13A.2 An Hourly Climatology of MRMS MESH-Diagnosed Severe Hail

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ABSTRACT

The multi-radar/multi-sensor (MRMS) system generates an operational suite of derived products in the National Weather Service useful for real-time monitoring of severe convective weather. One such product generated by MRMS is the maximum estimated size of hail (MESH) that estimates hail size based on the radar reflectivity properties of a storm above the freezing level. The MRMS MESH product is commonly used across the NWS, including the Storm Prediction Center, to diagnose the expected hail size in convective storms. Previous work has explored the relationship between the MRMS MESH product and severe hail ($\geq$ 25.4 mm or 1 in.) observed at the ground and with severe hail reports. This work will provide an hourly climatology of severe MRMS MESH across the CONUS. Differences between severe hail reports and potential applications in operational forecasting will be explored.

1. Introduction

Hail contributes to a substantial portion of the total insurance damages for crops and other property in a given year (Changnon et al. 2009). Because of the potential societal impact of severe hail ($\geq$ 25.4 mm, or 1 in.), the ability to make skillful forecasts for the timing and location of severe hail is of great importance to operational forecasters. The Storm Prediction Center (SPC) provides operational probabilistic forecasts for severe hail for the Day 1 (current day) period. These probabilities are valid for the full convective day (12Z–12Z). However, with a desire to provide additional severe hazard risk forecasts on shorter timescales (i.e., FACETS; Rothfusz et al. 2018), SPC has been exploring how to provide useful probabilistic guidance on a more frequent basis. One method of providing users probabilistic forecasts on shorter timescales at SPC has been through Mesoscale Discussions (MDs). Figure 1 shows an example of highlighting an area of relatively greater risk for severe hail, increasing probabilities from 5% to 10% for a few hours.

In order to provide meaningful and accurate guidance for any severe hazard on a sub-daily timescale, a forecaster needs to be calibrated by baseline climatological values of risk on that timescale. Some work has been done to address these needs. (Krocak 2017) and (Krocak and Brooks 2018) offer guidance on hourly climatological risk for hail and tornadoes, respectively. Those studies utlized severe hail and tornado reports from the NCDC *Storm Data* publication. For hail, which is the focus of the present study, the *Storm Data* report database contains known issues which are well-described by Allen and Tippett (2015). The issues with estimated versus measured hail sizes, which has implications for the consistency of the data, as well as the overall lack of spatiotemporal coverage are of particular concern in the context of using the data for climatological and verification purposes.

One tool that forecasters at SPC use in a situational awareness and nowcasting sense is the Maximum Estimated Size of Hail (MESH; Witt et al. 1998) product from the NSSL Multi-radar/Multi-sensor (MRMS; Smith et al. 2016) product suite. The MESH is a radar-based hail estimate (described in section 2) that bases its estimate on radar reflectivity within preferred temperature layers for hail growth. This product is useful to forecasters owing to the overall consistency, known biases, and spatiotemporal coverage in areas that receive very few severe hail reports. Leveraging these desirable qualities of the MESH, this study seeks to extend the work of Krocak and Brooks (2018), using the MESH as an estimate of severe hail occurrence to create an hourly climatology. With an hourly climatology of MESH-diagnosed severe hail, questions can be answered on where and how the MESH-based climatology differs from a the *Storm Data*-based climatology. Of particular interest is how they differ during the evening when receiving a report of severe hail is less likely (Ashley et al. 2008).

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This paper is organized as follows: section 2 describes the data and quality control used. Section 3 describes the methods used to obtain the hourly climatologies of MESH and *Storm Data* hail reports, section 4 presents the results of the analysis, and section 5 discusses the implications of the findings and how they can be applied to SPC operational forecasts.

2. Data

The MESH is a radar-derived, gridded hail size estimate based on an exponential fit to the Severe Hail Index (SHI; Witt et al. 1998). The SHI is a reflectivity-weighted vertical integration of reflectivity from the melting level to the top of the storm, neglecting any reflectivity values less than 40 dBZ. Caveats to the accuracy of the MESH are 1) it will give more accurate estimates when multiple radars are sampling a storm (Ortega et al. 2005, 2006) and 2) the algorithm was designed to be an overforecast such that 75% of all observed hail will fall below the radar estimate (Witt et al. 1998). The data are on an approximately 1-km grid that spans the entirety of the CONUS from 2012–2017. The spatiotemporal coverage of the MESH is a quality that makes it desirable for use in forecast operations as it provides a forecaster information for locations that are less likely to have public reports of severe hail. To gain the most information about MESH, this analysis compares climatological characteristics between the MESH and severe hail reports from the *Storm Data* publication over the same 2012–2017 period. For the purposes of this study, all references to hail refer to severe hail, which will be defined in section 3b. Furthermore, any reference to reports is synonymous with hail reports from the *Storm Data* publication.

3. Methods

a. Data quality control

To ensure that MESH data were not a product of anomalous radar beam propagation or other artifacts, a similar quality control procedure as in Wendt et al. (2016) was used. Hourly MESH data were used in this step to ensure that MESH output was associated with thunderstorms through an hourly lightning quality control step. First, a Gaussian filter with a σ, or spatial smoothing, parameter value of 3 grid cells ($\approx$ 3 km) is applied. This smoothed MESH field is then used as a mask on the raw MESH field to eliminate isolated pixels. The next step involves using quality-controlled National Lightning Detection Network (NLDN) cloud-to-ground lightning data to determine if MESH pixels are associated with a thunderstorm. Those MESH pixels that fall within 40 km of a detected flash are included in this study. MESH values above 127 mm (5 in.) were removed as there is evidence to support those values being very rare and likely spurious (Cintineo, 2016, personal communication; Blair et al. 2011).

Storm Data hail reports are either measured or estimated. Given the potential for estimation error to cause issues around the 1 inch severe definition, this study only uses *Storm Data* reports that are 1.25 inches or greater as was done in Krocak (2017). This filtering is meant to give a cleaner comparison to the radar estimates that already tend to overforecast severe hail.

b. Hourly climatology creation

Creation of hourly climatological estimates of MESH-diagnosed severe hail and *Storm Data* severe hail reports largely followed the methods of Krocak and Brooks (2018). Severe hail from the MESH product is defined as values greater than or equal to 29 mm (1.14 in.). Previous work showed that this value has the most skill when comparing MESH to observed hail reports (Cintineo et al. 2012). Severe MESH and *Storm Data* severe hail reports were then regridded to an 80-km Lambert Conformal Conic (LCC) grid, which is similar to the grid that SPC uses to verify its outlooks. The interpolation used was a maximum nearest-neighbor method where, for each grid point and each hour, the maximum hail size is mapped to the nearest 80-km LCC point. While detrending of the hail report database was done in Krocak (2017), the short timeseries of data (i.e., 6 years) used in this study did not show a significant trend. No detrending of either reports or MESH were done in this study.

Yearly grids of all data were compiled with an extra day inserted for non-leap years. The grid points that were equal to or above the defined severe thresholds were then made into a binary grid where values of one represent a severe report, with zeroes assigned at all other grid points. Binary grids were smoothed first in space using:

$$P = \sum_{n=1}^{n} \frac{1}{2\pi\sigma^2} e^{-d^2/2\sigma^2} \qquad (1)$$

where P is the kernel density estimate (KDE) of probability, N is the total number of grid boxes with severe hail events, d is the distance from grid point to the severe hail location, σ is the smoothing parameter for the Gaussian filter. The σ value chosen for this study was 120 km as was done in Brooks et al. (2003), produces results that are qualitatively similar to SPC outlook areas. Next, each hourly grid was then smoothed in time using:

$$P = \sum_{n=1}^{n} \frac{1}{2\pi\sigma^2} e^{-t^2/2\sigma^2} \qquad (2)$$

which is exactly as in equation 1, but now distance is measured in time, t. Smoothing in time was done in two different ways: 1) using σ = 15 days and 2) σ = 2 hours. To illustrate using an example, the 15 day smoothing parameter would smooth across the same hour from each day (i.e., all 1800 UTC) to preserve the seasonal cycle. The 2 hour smoothing parameter smooths adjacent hours to preserve the diurnal cycle. After all the smoothing, the yearly grids with all hours for the year were averaged to produce a KDE of severe hail hours per year.

c. *Daytime and nighttime severe hail risk*

To analyze the severe hail events during the day and night separately, an hourly binary grid representing daytime (sunrise to sunset) and nighttime (sunset to sunrise) was created. Calculations were handled by the Python astronomical calculations library, *PyEphem* (v3.7.6.0; Rhodes 2015). Using this grid as a mask, calculations on hail occurrence during daytime and nighttime hours could be performed.

4. Results

a. *Comparing MESH to hail reports*

Climatologies for both MESH and *Storm Data* severe hail were computed, the results of which are shown in Figure 2. This figure shows severe hail hours per year (i.e., how many hours during a given year an 80-km grid cell experiences severe hail). There are two main differences between the MESH and *Storm Data* estimates. The first is the difference in magnitudes. Even in areas where the population density is relatively high, the estimated severe hail hours from the MESH can be 5–6 times as great as those estimated from *Storm Data*. In areas where population density is low, the differences can be much higher. Secondly, the MESH analysis shows an extension of estimated severe hail hours into areas of low population density farther south—near the Big Bend region of Texas—and farther west—into more of the High Plains, Raton Mesa, and along and south of the Mogollon Rim in Arizona. The differences are further highlighted when taking a difference field between MESH and *Storm Data* (Fig. 3). For this analysis, the MESH estimates of severe hail hours per year are higher at all CONUS locations compared to estimates from reports.

These differences can be broken down by hour as well, which is seen in Figure 4. Only a few hours are shown as a summary. Here, the MESH severe hail hours estimates are plotted in filled contours. The scale was allowed to vary to see the relative maxima across the convective day. White contours represent the $z = 3, 3.5, 4$ z-scores (i.e., the number of standard deviations away from the mean estimated hail hours) for the report-based severe estimates. This was done to compare the locations of the relative maxima between the two datasets. Overall, the MESH and report-based severe hail estimates highlight similar geographical areas throughout the day. However, the MESH maximum is shifted farther west during the late-morning and afternoon periods (roughly 16–00 UTC).

b. *Comparing Day and Night*

With an hourly climatology, comparisons between daytime and nighttime hours can be made. The difference between day and night severe hail hours per year for *Storm Data* (Fig. 5) and MESH (Fig. 6) were computed. For the report-based data, there is a small tendency for more reports to happen during the day over the Central Plains and Ohio Valley. Elsewhere, little difference is observed. Stronger differences are evident in the MESH diurnal climatology. During the day, more MESH-diagnosed severe hail occurs from the Texas Big Bend into the High Plains and southern Rockies of New Mexico and Colorado. The same holds true for areas east of the Mississippi River. During the early evening (i.e., just after sunset), however, the MESH denotes more severe hail hours occurring in the Plains, particularly in the Platte River Valley into north-central Kansas.

c. *Characteristics of multiple severe hail reports*

The analysis so far has focused on the probability of the occurrence of severe hail during a given time frame. What areas are most vulnerable for multiple occurrences of severe hail? Using the MESH data, each grid point was examined for convective days that had more than one severe hail hour, irrespective of time between events (Fig. 7). As with the other MESH analyses, the favored locations for multiple events are a broad area of the High Plains along with the portions of the central and southern Plains. The maximum number of events occurs near the Black Hills in South Dakota.

Analysis done by Krocak and Brooks (2016) has shown that over 95% of *all* severe weather reports occur within a single four-hour period within a convective day. As part of this work, the question was posed as to whether the MESH data would show the same signal. Figure 8 shows a histogram of the counts of multiple MESH-diagnosed severe hail events in a day. The bins represent the number of hours between two severe hail events. A cumulative distribution of the percent of events that occur within a given time window is also shown. There is a clear signal that an overwhelming majority of severe hail events occur within 3–4 hours of each other. The blue dashed line represents where 95% of all MESH severe hail has occurred, which is just below 3 hours. For 96.7% of all days with multiple severe hail events, the hail occurs within a four-hour period.

Given that so many events occur within 3–4 hours of one another, the next logical question to ask is where do these events occur outside of that window? Figure 9 is a spatial representation of where events occur at or beyond four-hours apart. The signal here is less coherent than in

7, but a few areas stand out. Both the High Plains—with particular focus on the Black Hills, Raton Mesa, and Big Bend—as well as portions of the eastern Plains—Missouri Valley of Nebraska and central/eastern Oklahoma—show relative maxima of multiple severe hail events outside of a four-hour window.

5. Discussion

This study highlights the greater occurrence of MESH-diagnosed severe hail probabilities than report-based severe hail. Given that the design of the MESH algorithm is to increase probability of detection of severe hail, it is not at all surprising that a climatology based on these data show much higher estimates than that of one based on reports. The true risk for severe hail likely resides in between the estimates based on reports and MESH. Future work should focus on ways of better calibrating the MESH to increase the accuracy of climatological estimates such as this one.

When looking at severe hail during the daytime versus the nighttime, a clear benefit of the MESH-based severe climatology is the ability to provide better information on hail occurrence to forecasters during the evening when hail reports are less likely. The broader spatial coverage of the MESH data also helps to better delineate areas that are commonly affected by hail.

a. Comparison to previous hail climatologies

Previous work by Cintineo et al. (2012) on a daily MESH-climatology using the methods of Brooks et al. (2003), showed similar spatial patterns across the Plains and portions of the western CONUS when compared to the result in this study. They also compared their MESH-based data with reports, but found that severe reports were more common in the eastern CONUS than MESH-based severe events. This is in contrast to what was found in this study. The likely culprit in this case is the use of the 19 mm (≈ 0.75 in.) threshold for severe reports. This choice was out of necessity as they analyzed data before the threshold was officially raised to 25.4 mm (1 in.). Furthermore, the threshold was increased in this study to 1.25 in. in order to reduce estimation errors in hail reports.

Krocak and Brooks (2016) found that over 95% of all severe reports occur within a four-hour window using *Storm Data* reports. The results in this study show that this also holds for MESH-diagnosed severe hail as well. Coupled along with general spatial and temporal agreement with severe hail reports of where severe hail occurs, this gives credence to the MESH data in terms of how useful it can be in a climatological and verification context.

Also of interest is where severe hail events occur outside of the typical four-hour window. In this study it was shown that there are preferred areas where these multiple rounds of severe hail occur more frequently. These areas tend to be around areas of higher terrain which are more likely to initiate storms should continued influx of buoyant air flow up the slopes throughout the day. A secondary maximum of these events also occur in areas of the Plains where the overall severe hail risk is higher throughout the day. From a risk communication standpoint, knowing where multiple events are more likely to occur with significant lulls in between them is important as people are likely to think the risk has ended after an event.

b. Potential SPC forecast applications

The SPC has been exploring ways in which to communicate severe weather risks on shorter timescales. Having probabilistic information from an hourly severe MESH climatology (e.g., Fig. 10) helps the forecaster understand what the baseline risk is for a given area and time. While the current estimates from the MESH may be too high, the overall spatial coverage and ability to correctly highlight areas not captured by reports is still quite beneficial. Future work on any MESH climatology should focus on ways to better calibrate the MESH so as to retain the desirable qualities of the dataset and create more accurate estimates of the hourly risk. The potential also exists for the MESH to be used as a way to verify SPC forecasts as the MESH is less prone to non-meteorological artifacts (e.g., population density affecting report frequency, etc.).

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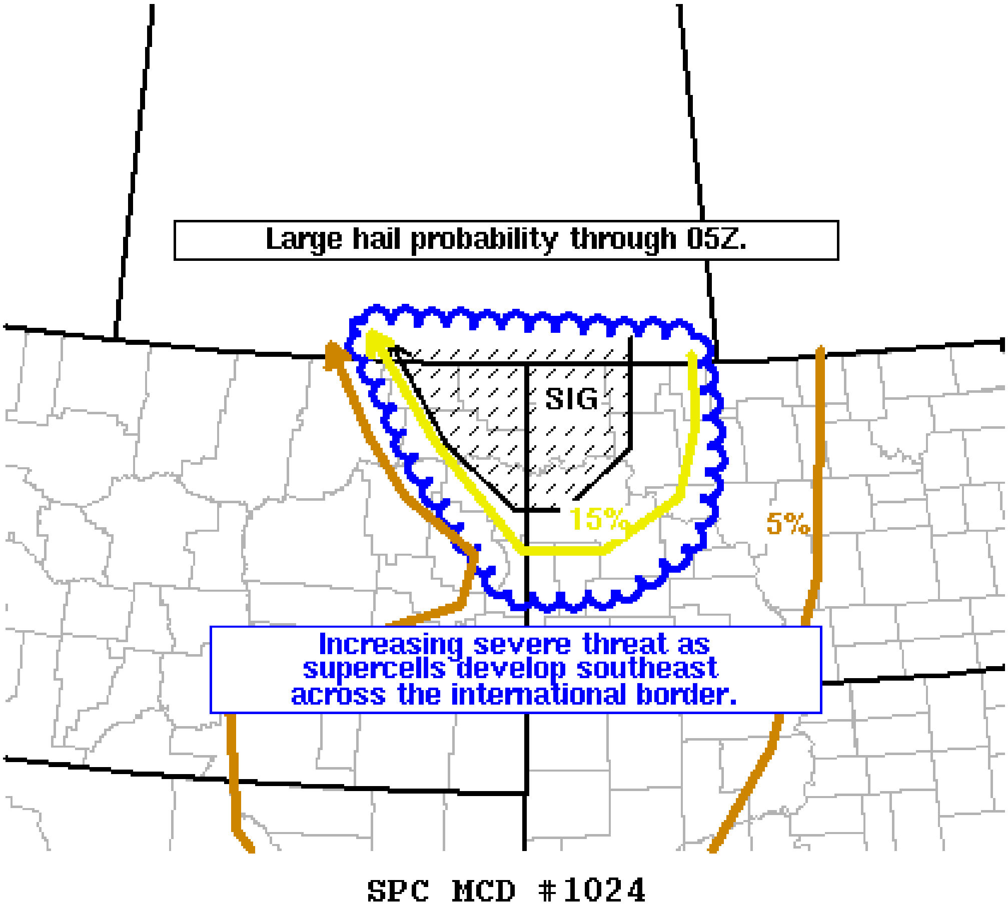

FIG. 1. Mesoscale Discussion #1024 issued by Jeremy Grams and Chris Broyles on 09 July 2018. A 10% severe hail risk (yellow) as well as a 10% or greater risk for significant (black hatched; $\geq$ 2 in.) hail was introduced within the discussion area (blue scallops). This is an example of highlighting a corridor of relatively greater risk in a short-term product.

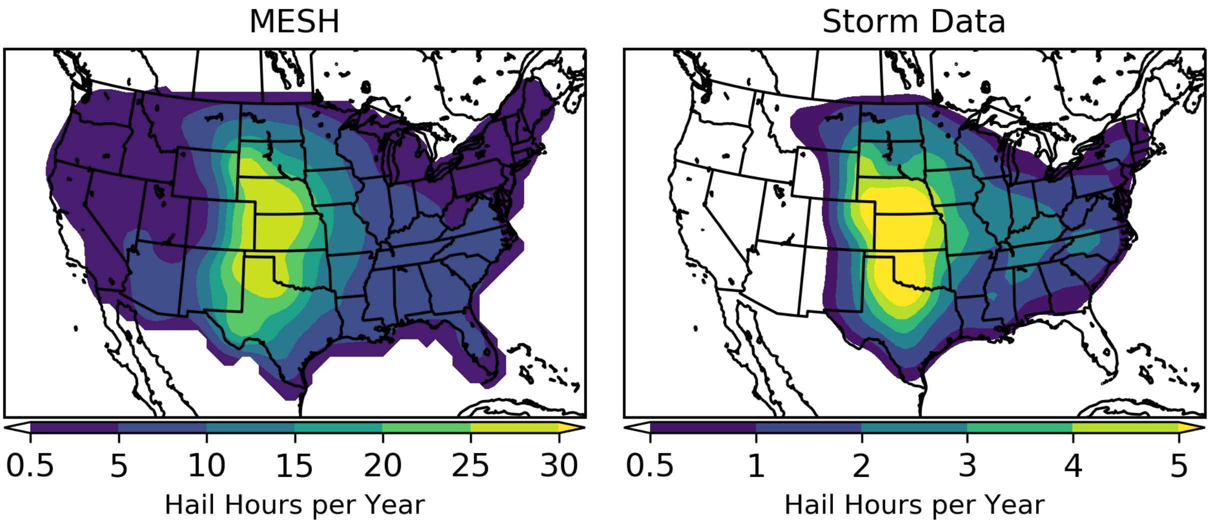

FIG. 2. Estimated severe hail hours per year using MESH (left) and *Storm Data* (right). Note that scales are different for each plot.

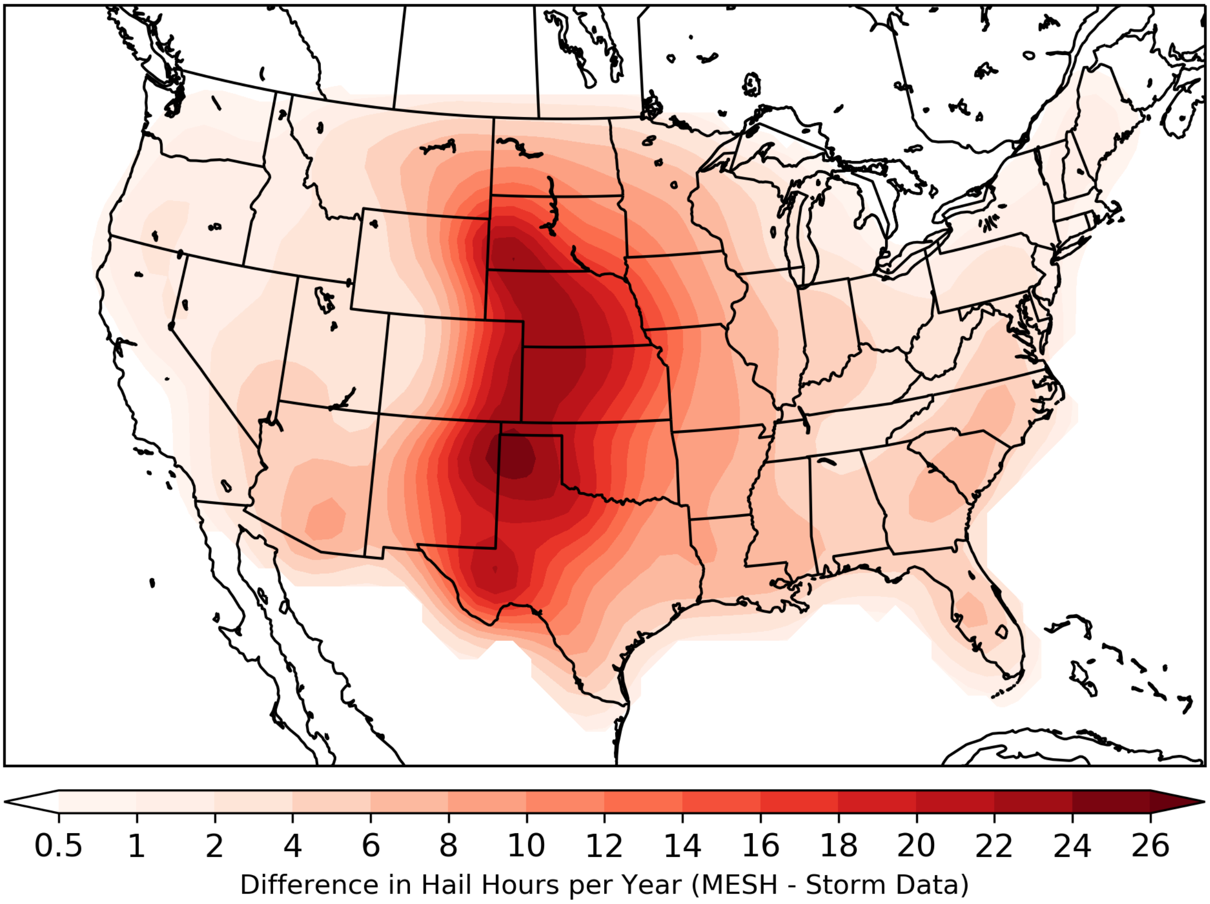

FIG. 3. Difference in severe hail hours per year (MESH - Storm Data).

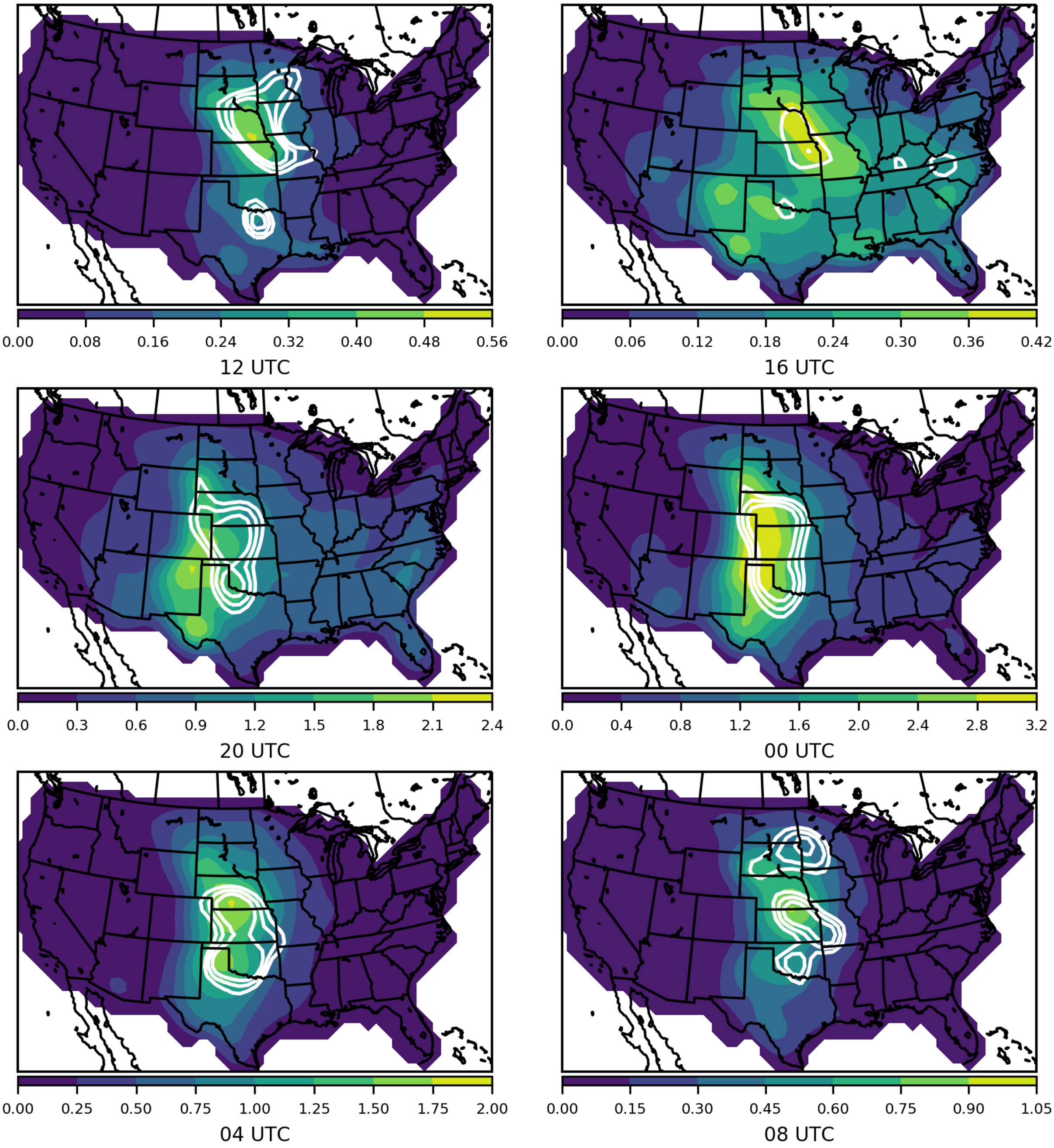

FIG. 4. A comparison of severe hail hours for 12, 16, 20, 00, 04, and 08 UTC. For MESH (color fill), units are severe hail hours per year for the labeled hour. For *Storm Data* (white contours), z-scores are plotted at $z = 3, 3.5, 4$ to show where the relative maxima of reports are compared to MESH. Please note the changing scales for the MESH color fill.

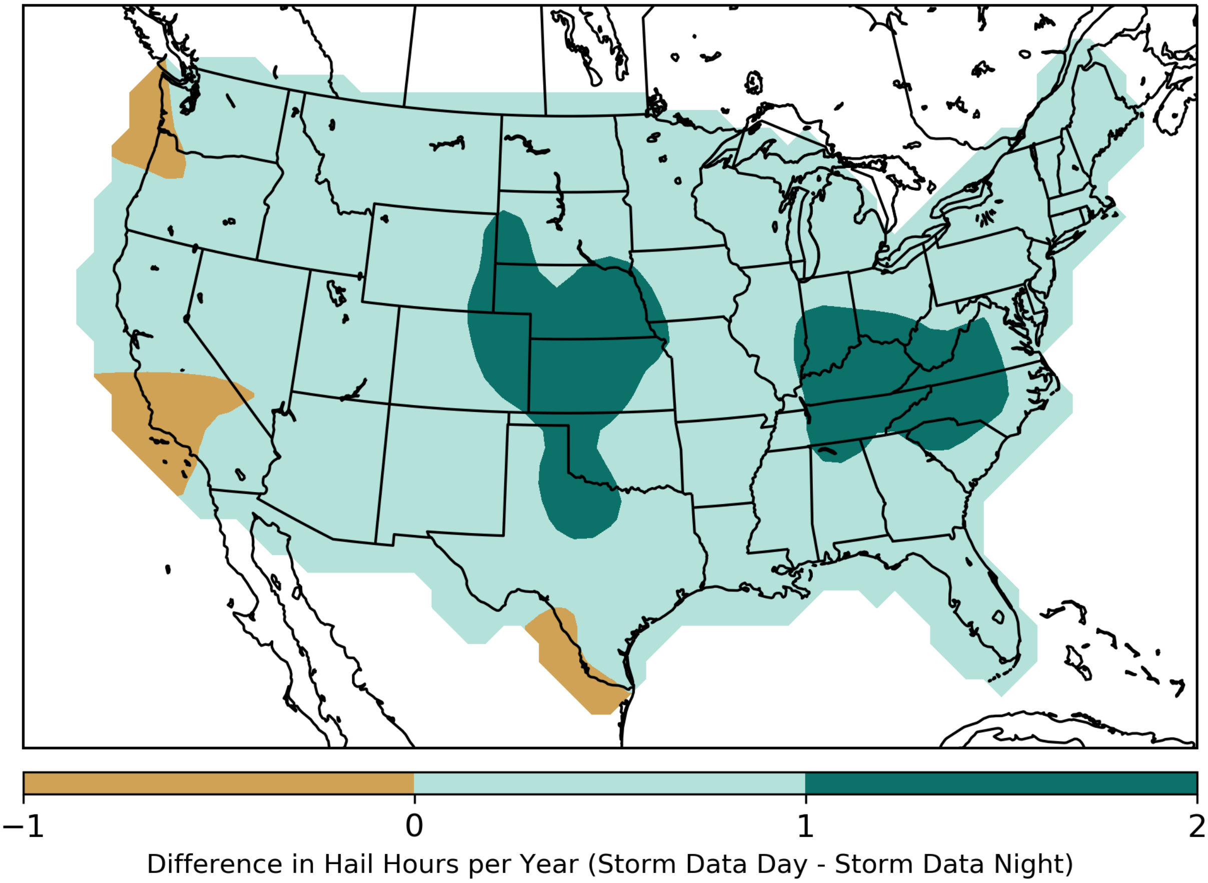

FIG. 5. Difference in *Storm Data* severe hail hours per year between day and night.

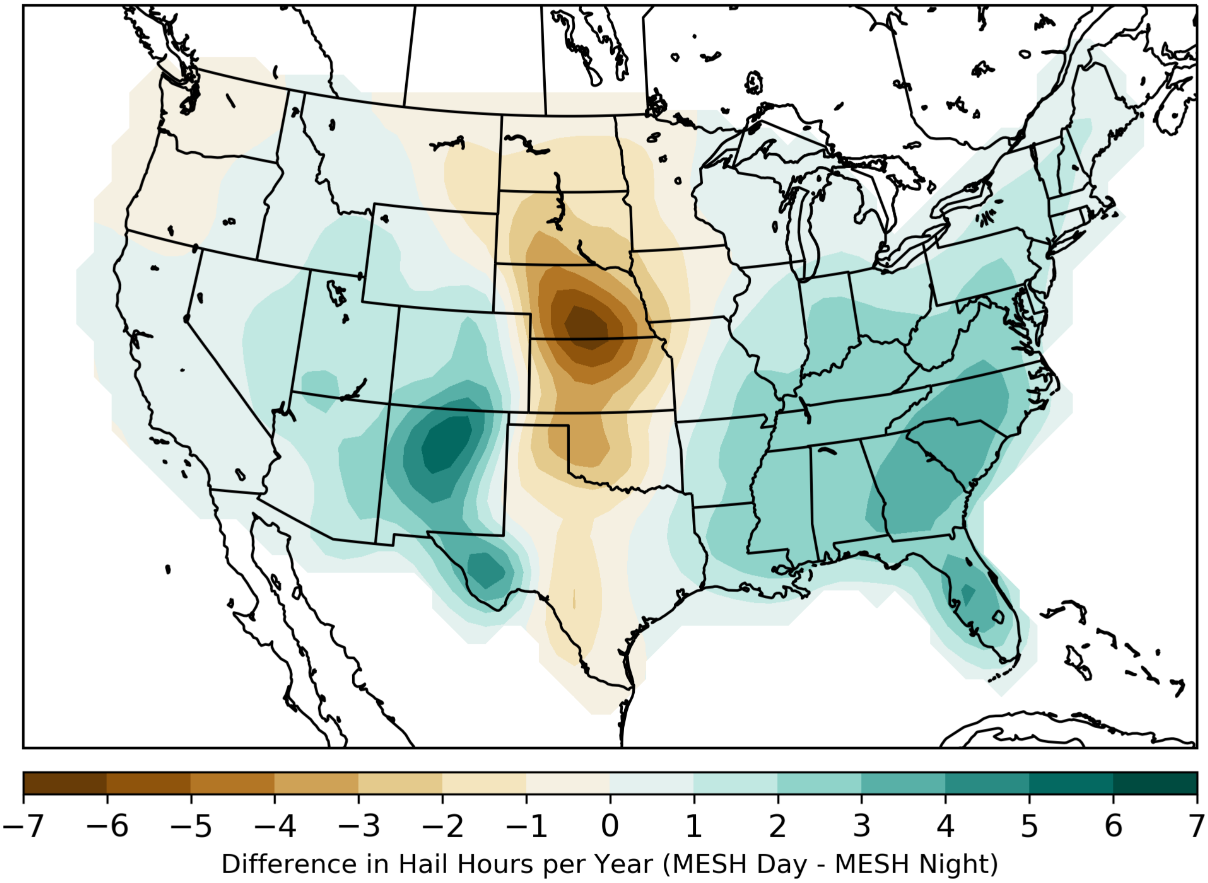

FIG. 6. Difference in MESH severe hail hours per year between day and night.

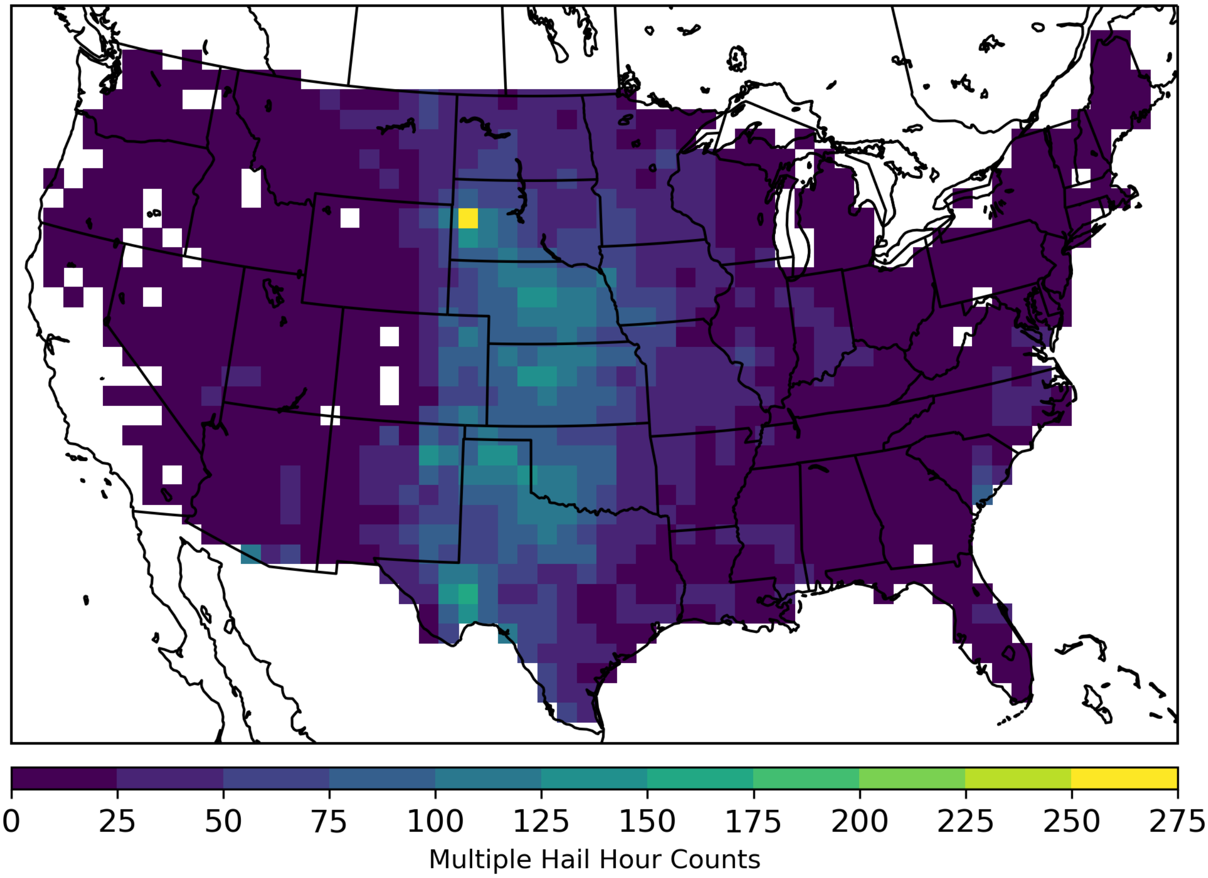

FIG. 7. Number of convective days with multiple MESH-diagnosed severe hail hours during the 2012–2017 period.

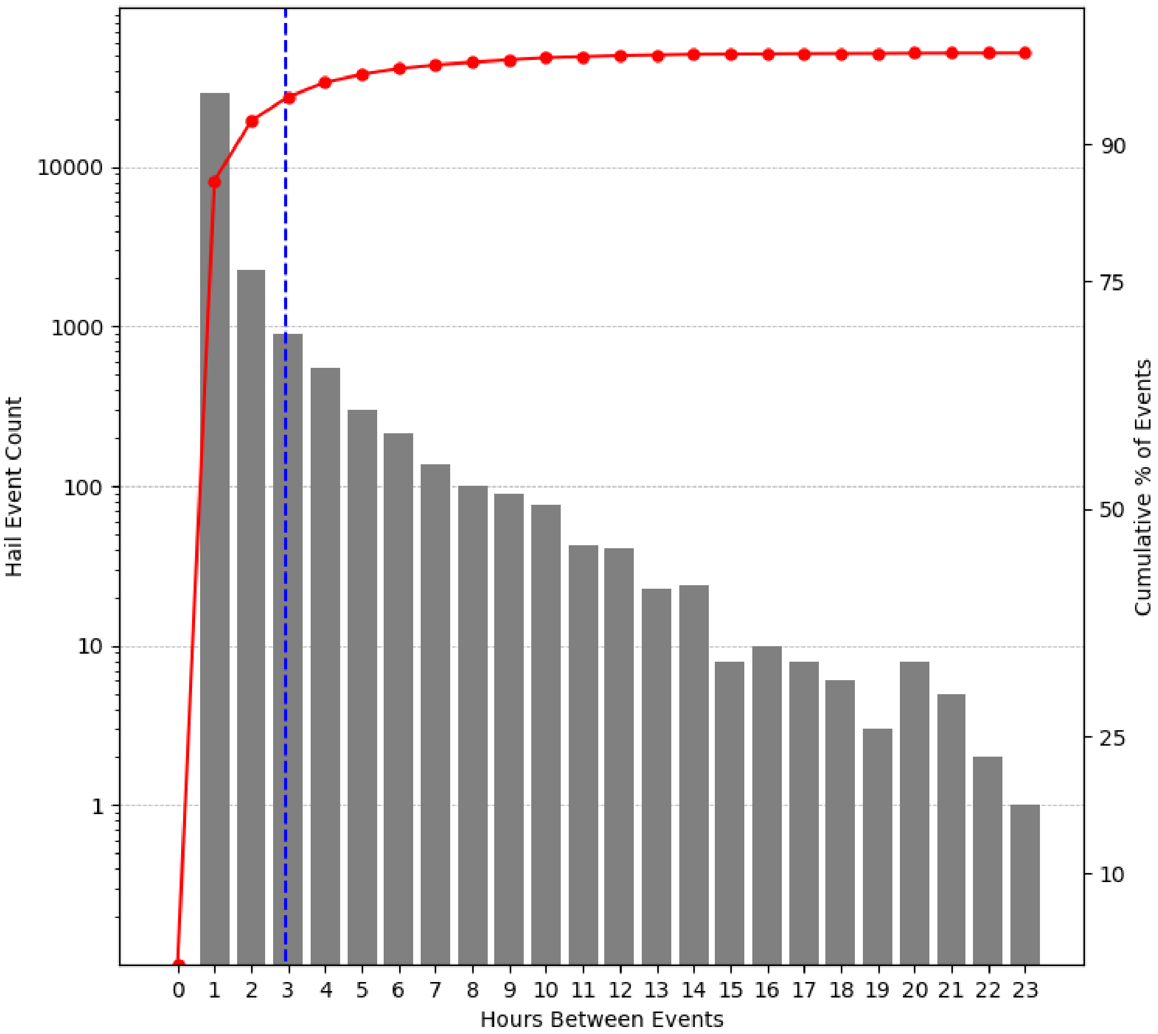

FIG. 8. Statistics for multiple MESH-diagnosed severe hail events. Binned by the elapsed time between two events, the histogram shows the count (left vertical axis, log scale) of how many events occurred within that amount of elapsed time. The cumulative distribution of the percentage of events each bin total takes up is plotted in red (right vertical axis). The blue dashed line denotes the time where 95% of events have occurred.

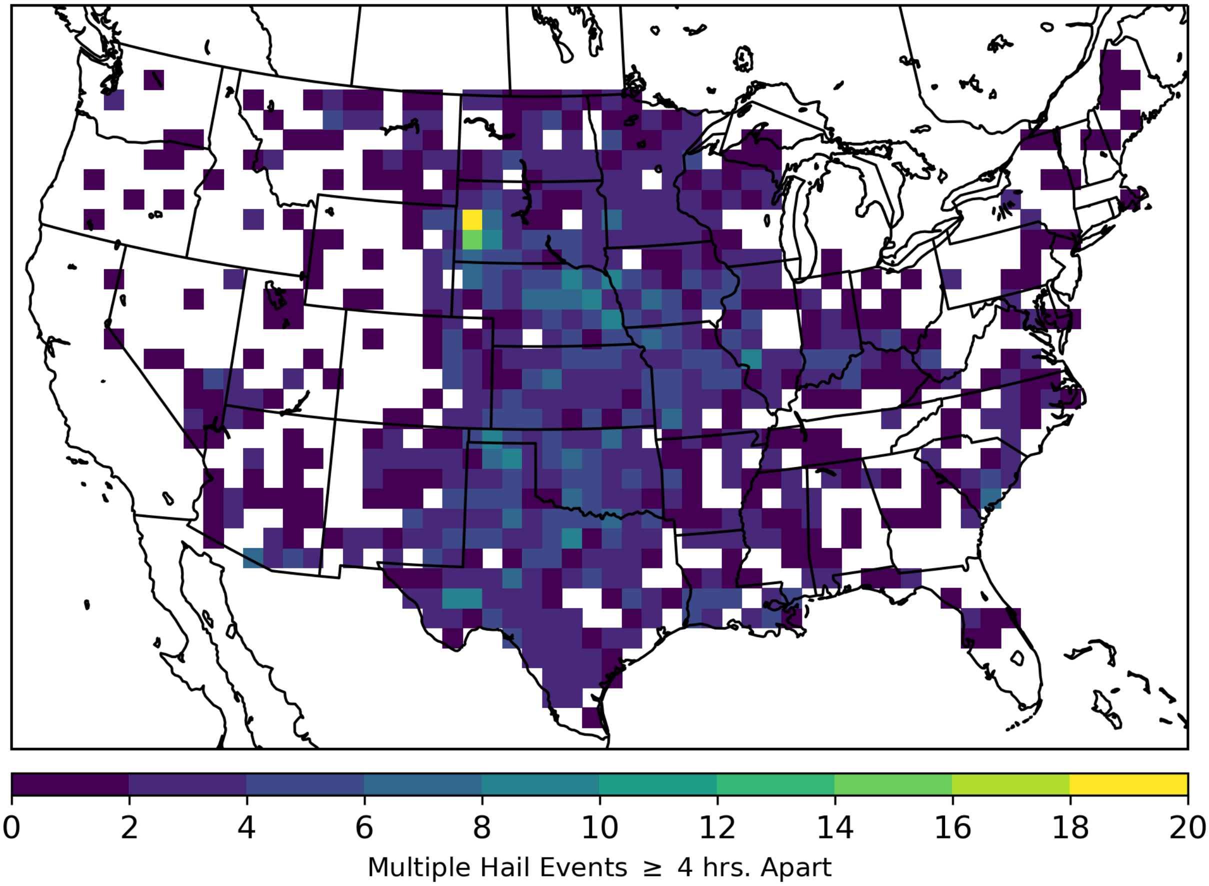

FIG. 9. As in Fig. 7, but MESH-diagnosed severe hail that was greater than or equal to four-hours apart.

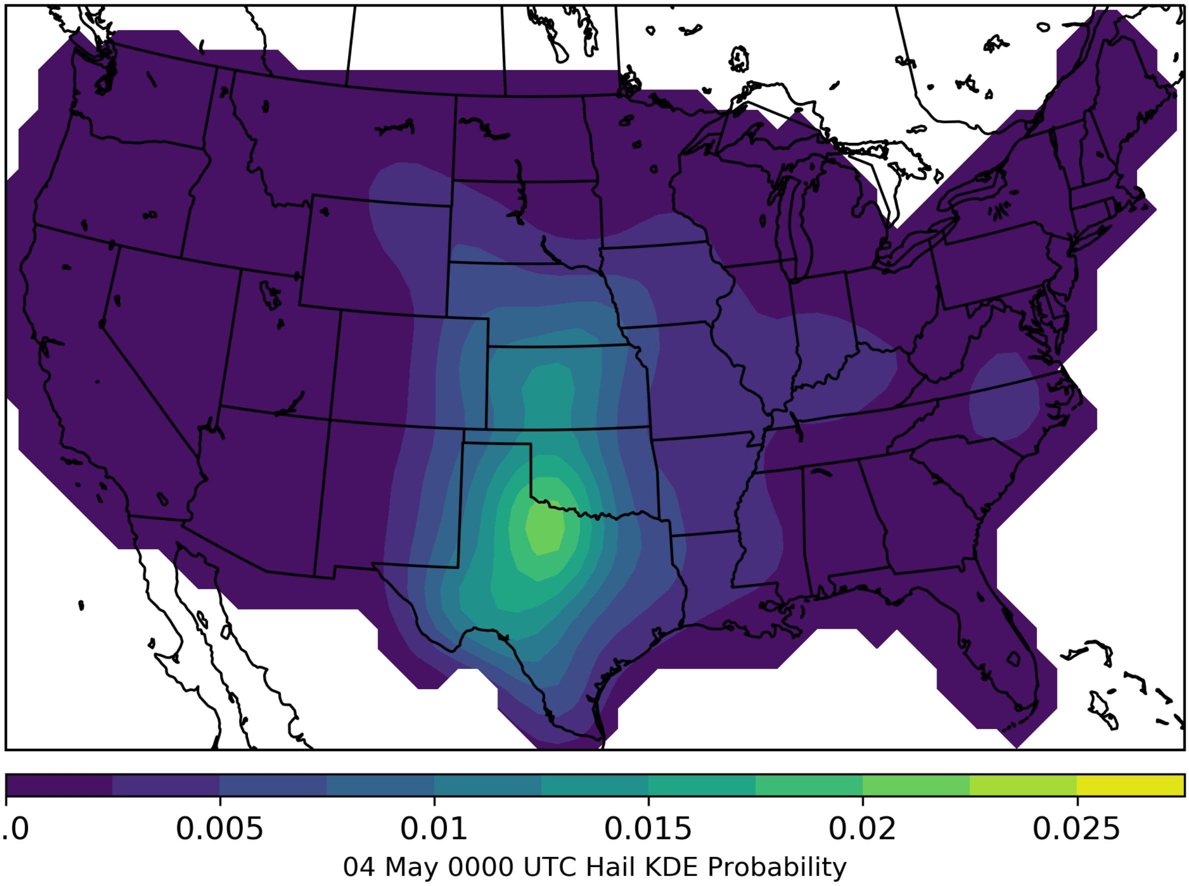

FIG. 10. KDE estimated MESH-diagnosed severe hail probability for 04 May 0000 UTC.