8.4B

HREF Climatology of Storm-Attribute Fields

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1. INTRODUCTION

The High-Resolution Ensemble Forecast (HREF) system became the first operational convection-allowing model (CAM) ensemble in the NWS in 2017. The convection-allowing aspect of the HREF provides unique and valuable probabilistic information on thunderstorm timing, mode, coverage, and intensity. Given the utility of the HREF in forecasting rare events and over five years of archived data available, it would be useful to generate a climatology of storm-attribute forecasts, so that current forecasts can be placed in the context of past forecasts. For example, this would allow us to answer questions like the following: 1) How rare are certain storm-attribute probability forecasts?, and 2) What was the outcome on those days?

This paper provides an overview of the HREF, including a brief history of configuration changes, a description of the storm-attribute fields examined in this study, a description of the methodology used to create the climatology, and a discussion of the results.

2. OVERVIEW OF THE HREF

The HREF was implemented operationally in November 2017 as the first operational CAM ensemble in the NWS, following favorable results from the SPC Storm-Scale Ensemble of Opportunity (Jirak et al. 2012) during several Hazardous Weather Testbed (HWT) Spring Forecasting Experiments (Jirak et al. 2016). The HREFv2, an eight-member ensemble (without HRRR members), was running in parallel by April 2017, which constitutes the beginning of the HREF archive used in this study. SPC included two HRRR members in version 2.1 of the HREF (i.e., HREFv2.1) in April 2019, but only the non-time-lagged HRRR member covered the full convective day from 00Z, so HREFv2.1 had nine full members until December 2020. At that time HRRRv4 was implemented, which included a forecast extension to 48 hours and allowed for ten full HREF members. Finally, the last HREF change was implemented in May 2021 as HREFv3 when the HiRes Window NMMB runs were replaced by the HiRes Window FV3 runs (Table 1). HREFv3 consists of ten (10) members with half of the members being time-lagged runs. The models are run at ~3-km grid spacing, using a multi-model (WRF-ARW, NMMB, FV3), multi-initial condition (NAM, RAP, GFS), and multi-physics approach to diversify forecast solutions (Table 1).

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Table 1. HREFv3 member configuration showing initial conditions (ICs)/lateral boundary conditions (LBCs), planetary boundary layer (PBL) schemes, and microphysics schemes. *SPC uses the 12-h time-lagged NAM Nest while NCO uses the 6-h time-lagged NAM Nest in HREFv3 products.

Member	ICs/LBCs	PBL	Micro
HRW NSSL	NAM/NAM	MYJ	WSM6
HRW NSSL -12h	NAM/NAM	MYJ	WSM6
HRW ARW	RAP/GFS	YSU	WSM6
HRW ARW -12h	RAP/GFS	YSU	WSM6
HRW FV3	GFS/GFS	EDMF	GFDL
HRW FV3-12h	GFS/GFS	EDMR	GFDL
NAM Nest	NAM/NAM	MYJ	F-A
NAM Nest -12h*	NAM/NAM	MYJ	F-A
HRRR	RAP/RAP	MYNN	Thompson
HRRR -6h	RAP/RAP	MYNN	Thompson

The unique aspect of a CAM ensemble is the probabilistic information provided about explicit storm-attributes, like storm rotation and intensity. For this study, three storm-attribute fields were included in the climatology:

- **Updraft Helicity** (**UH**; m^2s^{-2}): integrated from 2-5 km AGL for identifying a rotating updraft in a simulated supercell
- **Updraft Speed** (**UP**; ms^{-1}): column maximum from surface to 100 mb for convective overturning and hail potential
- **Wind Speed** (**WS**; kts): 10-m AGL and masked by updraft speed to identify convective wind gusts from any storm mode (Fig. 1)

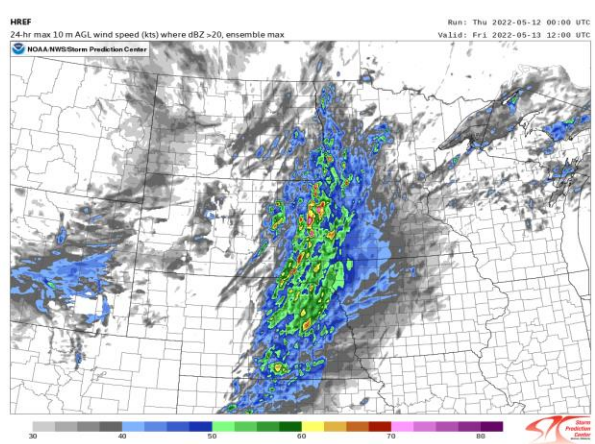

Figure 1. 0000 UTC HREF 24-h maximum 10-m wind speed (kts) valid for the convective day of 12 May 2022.

3. METHODOLOGY

The HREF climatology presented in this study is based solely on storm-attribute probabilities. Specifically, the neighborhood maximum ensemble probability (NMEP; Schwartz and Sobash 2017 and Roberts et al. 2019) is calculated from the 0000 UTC HREF and valid for the 24-h convective day (i.e., forecast hours 12 to 36) for three storm-attribute fields at two thresholds:

- **UH** @ 75 and 150 m^2s^{-2} (**UH75** & **UH150**)
- **UP** @ 20 and 30 ms^{-1} (**UP20** & **UP30**)
- **WS** @ 30 and 50 kts (**WS30** & **WS50**)

These thresholds were chosen based on results from previous studies (e.g., Sobash et al. 2016) and availability as standard options on the SPC HREF web viewer (https://www.spc.noaa.gov/exper/href/). Note that the UH climatology for the HRW-FV3 is notably different than the other HREF members, so the HRW-FV3 UH values were normalized here to more closely match other HREF members by dividing by 2.4 based on a preliminary analysis of UH data. Finally, the NMEP forecasts were smoothed using a 2-D Gaussian kernel density estimate using a smoothing parameter of 40 km.

Given the smoothed NMEP forecasts for these six fields across the CONUS for each day between April 2017 and September 2022 (~2000 days), there were two approaches used to calculate the climatology:

1. **Average Number of Days** – For this approach, the number of days when the NMEP forecasts exceeded 10, 30, 50, 70, & 90% were counted at each grid point across the CONUS to calculate a spatial climatology (i.e., the average number of days that locations exceeded forecast thresholds and probabilities; Fig. 2).

2. **Daily Maximum Probabilities** – In this approach, the daily maximum value of the smoothed NMEP forecasts was extracted from the CONUS and recorded along with the daily maximum practically perfect hindcast (PPH; Hitchens et al. 2013) based on severe weather reports and the peak SPC Outlook category. While this method does not check for spatial agreement of these maximum values, it does allow for the exploration of the relationship between HREF NMEP forecasts and the resultant severe weather. (e.g., the distribution of PPHs or the most-likely SPC Outlook category for a given HREF forecast probability; Fig. 3).

The PPH values were calculated and recorded for each convective day in the study period through June 2022 using NCEI's *Storm Data.* The daily maximum PPH values were extracted separately for tornadoes (EF0+), significant tornadoes (EF2+), severe hail (1"+), significant severe hail (2"+), measured severe wind (50kts+) and measured significant severe winds (65 kts+).

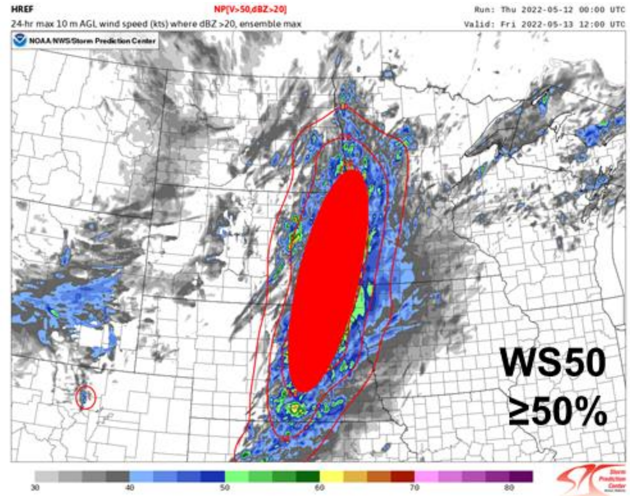

Figure 2. Same as Fig. 1, except for the smoothed NMEPs of WS50 are included as red contours (i.e., 10%, 30%, & 50%), with the ≥50% probability shaded in red. In this example, the climatological count would increase by 1 for WS50 ≥50% for grid boxes in the shaded region.

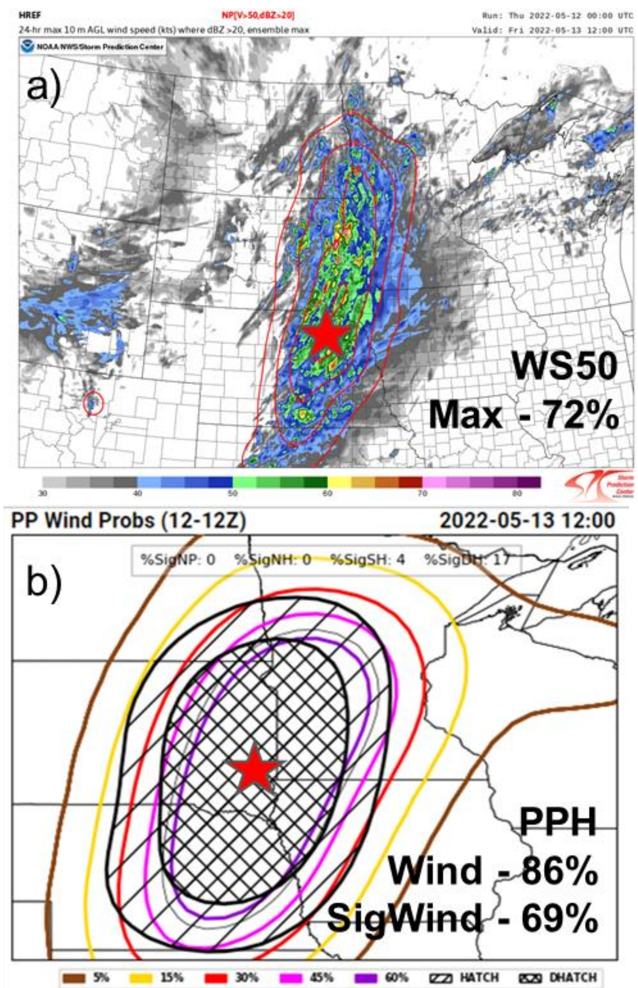

Figure 3. Same as Fig. 2, except for a) the maximum smoothed NMEP of WS50 (72%) and b) the maximum PPH for measured wind (86%) and measured significant wind (69%).

4. HREF CLIMATOLOGY RESULTS

Spatial plots of the average number of days per year were generated for each of the six smoothed NMEP fields at five probability thresholds (i.e., 10, 30, 50, 70, & 90%). Clearly, that is too many plots to show in this extended abstract, so only a select few will be highlighted here. In addition, the same type of plots were created for the average number of days per month across the different fields and thresholds, which allows for an examination of the annual cycle of HREF forecasts. Again, only one example is shown here for UH75 given the volume of figures produced in this analysis. For the daily maximum probabilities, the focus again will be on UH75 given that the strongest and most interesting signal resides with this field and to keep the analysis focused in this paper.

4.1 Average Number of Days

The frequency of UH75 forecasts exceeding 10% is maximized over central Plains with over 30 days per year on average while a distinct minimum is apparent west of the Rockies (Fig. 4). Forecasts of UH75 exceeding 50% are much more rare with a peak value of only 5 days per year on average in the central Plains (Fig. 5).

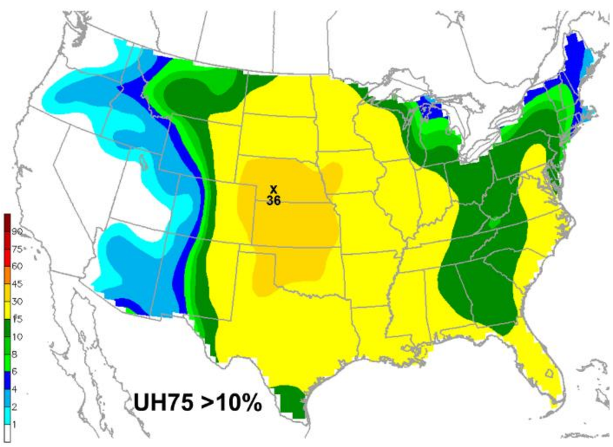

Figure 4. Average number of days per year (2017-2022) where the smoothed HREF NMEP forecast of UH75 exceeded 10%.

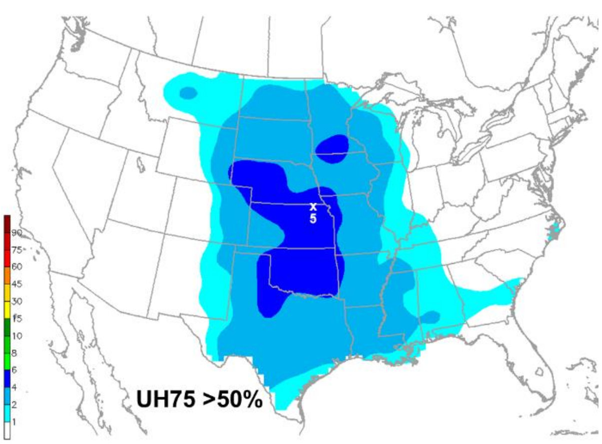

Figure 5. Same as Fig. 4, except for UH75 exceeding 50%.

The occurrence of UP20 forecasts exceeding 10% is much more common than UH75 forecasts and has a different spatial pattern. UP20 forecasts exceeding 10% are most common along the Gulf Coast and Florida with a maximum of over 150 days on average per year in southern Florida (Fig. 6). Increasing the updraft speed threshold to 30 ms^{-1} and the probability threshold to 50% greatly reduces the frequency to a peak of 7 days per year on average over the central U.S. (Fig. 7) and results in a spatial pattern that more closely resembles the UH75 forecast frequency.

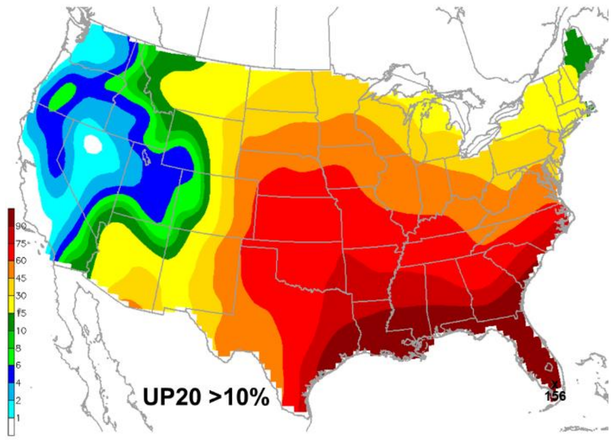

Figure 6. Same as Fig. 4, except for UP20 exceeding 10%.

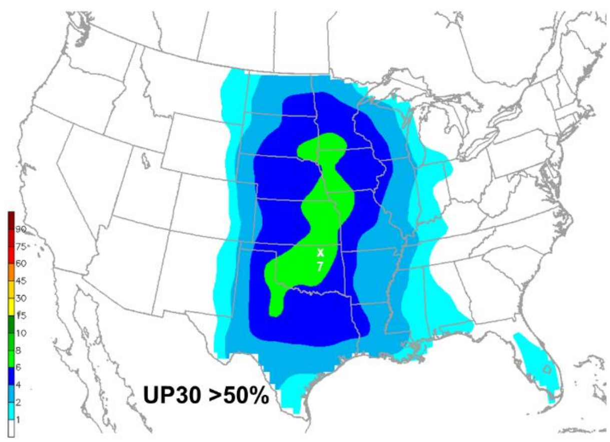

Figure 7. Same as Fig. 4, except for UP30 exceeding 50%.

For WS30 forecasts exceeding 10%, the highest frequency of occurrence is along the Gulf Coast, across Florida, and up to the mid-Atlantic Coast (Fig. 8). A clear secondary maximum occurs in the central and southern High Plains where WS30 forecasts exceed 10% over 60 days per year on average (Fig. 8). Increasing the threshold to 50 knots, or to severe-wind criteria, not only greatly reduces the frequency of forecast occurrence to just over 10 days per year on average, but focuses primarily over the High Plains (Fig. 9). This agrees fairly well with the highest frequency of occurrence of measured severe convective winds (not shown).

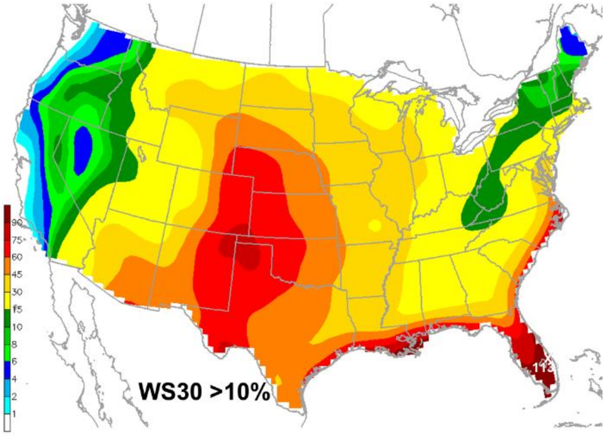

Figure 8. Same as Fig. 4, except for WS30 exceeding 10%.

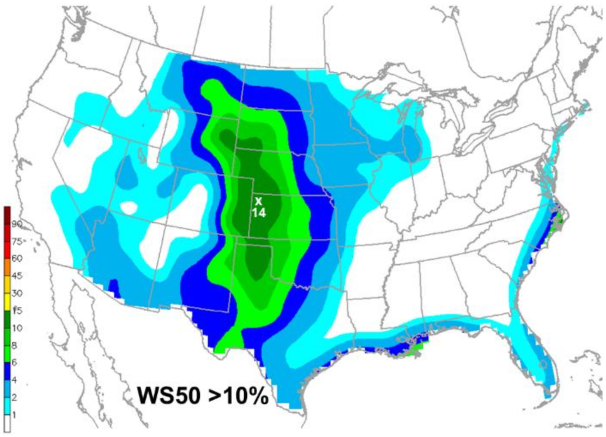

Figure 9. Same as Fig. 4, except for WS50 exceeding 10%.

The average number of forecast days per month of UH75 exceeding 10% is shown in Fig. A1 (in the Appendix) to visualize the annual forecast cycle. UH75 probabilities are largely confined to the Gulf or Gulf Stream until March and April when the frequency of UH75 forecasts increases across the Southeast and southern Plains. In May, the forecast frequency of UH75 ramps up across the southern and central Plains. By June, the highest frequency of UH75 forecasts shifts northward to the central Plains. A farther northwestward shift occurs into July before the pattern begins to shift back slightly southward in August. The frequency of UH75 forecasts drops sharply in September and continues to decrease through the end of the year, with little indication of a secondary peak in the fall for this five-year period.

4.2 Daily Maximum Probabilities

The distribution of daily maximum NMEP forecasts of UH75 across the CONUS are shown for each month in Fig. A2 (in the Appendix). The winter months (Dec/Jan/Feb) are dominated by forecasts with UH75 <10%. A sharp increase in the frequency of higher UH75 probabilities occurs through the spring, with over half of the days in May having a maximum UH75 probability over 70%. June has similar frequencies of UH75 forecasts as May, but the heart of the summer (July and August) see a decrease in higher UH75 probability forecasts, though over half of the days still have maximum UH75 probabilities over 50%. The fall months (Sep/Oct/Nov) show a steady drop in the frequency of higher UH75 probability forecasts.

Viewing the same data another way in Figs. 10 and 11 shows that daily maximum UH75 forecasts exceeding 50% are rare from November through February, but are relatively common in May and June (Fig. 10). About half of the days in April, July, and August see maximum UH75 probabilities over 50%. The result that really stands out is the rare nature of UH75 probabilities exceeding 90%. On average, only about four days in May, three days in April, and one day in June and July have maximum UH75 forecasts over 90%. The average is less than one day for the other months of the year. Thus, it is rare for all of the members of the HREF to forecast strongly rotating storms in the same neighborhood.

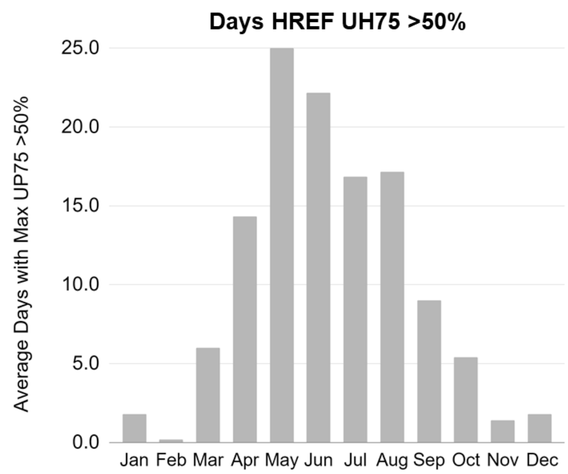

Figure 10. Average number of daily maximum NMEP forecasts of UH75 exceeding 50% by month.

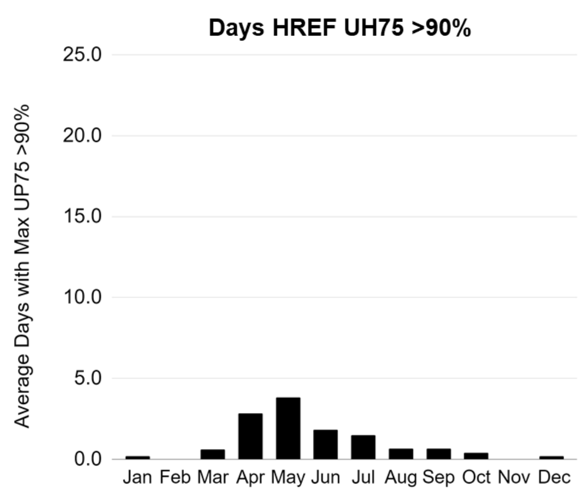

Figure 11. Same as Fig. 10, except for UH75 exceeding 90%.

The natural follow-up question is whether these results have any meaning in terms of predictive skill regarding the amount of severe weather activity. In this study, we measure the amount of severe weather activity using PPHs based on reports in *Storm Data*. When examining the distribution of maximum daily PPHs of tornadoes binned by HREF NMEP forecasts of UH75 (Fig. 12), there is a positive correlation. As the forecast probability of UH75 increases, the distribution of tornado PPHs generally increases as well, especially at the higher probability bins. For example, when the UH75 forecast is >90% somewhere across the CONUS, it is likely that at least 10% coverage of tornadoes will verify. There is also utility at the low end, where a UH75 forecast <10% almost always verifies with a tornado PPH <2%.

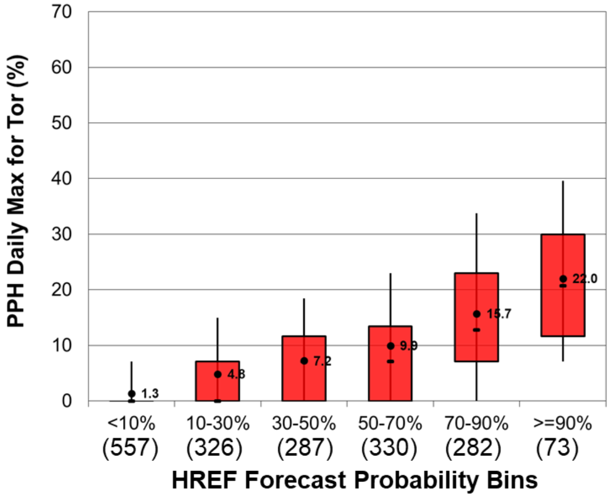

Figure 12. Distribution of daily maximum tornado PPH binned by HREF daily maximum NMEP forecasts of UH75. The number of forecasts in each bin is indicated in parentheses below the box-and-whisker plot.

An even stronger signal appears for severe hail. The distribution of PPHs for severe hail nicely increases in a monotonic fashion for increasing UH75 probability bins (Fig. 13). At low forecast probabilities (<10%) of UH75, the resultant coverage of severe hail is likely to remain below 5% across the CONUS. For mid-range probabilities (50-70%) of UH75, the coverage of severe hail is typically greater than 15%. At high forecast probabilities (>90%) of UH75, the resultant coverage of severe hail is likely to exceed 30%.

A similar relationship of UH75 forecasts is also seen for PPHs of measured wind, though the relationship is not quite as strong as the one for severe hail. As the forecast probabilities of UH75 increase, the distribution of PPHs for measured severe wind also increases (Fig. 14), though there is more overlap of the interquartile ranges than seen for hail (Fig. 13). Nevertheless, there is still some forecast utility in predicting the PPH coverage of measured wind simply by knowing the daily maximum UH75 forecast probability. For example, a UH75 forecast probability <10% is likely to verify with a PPH below 5% while a UH75 forecast >70% is likely verify with a PPH of measured severe wind gusts above 15%.

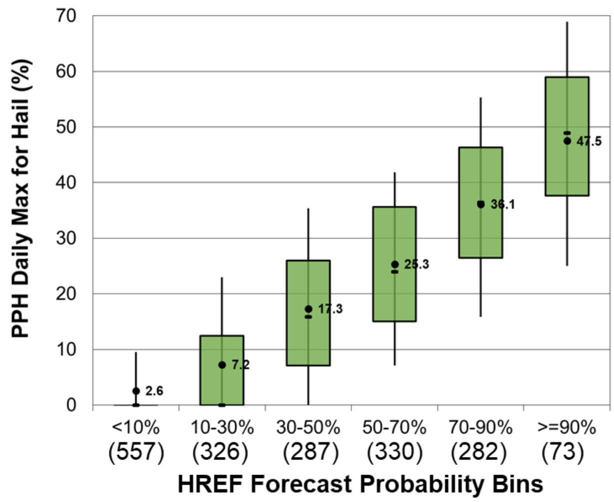

Figure 13. Same as Fig. 12, except for hail.

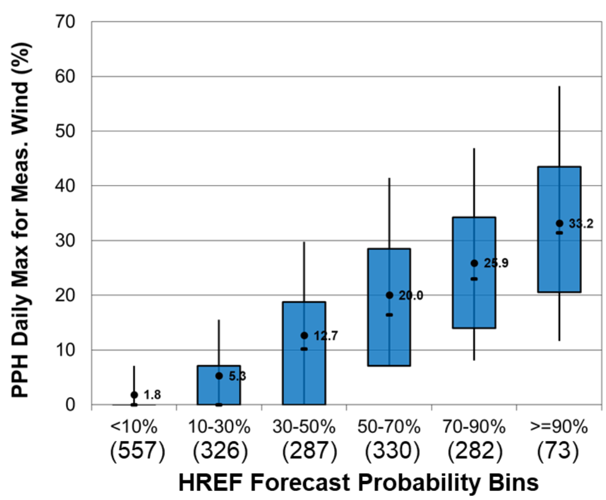

Figure 14. Same as Fig. 12, except for measured severe wind.

Lastly, there was some curiosity regarding how the HREF NMEP forecasts relate to SPC Outlooks. It is necessary to note that most 0600 UTC SPC Outlooks are informed by the 0000 UTC HREF, so this is not an independent assessment. Nevertheless, the distributions of the daily maximum HREF NMEP forecasts of UH75 were analyzed for the peak categorical risk from the 0600 UTC SPC Day 1 Outlook. There is a very strong correlation between the UH75 forecast probabilities and the SPC categorical risk (Fig. 15). The distribution of UH75 probabilities shifts upward as the categorical risk increases. If the maximum UH75 probability across the CONUS is <10%, then most of the time there is no categorical risk of severe weather (i.e., just general thunderstorms; level 0 of 5). However, if the maximum UH75 probability is 50%, then the categorical risk is almost always at least at Slight (level 2 of 5). When the

UH75 probability is 90% (a rare forecast as established previously), then the categorical risk is typically at Moderate (level 4 of 5) or High (level 5 of 5). Thus, a very simple check of a single forecast number (i.e., CONUS daily maximum NMEP forecast of UH75) can provide a reasonably good estimate of the peak categorical risk for a given convective day.

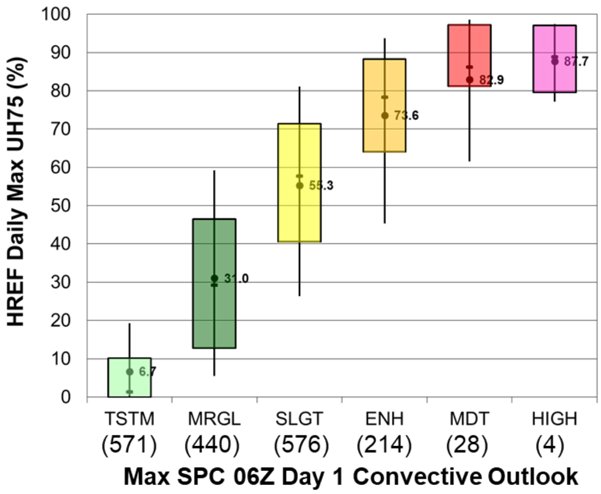

Figure 15. Distribution of daily maximum HREF NMEP forecast of UH75 binned by maximum SPC 0600 UTC Day 1 Convective Outlook categorical risk [i.e., general thunderstorms – TSTM (level 0); Marginal – MRGL (level 1); Slight – SLGT (level 2); Enhanced – ENH (level 3); Moderate – MDT (level 4); and High – HIGH (level 5)].

5. SUMMARY AND CONCLUSIONS

Through evaluation in the HWT and SPC operations, the HREF has proven to be a very useful and skillful CAM ensemble for forecasting convective and severe weather. The HREF has been operational in the NWS for five years, and the convection-allowing resolution of the HREF can be leveraged to provide explicit probabilistic information about storm attributes, like updraft rotation and speed. An HREF climatology of three storm-attribute probabilities was developed to explore the rarity of these forecasts and the relationship to severe weather activity. Based on the results of this study, the HREF storm-attribute probability forecasts examined were found to be rare for any given location, especially at higher thresholds and probabilities. Even without considering the synoptic pattern or environment, the HREF storm-attribute probability magnitudes were also found to be strongly correlated with severe weather activity and the peak SPC Outlook categorical risk. Thus, simply knowing where a current HREF storm-attribute probability forecast lies within its five-year climatology can provide valuable information on the likely outcome.

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APPENDIX

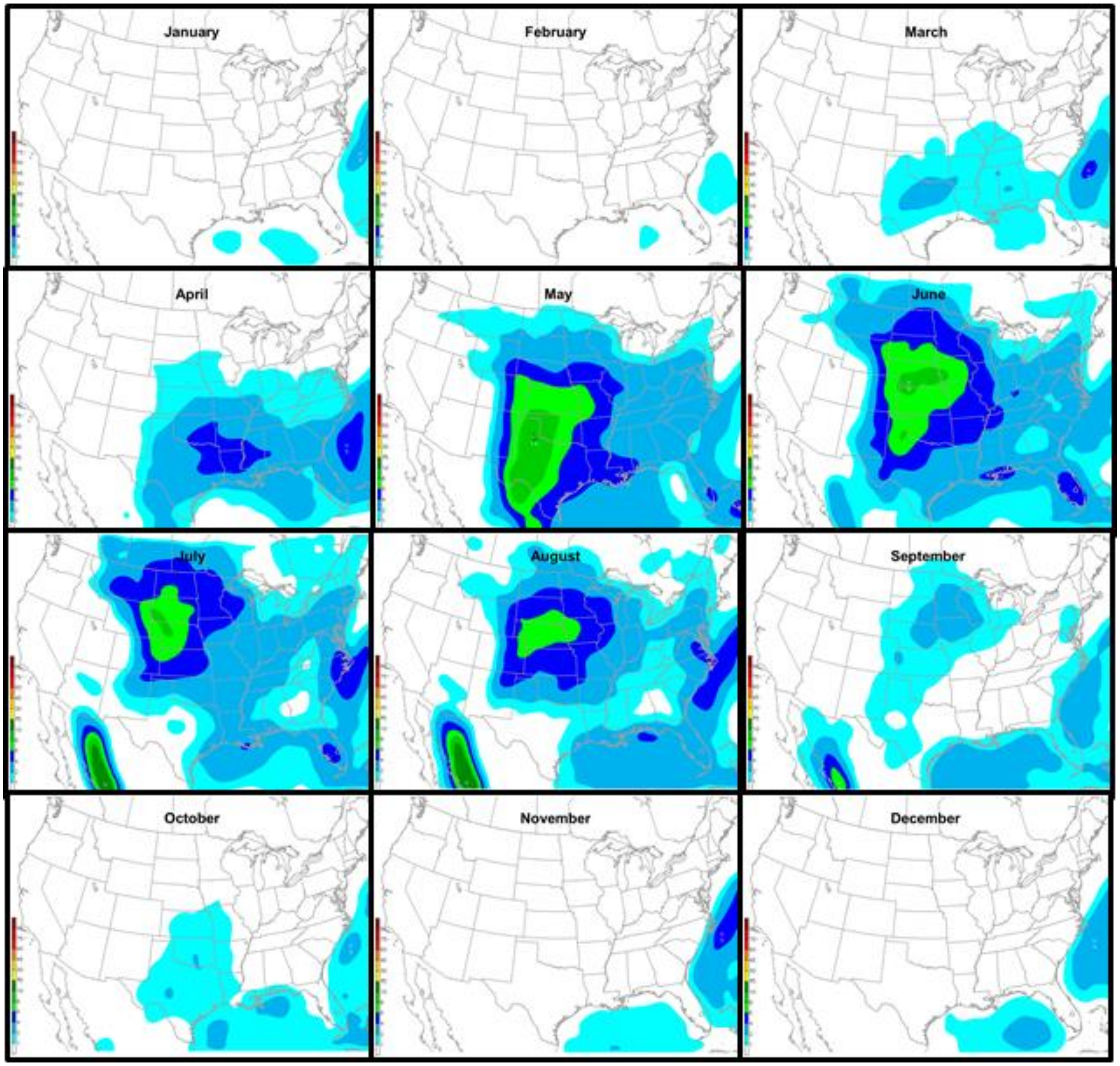

Figure A1. Average number of days per month (2017-2022) for January through December where the smoothed HREF NMEP forecast of UH75 exceeded 10%.

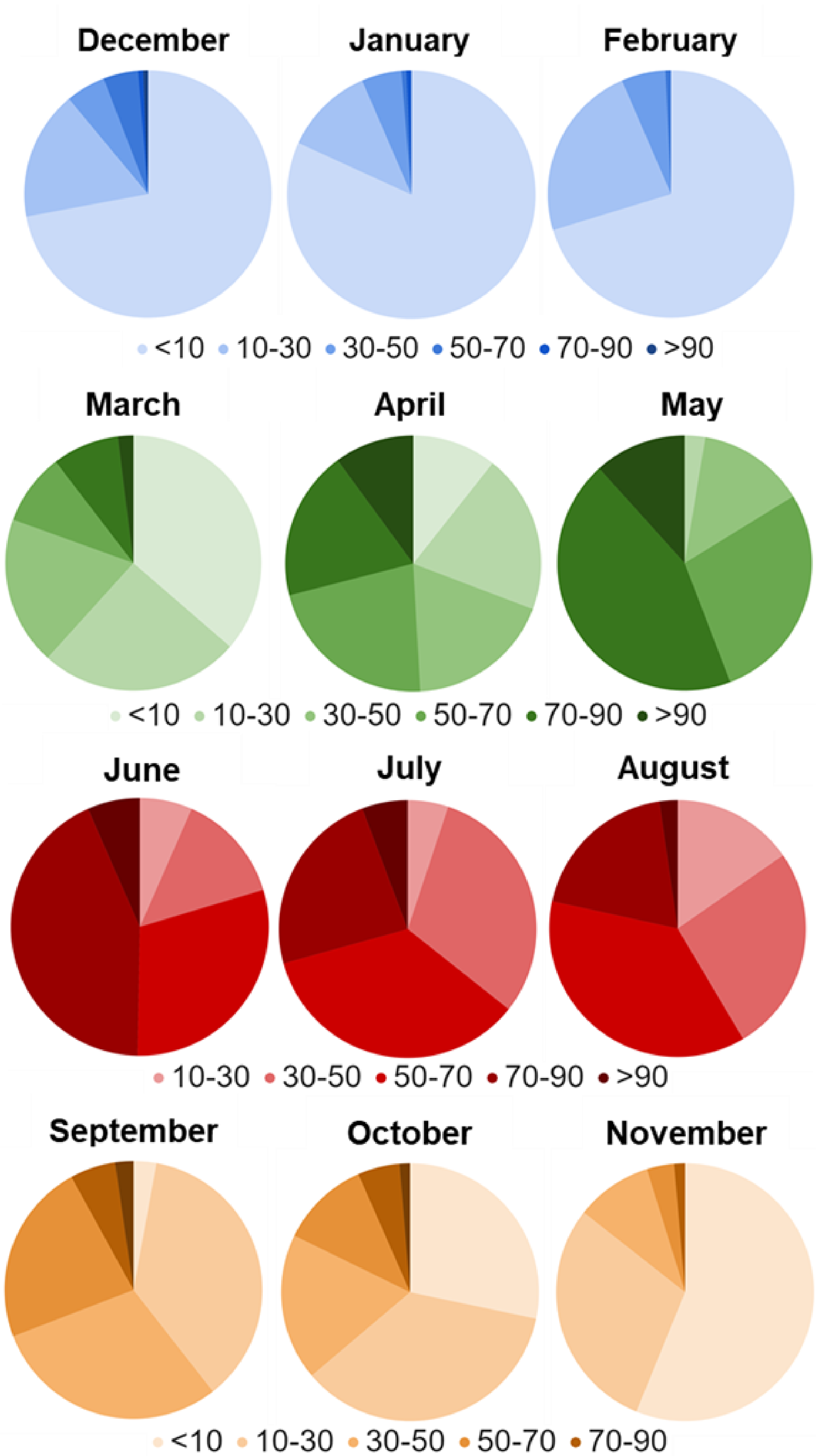

Figure A2. Distribution of daily maximum NMEP forecasts of UH75 across the CONUS by month. The daily maximum UH75 forecasts are binned into six categories: <10, 10-30, 30-50, 50-70, 70-90, and >90%.