policy on warnings. Fig. 3 shows the normalized average number of warnings for each WFO from 2005-2012, obtained by dividing the average number of warnings per year by the office's CWA. This was done so that offices with larger than average areas would not stand out in the number of warnings issued, as it makes sense that an office with a larger area would issue more warnings. As seen in the figure, offices in the western U.S. have a low normalized number of warnings per year. It is consistent across the board, and can be attributed to the fact that there are fewer severe storms in this part of the country (see Figs. 4, 5, and 6, taken from the National Severe Storms Laboratory website). The office that stands out the most here is Huntsville, AL (HUN). As will be shown later, the Huntsville office tends to issue smaller and shorter warnings, which contribute to the high number of warnings issued. Key West, FL (KEY) also stands out as an office that issues more warnings, but is not visible on the map due to its small size.

B. Length and Lead Time

Length of warnings issued by each WFO were averaged over the eight year time period of this project and plotted in a CWA map in seconds (Fig. 7). From this figure, it is evident that warning length is fairly irregular within the U.S., and the variability does not seem to be by NWS Region. One could make the case visually that Eastern Region has generally longer warning lengths, while the Western Region, particularly the West Coast, has shorter lengths. One anomaly that seems to be present in the Western Region is the much longer warnings (average of 55 minutes and 37 seconds) of Pendleton, OR (PDT). This was associated with larger sized warnings than the surrounding offices, especially during the SBW era, which will be discussed later. It is reasonable that larger warnings would be associated with a longer time period so that the whole of the warned area would be covered temporally by a warning. Overall, average length of all warnings was 42 minutes and 33 seconds.

The average lead time of all warnings with LSRs was 16 minutes and 23 seconds. Average lead time tended also to be quite discontinuous between WFOs, and no real pattern exists by NWS region or other apparent quantitative factors (Fig. 8). It seems that states along the Canadian border, as well as Texas WFOs, have higher lead times. Lower lead times are found in parts of the Upper Midwest and the Ohio Valley. The office with the highest lead time is Los Angeles, CA (LOX). It had a small number of warnings, as seen by Fig. 3, and an even smaller number of verified warnings. One lead time of 1 hour and 15 minutes likely weighted this data of small sample size. Note that Seattle, WA (SEW) and San Francisco, CA (MTR) had no LSRs that verified warnings.

Fig. 9 is a graph of change in lead time from the CBW era to the SBW era. The y-axis is average lead time for each WFO during the SBW era minus the average CBW lead time. Thus, positive values represent an increase in lead time, while negatives show a decrease. The x-axis displays every WFO that had warnings with LSRs for both the CBW and SBW eras, ordered by the number of warnings that office issued from least to greatest. WFOs with fewer warnings had the greatest lead time change, most likely due to the small sample size of the data. As the number of warnings increases, the variance of the lead time change decreases, and the changes are normally only a couple of minutes or less. 58 offices increased in lead time, while 54 decreased. As a whole, most WFOs did not have much of a lead time change from CBW to SBW.

C. Size and Related Parameters/CWA Border Cases

In addition to length and lead time statistics, another measure of severe weather warnings is the size and shape of these warnings. Prior to October 1st, 2007, warning size was purely dictated by county size of the counties included in the warnings. Once the switch to storm-based warnings occurred, WFOs were free to draw warnings of any size and shape. Examining how offices handled the change from CBWs to SBWs in terms of area covered and whether offices have continued to issue CBWs in the SBW era are key to determining office policy differences.

During the county-based warning era, if there was a severe storm in any part of a county the whole county would be put under the warning. The biggest problem with these types of warnings is that it is possible to be under a warning but not feel the impacts of it due to the storm being on the other side of the county. The bigger the county, the more this was an issue. The average CBW size is shown in Fig. 10. In the east, most of the counties are smaller, so the average size of the warnings is less than 2,500 square kilometers. West of the Rocky Mountains, counties get much larger. The average size of CBWs rapidly increases from around 10,000 square kilometers for offices like Albuquerque, NM (ABQ) and Billings, MT (BYZ) to upwards of 40,000 square kilometers for Las Vegas' WFO (VEF). There are several warnings, especially in the Las Vegas CWA, where the warned storm may only cover about 2,000 square kilometers, but the warning would be over 100,000 square kilometers if it were county-based due to the large county size. Something had to change to avoid warning such a large area and so many people for a very localized event.

With the switch to SBWs in 2007, warning size became more normalized across the board (Fig. 11). The graphic, which is on the same color scale as Fig 10, shows that the large variation between warning size due to county size is now gone. While some variability still exists, it is much less than before. Fig. 12 displays the average SBW size from 2007 through 2012 on its own color scale. The variation in warning size has reduced from over 40,000 square kilometers between CWAs to just 3,500 square kilometers. The largest SBWs tend to occur along the United States/Canadian border. The CWA that stands out the most belongs to Pendleton, OR (PDT) in the Northwest. Two contributing factors to this include that PDT issues very few warnings a year on average (Fig. 13), and that these warnings tend to be for longer lengths (Fig. 7). While SBWs reduced the size of warnings by a great deal, some variation still exists between offices on the size of these SBWs.

For each warning issued by the National Weather Service, IEM Cow calculates a size percentage. The size percentage is defined as the percent reduction in size from a CBW to a SBW; thus, a higher size percentage value means a greater reduction in size. The warnings mentioned above in the Las Vegas CWA had size percentage values greater than 95%. Fig. 14 shows a map of the average size percentage of each CWA during the SBW era. You can see that the switch to SBWs has reduced warning size by at least 30% nationwide. The areas with the biggest size reduction are in the west, where the large county size led to large size reductions on the order of 80-95%. Even where counties are small in the Central Plains, Ohio Valley, and Southeast U.S., the size reduction is still on the order of 50-70%.

This means that one of the purposes of SBWs—to reduce the area and number of people warned—was achieved by the switch.

Perimeter Ratio is another variable that can be used to analyze warning shape characteristics. It is measure of the overlap between political boundaries (specifically county borders) and NWS warning borders (Iowa Environmental Mesonet 2013). This variable will be key in determining whether an office still issues pseudo-county-based warnings or if they have truly switched to a storm-based warning. A value of 100 for perimeter ratio means that every border of a warning directly coincides with a political boundary. The average perimeter ratios during the storm-based warning era can be seen in Fig. 15. The first thing to notice about this map is that the perimeter ratio in the west is rather low; this, again, is due to the large county size. Additionally, most of the offices with the highest perimeter ratio have a large metropolitan area located within their CWA. The highest average perimeter ratio belongs to the Dallas/Fort Worth, TX WFO (FWD). To see why this was the case, the Warning Coordinating Meteorologist (WCM) from FWD was contacted. His response made it clear that the office policy was to meet the local needs, which caused the perimeter ratio to be so high. When asked why the ratio was so high, he replied, "This is in direct relation to Emergency Manager feedback….We issue warnings so others can make decisions. In our part of the world, those decisions are based at the county level" (Fox 2013, personal communication). The takeaway is that warnings are local decisions, and comparing offices by size, shape, or whether they still issue CBWs, though one measure of warning quality, may not be the best way to judge warning success.

Another aspect of storm-based warnings, shape, comes into play when storms are along CWA boundaries. In Fig. 16, two different CWA boundary examples can be seen. The graphic on the left is from the Springfield, MO (SGF) and Little Rock, AR (LZK) offices on January 29, 2013, and the graphic on the right is from the Houston, TX (HGX) and Lake Charles, LA (LCH) offices from February 21, 2013. In each case the boundary between CWAs caused some discrepancy in the warning process. In the first example a storm is moving right along the CWA boundary. Because one office cannot issue a warning in another office's CWA, the warnings stop at these boundaries. Springfield issued a tornado warning for this particular storm, while Little Rock only issued a severe thunderstorm warning. This discrepancy highlights the need for communication between WFOs. For anyone living along the Arkansas/Missouri border, a mixed message was being sent about the severity of this storm. In the Houston/Lake Charles example, Houston had issued a tornado warning on a storm right along the CWA boundary. Lake Charles does not have a warning on this storm at all. The issue was exacerbated because the CWA boundary occurs at a kink in the borders of two counties in Texas. Due to the shape of the counties and the fact that the warning took place along a CWA boundary, there is an area in the northwest corner of the unwarned county that would be under the tornado warning had the Houston office not had to conform to its CWA boundary. The Lake Charles office chose to not warn their county that neighbored Houston's tornado warning at all, which left a small area of unwarned county with warnings on either side. This again is a case where the public is receiving mixed messages due to storm-based warning shape.

One cannot say from this data whether an office is issuing warnings the "right" or "wrong" way, but offices like Pendleton, OR's larger SBW sizes or Fort Worth's more CBWs do stand out. This may be because the local needs of each CWA are different. Office communication then becomes key to avoid confusion amongst the public, especially when warnings are occurring right along CWA boundaries.

D. Forecast Quality Statistics

The best way to compare forecast statistics for different WFOs is to look at POD and FAR for each WFO at the same time. To do this, a performance diagram was adapted from Roebber (2009) that displays POD on the vertical axis and SR on the horizontal axis. Fig. 18 shows the performance diagram for WFOs during the CBW era, while Fig. 19 shows the same for after the Weather Service switched to SBWs. By using SR instead of FAR, the graph increases linearly with a positive slope. For example, an office at the top right-hand corner of the diagram would have a 100% POD and a 100% SR (0% FAR) while an office at the origin of the diagram would have a 0% SR (100% FAR) and 0% POD. Comparing the two figures, it is easily seen that most of the WFOs increased their POD and SR with the switch to SBWs, as there is a jump toward the top right-hand corner from the first diagram to the second.

A few offices stand out in these analyses. As stated previously, the data collected for the Springfield, MO office (SGF) had some errors. Because of this, the SR and POD statistics could not be calculated for the time period in which the office was still issuing CBWs, although they could be calculated for the SBW era. However, this means that a direct comparison of the changes the switch made for the Springfield office with respect to SR and POD cannot be seen. Another office that stands out is Medford, OR (MFR). For the CBW era, Medford had one of the lowest POD and SR. During the SBW era, however, the SR was very high. This can be attributed to the fact that the Medford office issues a small number of warnings per year (average of 13.5 per year from 2005-2012), and therefore this analysis is not necessarily a good representation of an average warning issued out of the office.

There are a two offices that show a 0% POD and 0% SR both before and after the switch to SBWs. These offices, San Francisco (MTR) and Seattle (SEW), issued a total of 25 and 24 warnings respectively in the span of the entire eight years studied. Because of the small number of warnings issued, these statistics can be misleading. It is highly unlikely that every warning issued by these offices will always turn out to be a false alarm. Care must be taken when analyzing these statistics in this way.

A few offices that border each other are very consistent in their POD and SR values. This can be seen by the fact that they are very close or overlapping in Fig. 19. Both the San Angelo, TX (SJT) and Midland, TX (MAF) offices have a POD of approximately 73% and an SR of about 28%. While this certainly is not the highest SR that an office has, it is notable because of the bordering of the two offices. Similar pairings are the Topeka, KS (TOP)/Dodge City, KS (DDC) offices and the Quad Cities, IA (DVN)/La Crosse, WI (ARX) offices. These consistencies could suggest possible similarities in office policy regarding the issuance of warnings or an increased amount of communication between the two offices compared to other offices across the U.S.

Fig. 19 shows the same data as Fig. 18 but is colored-coded by NWS Region. As shown in the graph, Eastern Region offices are clustered together toward the upper right, indicating a higher POD and SR. A possible explanation for this is that the East Coast tends to have higher population densities than in other regions, so more people are available to submit LSRs. There could also be differences in warning procedure that contribute to these better quality statistics. Additionally, it is evident that offices in the Western Region have more variance in POD and SR, but in general are worse than offices in other regions. This could be explained by lower population densities (which could lead to a lower number of severe events being reported in LSRs), but could also be because of the lower number of warnings issued by these offices in a given year (see Fig. 3). As with Medford, Seattle, and San Francisco, other offices in the Western Region may have statistics that don't accurately represent the quality of forecasts due to their small sample sizes.

While most offices improved in POD and SR, some offices did not. In fact, eight offices decreased in both POD and SR. Four of these offices were from the Western Region: Elko, NV (LKN), Los Angeles, CA (LOX), Salt Lake City, UT (SLC), Tucson, AZ (TWC). There were also two from each the Central Region: Gaylord, MI (APX) and Marquette, MI (MQT), and the Southern Region: Key West, FL (KEY) and Lake Charles, LA (LCH). Eight offices out of 116 decreasing in POD and SR means that the majority of offices increased in POD and SR with the switch from CBWs to SBWs. Thus, the NWS did generally achieve its goal of improving warning quality, at least with regards to POD and SR.

IV. Future Work

This project has just scratched the surface of warning verification and how offices differ when issuing warnings. The groundwork has been laid for later study regarding statistics on lead time, warning length, size and shape of warnings, and forecast quality, but the social side of warning verification remains untouched.

An additional characteristic that could be studied is the total amount of time spent under warnings for each WFO. This would combine the length of warning data with the normalized number of warnings per year data. The benefit would be to see if different

WFOs have warnings in place more often, rather than just looking strictly at the number of warnings issued. One office may issue many shorter warnings, while a different office issues fewer but longer warnings. For statistics concerning warning size, the data could be normalized by the average county size in a given CWA. This would change maps like the size percentage map (Fig. 14) by showing the reduction in warning size from CBW to SBW, without regards to county size. This would allow for better comparison of the offices in the Western U.S. to the offices in the Eastern U.S. in terms of size reduction.

For both the lead time/length data and the size/shape data, statistical analysis can be applied. A useful analysis in this case would be the Weibull distribution, which would compare offices not only on the basis of mean values, but also their variance. Examining trends in each specific office for each of the calculated variables would show how offices have changed over time in their warning issuing procedures.

Accounting for bad data is another task that will need to be undertaken. IEM Cow was used because it already contained the time and size data for each warning, but there were several holes in the LSR data acquired. As stated previously, the Springfield, MO (SGF) office had data issues which prevented the calculations of lead time and other statistics. Possibly getting information from the National Weather Service directly and comparing it to the IEM Cow data for accuracy would assure that the correct data was used for the various analyses.

The social side of warning verification is a key element that was not discussed in this paper, but is an area that needs extensive study. Peter Wolf (2009) emphasizes the social aspect when he writes, “Warning accuracy and timeliness statistics are not meaningful if the products are not received and utilized by the public in a timely manner.”

The question this raises is whether national standards on warning verification are valuable in determining warning success when the purpose of warnings are to spark actions and response on a local level.

Mark Fox, the WCM at the Fort Worth office, stated that warnings are local decisions and the local WFOs know the local needs best (Fox 2013, personal communication). These needs include how emergency managers, the media, and the public best respond to the various warning situations. Do these groups of people like larger warnings, or would they prefer smaller warnings that geographically overlap each other? The local offices are the ones that hear this feedback, so they make adjustments accordingly. In a paper by Call (2009), WCMs were surveyed to find out which watch and warning procedures were used during ice storms. The study found that forecasters at various offices take into account hazards that are specific to their local area, and these results can likely be applied to severe warnings as well. The paper also noted that “an accurate warning that is not heard or acted upon is of limited value.”

The question of how to go about measuring these social responses is a tough one to answer. Different types of people will respond differently to warnings based on location, background, economic status, and many other factors. Meteorology has recognized the need to study the social aspect of weather warnings, but it has yet to associate the response with official verification. Some studies have started to examine how the public reacts to severe weather warnings. Hoekstra et al. (2010) found that the public actually prefers a certain range in lead time that allows them time to react to the oncoming hazard, but also is not so far in advance that they won’t react with urgency. The meteorological aspects that govern lead time, warning size, and the quality of warnings are well documented, but the social part of warning verification will continue to evolve as social science becomes a key complement to meteorology.

V. Conclusion

This study analyzed severe thunderstorm and tornado warnings issued in the continental U.S. from 2005 to 2012. Characteristics examined for each WFO included: average number of warnings per year, average length and lead time of warnings, warning sizes and shapes, and forecast quality statistics. These characteristics were then compared by NWS Region and the switch from county-based warnings to storm-based warnings, which occurred in 2007. From the analysis, it was concluded that the switch did in fact help to standardize the size warnings issued across the nation. It also improved forecast accuracy by increasing both the Probability of Detection and Success Ratio, which was one of the goals of switching to a system where storms were warned using polygons instead of counties.

On the other hand, the average amount of lead time a person could expect from a storm did not significantly change from the CBW era to the SBW era. In general, as the number of warnings issued by each WFO increased, the amount of change caused by the switch was decreased, and the number of offices that increased in lead time was about the same as the number of offices that decreased. It was also determined that both lead times and lengths of warnings were variable across the U.S., and did not conform to an easily distinguishable pattern.

From looking at the perimeter ratio statistics, it is obvious that even after the switch to storm-based warnings, some offices continued to warn a moderate portion of storms along county boundaries. This can, at least in part, be explained by the office's desire to issue warnings based on local needs. The decision of how to warn a storm is not purely a meteorological one, as the forecasters must also consider how the public can best understand the warning that is issued. The social aspects of warning storms are something that will need to be studied further in the future.

Acknowledgements

The authors would like to thank their mentors, Dr. Harold Brooks and Kim Klockow, for their consistent help and advice, as well as Dr. Brian Fiedler and Dr. Patrick Marsh, both of the University of Oklahoma, for assisting us with Python scripting. They would also like to thank Daryl Herzmann for providing them with data from the Iowa Environmental Mesonet.

References

Brooks, H. E., 2004: Tornado-warning performance in the past and future: a perspective from signal detection theory. *Bull. Amer. Meteor. Soc.*, **85,** 837-843.

Call, D. A., 2009: An assessment of national weather service warning procedures for ice storms. *Wea. Forecasting*, **24**, 104–120.

Hoekstra, S., H. Brooks, J. Brotzge, S. Erickson, K. Klockow, and R. Riley, 2010: A preliminary look at the social perspective of warn-on-forecast: preferred tornado warning lead time and the general public's perceptions of weather risks. *Wea. Climate Soc.*, **3**, 128-140.

Iowa Environmental Mesonet, cited 2013: IEM Cow (NWS Storm Based Warning Verification). [Available online at http://mesonet.agron.iastate.edu/cow/.]

National Severe Storms Laboratory, cited 2003: Hail Days Per Year (1980-1999). [Available online at http://www.nssl.noaa.gov/projects/hazard/img/thai8099.gif.]

National Severe Storms Laboratory, cited 2003: Tornado Days Per Year (1980-1999). [Available online at http://www.nssl.noaa.gov/projects/hazard/img/ttor8099.gif.]

National Severe Storms Laboratory, cited 2003: Wind Days Per Year (1980-1999). [Available online at http://www.nssl.noaa.gov/projects/hazard/img/twin8099.gif.]

National Weather Service, cited 2008: Why Storm-Based Warnings?. [Available online at http://www.nws.noaa.gov/sbwarnings/.]

National Weather Service, cited 2010: National & Regional Offices. [Available online at http://www.srh.noaa.gov/jetstream/nws/regions.htm.]

National Weather Service, cited 2012: Weather Forecast Offices. [Available online at http://www.srh.noaa.gov/jetstream/nws/wfos.htm.]

Roebber, P. J., 2009: Visualizing multiple measures of forecast quality. *Wea. Forecasting*, **24**, 601–608.

Wolf, P. L., 2009: Warning success rate: increasing the convective warning’s role in protecting life and property. *Electronic J. Operational Meteor.*, **10 (7)**, 1–17.

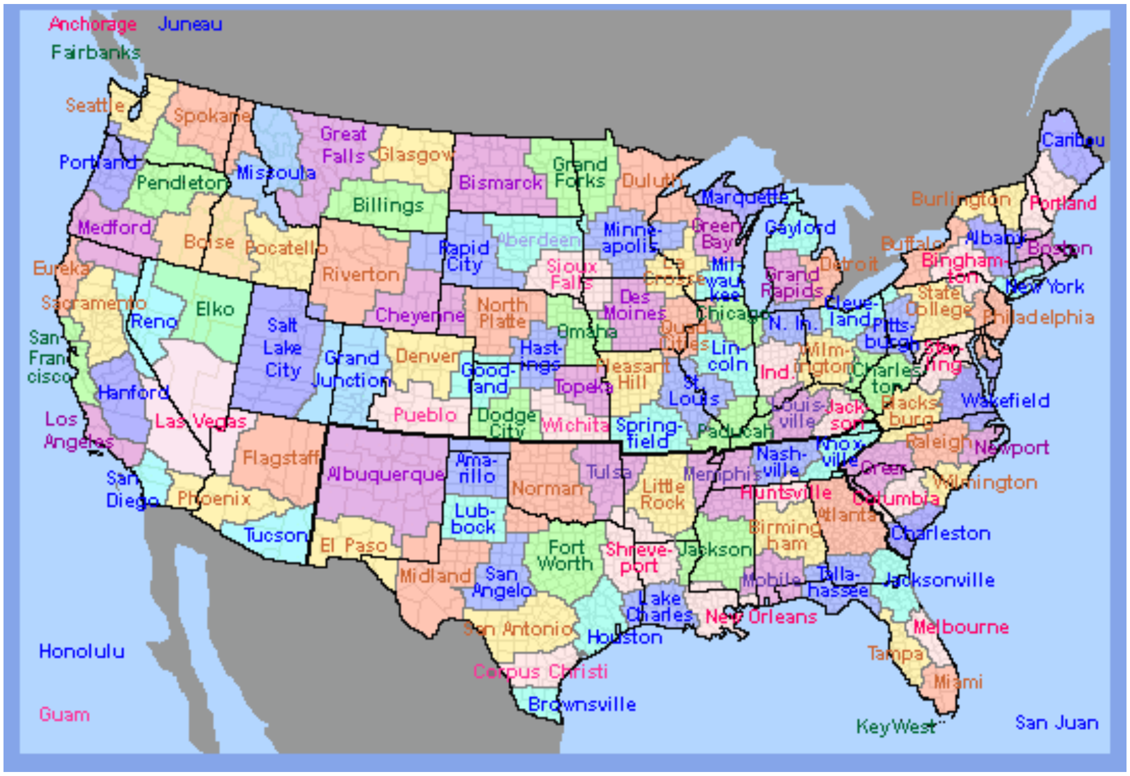

Figure 1 : Map of National Weather Service County Warning Areas (National Weather Service)

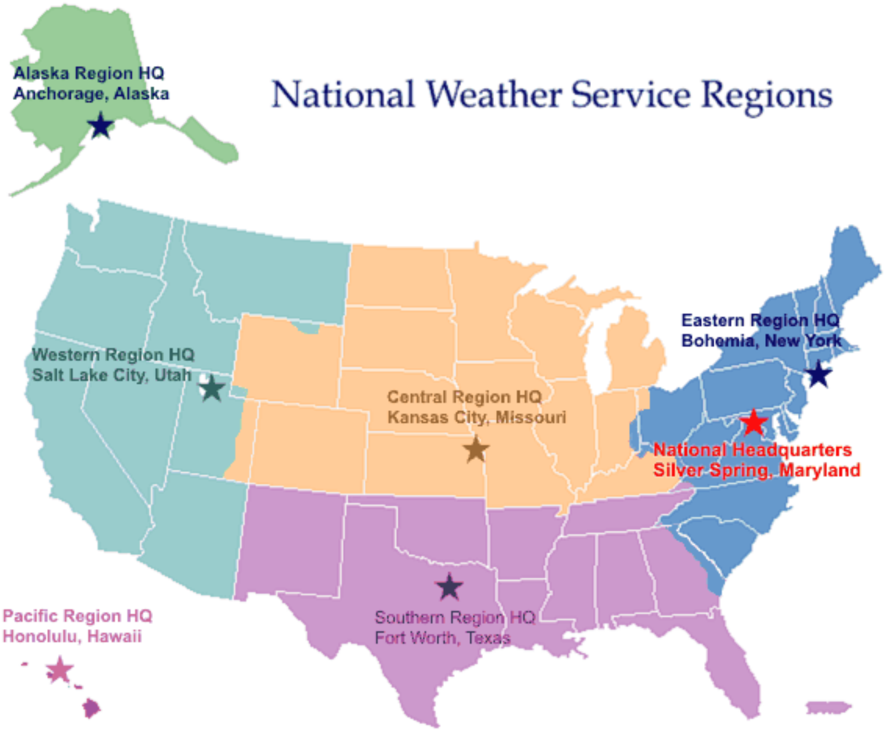

Figure 2: National Weather Service Regions (National Weather Service)

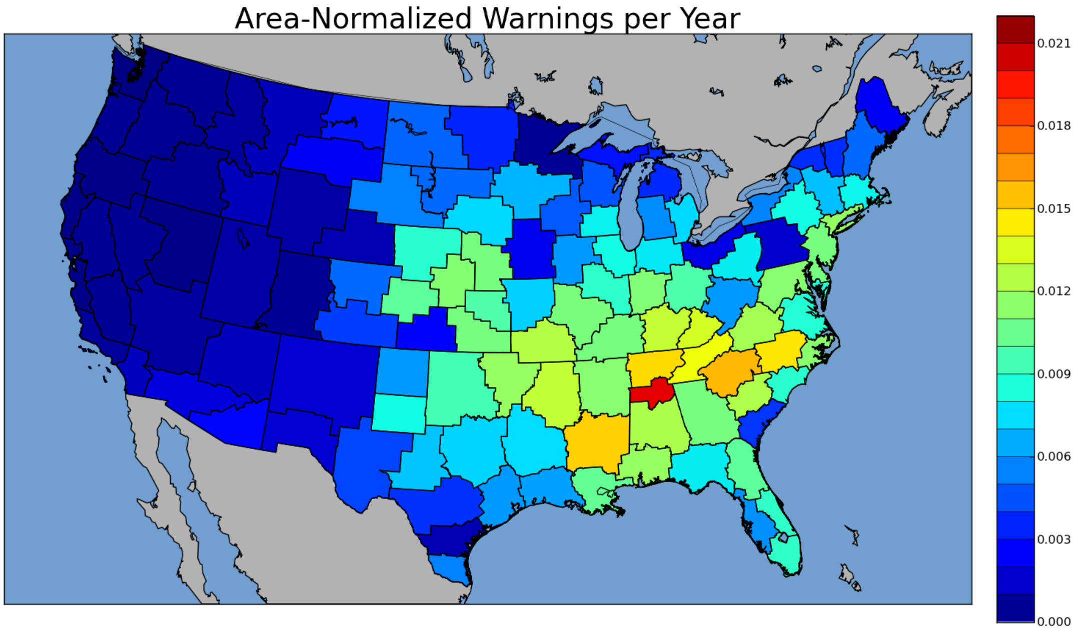

Figure 3: Area-Normalized Warnings Per Year

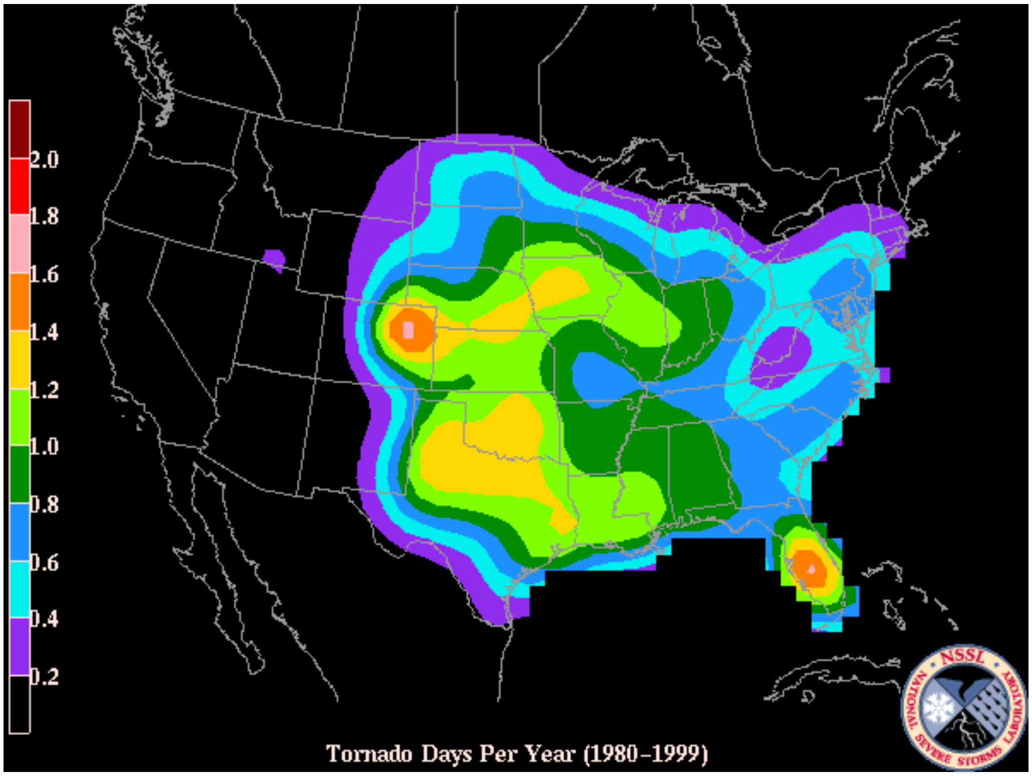

Figure 4: Tornado Days Per Year (National Severe Storms Laboratory)

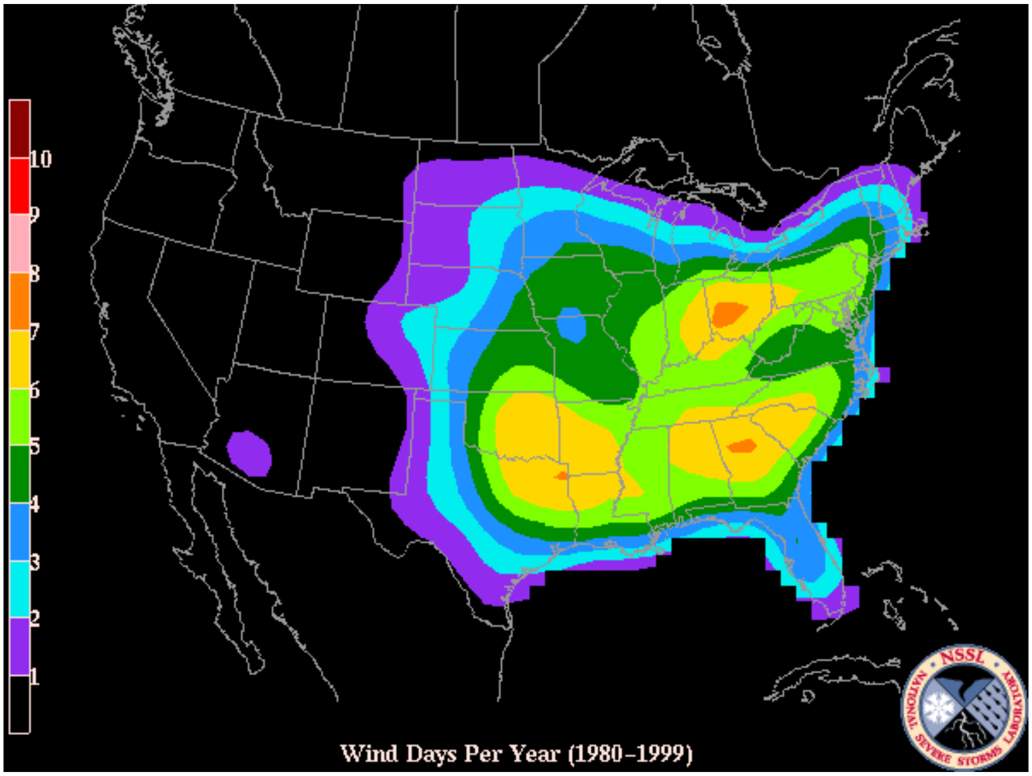

Figure 5: Wind Days Per Year (National Severe Storms Laboratory)

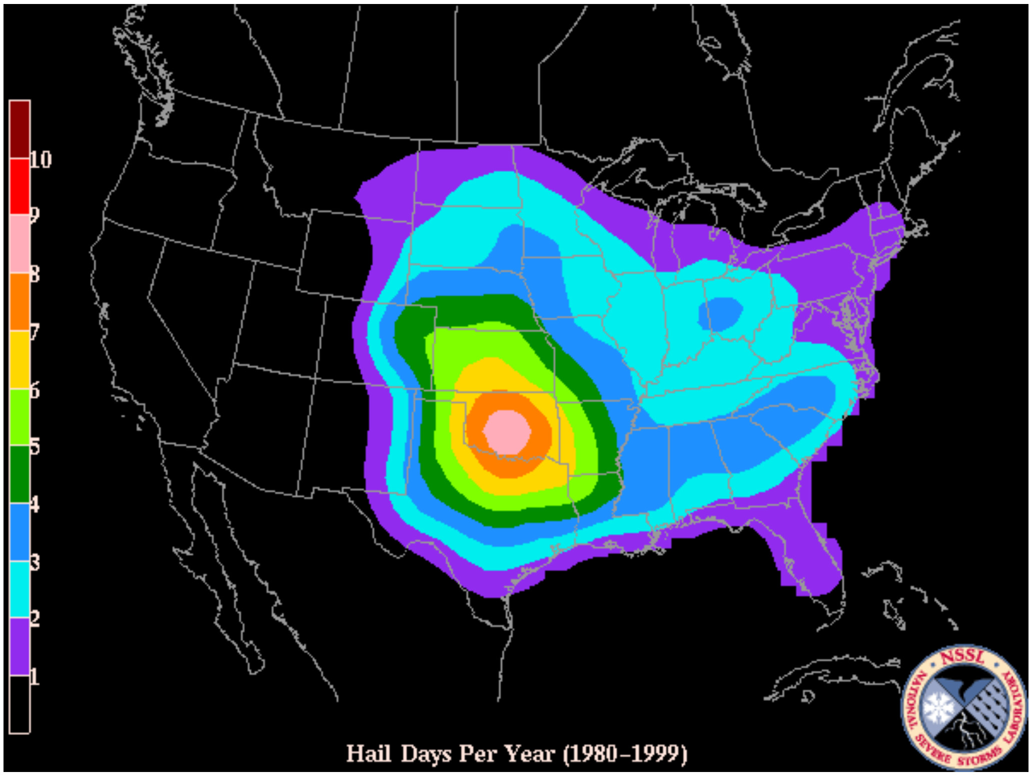

Figure 6: Hail Days Per Year (National Severe Storms Laboratory)

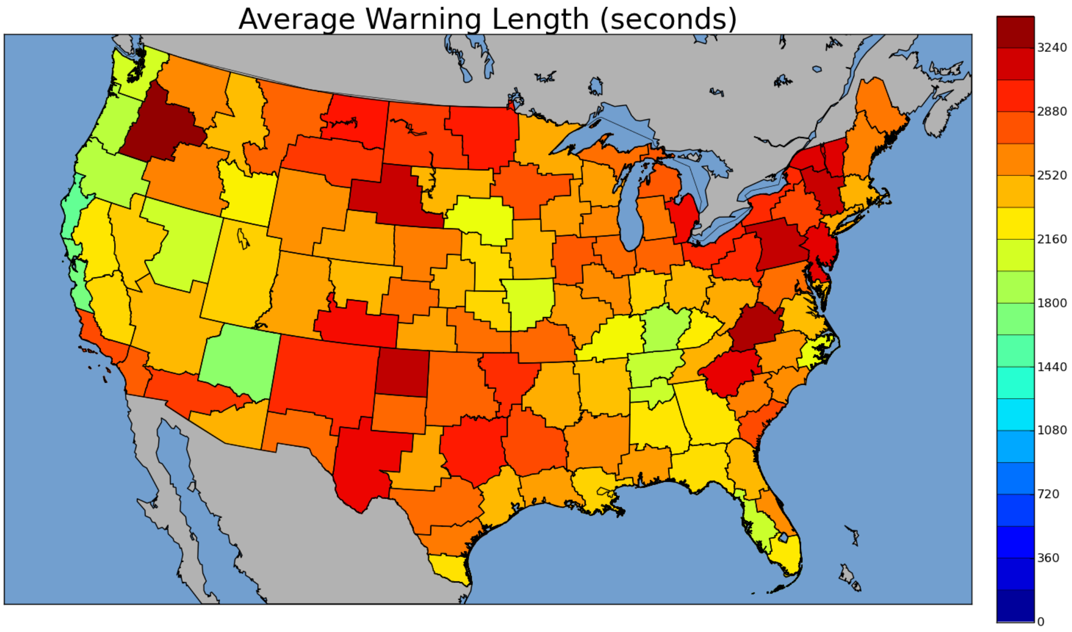

Figure 7: Average Warning Length in Seconds from 2005 – 2012

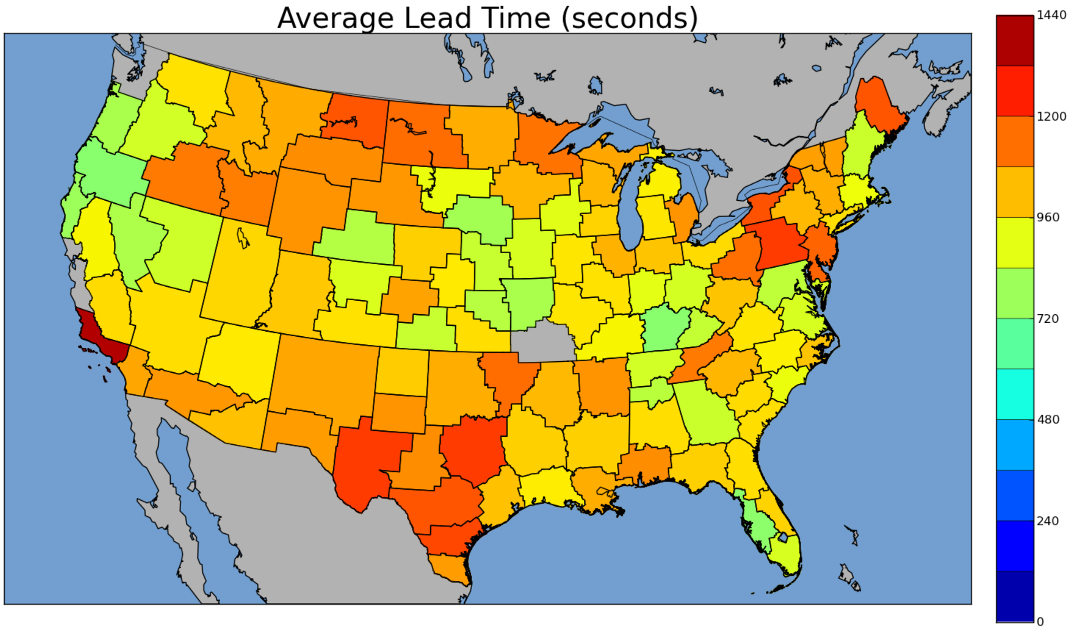

Figure 8: Average Warning Lead Time in Seconds from 2005 - 2012

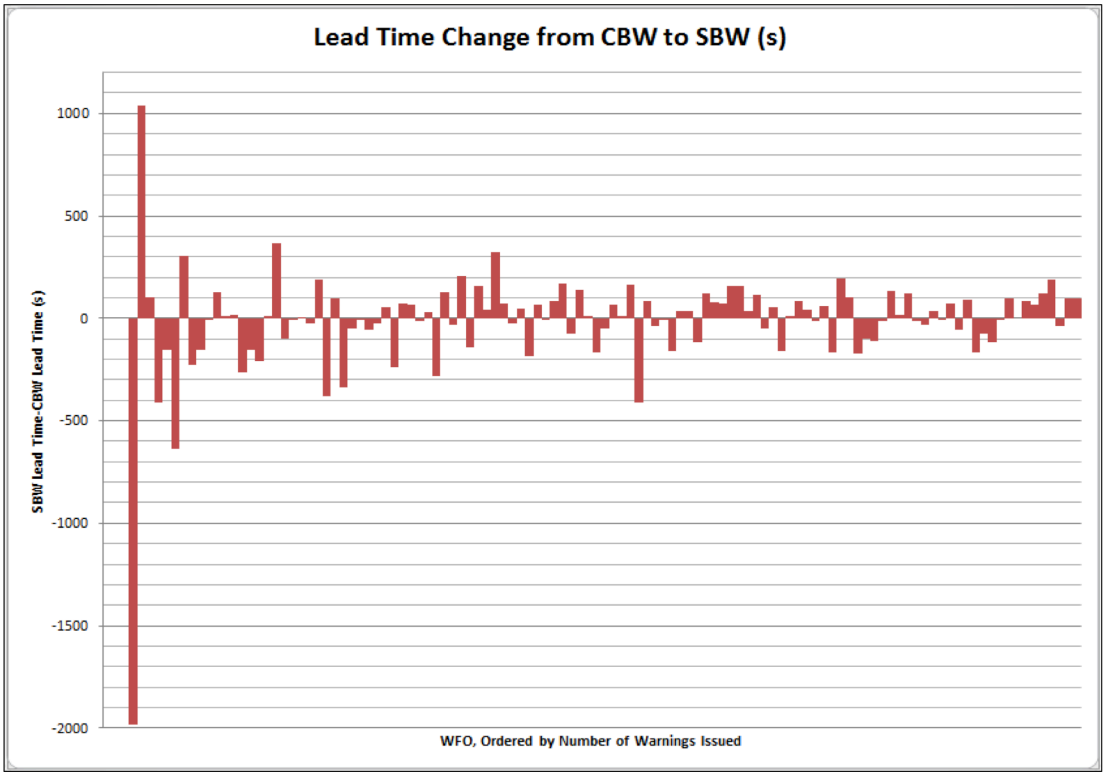

Figure 9: Lead Time Change from County Based Warning to Storm Based Warning in Seconds

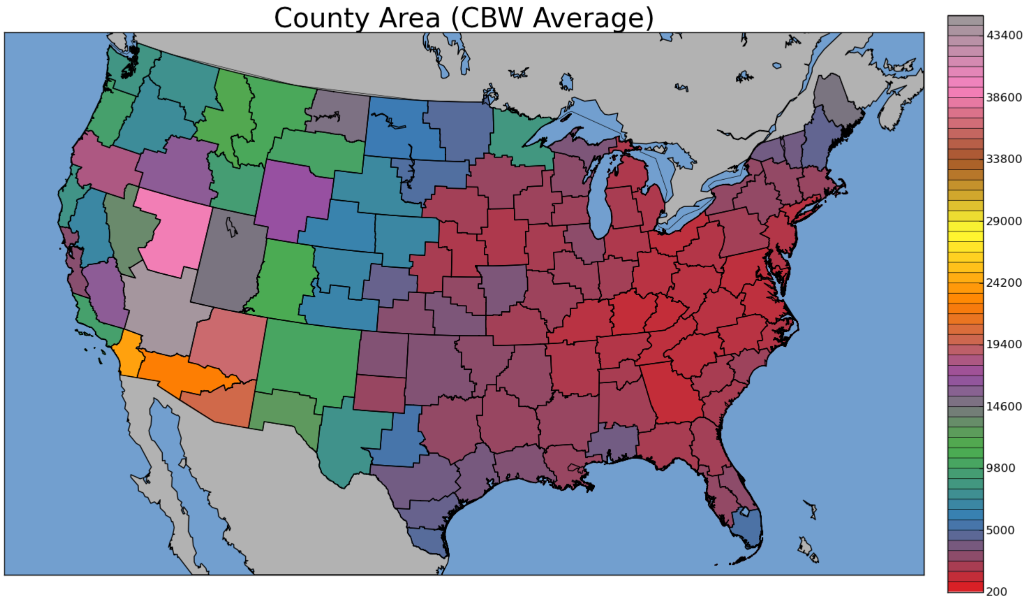
County Area (CBW Average)

Figure 10: Average County Based Warning Size during the County Based Warning Era in Kilometers Squared

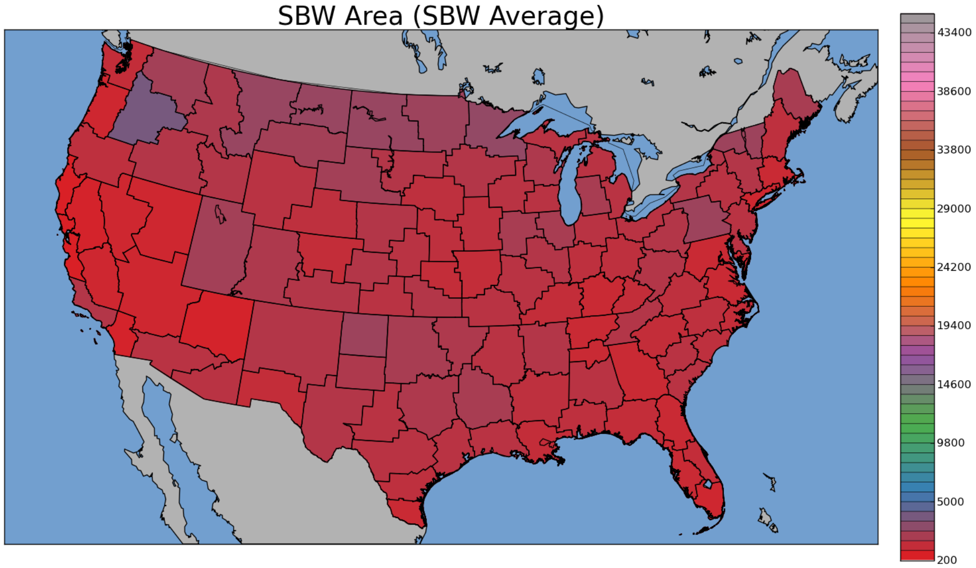
SBW Area (SBW Average)

Figure 11: Average Storm Based Warning size during the Storm Based Warning Era in Kilometers Squared. This image is in the same color scale as Figure 10 to show the size reduction and the uniformity in warning size.

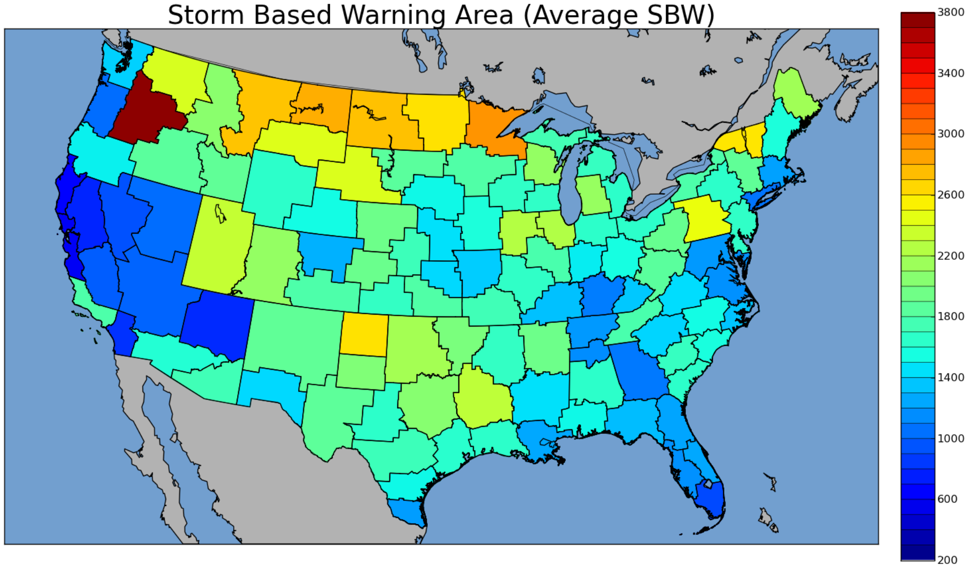

Figure 12: Average Storm Based Warning size during the Storm Based Warning Era in Kilometers Squared.

This figure uses a different color scale to show the variation between offices.

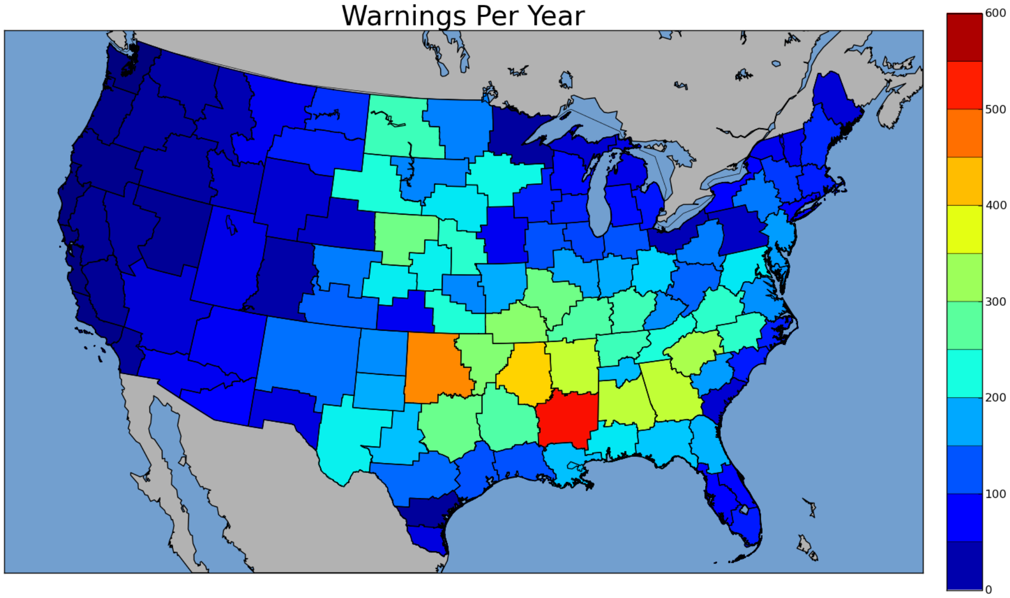

Figure 13: Average Warnings Per Year.

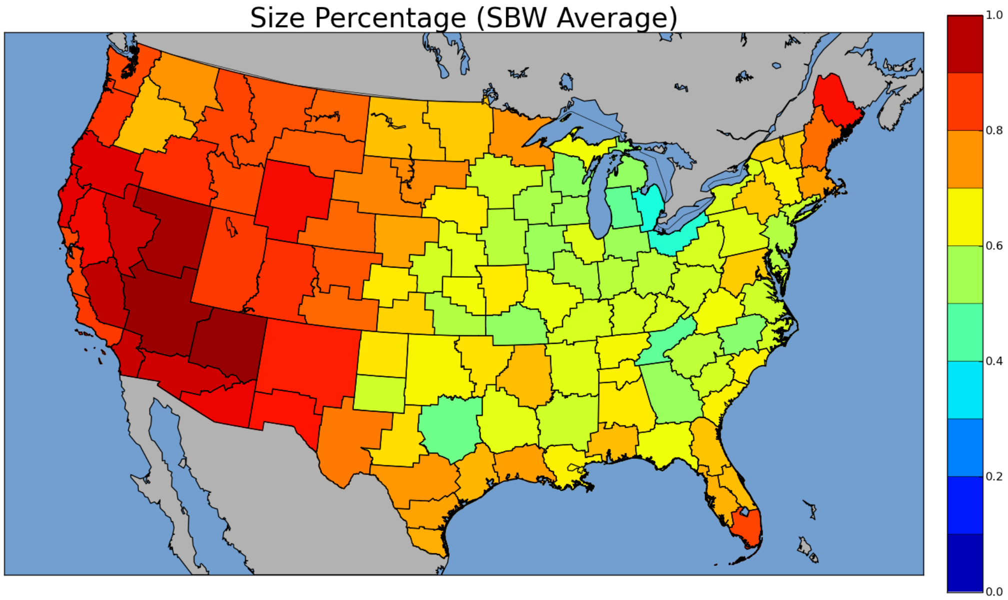

Figure 14: Warning Size Percentage. This shows the percent reduction in size from the County Based Warning to Storm Based Warning.

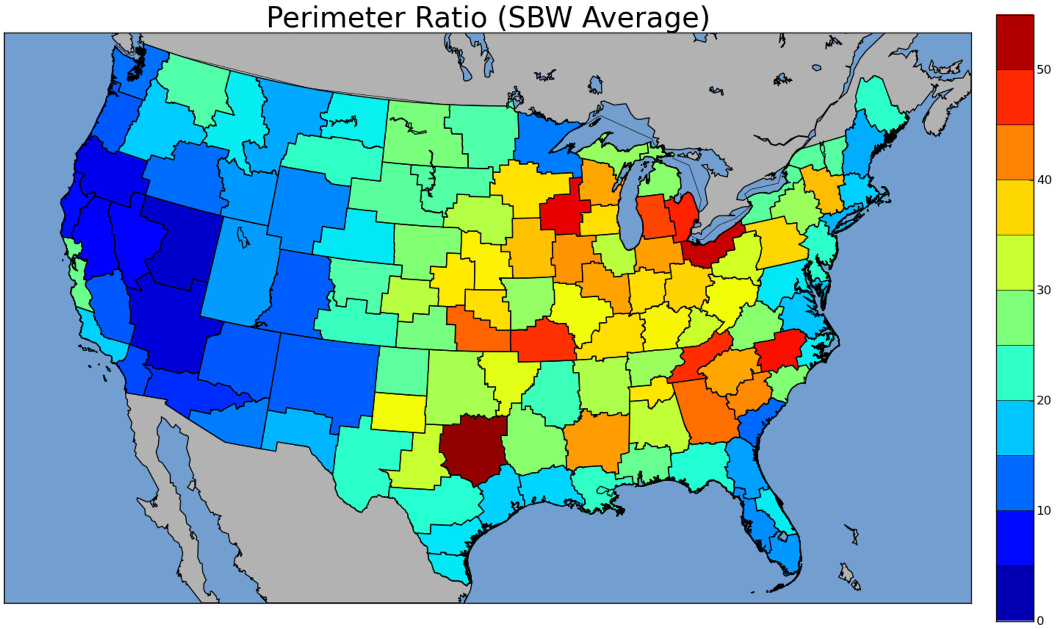

Figure 15: Perimeter Ratio during the Storm Based Warning Era

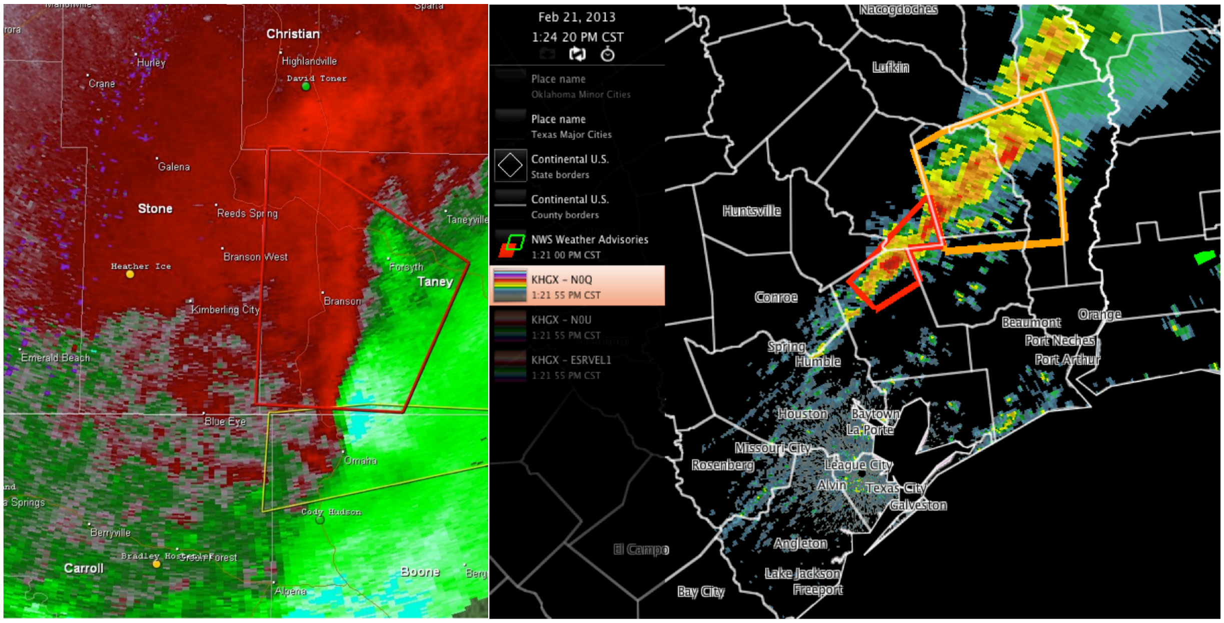

Figure 16: CWA Border Case Study.

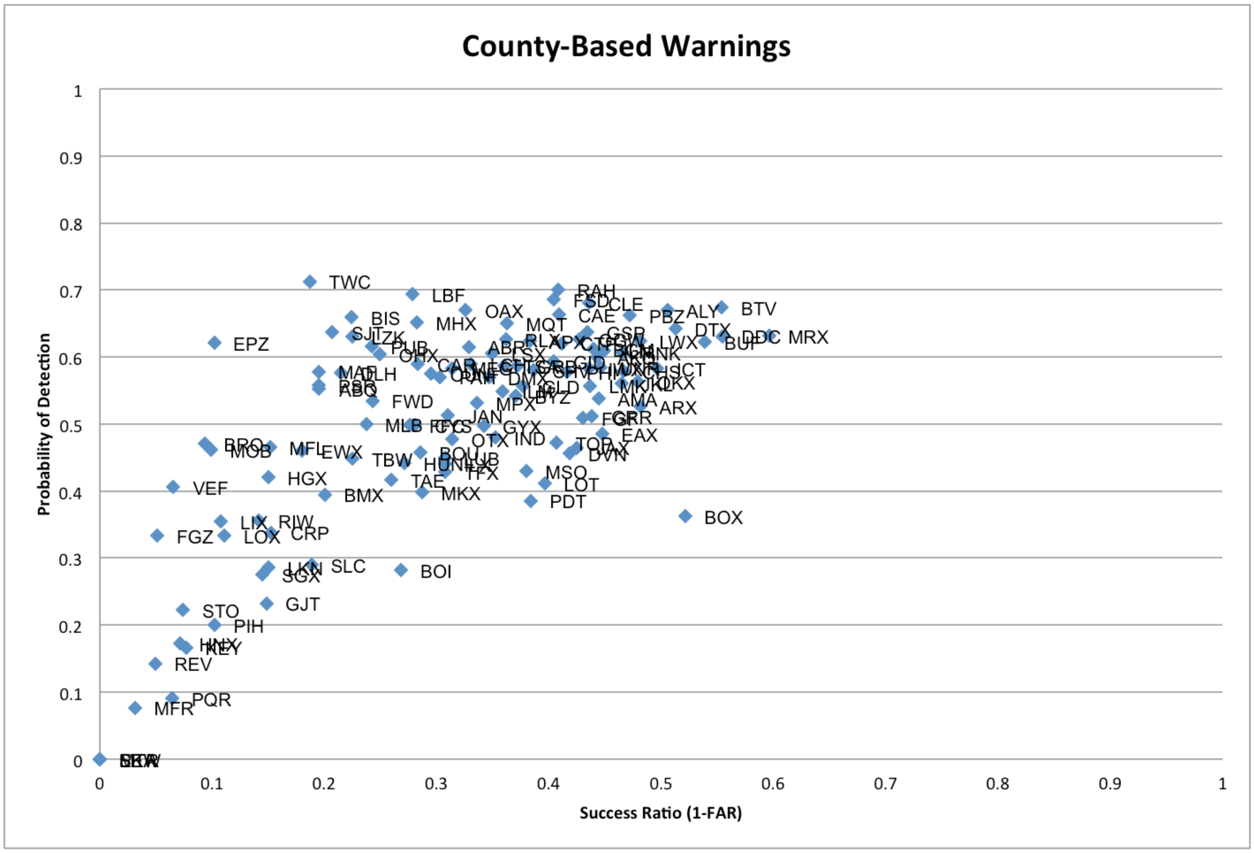

Figure 17: Performance Diagram for the County Based Warning Era

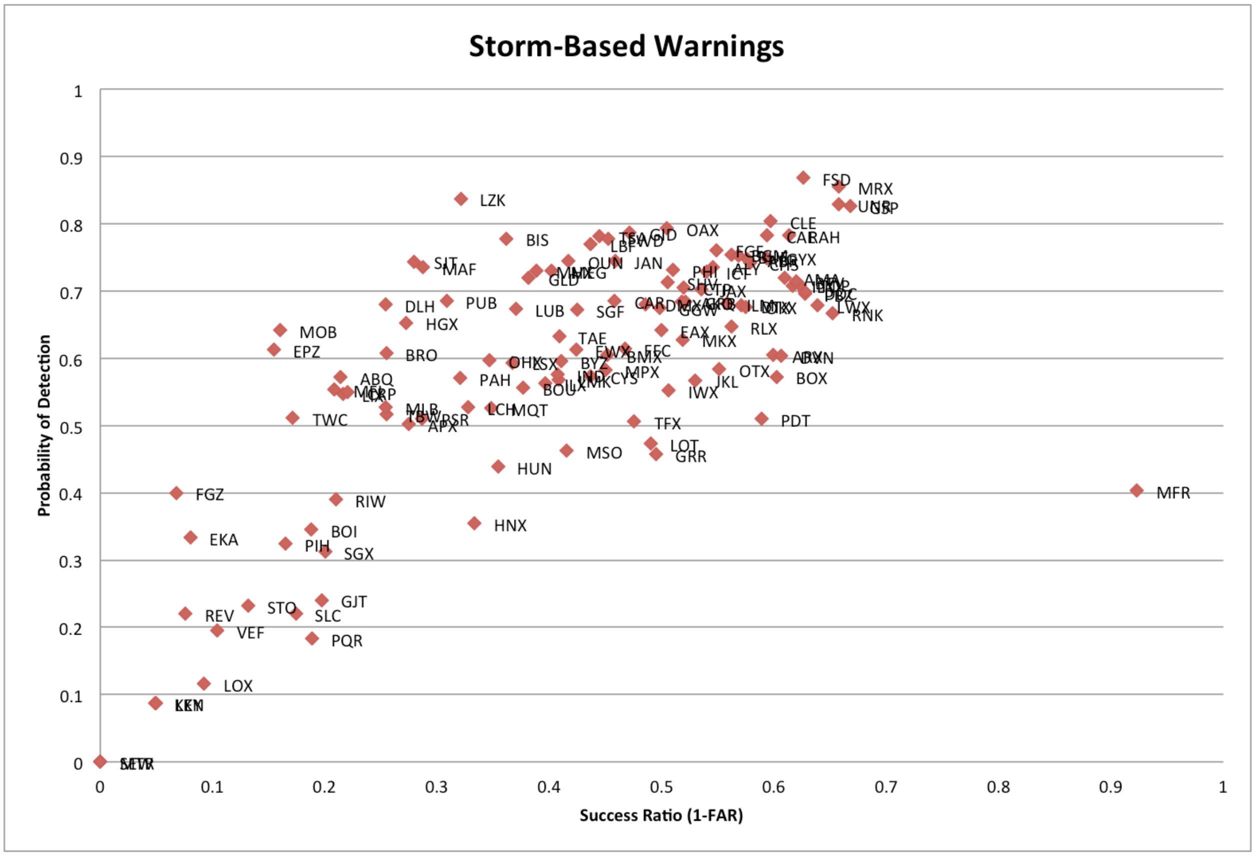

Figure 18: Performance Diagram for the Storm Based Warning Era

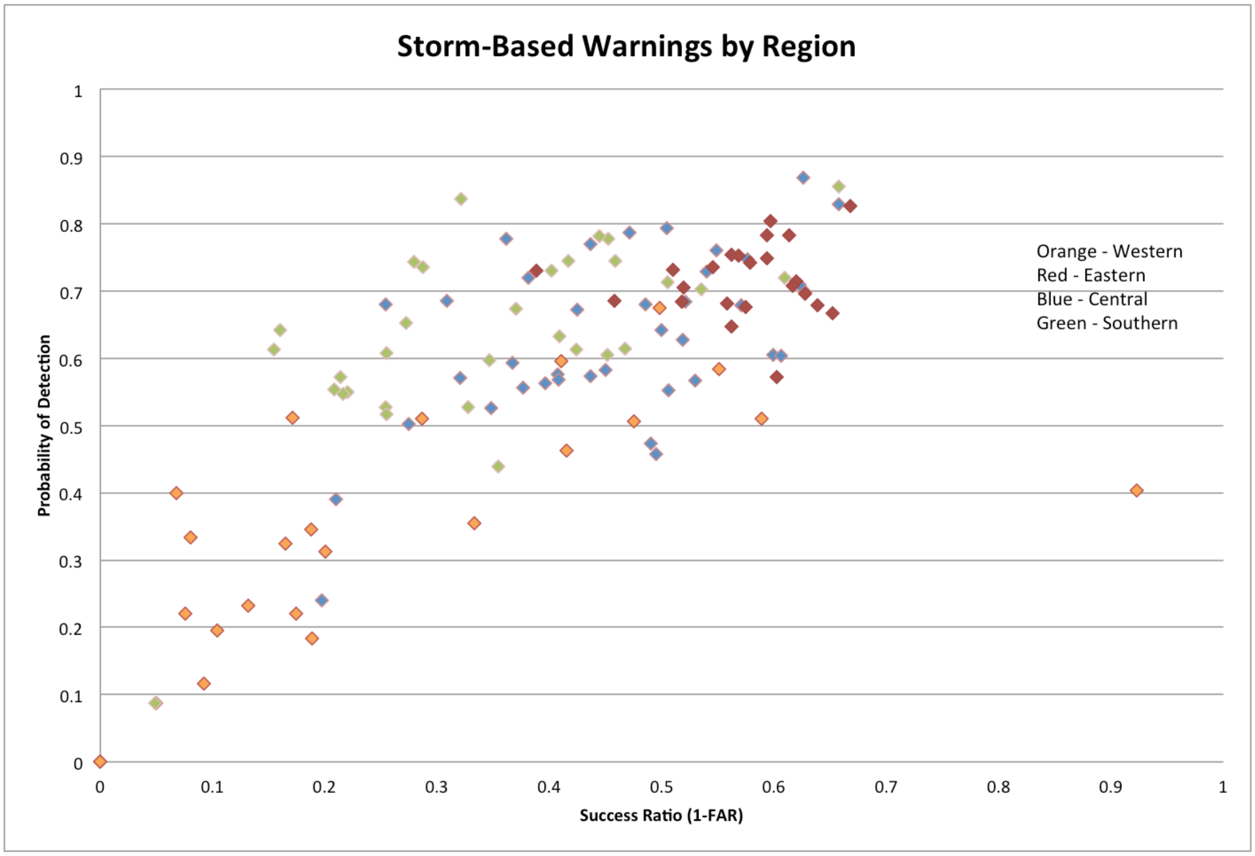

Figure 19: Performance Diagram for the Storm Based Warning Era Color-Coded by Region