

A Climatology of Operational Storm-Based Warnings: A Geospatial Analysis

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ABSTRACT

This study provides a quantitative climatological analysis of the fundamental geospatial components of storm-based warnings and offers insight into how the National Weather Service (NWS) uses the current storm-based warning system under the established directives and policies. From October 2007 through May 2016, the NWS issued over 500 000 storm-based warnings and severe weather statements (SVSs), primarily concentrated east of the Rocky Mountains. A geospatial analysis of these warning counts by county warning area (CWA) shows local maxima in the lower Mississippi valley, southern plains, central plains, and the southern Appalachians. Regional uniformity exists in the patterns of average speed and direction provided by the time/motion/location tags, while the mean duration and polygon area varies significantly by CWA and region. These observed consistencies and inconsistencies may be indicative of how local weather forecast office (WFO) policy and end-user needs factor into the warning issuance and update process. This research concludes with a comparison of storm-based warnings to NWS policy and an analysis of CWAs with the greatest number of warnings issued during a single convective day.

1. Introduction

On 1 October 2007, the National Weather Service (NWS) began issuing storm-based warnings, which use a dynamically created polygon and text product to convey information about meteorological hazards such as tornadoes, hail, and damaging winds. Storm-based warnings, which replaced the original method of issuing warnings based on geopolitical boundaries, hypothetically allow NWS meteorologists to alert only those in immediate danger from a storm and provide the public with more specific information about the potential impacts of the hazard (NWS 2009). After an initial warning is transmitted to the public, forecasters are able to issue updates for that warning via a separate product, known as a severe weather statement (SVS). An SVS can be used to update a warning with new information such as a spotter report, correct errors in a warning, notify the public that a warning will be allowed to expire, or cancel a warning if the storm moves out of the warned area or weakens below severe thresholds.

When storm-based warnings were initially introduced, it was believed that they would be able to significantly reduce the area covered by a warning and minimize the impact on residents outside the threat area (NWS 2009). Sutter and Erickson (2010) quantified this point by determining that storm-based warnings reduce the amount of time spent under a tornado warning by as much as 66 million person hours per year with an economic impact of about \$750 million annually. Despite these improvements, many of the issues previously associated with county-based warnings are still present under the new warning system. For example, both Nelson et al. (2012) and Klockow et al. (2012) identified undesirable public response as a contributing factor to the number of casualties that resulted from the 27 April 2011 tornado outbreak despite above-average lead time and probability of detection (POD). Similarly, Brotzge and Donner (2013) recognized warning dissemination and public response as two challenges that limit the effectiveness of the current warning system. Because of these inadequacies, there has been a push in recent years to develop new methods of creating and disseminating critical weather

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SVSOUN

SEVERE WEATHER STATEMENT
NATIONAL WEATHER SERVICE NORMAN OK
401 PM CDT MON MAY 20 2013

OKC027-202111
/O [CAN] [KOUN] TO.W [0029] 000000T0000Z-130520T2115Z/
CLEVELAND OK-
401 PM CDT MON MAY 20 2013

...THE TORNADO WARNING FOR EXTREME NORTHEASTERN CLEVELAND COUNTY IS
CANCELLED...

THE TORNADIC THUNDERSTORM WHICH PROMPTED THE WARNING HAS MOVED OUT
OF THIS AREA. THEREFORE THE WARNING HAS BEEN CANCELLED.

LAT...LON 3541 9704 3542 9720 3545 9726 3553 9705
TIME...MOT...LOC 2101Z 242DEG 27KT 3545 9717
$$

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FIG. 1. Example of a typical severe weather statement for a tornado warning. The product action code, CWA, event tracking number, polygon vertex coordinates, and time/motion/location tag have been annotated.

information to those threatened by severe storms, such as Forecasting a Continuum of Environmental Threats (FACETs; Rothfus et al. 2014; Karstens et al. 2015).

Before new warning systems can be fully developed and implemented, it is crucial to have an understanding of how NWS meteorologists use the existing system. For instance, how many warnings were issued annually, and how did warning forecasters make use of SVS updates? How did the warnings vary by county warning area (CWA)? Did the warnings follow NWS directives and recommendations? Were the warnings generally representative of the speed, direction, size, and duration of the observed phenomena? These and similar questions could potentially play a major role in the development of new policy and software. However, up to now there have been few formal studies that climatologically analyze such fundamental components of storm-based warnings. It is the objective of this study to address the aforementioned questions and provide a climatological geospatial analysis of storm-based severe thunderstorm (SVR) and tornado (TOR) warnings, along with attendant SVS products, issued since October 2007, and to identify any emerging patterns in the data. Furthermore, the results of this study will ideally establish a foundation for future research that may contribute to the development of a new or improved warning paradigm.

2. Data and analysis procedures

This study focuses exclusively on TOR and SVR storm-based warnings and associated SVS products issued within the continental United States (CONUS)

between 1 October 2007 and 31 May 2016. Archived products were obtained from the Iowa Environmental Mesonet (2002), and information was systematically extracted from the warning text and converted into shapefile format. For example, information representing the fundamental characteristics of a storm-based warning (i.e., start time, end time, speed, direction, area, and duration at time of issuance) were placed into columns of the shapefile attribute table, while the geospatial representation of the warning (i.e., polygon vertices) was used to create polygon features within the shapefile. In addition, warnings were categorized by CWA, product, action code, and event tracking number (ETN). For the purpose of this article, the product type was limited to TOR, SVR, or SVS. Similarly, a warning's action code was defined as a new warning (NEW) while SVS updates were classified as a continuation (CON), correction (COR), cancellation (CAN), or expiration (EXP) of the original warning based on the tag provided in the header of the product text (Fig. 1). Two SVSs within the dataset did not fall into any of the previously described categories and were excluded when performing calculations based on action code. A full list of the variables and their units can be found in Table 1. Because data were obtained from a third-party source, some of the analyses presented hereafter may differ slightly from the official numbers offered by the NWS.

Storm-based warnings are designed to replace the method of warning storms based on geopolitical boundaries, yet they are still coded by the counties or parishes that they cover. As a result, SVSs that reduce the size of a

TABLE 1. Variables obtained or derived from the product text.

Variable	Unit/format
County warning area	
Product	TOR, SVR, or SVS
Event tracking No.	
Action code	NEW, CON, COR, EXP, or CAN
Start time	hhmmz
End time	hhmmz
Speed	kt
Direction	°
Area	km ²
Duration	min
(at time of issuance)	

warning polygon to completely remove a previously covered county automatically include a CAN for the excluded county along with a CON for the updated warning. To avoid inflating the number of CANs issued by each CWA, SVSs that included both a CON and a CAN were considered to be a single CON product. Therefore, CAN in this study refers to warnings that were explicitly canceled by warning forecasters.

To better analyze the characteristics of SVS and their relationships with storm-based warnings, it was often necessary to look at warning events rather than each product individually. A warning event was defined as one NEW warning and any SVS that contained a matching ETN. Because ETNs are only unique in a single CWA for a single year, the products had to first be divided up by CWA and year before they could be organized into warning events. In a few cases, some products were issued hours apart but erroneously contained the same ETN. To remedy this, any products issued more than 3 h after the first NEW warning in a warning event were assigned a different ETN carefully chosen to not conflict with any other warnings in the subset.

Along with the 10 attributes mentioned previously, this study also looked at two items derived from the base information: warning update frequency and CWA warning production. Here, the warning update frequency was defined as the amount of time between the start times of a NEW warning and any SVS update in a single warning event. This derived attribute, combined with the 10 primary attributes listed previously, is hypothesized to offer insight into the operational use of SVSs in the present warning system. Of particular interest to this study was the CWA warning production on a given severe weather day. For this paper, the CWA warning production was defined as the number of NEW warnings issued across a single CWA during one convective day (1200–1200 UTC) for all days with at least one warning issued. To avoid introducing a bias from warning events with multiple

SVS updates, SVSs were excluded when calculating warning production.

3. Results and discussion

a. Overview

The NWS issued 507 064 storm-based warnings and accompanying SVS products between 1 October 2007 and 31 May 2016 with an average of about 69 102 warning-related products per year. Of these products, there were 24 990 TORs and 167 025 SVRs within the dataset, averaging about 3363 and 22 780 per year, respectively. A yearly breakdown of warning-related products is provided in Fig. 2a for reference. TORs in particular exhibited a significant reduction (56%) in the total number of warnings issued during the years 2012–15 compared with those issued during 2008–11. This reduction corresponds to a 47% decrease in the total number of tornado reports received during the respective periods (SPC 2016). Note that 2007 and 2016 are incomplete datasets and were excluded when calculating yearly averages.

NEW warnings made up about 37.9% of all action codes issued during the 8-yr period, with a total of 192 015. The remaining 315 049 SVSs were divided up into 211 259 CONs, 66 828 EXPs, 36 536 CANs, and 424 CORs. As mentioned in the previous section, two SVS products did not match any of these action codes and were excluded. A yearly breakdown of warning-related products by action code can be seen in Fig. 2b. Overall, CON updates made up the largest portion of all action codes at about 41.7%. EXPs made up about 13.2% and CANs had approximately 7.2%. Less than 0.1% of the products issued were CORs.

A majority of the products issued between October 2007 and May 2016 were for locations in the eastern two-thirds of the CONUS or roughly east of the Rocky Mountains. In particular, four distinct maxima in the total number of warning-related products emerged geospatially after sorting the products by CWA (Fig. 3a). The two largest maxima spanned the southern plains and lower Mississippi valley regions and overlapped at the Little Rock, Arkansas (LZK), CWA. In the southern plains, Norman, Oklahoma (OUN), issued 13 266 warnings-related products while Jackson, Mississippi (JAN), issued a total of 15 064 in the lower Mississippi valley. A third maximum occurred in the central plains and was centered over North Platte, Nebraska (LBF), which issued 9506 total warnings and SVSs. The final maximum and spatially smallest of the four occurred in the southern Appalachians region and was attributable to the Greenville, South Carolina (GSP), CWA where 10 423 products were issued during the 8-yr period.

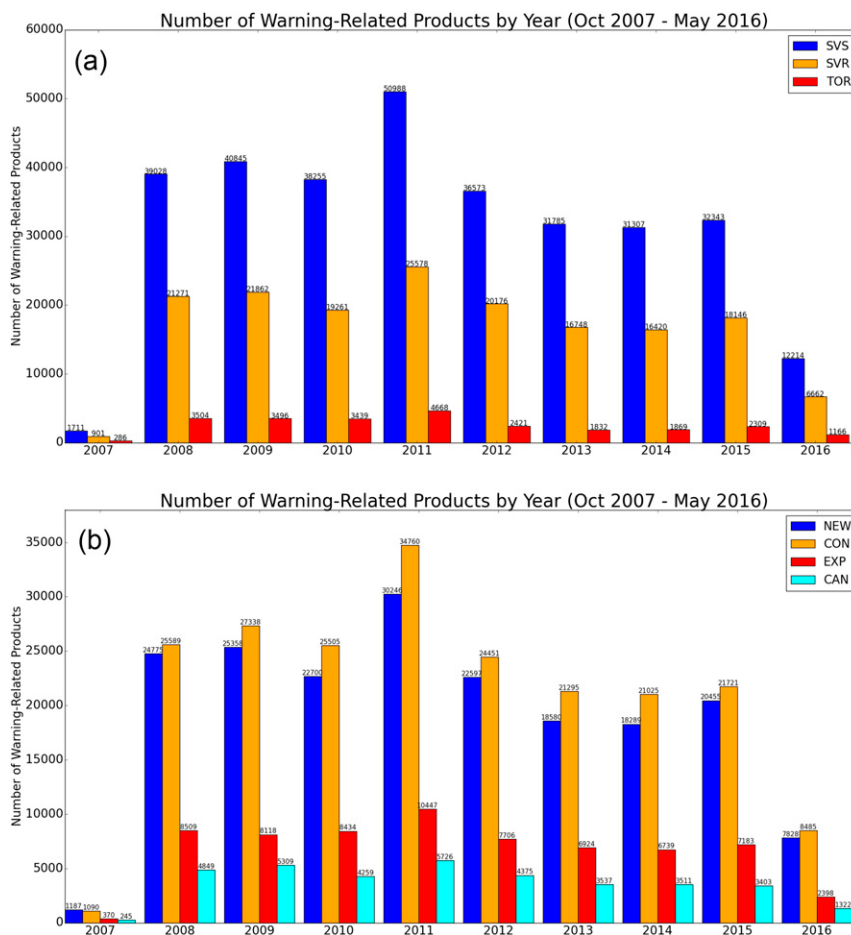


FIG. 2. Number of warning-related products issued between October 2007 and May 2016 displayed by year. (a) Number of products per year. (b) Number of each type of product action code per year.

As one might expect, these maxima regions remained roughly the same when the products were filtered to include only SVRs (Fig. 3b) and only SVSs (Fig. 3d). However, when just the TOR were analyzed (Fig. 3c), the maxima in the number of warnings were significantly amplified in the lower Mississippi and Tennessee valleys, where JAN issued the largest total of 1030 TORs followed by Birmingham, Alabama (BMX), with 763. In contrast, the southern plains maximum, OUN, issued 616 TOR during the same time frame. A third maximum also developed in the central Rockies where Boulder, Colorado (BOU), issued a total of 500 TOR warnings.

Overall, JAN issued the most TORs and SVSs of all CWAs, making up about 4% and 3% of the national total, respectively. Similarly, OUN made up about 3% of all SVRs, with a national maximum of 5211. Seattle, Washington (SEW), issued the fewest warning-related products at only 39 while Key West, Florida (KEY), had the fewest SVRs with 16 total. Medford, Oregon (MFR);

Eureka, California (EKA); and Missoula, Montana (MSO); did not issue a single TOR between October 2007 and May 2016. On average, there were approximately 215 TORs and 1439 SVRs issued per CWA during the period.

Sorting the warnings by action code resulted in many similar geospatial features, as seen during the product analysis. However, several notable discrepancies appeared among the four primary codes. For instance, filtering the data to only display NEW warnings resulted in distinct local maxima in the southern plains and lower Mississippi valley, but no well-defined maximum in the central plains (Fig. 4a). When sorted to show only CON updates (Fig. 4b), the maximum in the lower Mississippi valley expanded eastward and the central plains maximum returned to better match the total warning distribution seen in Fig. 3a. EXP updates exhibited far less regional consistency than the other issue types, with at least five local maxima spread across the CONUS (Fig. 4c). The central plains, primarily Nebraska and Iowa,

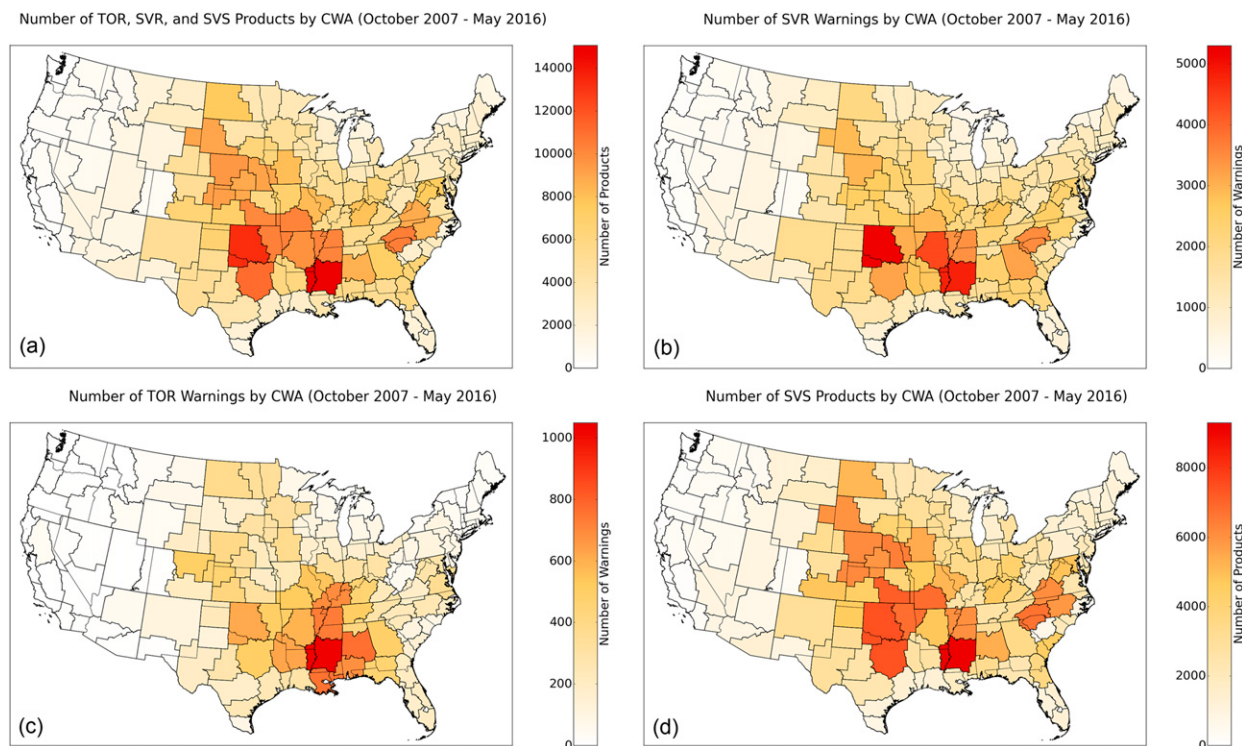


FIG. 3. Number of warning-related products issued from October 2007 to May 2016 by CWA. (a) Number of all storm-based warnings and SVSs issued per CWA. (b) Number of SVR warnings issued per CWA. (c) Number of TOR warnings issued per CWA. (d) Number of SVSs issued per CWA.

exhibited the greatest concentration of EXPs, followed by the middle Mississippi valley, the Ohio valley, and the mid-Atlantic region. The Dallas–Fort Worth, Texas (FWD), CWA made up the fifth local maximum with a total of 1590 EXP updates. The geospatial distribution of CAN notifications showed slightly more regional consistency and contained three distinct maxima centered over JAN, GSP, and Springfield, Missouri (SGF) (Fig. 4d).

Nationally, JAN once again issued the most NEW warnings, CON updates, and CAN notifications with 5832, 6906, and 1426, respectively. Louisville, Kentucky (LMK), had the greatest number of EXPs, at 1779 total. Although COR products were not analyzed geospatially, Sioux Falls, South Dakota (FSD), issued the most warning corrections with 16 over the 8-yr period.

b. Representation of storm characteristics

Because storm-based warnings are intended to convey information about a particular storm, it can be argued that a warning should, to some extent, be representative of the physical diagnostic characteristics of the warned storm. To examine the validity of this statement, the speed and direction tags assigned to each warning were sorted by CWA and averaged. The

mean warning direction proved to be largely uniform in CWAs east of the Rocky Mountains, with all but one averaging between 200° and 270° (Fig. 5a). Direction in CWAs along and west of the Rockies was more variable and averaged between 100° and 190° . Care should be taken when interpreting averages west of the Rockies as sample size was limited in this region, and the results may have been skewed by one or two events. Nationally, storm-based warnings had an average warning direction of 247° . This southwest-to-northeast movement is consistent with historical meteorological models of typical severe storm movement in the United States (e.g., Beebe 1956).

A seasonal breakdown of the mean warning direction (not shown) yielded very similar results for winter (December–February), spring (March–May), and fall (September–November), with national average motions of 244° , 244° , and 240° , respectively. Warnings issued during the summer months (June–August) were slightly different, with a national mean direction of 262° out of the west/southwest. CWAs in the southern CONUS in particular tended toward average values between 270° and 300° during the summer, while those along the western Gulf Coast had average motions out of the north/northwest between

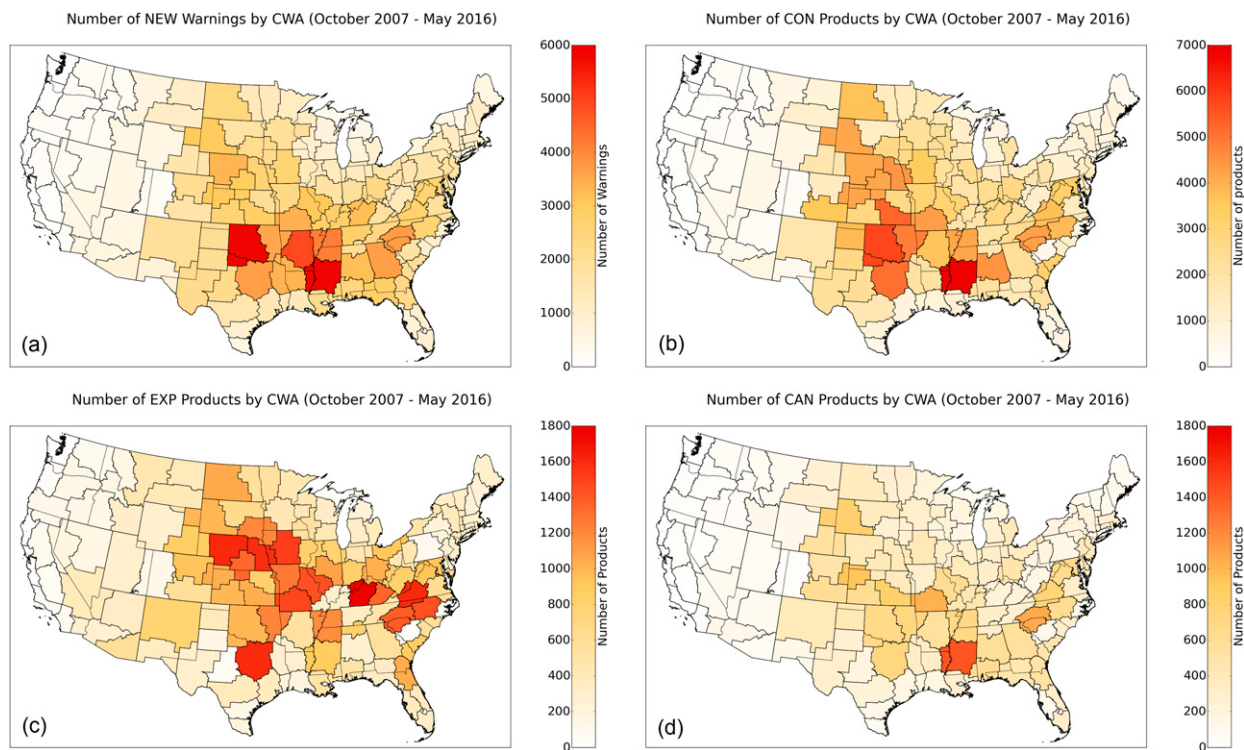


FIG. 4. Number of products by action code issued between October 2007 and May 2016. (a) Number of NEW warnings issued per CWA. (b) Number of CON updates issued per CWA. (c) Number of EXP notifications issued per CWA. (d) Number of CAN notifications issued per CWA.

300° and 20°. [Suckling and Ashley \(2006\)](#) noted a similar seasonal and geospatial trend in observed tornado tracks, where it was found that 25% of all tornado occurrences during the summer months propagated from the north or northwest.

Because the warning direction analysis used mean values to compare with existing research, it was necessary to ensure the averages were truly representative of the data before any conclusions could be drawn. To accomplish this, several CWAs were polled and plotted as a violin plot, two of which are shown in [Fig. 6a](#). In each case, warnings were distributed approximately normally with minimal skew, suggesting that the mean was in fact a good representation of the data.

A similar analysis was performed for the mean storm speed, as shown in [Fig. 5b](#). This time, the values varied more overall but exhibited remarkable regional consistency across the CONUS. Mean storm speeds were slowest in the southwest United States and gradually increased to the east, where a local maximum occurred in the Great Lakes and Ohio valley regions. Central Illinois (ILX); Grand Rapids, Michigan (GRR); Milwaukee, Wisconsin (MKX); Northern Indiana (IWX); and Paducah, Kentucky (PAH); all tied for the fastest average storm speed, with a mean of 34 kt (where $1 \text{ kt} = 0.51 \text{ m s}^{-1}$). Tucson,

Arizona (TWC), had the slowest average speed of 11 kt, and the national average was about 25 kt. The smooth gradients from one region to the next combined with the placement of the local maximum implies a systematic relationship between the speed assigned to a warning and regional location. Furthermore, findings by [Smith et al. \(2012\)](#) on the frequency of quasi-linear convective systems (QLCSs) in the Ohio valley would lend evidence to support a potential relationship between mean regional storm mode and the higher mean storm speeds indicated by the warnings. However, the higher mean storm speeds in the Great Lakes region could also indicate a dearth of slower-moving pulse severe storms that perhaps could be more common elsewhere in the CONUS. Without further research, the phenomenological relevance of this pattern can only be speculated upon at this time.

A seasonal breakdown of the mean storm speed is shown in [Fig. 7](#). To avoid skewing the results with CWAs that issued a relatively small number of warnings over the analyzed time period, only CWAs that issued at least 20 warnings during the specified season were included in the analysis. Storm speeds were considerably faster during the winter months than any of the other seasons, with a national mean speed of 42 kt. This diminished to about 28 kt in the spring and reached a minimum of 22 kt

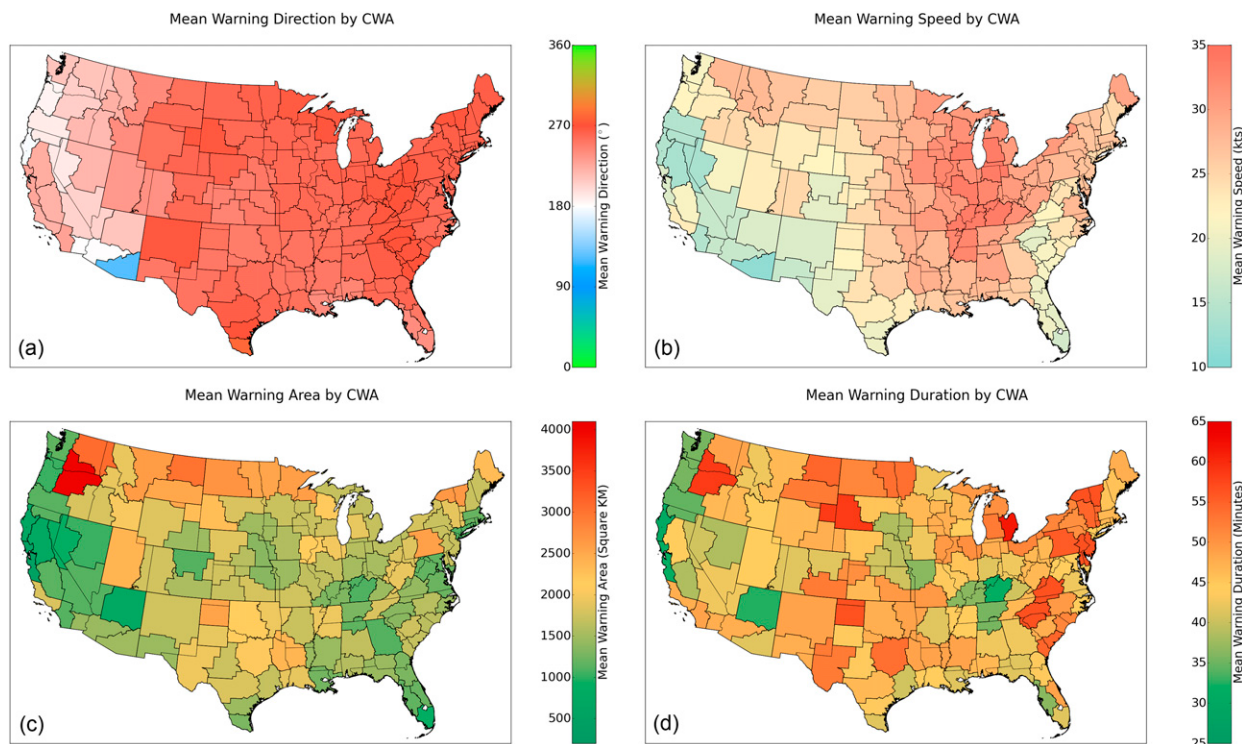


FIG. 5. (a) Average warning direction calculated from the storm motion tag in each warning for each CWA. (b) Average storm speed calculated from the storm motion tag in each warning for each CWA. (c) Mean warning area by CWA. (d) Mean warning duration by CWA.

during the summer months. Warnings issued during the fall had a national mean storm speed of 29 kt. Although the overall region of faster storm speeds shifted north-westward during the latter half of the convective season, the Ohio valley and Great Lakes region consistently exhibited the greatest storm motions of the CONUS.

Again, because mean values were used, several CWAs were selected for a distribution analysis. Like before, each CWA sampled contained an approximately normal distribution with minimal skew (Fig. 6b). Given this and the information discussed previously, it would appear that storm-based warnings are a good representation of climatological severe storm motion in the United States. Because warnings were not compared to radar data in this study, future research would be required to make any claims about warning representativeness of individual storms or other phenomena.

Despite the strong regional consistency found in the mean storm motion parameters of storm-based warnings, the average size and duration of the warnings varied considerably by CWA and showed diminished regional uniformity. The mean warning area generally increased from south to north, and there was a broad maximum located in the northern plains and northern Intermountain West regions along the Canadian border

(Fig. 5c). Overall, TOR warnings covered an average area of about 999 km^2 while SVR warnings had a mean size of 1802 km^2 . Pendleton, Oregon (PDT), had the largest average warning size with an area of 4027 km^2 , followed by Spokane, Washington (OTX), with 3071 km^2 . Note that PDT only issued 202 warnings from October 2007 to May 2016. A secondary maximum occurred in the southern plains, where Amarillo, Texas (AMA), averaged 2542 km^2 . KEY issued the smallest warnings overall, with a mean of 254 km^2 . The national average for SVRs and TORs combined was 1667 km^2 .

Mean warning duration proved to be a bit less regionally consistent than warning area and resulted in three broad maxima across CONUS (Fig. 5d). The first maximum was an approximate band of CWAs running from the northern plains westward into the northern Intermountain West region. Rapid City, South Dakota (UNR), and PDT issued the longest warnings in this maximum with an average of 58 min, followed by Glasgow, Montana (GGW), at 54 min. The second maximum was a more scattered band of CWAs covering the central and southern plains. AMA had the longest average duration in this domain at 56 min. The East Coast and Great Lakes regions made up the third maximum, where Detroit, Michigan (DTX), issued warnings with a mean

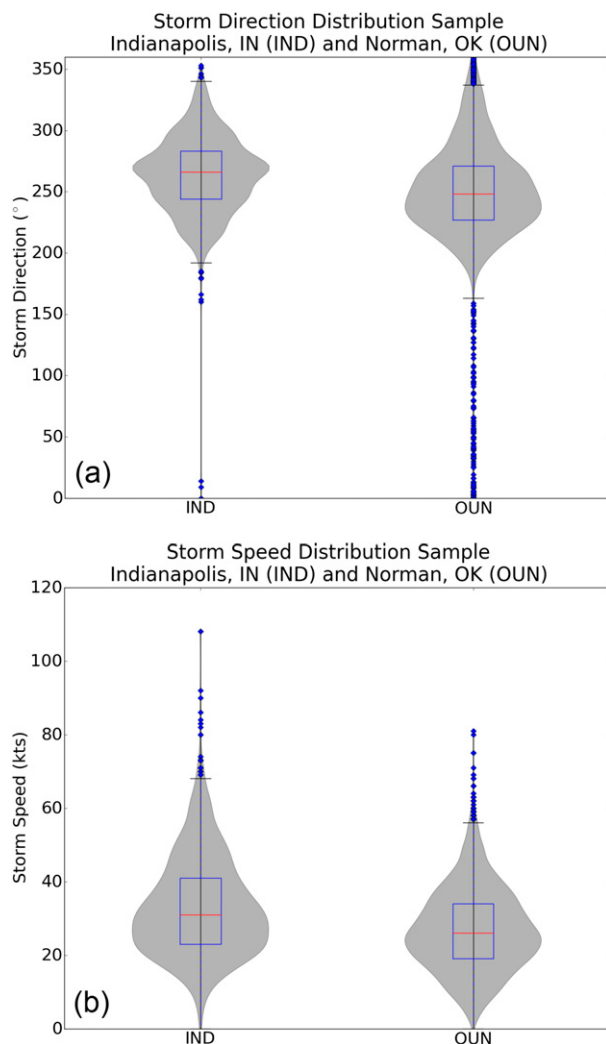


FIG. 6. Samples drawn from Indianapolis, IN (IND), and OUN showing the distributions of (a) warning direction and (b) storm speed. Each dataset displayed approximately normal characteristics.

duration of 61 min. EKA issued the shortest warnings on average, with a mean of 30 min for the 8-yr period. Note that EKA only issued 50 warnings during this time. TOR warnings were generally shorter than SVR, with mean durations of 38 and 53 min, respectively. The national average for SVRs and TORs combined was about 46 min.

There are many potential explanations for the existence of these maxima. For instance, [Bunkers et al. \(2006\)](#) note that the northern plains may be more susceptible to long-lived, isolated supercells, which could offer forecasters greater confidence in longer-duration warnings. Because the northern CONUS typically has a shorter convective season than the central and southern CONUS, it is conceivable that a lack of storms requiring shorter warning times would inflate the averages in the region. Similarly, the increased frequency of long-lived

QLCSs in the Great Lakes region ([Smith et al. 2012](#)) may lead to greater forecaster confidence and subsequent longer warning durations. Again, more in-depth analysis into the conditions surrounding each individual warning would be required to validate these hypotheses.

c. Directive verification

NWS directives state storm-based warnings should have valid times from 15 to 45 min from issuance for TORs and from 30 to 60 min from issuance for SVRs ([NWS 2014](#)). For thunderstorms that are expected to remain severe longer than the warning's valid time, it is recommended (but not mandatory) that NWS meteorologists issue a new warning. However, this is not always the case. From October 2007 to May 2016, 27% of all TORs had an initial duration in excess of 45 min. Similarly, 17% of all SVR warnings were valid for longer than 60 min. In one notable case, an SVR was issued with an initial duration of 147 min. The warning received five SVS updates before finally being canceled 76 min after issuance. Overall, 18% of all warning events were longer than the recommended maximum duration.

One likely source of this departure from suggested policy is in the way the warning issuance software, WarnGen, generates storm-based warnings. [Smith \(2002\)](#) recommends NWS offices configure WarnGen such that all warnings expire at 15-min intervals (i.e., with timestamps of 0000, 0015, 0030, or 0045 in an hour) to make it easier for broadcast media, the public, and warning forecasters to track what warnings are in effect and when they expire. As a result of this rounding, a warning issued at 0053 UTC with an intended duration of 45 min would in actuality expire at 0145 UTC and have a calculated duration of 52 min. Indeed, the violin plot of warning duration distributions ([Fig. 8](#)) reveals a local peak within 15 min of the recommended maximum duration for both TOR and SVR cases. To account for this, a 14-min buffer was added to the recommended warning durations, leaving only 5% of all TORs and 1% of SVRs longer than the duration threshold.

[Figure 9](#) shows the percentage of warnings longer than the recommended maximum duration plus a 14-min buffer for each product, calculated by CWA. Overall, most CWAs issued fewer than 5% of all warnings with a duration longer than this threshold, although CWAs in the northern mid-Atlantic tended toward slightly longer durations. The percent of TORs longer than the buffered threshold also tended toward greater values than for SVRs, with several CWAs issuing 15%–25% of all TORs longer than 59 min. Twenty-eight of the 92 TOR warnings issued by DTX were longer than 59 min, and 181 of their 797 SVR warnings were longer than 74 min. With 23% of all products longer than the buffered

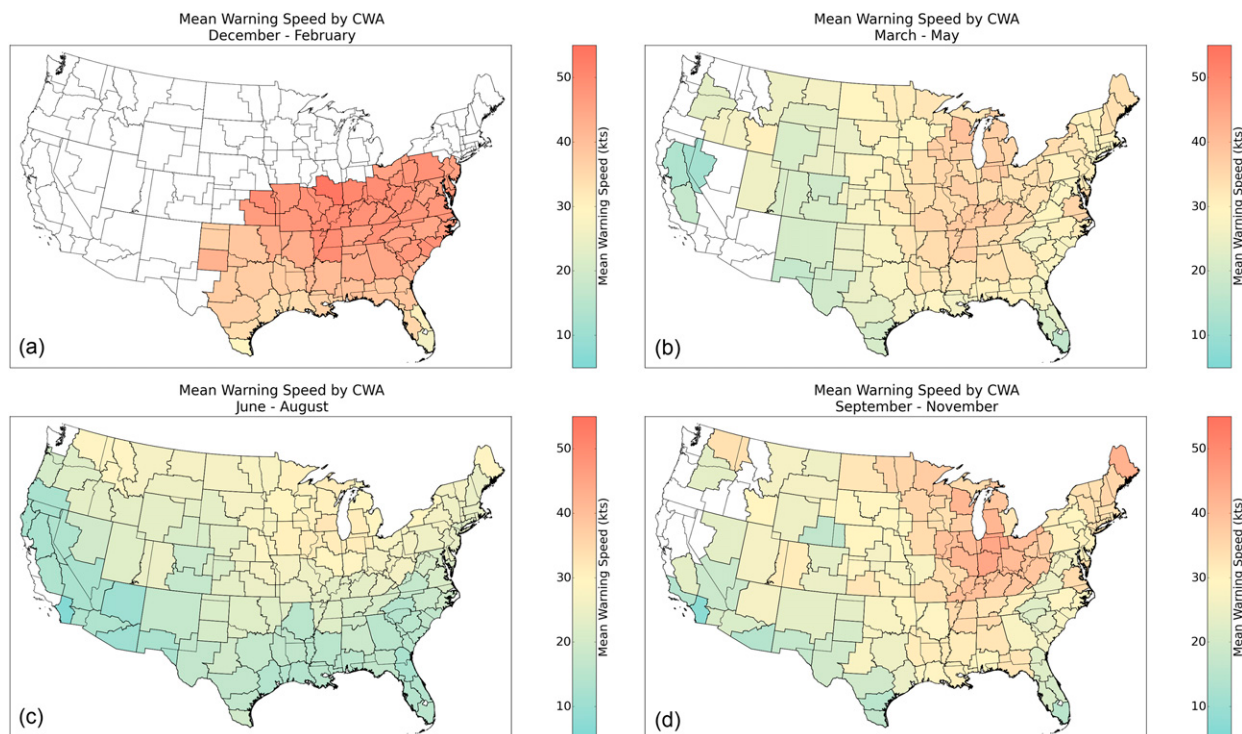


FIG. 7. Seasonal breakdown of the mean warning speed. CWAs without shading did not issue at least 20 warnings during the given season and were excluded. (a) Mean warning speed from December to February. (b) Mean warning speed from March to May. (c) Mean warning speed from June to August. (d) Mean warning speed from September to November.

threshold, DTX had the largest percentage of warnings longer than the recommended directive specifications.

Of the 1317 TOR warnings longer than 59 min, 503, or about 38%, were canceled before reaching their expiration time. This was slightly less for SVR warnings, with 816 out of 2322, or about 35%, canceled. DTX was also the CWA with the greatest percentage of warning cancellations, with 412 of 889 warnings (46%) canceled before the expiration time. This introduces questions about the situations in which durations were extended beyond the recommended directive specifications, particularly for TORs. Perhaps for some events, the predictability or speed of the phenomenon warranted extended durations. Another potential factor is a desire to meet end-user needs for long lead times. Further research into individual cases and local WFO policy is needed to explain this potential relationship.

At the time of this writing, it is NWS policy that all SVR and TOR warnings should (but are not required to) have at least one SVS during the warning's valid time (NWS 2014). Nationally, this policy was generally upheld, with about 87% of all warning events provided an SVS update. A total of 22 092 of 24 990 TOR, or about 88%, received an SVS update, while 145 162 of 167 025 SVR events, or about 87%, were given an SVS. This was

largely consistent for each CWA, although offices along the Gulf Coast and in the Northeast had slightly lower percentages than the rest of the CONUS (Fig. 10). Columbia, South Carolina (CAE), was the CONUS minimum, with only 563 of 1773, or about 32% of their

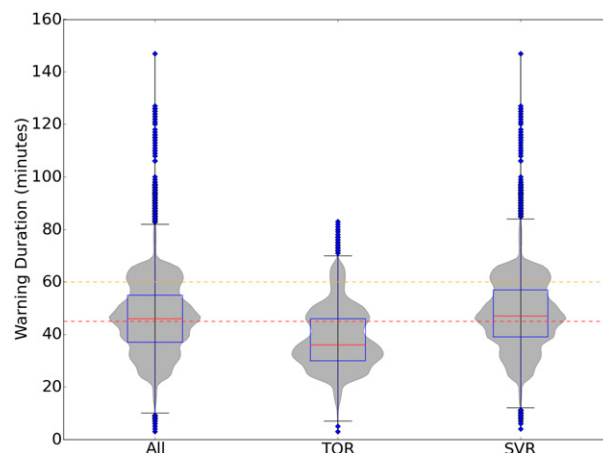
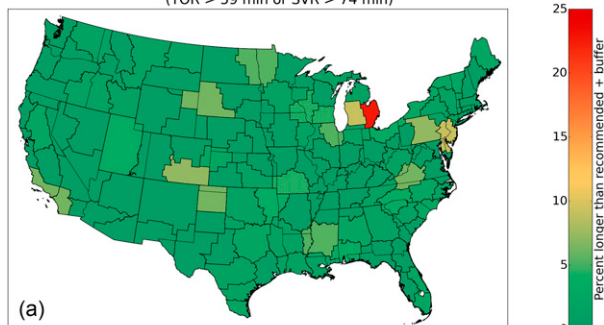
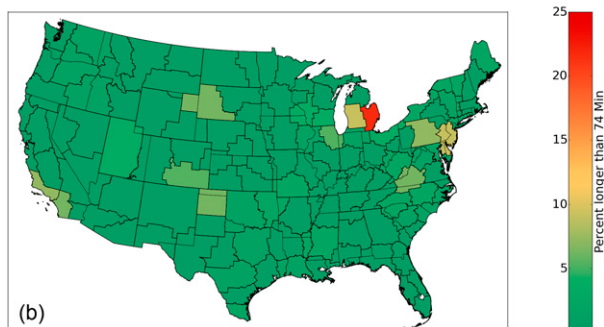


FIG. 8. Distributions of the duration of warnings by product. The yellow-dashed line represents the NWS policy recommended maximum SVR duration of 60 min. The red-dashed line represents the NWS policy recommended maximum TOR duration of 45 min.

Percent of Warnings Longer Than Recommended Duration + 14 Minute Buffer
(TOR > 59 min or SVR > 74 min)



Percent of SVR With a Duration > 74 Minutes



Percent of TOR With a Duration > 59 Minutes

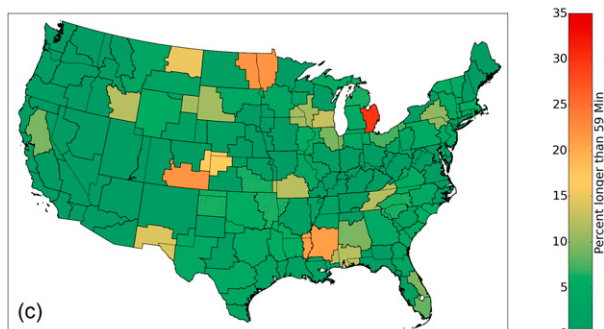
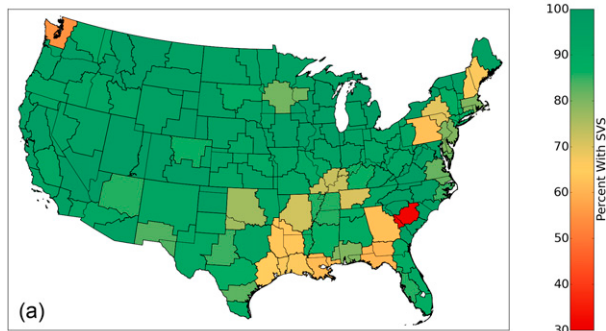


FIG. 9. (a) Percent of all warnings issued for a CWA with a duration longer than the recommended length plus a 14-min buffer. (b) Percent of all SVR warnings issued for a CWA with a duration longer than 74 min. (c) Percent of all TOR warnings issued for a CWA with a duration longer than 59 min.

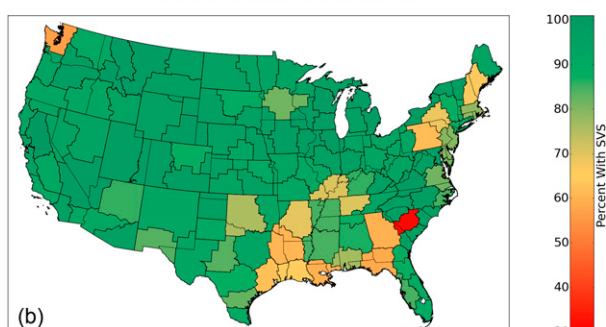
warning events receiving an SVS update. Notably, the number of SVSs per warning remained fairly consistent overall as the number of warnings issued in a convective day increased. There was an average of about 1.64 SVSs per warning nationally.

On average, SVS updates were issued 20.8 min after the initial NEW warning in a warning event. This was lower for TORs at 15.8 min compared with 21.6 min for SVR. Omaha, Nebraska (OAX); Pueblo, Colorado (PUB); and La Crosse, Wisconsin (ARX); had the most frequent SVS updates, with an average gap of about

Percentage of Warnings With an SVS by CWA



Percentage of SVR With an SVS by CWA



Percentage of TOR With an SVS by CWA

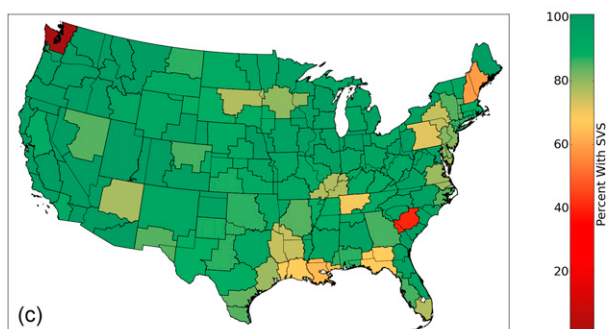


FIG. 10. (a) Percent of all warning events with at least one SVS. (b) Percent of all SVR warning events with at least one SVS. (c) Percent of all TOR warning events with at least one SVS.

14 min between the initial warning and the SVS. Violin plots of the percent of warnings with an SVS by CWA (Fig. 11a) and the mean SVS update frequency for all warning events (Fig. 11b) are shown.

d. Warning production

It was noted previously that 2011 was a large contributor to the warning dataset, likely as a result of the number of historic severe weather events that occurred during that year. This raises the question of how high warning production events, or events with a large number of storms requiring warnings, were distributed across the CONUS. For instance, which CWAs had the

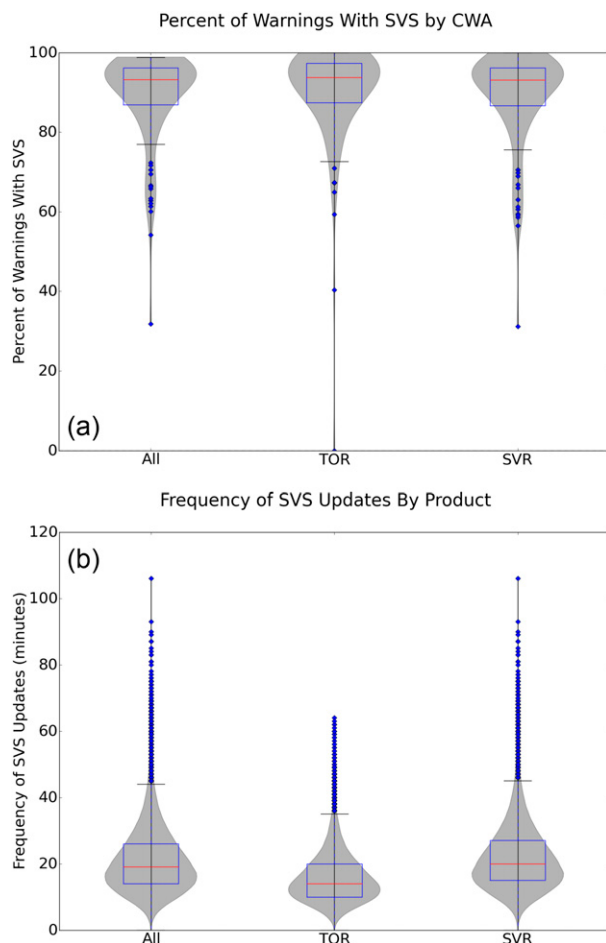


FIG. 11. (a) Distributions of the percentages of warning events with an SVS for each CWA. (b) Distributions of the amount of time from warning issuance to SVS update.

greatest average and maximum warning production (as defined in section 2)? Were particular regions more susceptible to high warning production events than others? To answer these and other questions, the average and maximum warning production of each CWA was calculated and plotted as shown in Fig. 12. When filtered to only display SVR warnings, a distinct maximum in average CWA warning production resulted across the Great Plains states and lower Mississippi valley (Fig. 12a). OUN exhibited the greatest SVR warning production average, with about nine SVR per active convective day. That is, OUN issued an average of nine SVR warnings for each convective day when at least one warning was issued. Nationally, there were about 5.2 SVRs per CWA per convective day from October 2007 to May 2016.

There was a significant shift in the location of the mean CWA warning production maximum when sorted to only display TOR (Fig. 12b). The central and

southern Mississippi valleys contained the largest mean CWA TOR warning production, where New Orleans, Louisiana (LIX), exhibited the greatest TOR warning production average of about 1.93 TORs per convective day. The national average was 0.77 TORs per CWA per convective day.

Ashley and Strader (2016), Fuhrmann et al. (2014), and Smith et al. (2012), have each identified the Great Plains, Midwest, and Southeast CONUS as having elevated risk for tornado outbreaks, with the maximum risk estimation centered over the lower Mississippi valley. Although the results in Fig. 12b do highlight the lower Mississippi valley for the greatest TOR production, they fail to also highlight the southern and central plains as much as would be suggested by existing research. This may be due in part to regional differences in the length of the convective season, storm morphology, or local and regional office policy differences. Additionally, more recent research, such as Ashley and Strader (2016), has noted a regional shift in long-term tornado risk throughout the period of record, with an increasing risk over the mid-South and a decreasing risk over the southern and central plains. While the cause of this shift is unclear, it has been hypothesized that a combination of meteorological and nonmeteorological effects, including the relatively short period of record, may be to blame. Smith et al. (2012) also concluded supercells associated with significant wind and hail events were more common in the central and southern plains, and this is better represented by the results in Fig. 12a.

The maximum CWA warning production was calculated by determining the convective day when each CWA issued the greatest number of warnings. Again looking at only SVRs, there were three distinct maxima in the maximum warning production in the southern plains and lower Mississippi valley, where LZK issued 75 SVRs on 26 April 2011 (Fig. 12c). This was closely followed by SGF, with 74 SVRs on 15 June 2009, and OUN, with 71 SVRs on 6 May 2015.

As before, the distribution of maximum CWA warning production was spatially shifted to the lower Mississippi valley and southeast United States when sorted for TOR. Huntsville, Alabama (HUN), had the greatest warning production for a single convective day, issuing 62 TORs on 27 April 2011. Morristown, Tennessee (MRX), issued 61 TORs on the same day, and JAN had 56 on 1 September 2008. Thirty of the 116 CWAs studied experienced their greatest TOR production during 2011.

For the remainder of this study, a warning outlier event was defined as a convective day where a CWA issued more warnings than two standard deviations above the national mean. The standard deviation for the number of warnings per CWA per convective day was

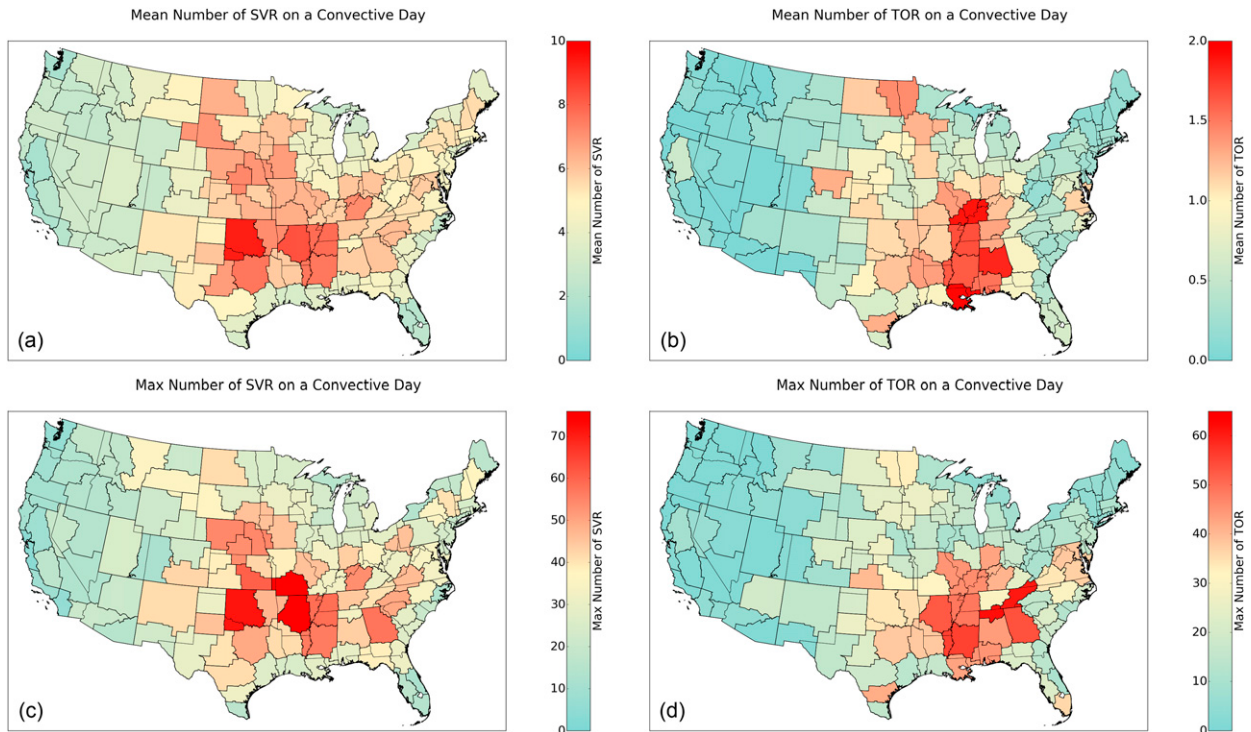


FIG. 12. (a) The mean number of SVR warnings each CWA issued per convective day (1200–1200 UTC). (b) The mean number of TOR warnings each CWA issued per convective day. (c) The maximum number of SVR warnings each CWA issued on a given convective day. (d) The maximum number of TOR warnings each CWA issued on a given convective day.

6.12 for SVR and 2.80 for TOR. Thus, warning outlier events were days when a CWA issued more than 17.4 SVR warnings or 6.37 TORs, not counting any associated SVSs. Reviewing only SVR outlier events, four distinct maxima were located in the central plains, southern plains, lower Mississippi valley, and southern Appalachians (Fig. 13a). LBF experienced 41 SVR warning outlier events, while OUN had 90 days with more than 17.4 SVR warnings. In the lower Mississippi valley, JAN had 75 days considered to be SVR warning outlier events, followed by GSP in the southern Appalachians with 44.

Again, TOR warning outlier events were most common in the lower Mississippi valley, with one clear maximum centered over JAN, which experienced 52 days with more than 6.37 TORs between October 2007 and May 2016 (Fig. 13b). Weaker maxima were centered over SGF, with 28 days, and OUN, with 29.

The number of warning outlier events also was calculated using the local CWA standard deviation and mean (Figs. 13c,d) to demonstrate the number of days that a given office issued significantly more warnings than is typical of that local office. OUN and the southern plains remained the region with the most common SVR outlier events, but the central plains, lower Mississippi valley, and southern Appalachians all saw a significant

increase in the number of outlier events relative to the rest of the CONUS. Notably, LZK actually saw a relative decrease in the number of SVR outlier events. This could indicate the CWA has more frequent events with numerous warnings issued compared with surrounding offices and thus a higher local mean and/or lower local standard deviation.

Similarly, JAN and the lower Mississippi valley remained the national maximum in the number of TOR outlier events, but more of the Southeast, central plains, and southern plains were also highlighted for anomalous days. In particular, SGF experienced 27 days with more TORs than two standard deviations above the local mean.

4. Conclusions

Fundamental attributes of storm-based warnings and SVS statements from October 2007 to May 2016 were analyzed and plotted geospatially to reveal regional and interoffice patterns. A majority of severe weather warnings and SVSs were issued east of the Rocky Mountains, with the most warning-related products issued in the central plains, southern plains, lower Mississippi valley, and southern Appalachians. TOR

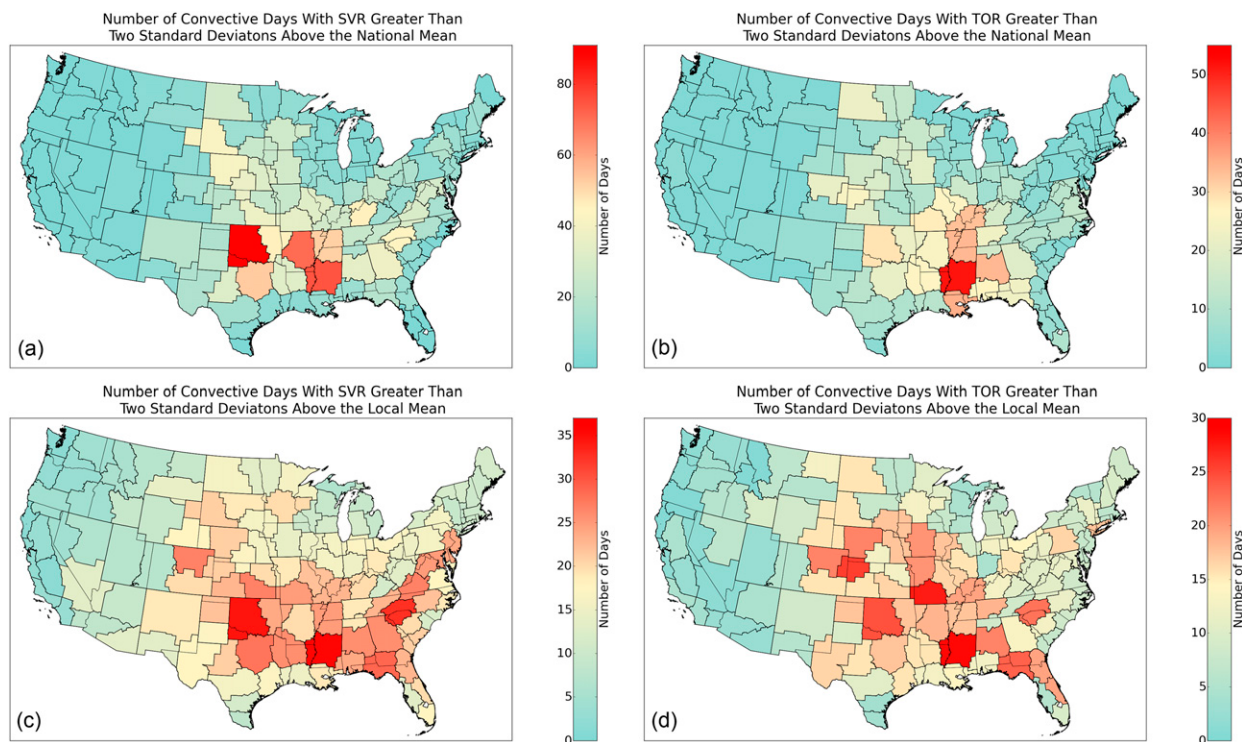


FIG. 13. (a) The number of days each CWA issued more SVR warnings than two standard deviations above the national mean (more than 17.6 SVR). (b) The number of days each CWA issued more TOR warnings than two standard deviations above the national mean (more than 6.52 TOR). (c) The number of days each CWA issued more SVR warnings than two standard deviations above the local mean. (d) The number of days each CWA issued more TOR warnings than two standard deviations above the local mean.

warnings were concentrated heavily in the lower Mississippi valley, while SVR warnings tended to be more evenly distributed across the central CONUS.

Strong regional uniformity was noted in the mean warning direction east of the Rocky Mountains, where all but one CWA averaged between 200° and 270° . Similarly, mean storm speed exhibited interoffice consistency, with a broad maximum in the Great Lakes and Ohio valley regions. Although it remains beyond the scope of this research to make any claims about the representativeness of storm-based warnings to individual weather hazards, the geospatial uniformity of these patterns among CWAs supports the notion that storm-based warnings are representative of climatological severe storm motion in the United States. By contrast, the average warning size and duration varied greatly by CWA and showed little correlation to storm speed or other diagnostic attributes. These inconsistent patterns may be heavily influenced by factors external to the individual weather hazard, such as local WFO policy or the relatively short period of record, but the data alone cannot offer a complete explanation.

Storm-based warnings were found generally to conform to current NWS policies. Nearly 90% of all

warnings issued since October 2007 received an SVS update before expiring, and 98% had a duration within recommended directive specifications. Of the 5% of TOR warning events longer than 59 min, 38% were canceled before expiring. Only 1% of SVR warning events had durations longer than 79 min, and 35% of those were canceled before expiring.

Finally, the Great Plains, and in particular the southern plains, issued the greatest average number of SVR warnings per convective day, while the lower Mississippi valley and Southeast regions tended to have larger TOR production. The southern plains and lower Mississippi valley were found to have the greatest number of SVR warning outlier events (i.e., number for days exceeding two standard deviations above the national mean), while the lower Mississippi valley maintained the most frequent TOR warning outlier days during the 8-yr span.

The results of this study raise some interesting questions. For instance, why were 5% of all TOR warnings longer than the recommended maximum length specified by NWS policy, even after applying a 14-min buffer? Did the hazards encompassed by these warnings have predictability beyond the time limits suggested by NWS

policy? Are forecasters accommodating the needs of their users by extending warning durations past these limits? Furthermore, was the number of warnings in a given CWA a direct result of the number of storms, or were the warnings influenced by other factors, such as the geospatial distribution of counties and cities in the area, software policies (county and CWA clipping), or local WFO policies? Hopefully, these shortcomings in our understanding of the storm-based warning system will motivate further research efforts, particularly within the social science disciplines.

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