An Analysis of Subdaily Severe Thunderstorm Probabilities for the United States

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ABSTRACT

One of the challenges of providing probabilistic information on a multitude of spatiotemporal scales is ensuring that information is both accurate and useful to decision-makers. Focusing on larger spatiotemporal scales (i.e., from convective outlook to weather watch scales), historical severe weather reports are analyzed to begin to understand the spatiotemporal scales that hazardous weather events are contained within. Reports from the Storm Prediction Center's report archive are placed onto grids of differing spatial scales and then split into 24-h convective outlook days (1200–1200 UTC). These grids are then analyzed temporally to assess over what fraction of the day a single location would generally experience severe weather events. Different combinations of temporal and spatial scales are tested to determine how the reference class (or the choice of what scales to use) alters the probabilities of severe weather events. Results indicate that at any given point in the United States on any given day, more than 95% of the daily reports within 40 km of the point occur in a 4-h period. Therefore, the SPC 24-h convective outlook probabilities can be interpreted as 4-h convective outlook probabilities without a significant change in meaning. Additionally, probabilities and threat periods are analyzed at each location and different times of year. These results indicate little variability in the duration of severe weather events, which allows for a consistent definition of an ''event'' for all locations in the continental United States.

1. Introduction and background

Experts in the field of weather risk communication show that end users generally understand the existence of underlying uncertainty in weather forecast information (e.g., Morss et al. 2008; Joslyn and Savelli 2010; Savelli and Joslyn 2012; Fundel et al. 2019). As such, research organizations have called for using probabilities to describe this forecast uncertainty, as it may be beneficial to residents when making response action decisions (National Research Council 2006; AMS Council 2008). Following these recommendations, the National Oceanic and Atmospheric Administration (NOAA) is currently developing a paradigm that includes rapidly updating probabilistic information for user-specific locations. The Forecasting a Continuum of Environmental Threats (FACETs) project aims to provide a continuous stream of probabilistic information to keep people up to date on weather, water, and climate threats from days or more out down to minutes before the event occurs (Rothfusz et al. 2018).

The current National Weather Service (NWS) product structure for severe weather consists of three product levels; the convective outlook [which is issued by the Storm Prediction Center (SPC) from 1 to 8 days in advance for the continental United States (CONUS)], severe thunderstorm and tornado watches (which are also issued by the SPC generally 1–4 h before the event occurs, with a mean size of 30 000 square miles, which is about the size of Maine), and then the warning (issued by a local NWS office 0–60 min before the event and has a mean size of 250 square miles). One of the early challenges of the FACETs project was the reliance of community infrastructure on these current products. For example, some communities often use a specific product (like a tornado watch) to activate procedures (Cross et al. 2019).

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Since transitioning from the current system will likely be evolutionary and take time and discourse, researchers have begun working on ways to provide more information within and in-between the current product levels. As part of this effort, research scientists and forecasters need to understand how the probabilities of these events change between different reference classes [i.e., the probability of a report within 40 km (25 mi) of my location versus the probability of a report at my house in the next 5 min] so that forecasters can assign correct values that are also meaningful to users. This work focuses on understanding the probabilities of severe weather on a subdaily scale, but larger than the warning scale (i.e., spatiotemporal scales between the convective outlook and watch, generally on a state to regional spatial scale and temporal scales between 1 and 24 h).

To begin this process, we start by analyzing the distribution of events within a day at any single location. We use the general SPC convective outlook probabilities as a simple starting point. While the probabilities are forecasted for up to a 24-h period, intuitively, many meteorologists know that at any location the probability of severe weather is actually near zero for a large portion of the day, then it increases to the forecasted probability shortly before the event begins, and then decreases back to near zero shortly after the event ends. Following this example, we define an event as a local storm report within 40 km (25 mi) of a point to match the spatial scales of the current SPC convective outlook probabilities (NOAA Storm Prediction Center 2019a). We then investigate how the events on a single day are distributed in time. Are they spread out across the day or concentrated within a smaller period of time? If there is a smaller window of time when most of the events are concentrated, when does that window start? Is there regional variability in the duration of severe reports or the start time of the smaller window of threat? Given that our analysis has nearly identical spatial scales to the current SPC convective outlook probabilities, knowledge of the climatological duration of severe weather events means the SPC convective outlook probabilities could be valid for a smaller window of the day. The forecasting challenge would then be to identify when that window starts and ends. From a communication standpoint, knowing the forecasted window of threat on a severe weather day could help the entire range of decision-makers, from emergency management and school officials to youth coaches and individuals, decide how to prepare in advance of the start of the event.

2. Data and methods

Hail, wind, and tornado reports from the SPC Severe Report Database (NOAA Storm Prediction Center 2019b) between 1950 and 2015 are used to calculate the spatiotemporal scales that severe events generally fit within (i.e., a spatial area and temporal duration that captures a majority of the daily events). While there are known issues with the report database, especially with regards to the increase in the number of reports (see Doswell and Burgess 1988; Trapp et al. 2006; Verbout et al. 2006), it is the most comprehensive severe weather occurrence database for the United States and we believe the data still provide useful insight into the general pattern of severe weather events.

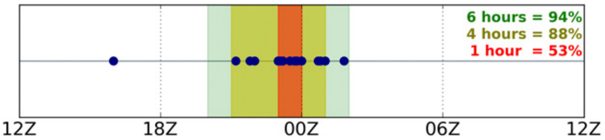

FIG. 1. An example of a daily time series of reports for a single location. The green shaded area represents 6 h, the yellow represents 4 h, and the red represents 1 h of the day. The percentages reflect the fraction of reports captured in each timeframe for this particular example.

We begin by identifying all of the reports within a specified radius (we test 10, 20, 40, 80, and 200 km) around a point in the CONUS. While we test multiple spatial scales, we focus most of our analysis on the 40-km radius so that our results could speak to the definitions of the current SPC products and allow for the testing and verification of new products within the SPC forecast domain.

Next, at each point with at least 20 reports over the 65-yr period, we create time series of the reports for each convective (1200–1200 UTC) day. An example of this time series is shown in Fig. 1. Using these time series, we calculate a variety of quantities including the maximum percentage of the daily reports that are captured within smaller timeframes (specifically within 1, 2, 4, 6, 8, and 12 h of the day), and the start time of the maximum daily window. The percentage of reports captured in smaller timeframes is calculated at each grid point as follows:

$$p_{\text{captured}} = \frac{\sum r_{\text{captured}}}{\sum r_{\text{total}}} \times 100,$$

where the numerator is the sum of the reports captured within the specified smaller timeframe on all days, and the denominator is the total number of reports that occurred at that grid point. In Fig. 1, the numerator would be the number of reports captured in the shaded areas (green showing 6 h of the day, yellow showing the 4 h of the day, and red showing 1 h of the day with the maximum number of reports captured), and the denominator

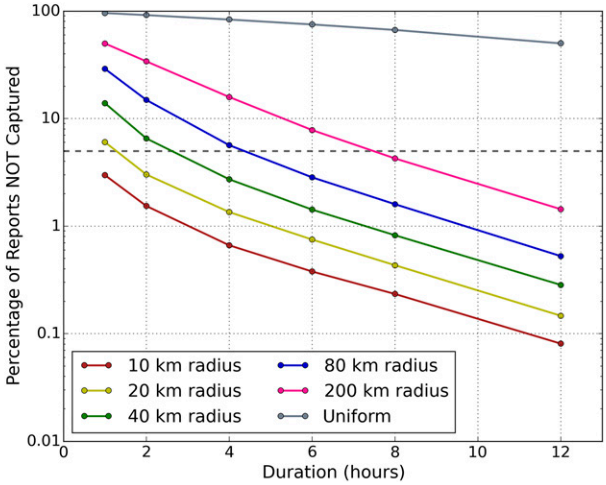

FIG. 2. The percentage of reports not captured (*y* axis) at differing time periods (*x* axis) within the 24-h convective outlook day. The percentages are expressed on a logarithmic scale to show detail at the smallest values. The dashed line indicates 5% of reports not captured.

would be the total number of reports shown in the time series. Obviously, if there is only one report at a point over the convective outlook day, then the total percentage of reports captured that day is 100%. Then the total number of reports in the numerator and denominator are aggregated over all days and all grid points. To analyze regional differences in the window start time, the timestamp of the start of the smaller timeframe is calculated for each day. Then the median start time at each grid point is calculated.

3. Results

To begin the analysis, we aggregate all of the points across the CONUS to obtain a holistic view of the spatiotemporal scales of severe weather events. First, we analyze all of the reports within 40 km of a point for all points across the CONUS (Fig. 2, green line). Within any single convective outlook day, more than 99% of reports will be contained within just 12 h of the full day. Furthermore, over 95% of daily reports within 40 km of any point occur in a 4-h period, and a single hour of the day still captures more than 80% of the daily reports. If we consider the probability behavior of uniformly distributed points (i.e., events occurring equally across the 24-h period), the percentage of reports captured drops to 50% at 12 h and just 16.7% at 4 h (Fig. 2, gray line). Clearly, severe weather events at any given point are concentrated in timeframes smaller than 24 h, with a vast majority of reports occurring in just 4 h of the day. Moreover, since the spatial scales of this analysis are nearly identical to the SPC's definition of an event (i.e., a report occurring within 25 nautical miles of a point), it follows that the SPC's probabilities at any given point can be interpreted as valid for 4 h of the day within a reasonable margin of error (over 95% of reports vs 100% of reports).

After analyzing severe weather probabilities on varying temporal scales, we also calculate the percentage of events captured within numerous radii around a point and numerous temporal durations (Fig. 2). For all radii, the percentage of reports that are not captured increases with increasing radii around a point and decreasing temporal durations. This probability behavior is largely intuitive because it takes longer for weather systems to cover a 200-km radius (similar to the north–south extent of Oklahoma) than a 40-km radius (similar to the size of the Oklahoma City limits). In other words, reports will be occurring for a longer period of time when looking at an area the size of Oklahoma versus an area the size of Oklahoma City. More than 95% of reports within 10 km of a radius are captured within a single hour of the day or longer (represented by the points below the dashed line in Fig. 2). Longer temporal durations are needed to capture more than 95% of daily reports at other radii. The 40-km radius needs at least 4 h, and the 200-km radius needs 8 h (Fig. 2).

While the main goal of this work is to understand how severe event probabilities behave within differing spatiotemporal scales, it is also critical to understand how these behaviors differ by location. To align with the current SPC definition of an event (defined as a severe weather report within 25 miles—or roughly 40 km—of a point; NOAA Storm Prediction Center 2019a) and still capture a majority of daily reports (see the green line in Fig. 3), the 40-km spatial scale and 4-h temporal scale are used for further investigation. To this end, the percentage of reports captured is calculated for each individual point across the CONUS on an 80-km grid (Fig. 3). More than 90% of all reports within 40 km of a point are captured in 4 h of the 24-h convective outlook day for all points east of the Rocky Mountains (where most severe events occur). Therefore, the current 24-h convective outlook probabilities forecasted by the SPC could be interpreted as 4-h probabilities with different start times depending on the location and day. This finding is important because any products that use this definition (like a convective outlook-type product) need to have consistent probabilistic definitions of events across the entire domain. Since there are no strong gradients in probability, any future products that use this definition will remain consistent no matter where the product is placed in the CONUS. An example of an experimental product might be a convective outlook that includes the probabilities of an event occurring

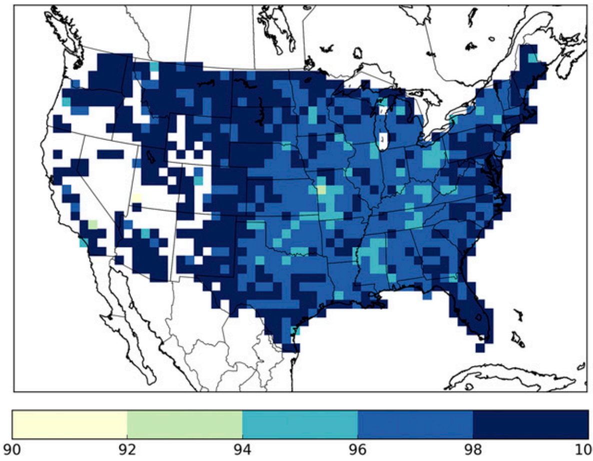

FIG. 3. The percentage of all daily reports within 40 km of a point captured in a 4-h period of a 24-h convective outlook day (1200–1200 UTC). Data are reported for grid points with at least 20 reports over the 65-yr study period.

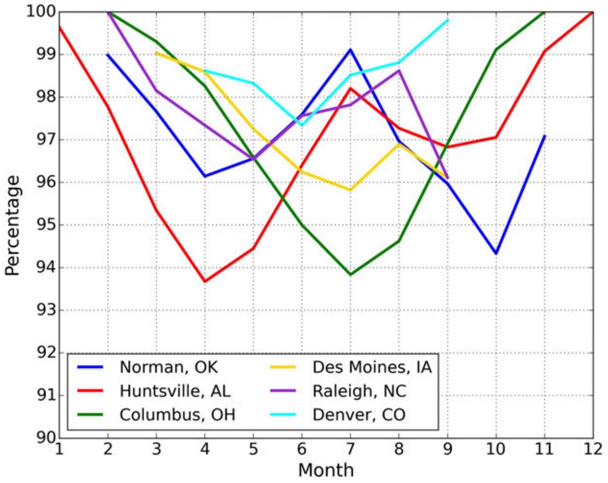

FIG. 4. The percentage of all daily reports within 40 km of a point captured in a 4-h period for Norman, OK; Huntsville, AL; Columbus, OH; Des Moines, IA; Raleigh, NC; and Denver, CO.

along with a forecasted 4-h timeframe of when that event may occur (Krocak and Brooks 2019). Since the percentages of reports that climatologically occur within 4 h at any given point are largely the same across the entire CONUS domain (Fig. 3), decision-makers can be sure that the product is valid no matter where severe weather is forecasted.

In addition to understanding how severe weather events vary by region, we also investigate how event durations at a single point vary by season. The same ratio of events in a 4-h period is calculated at each point for all 12 months. We focus on six locations (Norman, Oklahoma; Huntsville, Alabama; Columbus, Ohio; Des Moines, Iowa; Raleigh, North Carolina; and Denver, Colorado) because they illustrate the differences between regions of the CONUS (Fig. 4). There is a drop in percentage of reports captured at all locations during the peak tornado season (see Krocak and Brooks 2018), and then a subsequent increase afterward. Norman and Huntsville have relative minimums during April (the spring tornado season) and September/October (the secondary fall tornado season). Similarly, Raleigh has a relative minimum in May and a second decrease in September. Columbus and Des Moines both see the minimum percentage captured in July (again, aligned with the peak in tornado occurrence for those locations). Finally, Denver has a small decrease in June, which may be in part due to sample size as well as tornado seasonality. The dips in percentages may also be explained by overnight convection trailing into the morning hours, followed by a more substantial event starting in the afternoon and evening of the following day. Some of these trends may be muted because we chose to look at the totality of severe weather reports, instead of focusing on individual hazards. While there have been some studies that examine the spatiotemporal patterns of tornado reports in more depth (e.g., Krocak and Brooks 2018; Brooks et al. 2003), more work needs to be done to investigate how these trends hold up when looking at hail or wind occurrence.

Next, assuming that convective outlook probabilities can be interpreted as applying to smaller time periods within the day, we want to know when the climatological start time of those smaller time periods are. To accomplish this, the start time of the 4-h period on each day with severe reports is found and then the median of all the start times is calculated at each grid point. Start times in the Central Plains are generally around 0000 UTC and become progressively earlier toward the East Coast, where start times are around 2100–2200 UTC (Fig. 5). In addition to the local solar time (i.e., diurnal heating) being later relative to UTC moving from east to west across the CONUS, some physical mechanisms such as the elevated mixed layer (EML) inversion (Lanicci and Warner 1991), orographic lift, sea breezes, and the low-level jet may result in storms initiating later in UTC time for the plains relative to the East Coast.

The differences in severe weather timing can be seen even more clearly when the start times of the 4-h periods are grouped together by region (Fig. 6). We define the central United States as the region roughly between 91° and 105° longitude west and the eastern region roughly between 65° and 90° longitude west. The entire distribution of start times is shifted later in the day when comparing the central region to the eastern region.

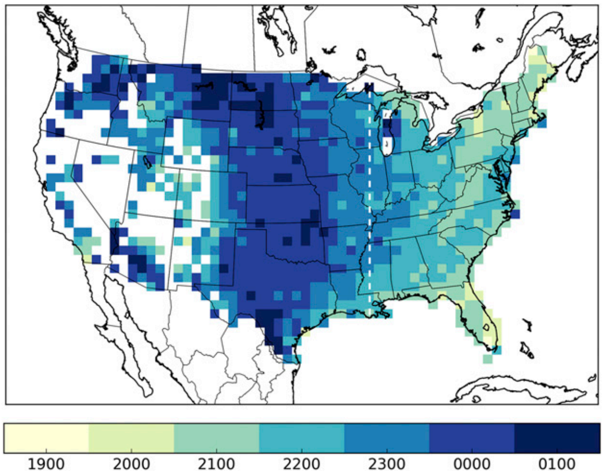

FIG. 5. The median daily start time (UTC) of the 4-h period that captures the highest percentage of the daily severe weather reports within 40 km of a point. Data are reported for grid points with at least 20 reports over the 65-yr study period. The dashed line indicates the delineation between the eastern and central United States used in Fig. 6.

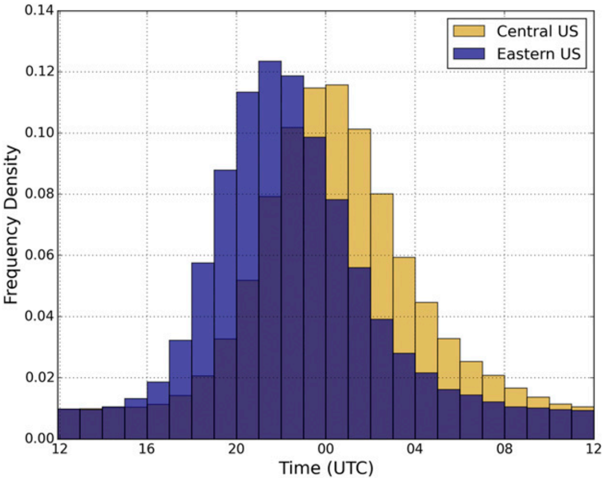

FIG. 6. Overlapping histograms of the daily start times of the 4-h period that captures the most daily reports within 40 km of a point for roughly 65°–90°W longitude and for 91°–105°W longitude.

While some of this change is due to the difference in local time and the diurnal cycle, there are still two distinct severe weather time periods: one for the eastern part of the country starting between 2000 and 2300 UTC, and one for the central portion of the country starting between 2200 and 0200 UTC. This equates to a majority of severe weather in the eastern part of the country occurring between 2000 and 0300 UTC for any given day, and a majority of severe weather in the plains occurring between 2200 and 0500 UTC. Regardless of location in the CONUS, these peak periods for severe weather are a good guide for potential impacts on late afternoon and evening activities and public safety.

4. Discussion

As a new generation of probabilistic severe weather products begins to take shape, researchers and forecasters are continually analyzing the best strategies for providing probabilistic information that is both accurate and useful to decision-makers. This study illuminates one possibility for using probabilistic information to transition from the current hazardous weather alert system to one with higher spatiotemporal granularity and objective consistency, at least on larger spatiotemporal scales. Some of this information has already been tested with forecasters and users (e.g., Wilson et al. 2019; Skinner et al. 2018), and others are still well in the development stage.

We hope that this work serves as a foundation for future product development by analyzing the probabilities of severe weather events on spatiotemporal scales smaller than the SPC convective outlooks, but larger than warnings issued by the National Weather Service. Results show that a vast majority of daily severe weather reports at any given point occur within smaller timeframes. In fact, more than 95% of reports within 40 km of a point occur in a 4-h period, meaning that the 24-h convective outlook probabilities assigned by forecasters in the SPC could be interpreted as 4-h probabilities within a reasonable margin of error. If such an interpretation is considered, then the forecasting question becomes ''which 4-hour period is it?'' While there are many NWS weather forecast offices that offer timing information for severe weather, this is not a standardized practice and it is not required of any forecast office. If there was a standardized, regularly issued product that showed timing information for severe weather well ahead of the event start time, decision-makers may be able to make informed preparedness decisions (like opening emergency operations centers, adjusting staffing levels, releasing employees or students early, etc.) with more advanced notice.

Probabilities of severe events are also analyzed spatially based on location in the United States. The 4-h percentages of reports captured show that those ratios are consistent across all portions of the country east of the Rocky Mountains, ranging between 90% and 100%. This result is promising as products placed across different regions would have consistent definitions and probabilities of events. These percentages are also relatively consistent across seasons, with most locations seeing at least 94% of reports captured during any given month. In addition to the percentage of reports captured, the start time of the maximum 4-h period is also analyzed spatially. The most notable trend is seen by the later start times in the plains and earlier start times on the East Coast. The peak start time in the plains is around 3 h later than the start times on the East Coast, although some of those differences are due to the differences in local solar time.

Ultimately, the goal of any forecasting system should be to provide users with accurate and useful information that can aid in the decision-making process. While some of the current system's product structure likely needs to remain as it is, additional information about the likelihood and timing of hazardous weather could be embedded within and in-between the current product levels. This work is meant to provide baseline knowledge of the concentration and spatiotemporal structure of severe weather events in the United States. Future work is needed to understand how events behave on warning scales such that forecasters can provide probabilistic information that is accurate, timely, and most importantly, useful to decision-makers within the severe weather communication system.

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