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RESEARCH ARTICLE

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A climatology of convective and non-convective high-wind events across the eastern United States during 1973–2015

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Abstract

This study investigates convective and non-convective high-wind events (CWEs and NCWEs) across the eastern U.S. during a 43-year climatological period (1973–2015) for spatial and temporal variations in wind speed and direction. Hourly surface wind observations were gathered from the National Centers for Environmental Information Data Center Integrated Surface Database (NCEI-ISD). This dataset includes quality-controlled wind observations from 391 first-order weather stations in the eastern U.S. Findings show that high-wind events (HWEs) meeting established National Weather Service criteria were most concentrated in the West North Central and South regions (High Plains) and fewer CWEs occurred during the study period compared to NCWEs. Gust CWEs increased significantly (1.95 days year^{-1}) while sustained NCWEs decreased significantly (−0.58 days year^{-1}). Mean wind directions were observed primarily in the southwest and northwest quadrants. Mean wind speed decreased at a statistically significant level for sustained CWEs, gust CWEs, and sustained NCWEs. Developing an extensive climatological understanding of convective and non-convective high-wind events is beneficial to mitigate damage and fatalities caused by these events.

1 | INTRODUCTION

High-wind events (HWEs) have resulted in approximately $300 million in property losses during the last six decades and nearly 1,500 fatalities from 1980–2005 (Ashley and Black, 2008; Changnon, 2009). During 2006–2015, 468 HWE fatalities were recorded in the NCEI Storm Data database. High-winds (as determined by National Weather Service classifications) occur in every region of the United States and are associated with almost every type of severe weather event, such as those occurring in a convective or non-convective environments. Nontornadic convective HWEs (CWEs) and non-convective HWEs (NCWEs) account for almost half of all wind-related fatalities, following tornadic HWEs (Ashley and Black, 2008). Seasonality and regional geography also have an effect on HWE characteristics such as frequency, speed, and direction (Kelly *et al.*, 1985; Johns and Hirt, 1987; Kapela *et al.*, 1995; Klimowski *et al.*, 2003; Martin and Konrad, 2006; Lacke *et al.*, 2007; Schoen and Ashley, 2011).

HWEs can also be categorized by weather type: convective, meaning thunderstorm conditions are present, or non-convective, meaning thunderstorm conditions are not present. CWEs and NCWEs produce similar hazards at the surface, but occur during different atmospheric conditions. CWEs can result from a variety of weather phenomena such as disorganized and organized mesoscale convective systems (MCSs) and supercell systems, as well as derechos, downbursts, and bow echoes. Annually, CWEs result in an average of 84 fatalities in the United States. (Schoen and Ashley, 2011). During 1980–

2005, tornadoes were the leading cause of convective wind-related fatalities, followed by thunderstorms and their associated features (Ashley and Black, 2008). Of these features, organized linear convective systems and bow echoes resulted in the most thunderstorm-related fatalities (Klimowski *et al.*, 2003; Schoen and Ashley, 2011). Convective weather systems occur most frequently in the summer months when convection-inducing parameters such as heat and moisture are greatest. Studies have shown an increase of nontornadic convective storms during summer, especially in the High Plains region (Kelly *et al.*, 1985; Klimowski *et al.*, 2003; Coniglio *et al.*, 2004; Ashley and Mote, 2005; Changnon, 2011). Likewise, convective-related wind fatalities have been observed more frequently in summer (Black and Ashley, 2010; Schoen and Ashley, 2011).

Non-convective high-winds are most commonly associated with extratropical cyclones (ETCs). Embedded within these weather systems are other contributing features like topography, dry slots or dry air intrusions, tropopause folds, and sting-jets (Browning and Golding, 1995; Kapela *et al.*, 1995; Niziol and Paone, 2000; Browning, 2004; Crupi, 2004; Hultquist *et al.*, 2006; Lacke *et al.*, 2007; Knox *et al.*, 2011; Durkee *et al.*, 2012). Fatalities caused by non-convective high-winds were almost equal to those caused by nontornadic convective high-winds and represented over 20% of all wind fatalities during 1980–2005 (Ashley and Black, 2008). In several studies analysing non-convective winds in the Great Lakes and northeastern U.S. regions, the majority of NCWEs indicated a southwesterly prevailing wind direction (Niziol and Paone, 2000; Lacke *et al.*, 2007; Durkee *et al.*, 2012). Additionally, NCWEs occur most frequently during winter and transitional seasons when ETC frequency is greatest and studies have indicated that HWE frequency is directly affected by storm track patterns (Lacke *et al.*, 2007; Changnon, 2009; Booth *et al.*, 2015; Ma and Chang, 2017).

While CWEs and NCWEs have been studied separately and on a regional scale, there is currently no climatological comparison of these HWE types for the central and eastern U.S. The purpose of this study is to

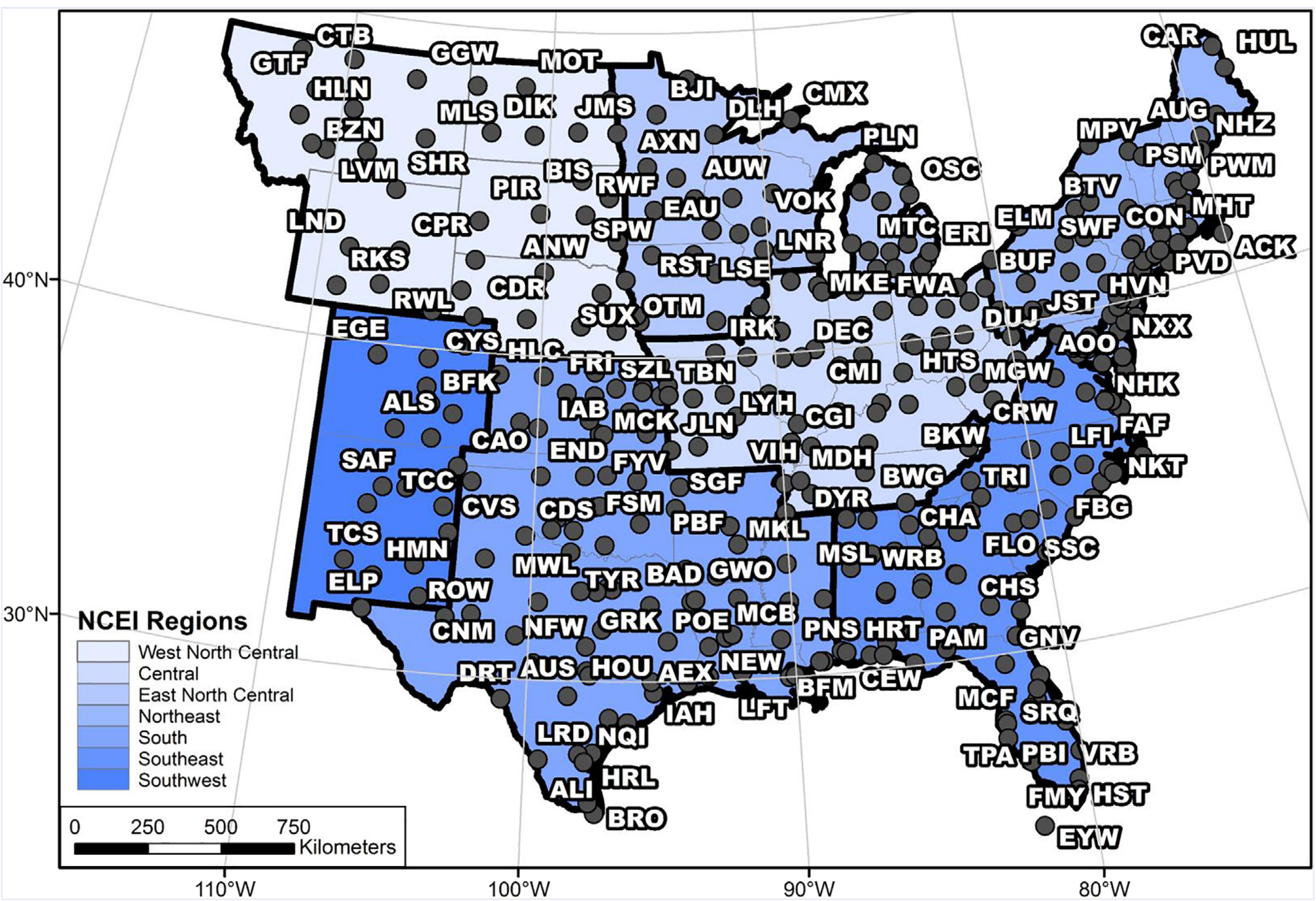

FIGURE 1 Spatial distribution of 391 first-order stations and NCEI climate regions used in the analysis [Colour figure can be viewed at wileyonlinelibrary.com]

investigate high-wind observations across the eastern U. S. during 1973–2015 with specific regard to spatial and temporal variations in frequency, speed, and direction between sustained and gust CWEs and NCWEs.

2 | DATA AND METHODS

Automated surface wind observations from 391 first-order weather stations in the eastern United States were gathered from the NCEI-ISD database (Figure 1). The database provided sustained and gust surface wind observations derived from hourly data and formatted in ms^{-1}. The 43-year period between 1973 and 2015 was chosen based on the quality and completeness of hourly high-wind observations via the National Centers for Environmental Information Data Center Integrated Surface database (NCEI-ISD). Lacke *et al*. (2007) identified the presence of erroneous observation times and missing data in the NCEI-ISD database between 1965 and 1972 (sustained wind observations were recorded every 3 hours instead of hourly); thus, stations with numerous missing records and observations prior to 1973 were excluded from this study. Lacke *et al*. (2007) also found a lack of gust observations in the NCEI-ISD database during the study period. Due to the discrepancies in the NCEI-ISD database, this study follows guidelines for high-wind observations set forth by Lacke *et al*. (2007), Kurtz (2010), and Gilliland *et al*. (2019) (Figure 2).

Likewise, inconsistent station anemometer heights and locations can present a problem in the quality of the data. Wind speeds increase in height due to a decrease in friction, thus anemometers at higher altitudes report faster wind speeds. Anemometers have been subject to location or height changes during their operational periods (Klink, 1999; Lacke *et al*., 2007; Pryor *et al*., 2007). In the 1960s, rooftop anemometers were repositioned to approximately 6.1 m above the ground The World Meteorological Organization (WMO) standardized anemometer heights to 10 m above the ground in the 1980s, thus changing anemometer heights once more. Other changes took place during the 1990s as automated surface and weather observing systems were deployed in the United States. Due to this potential discrepancy in the data, the wind profile power law was used to adjust all wind observations to the 10-m height:

$$V(z) = V(z_{\text{ref}}) \times \left(\frac{z}{z_{\text{ref}}}\right)^{\alpha}, \quad (1)$$

where $V(z)$ is equal to the observed wind velocity, z_{ref} is equal to the reference height of 10 m, and z is equal to the new height, assuming neutral stability ($\alpha = 1/7$) (Klink, 1999; Pryor *et al*., 2007). Height records were gathered from NCEI, as NCEI-ISD did not include metadata for all stations (Gilliland *et al*., 2019).

DeGaetano (1997) analysed data quality for hourly wind speeds and directions across 41 first-order weather stations in the northeastern U.S. Less than 0.1% of the data records failed the quality control test or had inaccurate observations. Observations in the dataset were checked using online resources such as the NCEI Climate Database Modernization Program (CDMP), Quality Controlled Local Climatological Data (QCLCD) and Unedited Local Climatological Data (ULCD) to confirm that they met NWS sustained and gust criteria. For the first-order weather stations used in this study, high-wind records that had questionable or invalid observations were removed from the dataset.

Wind observations were segregated into two high-wind categories for sustained and gust HWEs according to NWS criteria. The NWS classifies a high-wind as sustained when wind speeds are at least 18 $m{\cdot}s^{-1}$ for an hour or longer and gust when wind speeds are greater than 26 $m{\cdot}s^{-1}$ for any length of time. Miller *et al*. (2016) indicated NWS thresholds may not always represent HWE climatology appropriately, due to the majority of injuries and fatalities occurring below the high-wind warning criteria. While future revisions may be necessary, this study adhered to the currently accepted sustained and gust high-wind thresholds.

The date, time, wind speed, wind direction, and current weather conditions were included in the HWE dataset. High-wind data were further classified by using the provided weather codes to separate CWEs and NCWEs, following Lacke *et al*. (2007). Specifically,

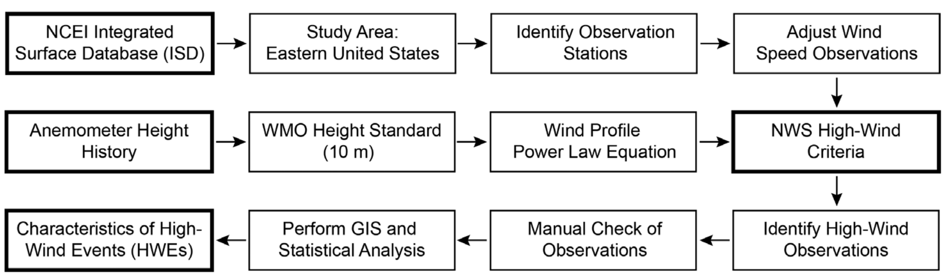

FIGURE 2 A flow diagram showing the data and methods used to characterize sustained and gust CWEs and NCWEs for the eastern U.S. (Gilliland *et al*., 2019)

weather codes associated with lightning, thunderstorms, or tornadoes were classified as CWEs. All other weather codes were classified as NCWEs. This method provided a conservative estimate of CWEs, although it is possible that some events classified as NCWEs involved convection if weather codes were absent or miscoded. Sustained and gust CWEs and NCWEs were analysed by station and NCEI climate regions in the eastern U.S.

Mean wind direction and speed were calculated and analysed for each station and region during the study period to determine spatial and temporal high-wind tendencies. Wind direction has been recorded on a 36-point scale ranging from 10 to 360° since 1964 (DeGaetano, 1997, 1998; Gilliland *et al*., 2019). The mean sustained and gust CWE and NCWE wind directions were plotted on wind roses for determine directional preferences in each region. Mean wind direction was calculated by converting to u and v vectors to eliminate vector cancellation. Figures displaying mean wind direction represent an average of all stations.

Different temporal and geographical analyses were completed to describe the sustained and gust NCWEs and CWEs patterns for the eastern U.S. from 1973 to 2015. Data were plotted linearly to display annual distribution. Further, Kendall's tau (τ) and the Mann-Kendall (M-K) test were performed to analyse annual HWE frequency on a temporal scale to determine overall statistically significant positive or negative trends during the 43-year study period (Mann, 1945; Kendall, 1975; Wilks, 2011). These additional statistical tests provided similar results as the initial linear analysis. Linear regression analysis may present possible biases due to outliers in the dataset (Wilks, 2011); however, due to the agreement between linear regression and Kendall's tau analyses, as well as results from previous high-wind studies (Pryor *et al*., 2007; Gilliland *et al*., 2019), we chose to include the linear results in this study. HWE frequency per region and meteorological season was also considered. Lastly, mean wind direction and wind speed per Julian day were examined to further investigate potential seasonal trends and influence from weather systems, such as tropical cyclones (TCs) (Gilliland *et al*., 2019).

3 | RESULTS

3.1 | Sustained CWEs

A total of 2,238 CWEs existed in the dataset. Sustained CWEs were rare in occurrence, with only 271 events in the dataset. 50% (163) occurred in the South and West North Central regions (Figure 3a). Sustained CWEs were least frequent in the Northeast with 4% (10) events observed. Stations averaged two sustained CWEs during the entire study period. Some stations recorded a sustained CWE only once, and some not at all. Mean direction was analysed by station and region to determine spatial patterns. 138 stations recorded at least one sustained CWE during the 43-year period. 51% (49%) of the stations recorded mean wind directions in the southwesterly (northwesterly) quadrant. Sustained CWEs displayed both southwesterly (36.5%) and northwesterly (36%) directional preferences (Figure 4a).

Frequency of annual CWEs was analysed using linear regression and Kendall's tau test to determine temporal trends in the dataset. Sustained CWEs decreased ($Z_s = -0.04$ days year^{-1}) during the study period at a statistically insignificant level (p = .26; τ = −0.13). There were approximately six sustained CWEs per year on average; however, oscillating periods of more or less frequent

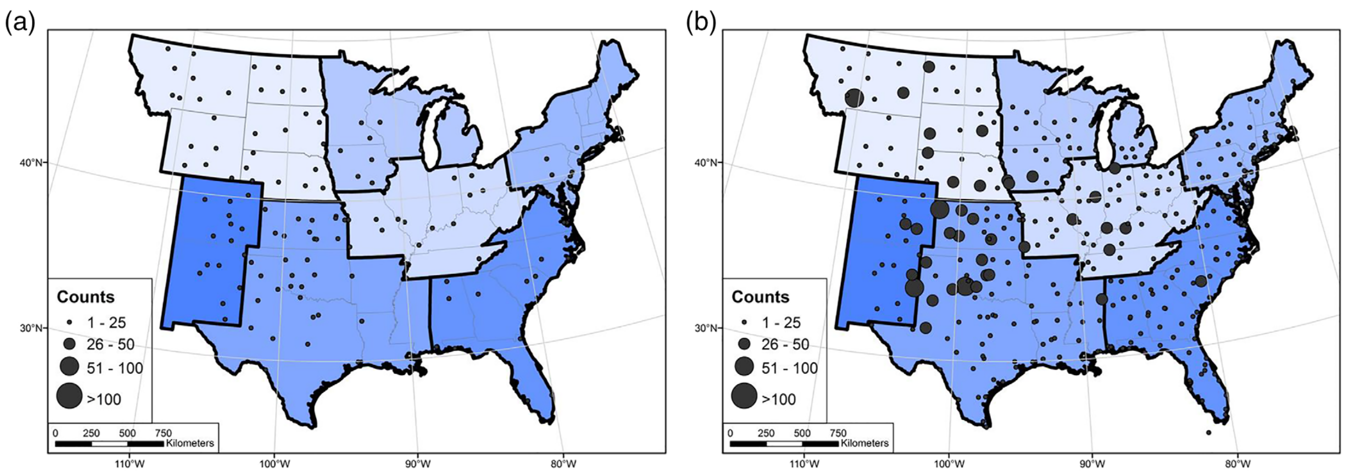

FIGURE 3 Frequency of (a) sustained and (b) gust CWEs by station during 1973–2015 [Colour figure can be viewed at wileyonlinelibrary.com]

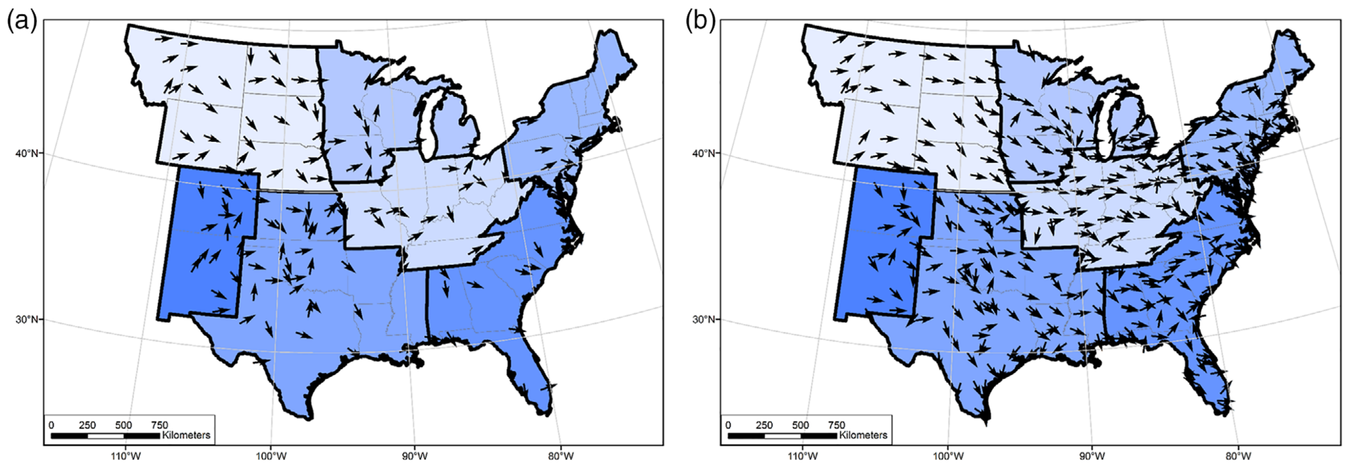

FIGURE 4 Mean (a) sustained and (b) gust CWE wind direction by station during 1973–2015 [Colour figure can be viewed at wileyonlinelibrary.com]

events can be observed (Figure 5a). Annual sustained CWE direction displayed much variability during the study period with alternating southerly and northerly directional preferences, but remained in the southwest quadrant (Figure 5b). Sustained CWE direction shifted northward ($0.75°$ year^{-1}) at an insignificant level (p = .45) and mean wind speed decreased at a rate of −0.04 ms^{-1} year^{-1} (p = .02). Mean wind speeds were also variable, but a noticeable oscillation was observed. Wind speeds tended to increase until the early 1990s and then decrease until the mid-2000s.

The majority of sustained CWEs occurred during the spring (31%) and summer (55%) months in every region (Figure 6a). The West North Central region recorded the greatest number of sustained CWEs during summer (56). Average sustained CWE direction and speed were plotted per Julian day and displayed much variability throughout the year. Sustained CWE directions fluctuated seasonally, but displayed an average wind direction in the southwest quadrant (180–270°) (Figure 7a). Due to the low frequency of sustained CWEs, there were some Julian days without the occurrence of an event, hence the missing days on the timeline; therefore, a 30-day moving average was plotted to show overall trends. Mean sustained CWE speeds displayed a peak in the warm season.

3.2 | Gust CWEs

Gust CWEs were more dispersed across the United States with 2,157 observations. 51% (1,094) were observed in the South and Central regions while only 6% of gust CWEs were observed in the Southwest region (Figure 3b). Stations averaged six gust CWEs during the entire study period and 369 stations recorded gust CWEs. Southwesterly directions were not as prominent for gust CWEs. 59% of the stations recorded a mean wind direction in the northwesterly quadrant (Figure 4b). Regionally, five of the seven regions experienced north or northwesterly gust NCWE directions more frequently. Both the East North Central and Southeast regions were divided between northwesterly and southwesterly directions, while the Central region recorded southwesterly directions more frequently.

Gust CWEs increased (Z_s = 1.95 days year^{-1}) at a statistically significant rate (p = .00; τ = 0.53). There were approximately 50 gust CWEs per year on average. During 1973–1991, a steady increase of gust CWEs was apparent. A sharp decline occurred between 1991 and 1993, but then the frequency increased overall from 1993 to 2015. Annual gust CWE direction remained within the southwest quadrant for the study period and shifted northward slightly ($0.14°$ year^{-1}) at an insignificant level (p = .54). Mean gust CWE speeds decreased significantly at a rate of 0.02 m·s^{-1} year^{-1} (p = .002) (Figure 5c).

Seasonally, gust CWEs displayed similar results as sustained and were most frequent in summer (51%), followed by spring (28%) (Figure 6b). The South recorded the greatest number of gust CWEs in summer (347). When Julian day was considered, a 10-day moving average of gust CWE direction and speed was plotted to show overall trends. Average gust CWE direction were variable with a shift from southwesterly to easterly during late summer, fall, and early winter. Additionally, mean gust CWE speeds increased during this period (Figure 7b).

3.3 | Sustained NCWEs

A total of 7,377 NCWEs existed in the dataset, which accounted for 77% of the total HWEs. 5,015 NCWEs were

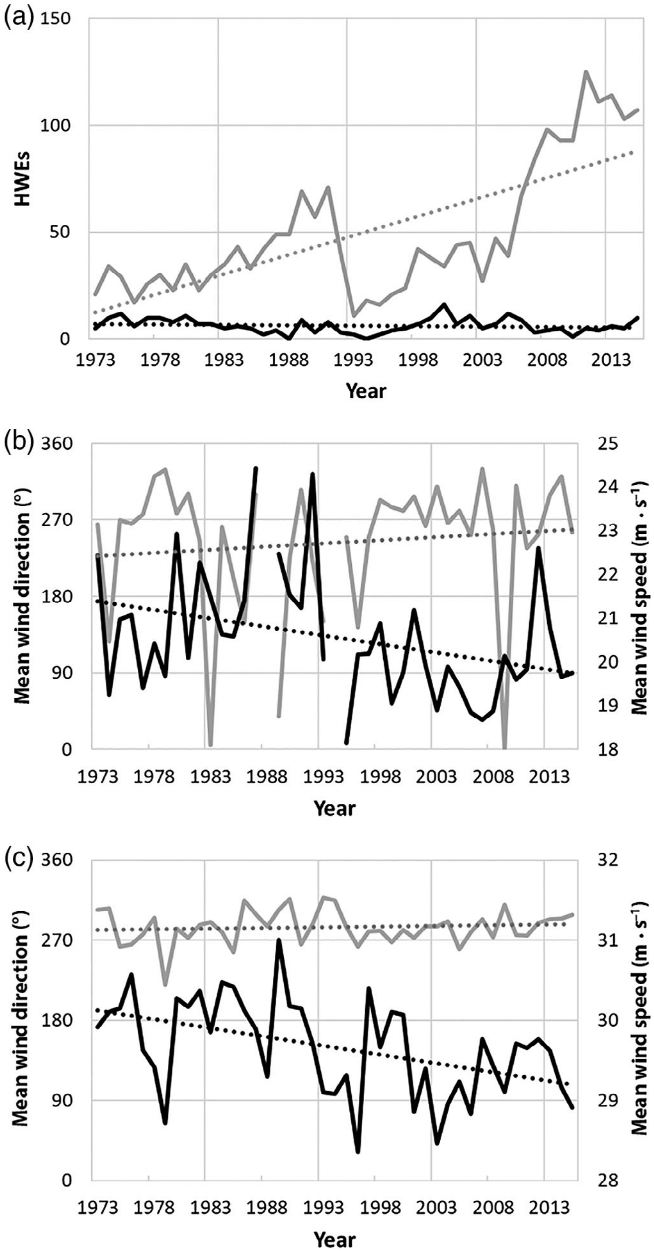

FIGURE 5 (a) Linear regression of annual sustained (black) and gust (grey) CWE frequency during 1973–2015. (b) Mean annual sustained and (c) gust CWE wind speed (black) and direction (grey) during 1973–2015 for all stations

sustained and 55% (2,760) occurred in the West North Central region alone (Figure 8a). Two stations in the West North Central region, specifically Montana, recorded more than 700 sustained NCWE events during the period (CTB and LVM); excluding these two stations yields an average of 12 sustained NCWEs per station during 1973–2015.

41% of stations recording sustained NCWEs displayed an average southwesterly (180–270°) directional preference (Figure 9a). 39% displayed an average northwesterly (270–360°) preference. Prominent southwesterly directions were observed for the West North Central, Central, and Northeast regions, while north-to-northwesterly directions occurred more frequently for the Southwest, South, and East North Central regions. The Southeast region experienced greater directional variability.

Sustained NCWE frequency decreased (Z_s = −0.58 days year^{-1}) at a statistically significant rate (p = .03; τ = −0.24). There was an average of 117 sustained HWEs per year, with periods of greater and lesser frequencies. Sustained NCWE directions displayed slight variability but remained in the southwest quadrant during the study period (Figure 10b). Shifts in wind direction were negligible; however, sustained NCWE mean annual wind speeds decreased (−0.01 m·s^{-1} year^{-1}) at a significant level (p = .00).

Seasonally, sustained NCWEs occurred most frequently in the spring for the East North Central, Southwest, Central, and South regions (Figure 11a), and in the winter months in the West North Central and Northeast regions. The Southeast was the only region to observe a fall maximum for sustained NCWEs. Average non-convective sustained HWE direction and speed were plotted per Julian day with 10-day moving averages displayed to show overall trends. Non-convective sustained HWEs displayed southwesterly and northwesterly preferences throughout the year with a directional shift to east/northeasterly in summer and fall (Figure 12a). Mean non-convective sustained wind speeds increased to approximately 27 m·s^{-1} near day 230.

3.4 | Gust NCWEs

5,703 of observed NCWEs were gust NCWEs, with 59% of the events occurring within the West North Central and South regions (Figure 8b). Once again, LVM recorded a large portion (1,011) of the events. Excluding this station yields an average of 12 gust NCWEs per station during 1973–2015. 53% of stations recording gust NCWEs displayed an average northwesterly preference and 32% displayed an average southwesterly preference (Figure 9b). The West North Central, East North Central, Central, and Northeast regions experienced frequent southwesterly directions, although the East North Central region had a prevalent northwesterly direction as well. Both the Southwest and South regions experienced northerly high-wind directions most frequently. The Southeast region was highly variable, thus no discernable pattern was evident.

Gust NCWEs increased (Z_s = 0.63 days year^{-1}), but the rate was not statistically significant (p = .14; τ = 0.16) (Figure 10a). There was an average of 133 gust HWEs per year, with periods of greater and lesser frequencies. Gust

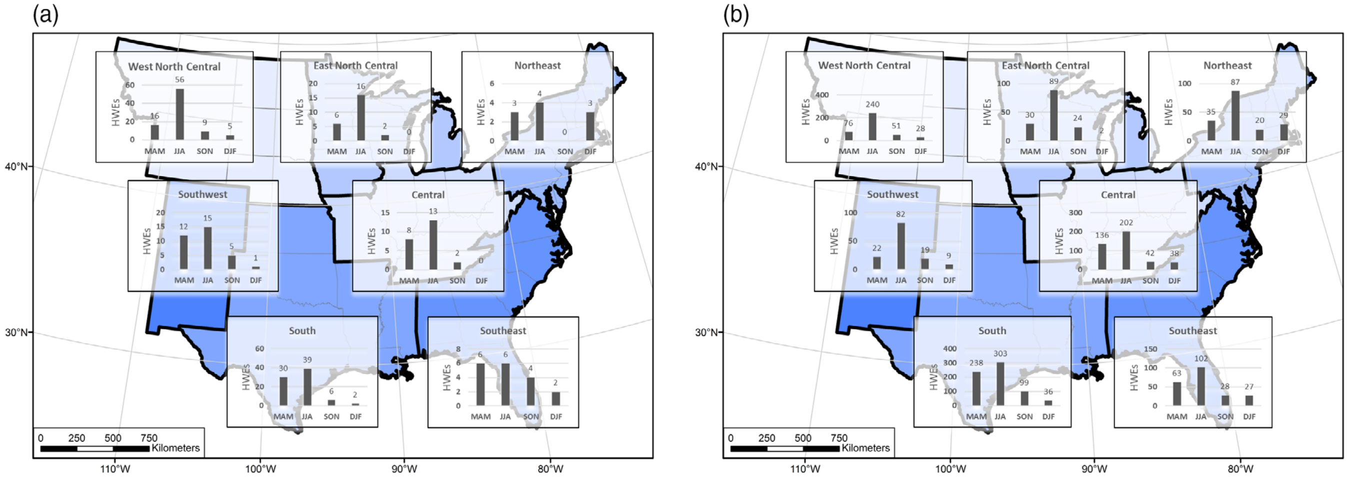

FIGURE 6 Frequency of (a) sustained and (b) gust CWEs by NCEI climate region and season (spring – MAM, summer – JJA, fall – SON, winter – DJF) during 1973–2015 [Colour figure can be viewed at wileyonlinelibrary.com]

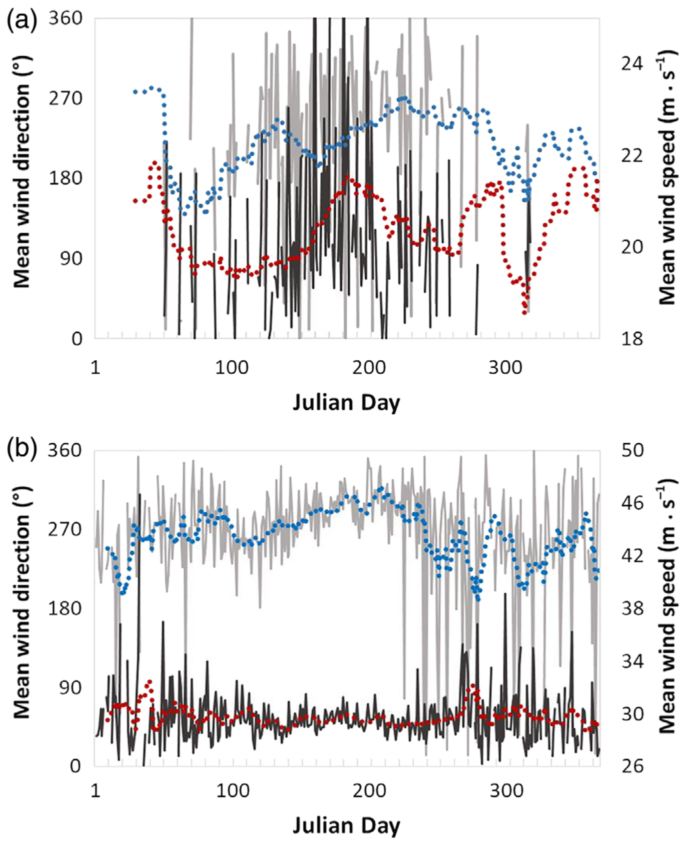

FIGURE 7 (a) Mean sustained CWE wind speed (black) and direction (grey) for all stations by Julian day during 1973–2015. A 30-day moving average (dashed) is shown for wind speed and direction. (b) Mean gust CWE wind speed (black) and direction (grey) by Julian day during 1973–2015. A 10-day moving average (dashed) is shown for wind speed and direction [Colour figure can be viewed at wileyonlinelibrary.com]

NCWE direction remained in the southwest quadrant as well, with the exception of a northerly mean wind direction in 2005 (Figure 10c). Any shifts in gust NCWE wind direction or speed was not significant.

Gust NCWEs also occurred most frequently in the winter months in the West North Central and Northeast regions. In the East North Central, Central, and Southeast regions, a summertime maximum of gust NCWEs

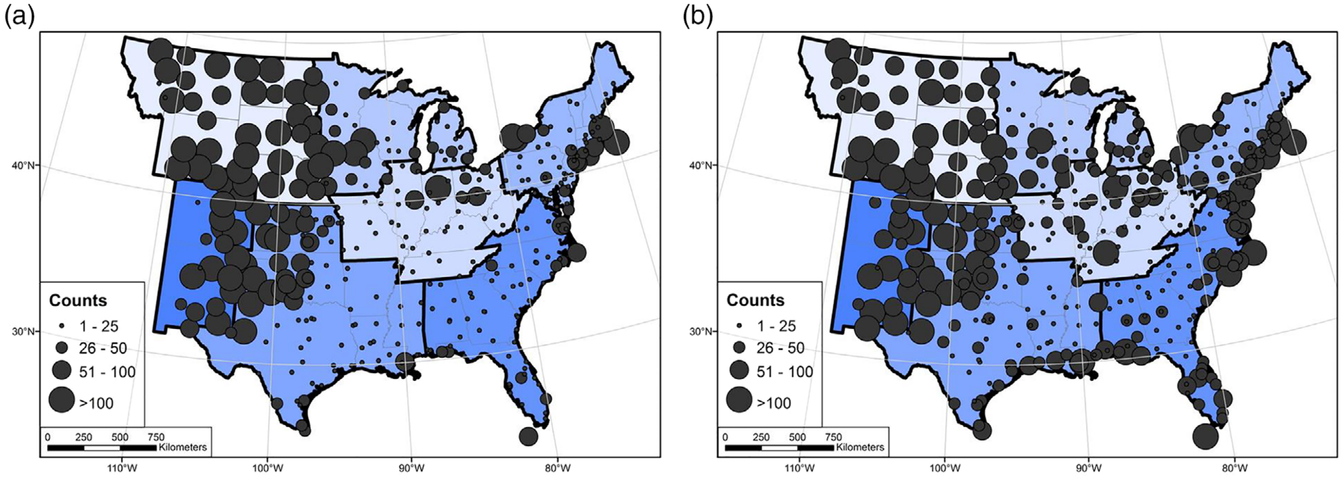

FIGURE 8 Frequency of (a) sustained and (b) gust NCWEs by station during 1973–2015 [Colour figure can be viewed at wileyonlinelibrary.com]

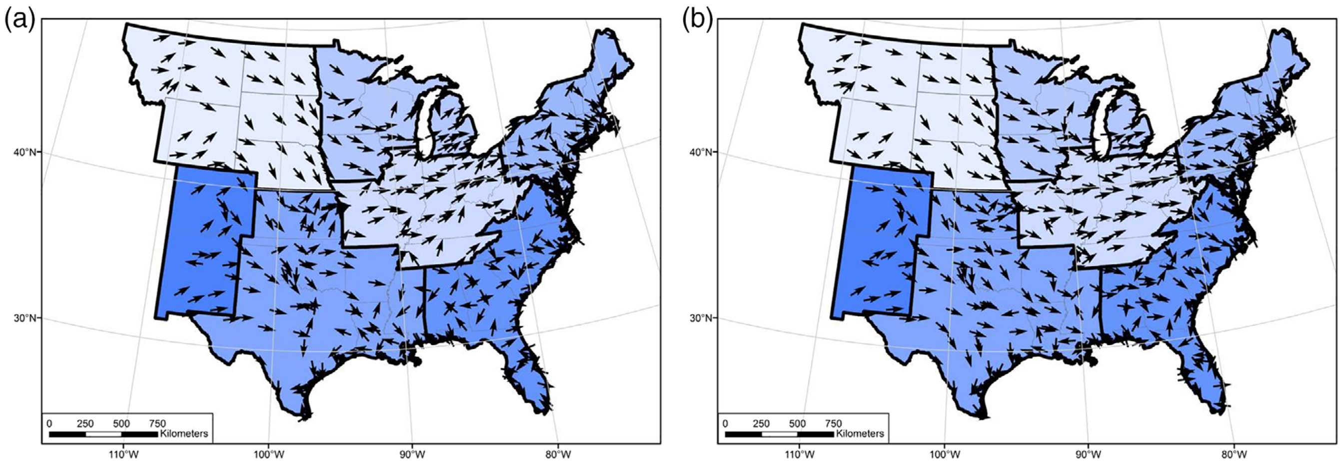

FIGURE 9 Mean (a) sustained and (b) gust NCWE wind direction by station during 1973–2015 [Colour figure can be viewed at wileyonlinelibrary.com]

was observed while the Southwest and South regions displayed a springtime maximum (Figure 11b). Average gust NCWE direction and speed were plotted per Julian day with 10-day moving averages displayed to show overall trends. Non-convective gust HWEs displayed similar mean wind directions and speed with a shift to east/northeasterly in summer and fall, as well (Figure 12b). Peak non-convective gust mean wind speeds were approximately 32 m·s^{-1} near day 300.

4 | DISCUSSION

This study has examined spatial and temporal characteristics of sustained and gust CWEs and NCWEs during 1973–2015 across the eastern U.S. The spatial results from this study are in agreement with Lacke *et al*. (2007), Kurtz (2010), and Gilliland *et al*. (2019); the West North Central and South regions (Great Plains) experience the greatest frequency of HWEs. Sustained CWEs were most frequent in the West North Central region and gust CWEs were most frequent in the South. Both sustained and gust NCWEs were most frequent in the West North Central region. These regions that experienced the greatest frequency of HWEs are typically prone to frequent ETC storm tracks and consequently have a greater probability of intense high-wind gusts (Letson *et al*., 2018). The Northeast region observed the least amount of sustained CWEs, Southwest observed the least amount of gust CWEs, and East North Central observed the least amount of sustained and gust NCWEs. Though regions may record less frequent HWEs than others,

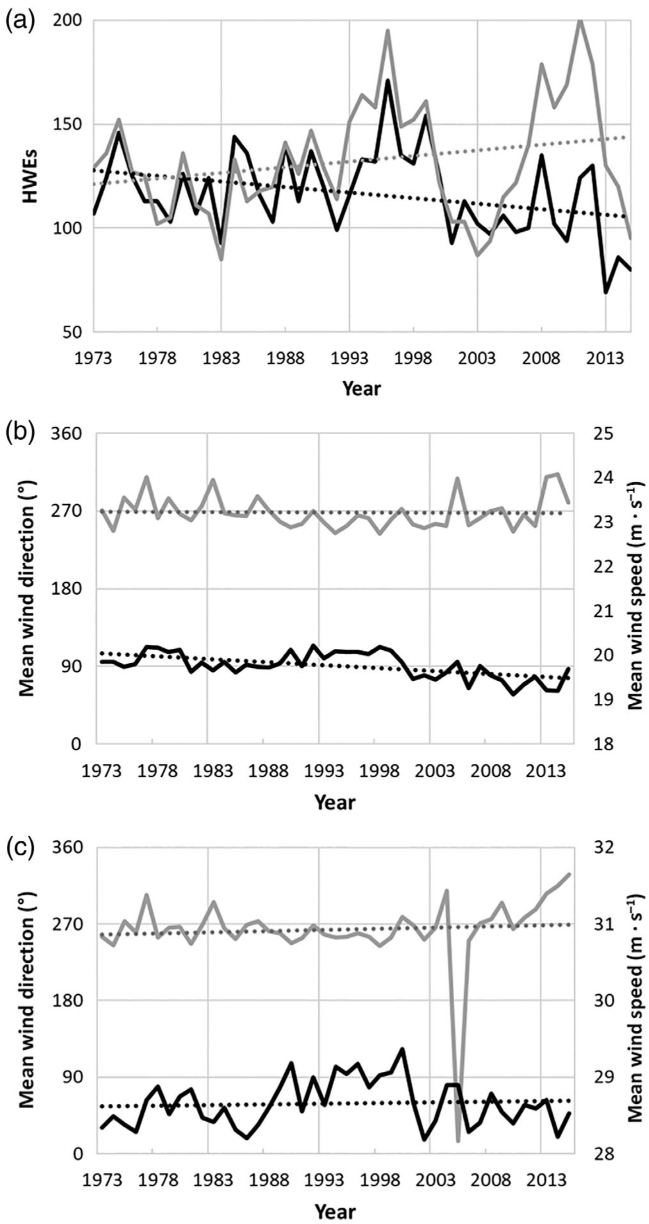

FIGURE 10 (a) Linear regression of annual sustained (black) and gust (grey) NCWE frequency during 1973–2015. (b) Mean annual sustained and (c) gust NCWE wind speed (black) and direction (grey) during 1973–2015 for all stations

analysing frequency alone does not provide an appropriate depiction of the effects. According to Changnon (2009), the most catastrophic wind-related loss occurred in the northeast, central, and western regions of the United States. These regions are more populated, thus the damage risk is potentially greater in these areas.

Temporally, gust CWEs (sustained NCWEs) increased (decreased) significantly during the 43-year period. Studies have indicated a direct influence of synoptic atmospheric patterns on HWEs. McCabe *et al.* (2001) analysed mid-latitude cyclone frequency and intensity across the northern hemisphere and the results showed a decline in the number of cyclonic systems over a 39-year period. The results also showed an increase in cyclone intensity over the same time period and a significant correlation of $r = -0.58$ (significant at a 99% confidence interval) between wintertime cyclone frequency and surface temperatures in the mid-latitudes. Vose *et al.* (2014) also discussed changes in wintertime ETCs, with a below-average frequency and intensity of mid-latitude cyclones during the late 1970s and 1990s. Likewise, the results from this study indicated less frequent convective HWEs during similar periods (Figure 5a). Additional research is needed to study the possible correlation between ETC intensity and HWEs.

Wind directions shifted more northerly for both sustained and gust CWEs; however, little directional shift was indicated by sustained and gust NCWEs. Mean wind speeds decreased slightly for the majority of CWEs and NCWEs. These findings align with a study of near-surface wind speeds during 1973–2005. Pryor *et al.* (2007) concluded that wind speeds were declining in the eastern U. S. and were likely linked to synoptic patterns.

For all high-wind categories, southwesterly wind directions were most common, followed by north-to-northwesterly. Lacke *et al.* (2007) also found a southwesterly preference in a study on non-convective high-winds in the Great Lakes which supports previous studies (Niziol and Paone, 2000; Durkee *et al.*, 2012; Gilliland *et al.*, 2019). Niziol and Paone (2000) suggested that high-winds typically occur southwest of a surface low-pressure system. As low-pressure systems track from west to east, high-wind directions tend to follow similar motion. Cyclonic systems that ultimately produce HWEs in the eastern U.S. tend to follow the overall synoptic circulation moving from west to east. Cyclones are typically associated with upper-level troughs that have a north-westerly or southwesterly projected track (Niziol and Paone, 2000; Martin and Konrad, 2006; Lacke *et al.*, 2007). Typically, the strongest winds occur within close proximity of cyclone centres, especially near the cold front due to weak low-level vertical stability, which leads to convective momentum mixing and possible ageostrophic forcing. (Booth *et al.*, 2015).

Convective high-winds – both sustained and gust – were mostly recorded during summer. Edwards *et al.* (2018) found similar results in a study comparing measured versus estimated convective gust reports in the United States. In this study, the most concentrated areas of mean annual gust CWEs included the South and Central regions. Many studies have shown a peak in convective activity in the warm season, which agrees with the regional results in this study (Kelly *et al.*, 1985; Klimowski *et al.*, 2003; Coniglio *et al.*, 2004; Ashley and Mote, 2005; Changnon, 2011).

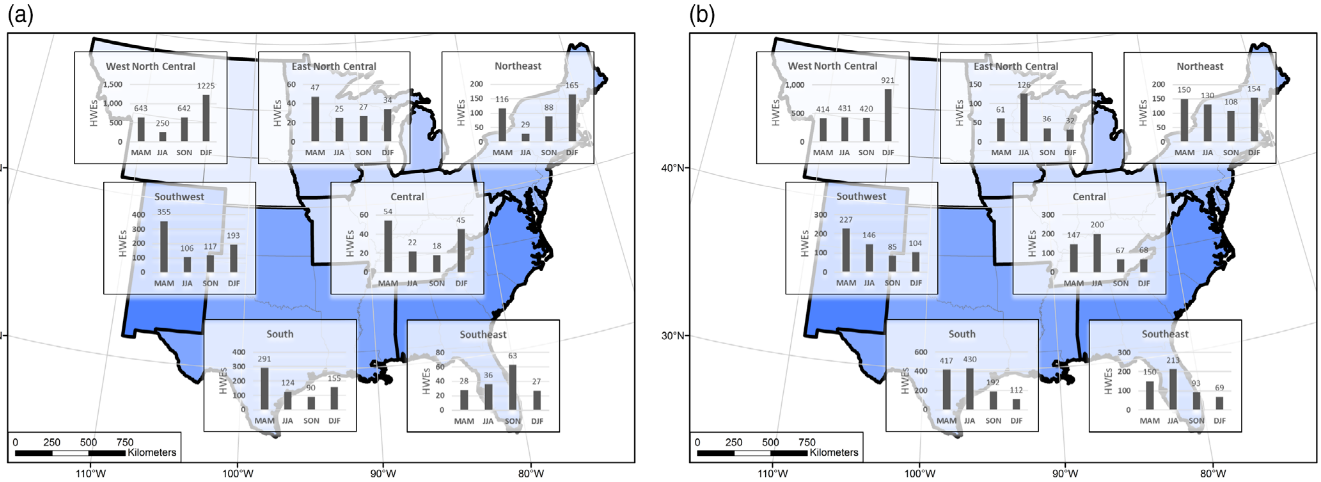

FIGURE 11 Frequency of (a) sustained and (b) gust NCWEs by NCEI climate region and season (spring – MAM, summer – JJA, fall – SON, winter – DJF) during 1973–2015 [Colour figure can be viewed at wileyonlinelibrary.com]

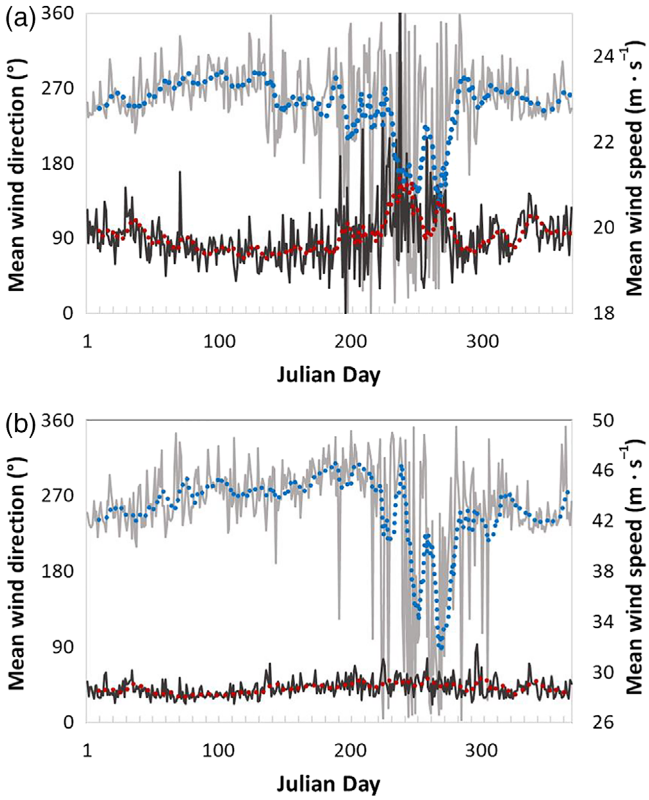

FIGURE 12 (a) Mean sustained NCWE wind speed (black) and direction (grey) for all stations by Julian day during 1973–2015. A 10-day moving average (dashed) is shown for wind speed and direction. (b) Mean gust NCWE wind speed (black) and direction (grey) by Julian day during 1973–2015. A 10-day moving average (dashed) is shown for wind speed and direction [Colour figure can be viewed at wileyonlinelibrary.com]

Non-convective high-winds occurred in the winter and transitional months. McCabe *et al.* (2001) found ETCs to be more numerous and intense during the cool season and other studies have also linked high-winds with cyclonic activity and storm tracks. The results are also in agreement with studies that show an increase in non-convective activity in the cool season (Niziol and Paone, 2000; Lacke *et al.*, 2007; Kurtz, 2010; Durkee *et al.*, 2012; Booth *et al.*, 2015).

The results from this study support the hypothesis that high-winds are directly influenced by synoptic and meso-scale atmospheric patterns. When analysed by Julian day, the majority of HWEs displayed a shift in mean wind direction from westerly to east/northeasterly in summer and fall. This could be caused by TC influence, as hurricane season stretches from June through November. Gilliland *et al.* (2019) indicated that TCs represent a small population of HWE observations and trends did not change significantly when TC-related events were removed from the dataset. Other explanations for wind shifts could include high-winds due to convective storm outflow (RFDs, downbursts, etc.), especially during the warm season. These outflows have the tendency to create omnidirectional wind gusts (Fujita and Wakimoto, 1981; Rose, 1996). Mean wind direction and speed for convective sustained HWEs indicated much variability throughout the year, but a larger dataset may provide better information on the seasonality.

For any given HWE, it is possible for both a convective and non-convective HWE to be recorded concurrently. A situation such as this may result from pre cold-frontal convective activity within the warm sector, followed by post cold-frontal non-convective high-winds. In this study, concurrent HWEs occurred in almost every season and region. The majority of concurrent HWEs occurred during the warm season months. The South recorded the greatest number of concurrent HWEs (N = 394, Gust = 95%). There were many more concurrent gust HWEs than sustained, which may be attributed to the correlation between strong cold fronts and wind gusts discussed in Pryor *et al*. (2014). It is also likely that HWEs occur across multiple regions in the same day, which would create duplications in the observations of HWEs.

5 | CONCLUSIONS

Damaging high-winds occur in every region and during every season in the United States. In the last few decades, interest has grown for high-wind research and numerous studies analysed regional high-wind characteristics (Niziol and Paone, 2000; Klimowski *et al*., 2003; Martin and Konrad, 2006; Lacke *et al*., 2007; Kurtz, 2010; Durkee *et al*., 2012; Booth *et al*., 2015). Such studies concluded that nontornadic high-winds produced similar damage and fatality rates as tornadic storms. Understanding the spatial and temporal tendencies of all types of high-winds could eventually lead to better mitigation efforts in reducing fatalities and property damage.

This study contributes to current high-wind research by providing a climatology of CWEs, and NCWEs across the entire eastern U.S. during the last 43 years. It provides a spatial and temporal high-wind analysis that contributes supporting results to other regional high-wind studies. Previous work has focused on high-winds that occur in a specific region or season and for shorter study periods. Although past research has broadened the scientific community's understanding and general awareness of the hazards associated with HWEs, this study has added an extensive climatology of sustained, gust, convective, and non-convective high-winds during every season and in almost every region of the United States from 1973–2015. This study found that every region in the study area has been affected by HWEs and that certain types, namely convective gust HWEs, may be increasing with time.

Future work would ideally analyse recognizable synoptic and meso-scale-level patterns associated with the varying types of HWEs. In addition, future studies should investigate possible teleconnection influences in the characteristics and frequencies of high-winds. This dataset should be updated regularly to monitor the potential changes in gust CWEs and NCWEs, as well as how it may affect the magnitude of catastrophic HWEs as discussed by Changnon (2009). While this study included a basic climatological analysis of mean wind direction and speed for the composite study area, future studies should include a more thorough regional analysis for these parameters. Furthermore, varied high-wind thresholds should be considered in future HWE studies, as outlined in Miller *et al*. (2016). More research is necessary to determine long-term trends in a warming climate, as well as recognize common atmospheric patterns and interactions leading to the creation of a HWE. Understanding how atmospheric parameters play a role in the climatology of HWEs could result in better forecasts and eventually reduce wind-related damage and fatalities.

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