Received: 19 July 2018 | Revised: 16 May 2019 | Accepted: 15 July 2019
DOI: 10.1002/joc.6233

RESEARCH ARTICLE

International Journal of Climatology RMetS

A climatology of high-wind events for the eastern United States

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Abstract

This study examines the spatial and temporal characteristics of high-wind events (HWEs) based on the National Weather Service high-wind criteria for 391 first-order weather stations in the eastern United States from 1973 to 2015. A geographical analysis on the frequency of sustained and gust HWEs shows that the highest occurrences were reported in the Great Plains and Great Lakes, while the lowest number of observations occurred in the Mid-South and Southeast. Linear trends show that the yearly frequency of sustained and gust HWEs are significantly decreasing (−0.579 days/year) and increasing (0.943 days/year) respectively during the 43-year study period. These trends do not persist when the HWE data are normalized (long-term mean is removed from the yearly count), but shows a cyclical anomaly pattern for both sustained and gust winds. Overall, 90 and 82% of all sustained and gust HWEs occur from the northwest or southwest quadrant, but when interpreted from a spatial perspective the mean wind direction of HWEs can be classified into specific regional wind groupings. However, this persistent southwesterly wind direction has gradually shifted to a more southerly (northerly) orientation for sustained (gust) HWEs over the study period.

KEYWORDS

GIS, regional climate, statistical regression, wind

1 | INTRODUCTION

Hazard studies have shown that wind-related events are capable of producing human casualties and major socioeconomic losses (Ashley and Black, 2008; Changnon, 2009; Black and Ashley, 2010; Barthel and Neumayer, 2012). Black and Ashley (2010) found that from 1977 to 2007, non-tornadic convective and non-convective wind events accounted for 49% (1830) of all recorded wind-related deaths in the United States. Most of these fatalities occurred outdoors, in vehicles, or while boating (Ashley and Black, 2008; Black and Ashley, 2010), which may indicate a lack of perception of these events as hazardous by the public (Williams *et al*., 2017). Further, wind causes an estimated 5–10% of tropical cyclone related fatalities in the United States (Rappaport, 2014). Changnon (2009) documented 176 wind-driven storms in the United States that produced more than $15 billion in total losses between 1952 and 2006. Lastly, a study by Barthel and Neumayer (2012) found the global (United States) average insured loss per windstorm from 1980 to 2008 was $21.1 ($33.6) million dollars.

In recent years, studies (e.g., Niziol and Paone, 2000; Lacke *et al*., 2007; Kurtz, 2010; Pryor *et al*., 2014; Zhang *et al*., 2014; Booth *et al*., 2015) have examined high-wind events (HWEs) in the mid-latitude regions of the United States and Canada and the conditions that lead to their occurrence. Acknowledging the potential for geographic influences on high winds, Niziol and Paone (2000) suggested that topographic channelling along Lake Erie was the major cause of southwesterly non-convective high-wind events (NCWEs) over western New York from 1977 to 1997. However, analysis of cold season (November–April) NCWEs by Lacke *et al*.

(2007) found that extratropical cyclone dynamics are the primary cause of the southwest preference found by Niziol and Paone (2000). Kurtz (2010) similarly documented that mid-latitude dynamics are the main factor driving cold season (September–March) NCWEs over the central Great Plains. A comprehensive review by Knox *et al*. (2011) concluded that non-convective wind dynamics are the result of many atmospheric processes, rather than one dominant contributor (pressure gradient). Analysis of a NCWE over the Great Lakes region by Durkee *et al*. (2012) further suggested that atmospheric processes such as isallobaric winds, friction, and horizontal and vertical advection all contribute to HWEs. Pryor *et al*. (2014) examined 95th percentile wind events at 85 stations across the eastern United States to determine the spatial extent of these events and to assess the influence of cold front intensity (temperature gradient across the front) on HWEs. They concluded that, while cold fronts are a major cause of high wind, the relationship between frontal intensity and wind gusts is modest (Pryor *et al*., 2014). Further, some HWEs extend over areas up to 1,000 km, with wind gusts frequently occurring for at least two hours at a given site and occasionally extending to 18 hr in duration, implying that synoptic-scale processes drive these events (Pryor *et al*., 2014).

While NCWEs are primarily generated by synoptic scale processes, convective high winds (CWEs) are the result of non-tornadic thunderstorms. Strong downdrafts (downbursts) can generate wind damage at the surface that can be comparable to that of a tornado (Wakimoto, 1985). Organized thunderstorm clusters such as mesoscale convective systems can produce long-lived clusters of downbursts that generate CWEs over large areas. Both Kelly *et al*. (1985) and Doswell *et al*. (2005) found that non-tornadic severe thunderstorm events are most common across a broad swath of the eastern United States during the summer months. Kelly *et al*. (1985) showed that non-tornadic severe thunderstorms producing gusts greater than 28.5 m/s were most common in June. While the highest wind gusts in the United States tended to be geographically related to convection and frequency of mid-latitude cyclones (Letson *et al*., 2018), landfalling tropical cyclones can also generate extreme winds. Compared to convective and non-convective wind events, landfalling tropical cyclones are relatively infrequent. Even in the locations where these storms most commonly make landfall the return period is around one storm every 2 years, with hurricane landfall occurring once every 3–6 years (Keim *et al*., 2007). Jagger and Elsner (2006) estimated that winds of 62 m/s related to tropical cyclone landfall can be expected to occur somewhere along the United States coast approximately once in every 5 years. Therefore, while tropical cyclone landfall is rare, it certainly can have an impact on the climatology of HWEs.

Despite the hazards posed by HWEs, no study has constructed a comprehensive climatology of high winds across the eastern United States. The majority of research on high winds is focused on non-convective winds across the Great Plains and Great Lakes. However, these are not the only regions within the United States that are prone to HWEs associated with non-convective winds. Further, the entire eastern United States is susceptible to convective wind (e.g., thunderstorms and tornadoes), while tropical cyclones can produce high wind across coastal areas, both of which contribute to the overall United States wind climatology.

The objectives of this paper are to: (a) understand the spatial and temporal patterns of HWEs from various meteorological origins (non-convective, convective, and tropical) across the eastern United States; (b) understand how the HWE frequency and vector characteristics have changed over time; (c) evaluate the typical wind directions associated with HWEs, their annual cycle, and how the yearly mean wind direction has changed through time; and (d) examine how HWE occurrences vary annually. To meet these objectives, geographic and temporal characteristics of HWEs are identified through statistical analysis of in situ observations for the eastern United States during 1973–2015.

2 | DATA AND METHODS

Figure 1 provides a summary of the data and methods used to characterize the high-wind climatology of the eastern United States from 1973 to 2015. Surface wind observations (sustained and gust) used in the analysis were derived from hourly data provided by National Centers for Environmental Information Data Center Integrated Surface Database (NCEI-ISD) (data available at: https://www.ncdc.noaa.gov/isd/). Data acquired from NCEI-ISD consisted of quality-controlled weather observations from 391 national and regional first-order stations for the eastern United States (Figure 2). Lacke *et al*. (2007) noted several issues with the NCEI-ISD archive data prior to 1973 while examining the climatological characteristics of NCWEs for the Great Lakes during 1951–1995. First, their work identified that between 1965 and 1972, observation times were incorrectly formatted, leading to missing sustained wind observations (every 3 hr instead of hourly records) in NCEI-ISD repository. Second, Lacke *et al*. (2007) found that NCEI-ISD did not include gust observations as part of its digital records prior to 1973. With these NCEI-ISD inconsistences, the scope of this paper was limited to the years beyond the problematic time period described by Lacke *et al*. (2007).

Another concern was historical metadata maintained for each wind anemometer used in the analysis. Studies document that weather stations have gone through relocations and height adjustments during their period of operational status (Klink, 1999; Lacke *et al*., 2007; Pryor *et al*., 2007). Most instruments during the 1960s were removed from building

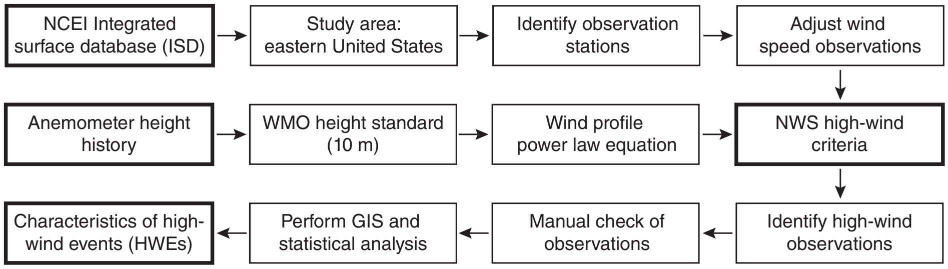

FIGURE 1 A flow diagram showing the data and methods used to characterize sustained and gust HWEs for the eastern United States

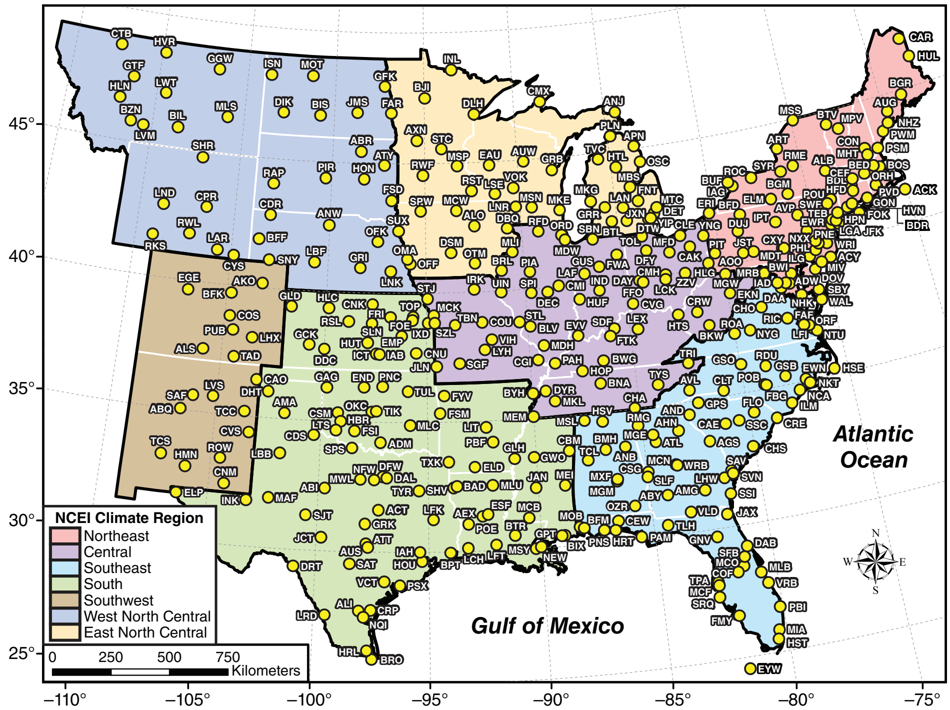

FIGURE 2 Spatial distribution of the 391 national and regional first-order stations and NCEI national climate regions (Karl and Koss, 1984) used in the analysis [Colour figure can be viewed at wileyonlinelibrary.com]

rooftops and relocated to ground surface locations. Further, weather stations that had their anemometers repositioned from the height of 6.1 to 10 m to meet the wind height standard set by the World Meteorological Organization (WMO). Wind stations also experienced height adjustments as automated surface/weather observing systems (ASOS and AWOS) were introduced in the United States during the early-to-middle 1990s. In their analysis of the high-wind climatology of the Great Lakes from 1951 to 1995, Lacke *et al.* (2007) found that anemometer heights were not standardized between 1950s and 1960s. Therefore, all sustained and gust speed measurements were adjusted to the height of 10 m using the wind profile power law (Equation 1) (Klink, 1999; Pryor *et al.*, 2007). This was accomplished by acquiring wind anemometer height records from NCEI, since metadata was not readily available for all stations through NCEI-ISD (Vose, R. Personal communication). The wind profile power law describes the variables used to adjust the wind speed, $V(z)$, based on the actual wind speed observed $V(z_{\text{ref}})$ at that particular reference height (z_{ref}), and to the new height (z), assuming neutral atmospheric stability ($\alpha = 1/7$).

$$V(z) = V(z_{\text{ref}})^* \left(\frac{z}{z_{\text{ref}}}\right)^{\alpha} \tag{1}$$

The next step in the analysis was to identify HWEs. A HWE was defined when one or more sustained or gust observation meets the National Weather Service (NWS) high-wind watch or warning criteria on a given Julian day for each weather station included in the study. The NWS defines high-wind warnings and watches based on two criteria: speed and duration. Specifically, a sustained (gust) high-wind observation was achieved when the wind speed met or exceeded 18 m/s for at least 1 hr (26 m/s for any duration). This sustained and gust HWE definition was the typical criteria exercised at most NWS regional offices. Based on a 17-year analysis, Miller *et al.* (2016) noted that these wind thresholds represent climatologically rare events, and in many portions of the eastern United States these thresholds exceed the rarest 1% of all gusts. Despite the fact that events over the high-wind watch/warning thresholds may be relatively rare, these criteria were used in this study to identify HWEs in order to be consistent with the NWS definition of high wind.

DeGaetano (1997) analysed the quality of hourly wind and directional data for 41 northeastern U.S. first-order stations and found that 0.1% of the records failed the quality control tests (i.e., removal of excessive wind variability and inaccurate wind observations). To ensure that each high wind observation (and HWE) did meet the NWS high-wind criteria, sustained and gust reports were inspected using additional official government online resources (e.g., NCEI Climate Database Modernization Program [CDMP] and Local Climatological Data [LCD]) to check for erroneous or questionable observations at each weather site.

The overall frequency of HWEs for each station and by NCEI climate region (Karl and Koss, 1984) was used to describe the geographical and temporal characteristics across the study area. Local Indicators of Spatial Association (LISA; Anselin, 1995) were also used to evaluate the significance of sustained and gust HWEs observed across the eastern United States. LISA measures the degree of spatial autocorrelation of each individual location through Local Moran's I (LMI). The number of sustained and gust HWEs observed at each station were compared to neighbouring locations with similar high or low HWEs. From these comparisons, LMI determined the overall geographical clustering characteristics of sustained and gust HWEs for the study area. Stations spatially identified as high-high (low-low) clusters exhibit a comparable number of high (low) HWEs when measured to its neighbours. For a location to be classified as an outlier, low (high) HWEs were surrounded by neighbours of high (low) occurrences.

Mean wind direction for each station and by NCEI climate region was calculated to describe the cardinal orientation of sustained and gust HWEs during 1973–2015. Wind direction observations acquired from NCEI stations were formatted in a 36-point compass. DeGaetano (1997; 1998) identified the wind compass format used by NCEI changed from a 16- to 36-point format in 1964 when analysing the quality characteristics of speed and direction for 41 northeastern U.S. stations. Therefore, all wind measurements since 1964 have been based on tens of degrees which range from 10 to 360° (i.e., 0° was classified as a calm wind with no direction in NCEI records). Before the average wind direction was determined, the speed and direction collected from each station had to be transformed from compass to vector component (u and v winds) format in order to properly calculate the directional tendency of HWEs. After the conversion was performed, daily and annual mean u and v winds were then computed for each individual station and the overall study region. Lastly, these orthogonal wind (u and v components) averages were converted back to its meteorological wind direction for additional geographical and temporal analysis.

Annual HWEs and mean wind direction were calculated for the study area to determine how the number of days and average direction of sustained and gust winds have changed over the study period. The statistical significance of annual sustained and gust HWEs and mean direction were tested using Mann–Kendall test (Mann, 1945; Kendall, 1975) and Sen's slope (Sen, 1968). These nonparametric regression tests were selected based on the distribution of the data and previous applications used to study extreme near-surface winds (e.g., Hundecha *et al*., 2008; Pes *et al*., 2017; Gilliland and Keim, 2018).

3 | RESULTS

3.1 | Spatial analysis of HWEs

Figure 3 shows the total number of sustained and gust HWEs observed at each station across the eastern United States during 1973–2015. The spatial distribution of HWEs has been characterized into three major geographical regions. The highest occurrences of sustained and gust HWEs were recorded leeward of the Rocky Mountains, which extended eastward to 95°W and southward to 30°N (i.e., West North Central, Southwest, and northern part of South region). On average, stations located in this region have documented 96 sustained and 75 gust HWEs, with the maximum frequency (i.e., 1,636 sustained and 1,247 gust HWEs) occurring north of Yellowstone National Park in Livingston, Montana (LVM) during the 43-year study period. Once east of the High Plains, a second axis of HWEs was located across East North Central and Upper Central regions (Midwest; 39–48°N and 80–95°W) and along the coastal Atlantic states of Maine to South Carolina (Northeast and Upper Southeast regions). Sites located in these regions typically observed between 15 and 20 (25 and 30) sustained (gust) HWEs. The final cluster of HWEs was located in the lower Central Valley (Mid-South; 35–38°N and 80–95°W) and portions of the South and Southeast (24–37°N and 80–100°W), where stations observed on average 5 (4) sustained and 25 (18) gust HWEs during the study period.

To further detect high-wind patterns, LMI (Anselin, 1995) was performed to understand the spatial autocorrelation of sustained and gust HWEs for the eastern United States (Figure 4). For sustained and gust winds, a high number of HWEs clustered west of 100°W. Stations defined for this cluster type represented a high value of sustained and gust HWEs when compared to other neighbouring sites found along the Rocky Mountains. This clustering pattern shifted to a constant (not significant) pattern in the number of HWEs documented with sustained winds in the Midwest and that continued into the Mid-South for gust HWEs. Most of the stations located in the Gulf and Atlantic Coast states

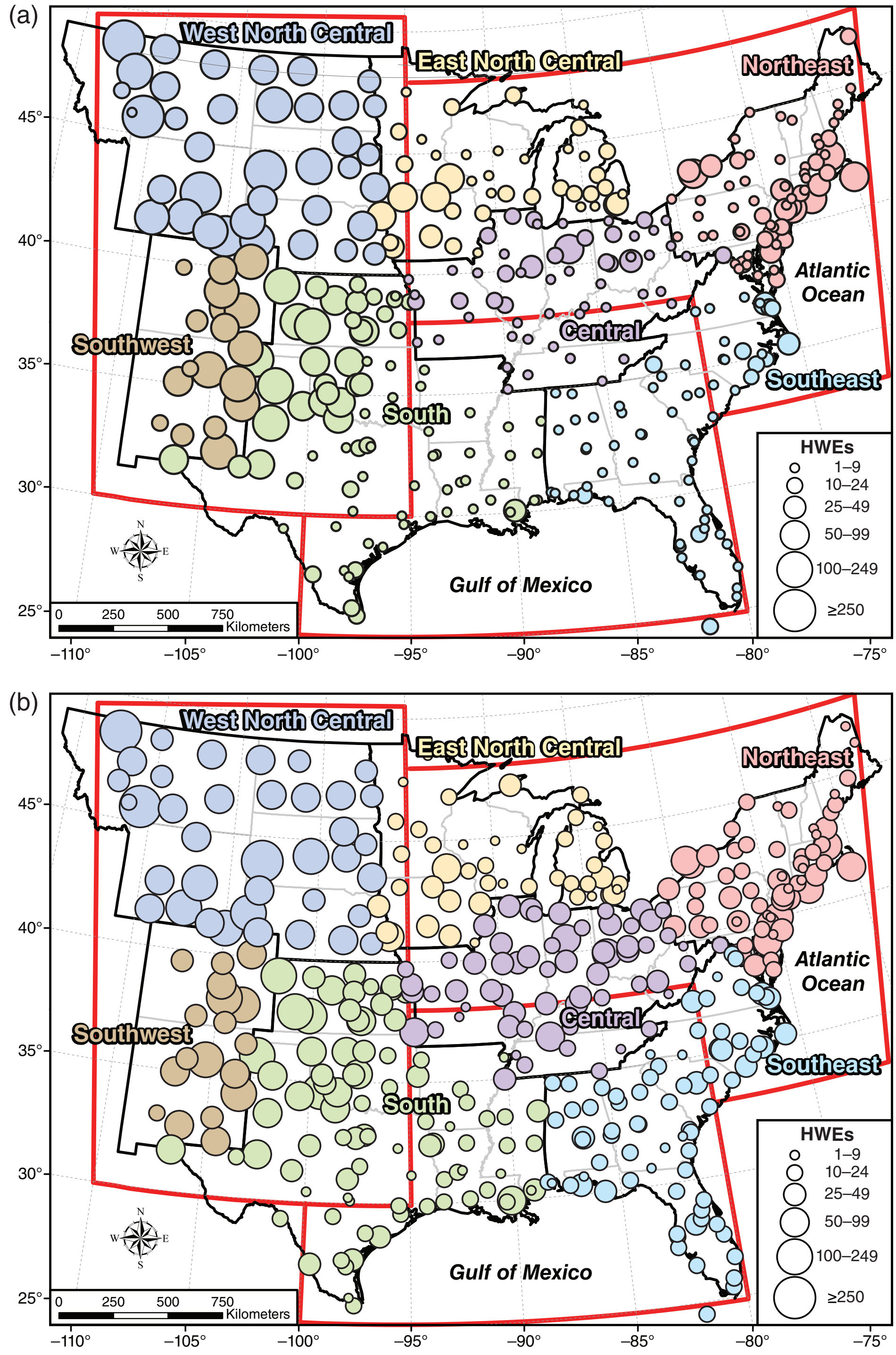

FIGURE 3 Overall frequency of (a) sustained and (b) gust HWEs by station from 1973 to 2015. A red box describes a major geographical area with each station labelled by its NCEI climate region as described in Figure 2 [Colour figure can be viewed at wileyonlinelibrary.com]

exhibited a low number of sustained and gust HWEs. While these three clustering patterns existed across the study area, two additional low clustering groups (low number of HWEs adjacent to similar reporting sites) were also observed in northern Michigan and Hudson and Champlin Valleys for sustained winds, which extended into the upper Midwest (Wisconsin and Minnesota) and New England states (New York, New Hemisphere, and Maine) for gust HWEs. A difference found between sustained and gust winds was the location of outliers identified in the eastern United States. Low (few HWEs surrounded by high occurrences) outliers were located inside and near the base of the Rocky Mountains for sustained winds, while additional outliers were found in Nebraska, Kansas, Oklahoma, and Texas for gust winds. The low number of sustained HWEs corresponds to stations located in the valleys of the Rocky Mountain range. High outliers were only identified with gust HWEs, which were located in five coastal and three

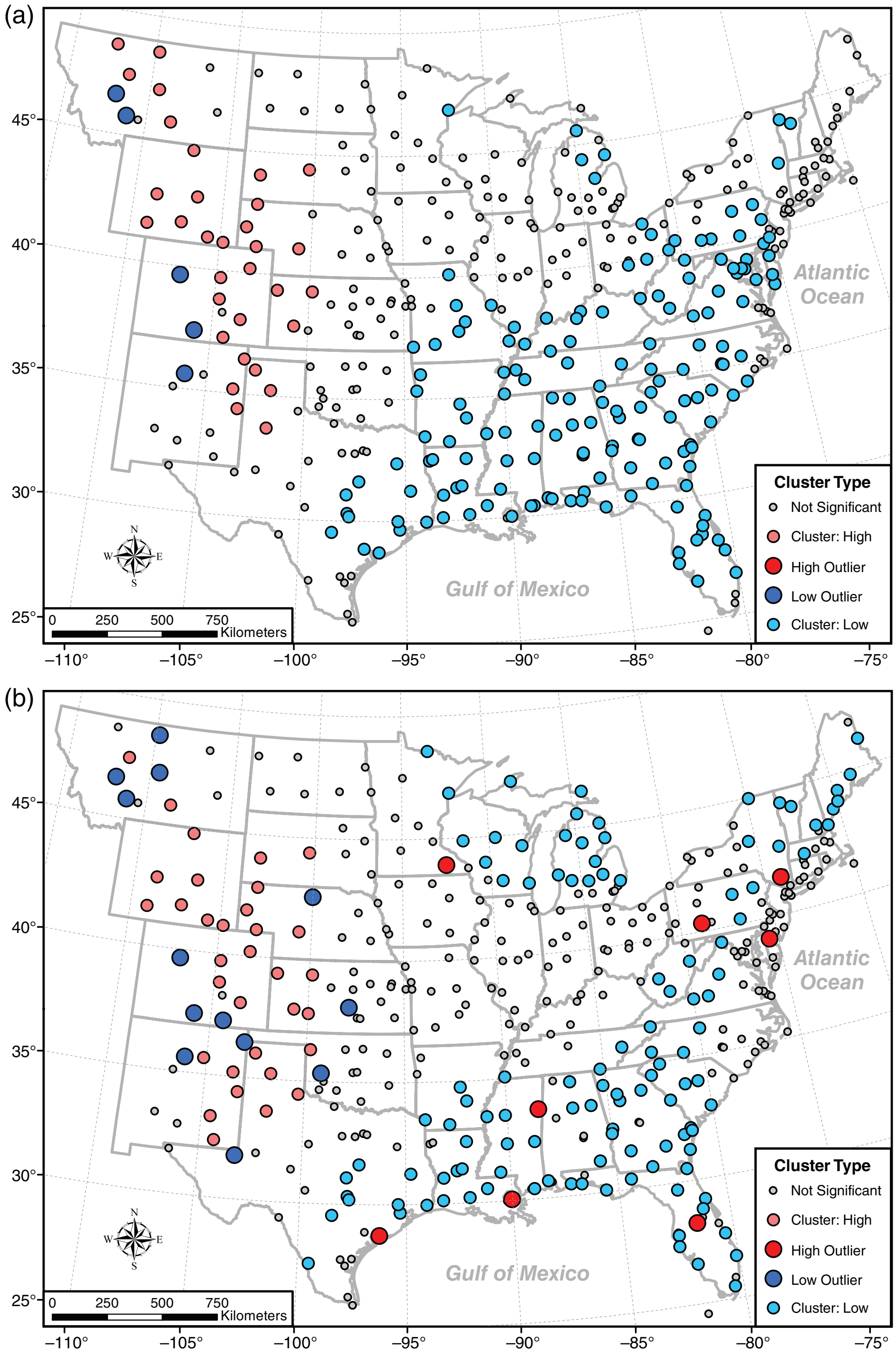

FIGURE 4 A cluster and outlier analysis on the frequency of (a) sustained and (b) gust HWEs using LMI. High (low) clusters represent locations consisting of similar frequency of high (low) number of HWEs when compared to its neighbours. A station labelled as a high (low) outlier indicated that nearby sites reported low (high) number of sustained or gust HWEs [Colour figure can be viewed at wileyonlinelibrary.com]

continental sites in the eastern United States. However, to understand the regional and site specific HWE outliers recognized in the study region warrant additional research.

3.2 | Temporal analysis of HWEs

During the 43-year study period, 5,167 (6,508) sustained (gust) HWEs were recorded for the eastern United States. An examination of these HWEs by Julian day showed that a seasonal lag existed between sustained and gust winds (Figure 5). That is, nearly 66% (3413) of sustained HWEs occurred during winter and spring, with the highest frequencies observed during March (12%; 622), December (13%; 666), and January (13%; 676) (Figure 5a). However, the greatest incidence (60%; 3,855) of gust HWEs was observed during spring and summer, with the maximum occurrences reported in May (10%; 649), June (12%; 780), and July (11%; 742) (Figure 5b).

A regional analysis further defined the seasonal frequency of sustained and gust HWEs from 1973 to 2015

(Figure 6). For the East North Central, Central, Southwest, and South, sustained HWEs occurred mostly in spring, while the West North Central and Northeast observed its highest frequency of sustained HWEs during winter. The only region that experienced its maximum frequency in sustained HWEs outside of winter and spring was the Southeast, which occurred during fall. Gust HWEs were most prevalent for the East North Central, Central, South, Southwest, and Southeast during

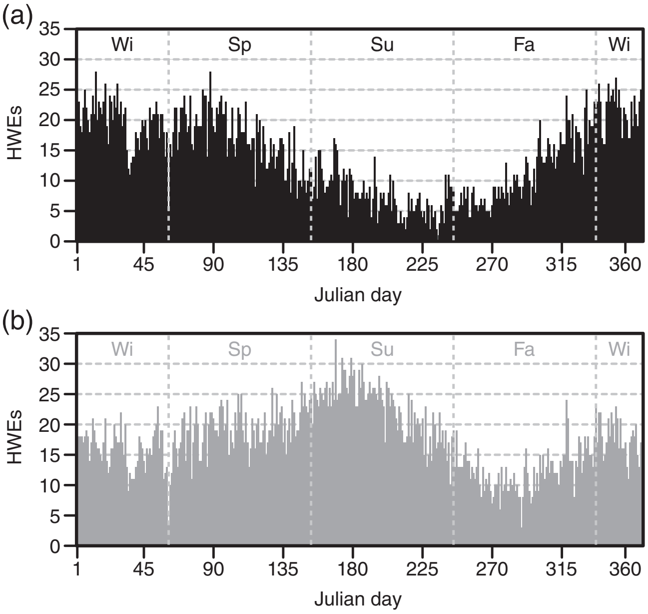

FIGURE 5 Frequency of (a) sustained and (b) gust HWEs by Julian day for the eastern United States during 1973–2015

spring and summer. In the West North Central and Northeast, the highest number of HWEs was reported in winter, with a secondary preference of sustained and gust HWEs during spring and summer.

A time series exhibits that the total annual number of sustained and gust HWEs has changed from 1973 to 2015 (Figure 7a). The overall linear trend shows the number of sustained HWEs has decreased (−0.579 days/year) at a statistically significant level ($p = .04$), while the annual frequency of gust HWEs has significantly ($p = .007$) increased at a rate of 0.943 days/year.

On average, 120 sustained and 151 gust HWEs were reported annually across the eastern United States based on the NWS high-wind criteria. However, to understand how the annual frequency of HWEs has changed over time, a normalization of the data was performed (i.e., deviations from the annual mean) based on the long-term averages described for sustained and gust winds from 1973 to 2015. Figure 7b shows that the annual HWE anomalies of sustained and gust winds can be categorized into three temporal periods. First, a negative anomaly pattern for gust HWEs was reported from 1973 to 1983, while sustained HWEs exhibited a varying pattern of positive and negative anomalies until 1993. Following this period, an above normal number of HWEs was described for sustained (gust) winds until 2000 (1999), with the highest positive departure from the long-term average observed during 1996. After reaching the positive anomaly peak, a below normal HWE pattern occurred for both wind criterion until 2006. This negative anomaly continued for sustained winds,

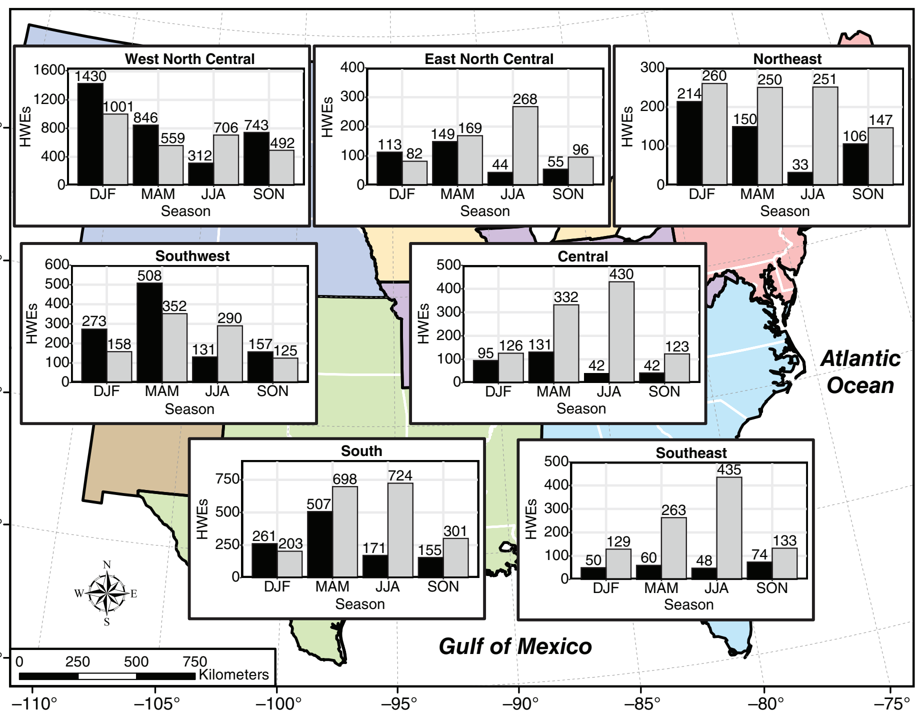

FIGURE 6 Number of sustained (black) and gust (grey) HWEs defined by NCEI climate region and season (winter – DJF, spring – MAM, summer – JJA, and fall – SON) from 1973 to 2015. NCEI climate regions outlined correspond to the colours illustrated in Figure 2 [Colour figure can be viewed at wileyonlinelibrary.com]

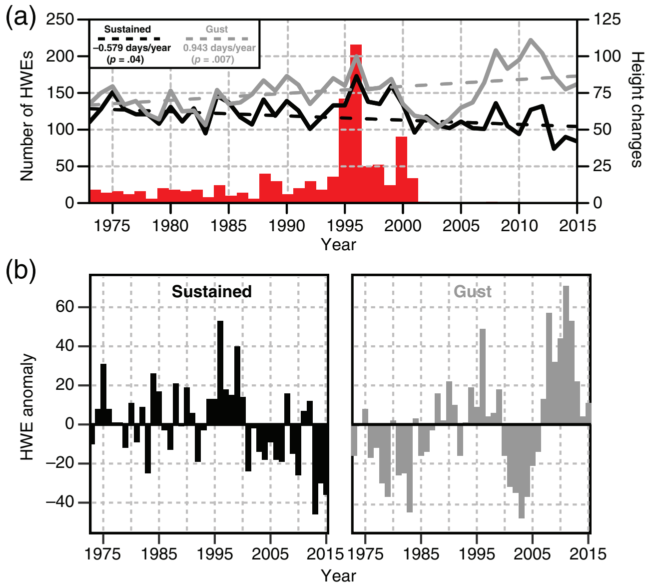

FIGURE 7 (a) Total annual number and linear trend (days/year) of sustained (black) and gust (grey) HWEs for the eastern United States from 1973 to 2015. Yearly number of anemometer height (red) changes is documented for the study period. (b) A time series of the mean annual HWE anomalies (departures from annual means) for sustained (black) and gust (grey) winds between 1973 and 2015 [Colour figure can be viewed at wileyonlinelibrary.com]

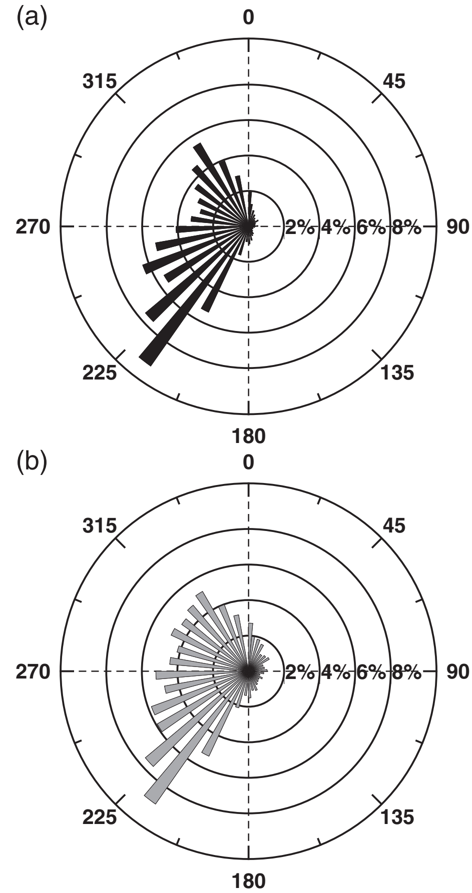

FIGURE 8 Wind rose frequency (%) based on direction of (a) sustained and (b) gust HWEs for the eastern United States during 1973–2015

while an above normal tendency was exhibited of gust winds for the remainder of the study period (2007–2015).

3.3 | Directional analysis of HWEs

An overall wind direction pattern was described for sustained and gust HWEs observed across the eastern United States. (Figure 8). The majority of high-wind observations were reported from the southwest (180–270°) and northwest (270–360°) quadrants. These two quadrants accounted for 90 and 82% of all sustained and gust HWEs included in the dataset (Figure 8a,b). Specifically, the most common wind direction of HWEs occurred within the wind sector between 220° and 250°, which represented 33% (27%) of all sustained (gust) wind observations. The lowest frequency of HWEs was reported from the southeast quadrant (100–170°) for sustained and gust winds. This wind quadrant represented just 7% (4%) of all sustained (gust) HWE occurrences found during 1973–2015.

While most HWEs were reported from southwest and northwest quadrants, a spatial wind direction analysis will provide a specific regional high-wind characterization of the study area (Figure 9). The most common quadrant reported for the West North Central and Central was from the southwest (180–270°) for sustained and gust HWEs. This southwesterly wind quadrant was observed for the Southwest, East North Central, and Northeast but high-wind observations were also reported from the northwest (270–360°) as well. This second axis was the primary direction that sustained and gust HWEs occurred in the South, with the highest frequency documented from the north–northeast (315–360°). The only region that did not support a southwest or northwest wind preference was the Southeast, which exhibited a northeast or southeast direction for sustained HWEs and a varying directional pattern in gust HWEs.

To further understand the characteristics of wind direction, an examination of the average wind direction by station was performed (Figure 10). The mean wind direction across the northern (southern) High Plains was a northwest (southwest) orientation, which converged in the central part (Kansas and Missouri) of the United States. After exiting this region, the average wind direction shifted to a westerly direction across Iowa. This westerly wind turned to a southwesterly direction within the Ohio Valley and Great Lakes, which persisted into the western Mid-Atlantic (Pennsylvania and New York). Upon reaching the Atlantic Coast, the wind direction was identified as offshore (onshore) or parallel to the coast from New Jersey to Maine (Maryland to North Carolina). Finally, the mean wind direction

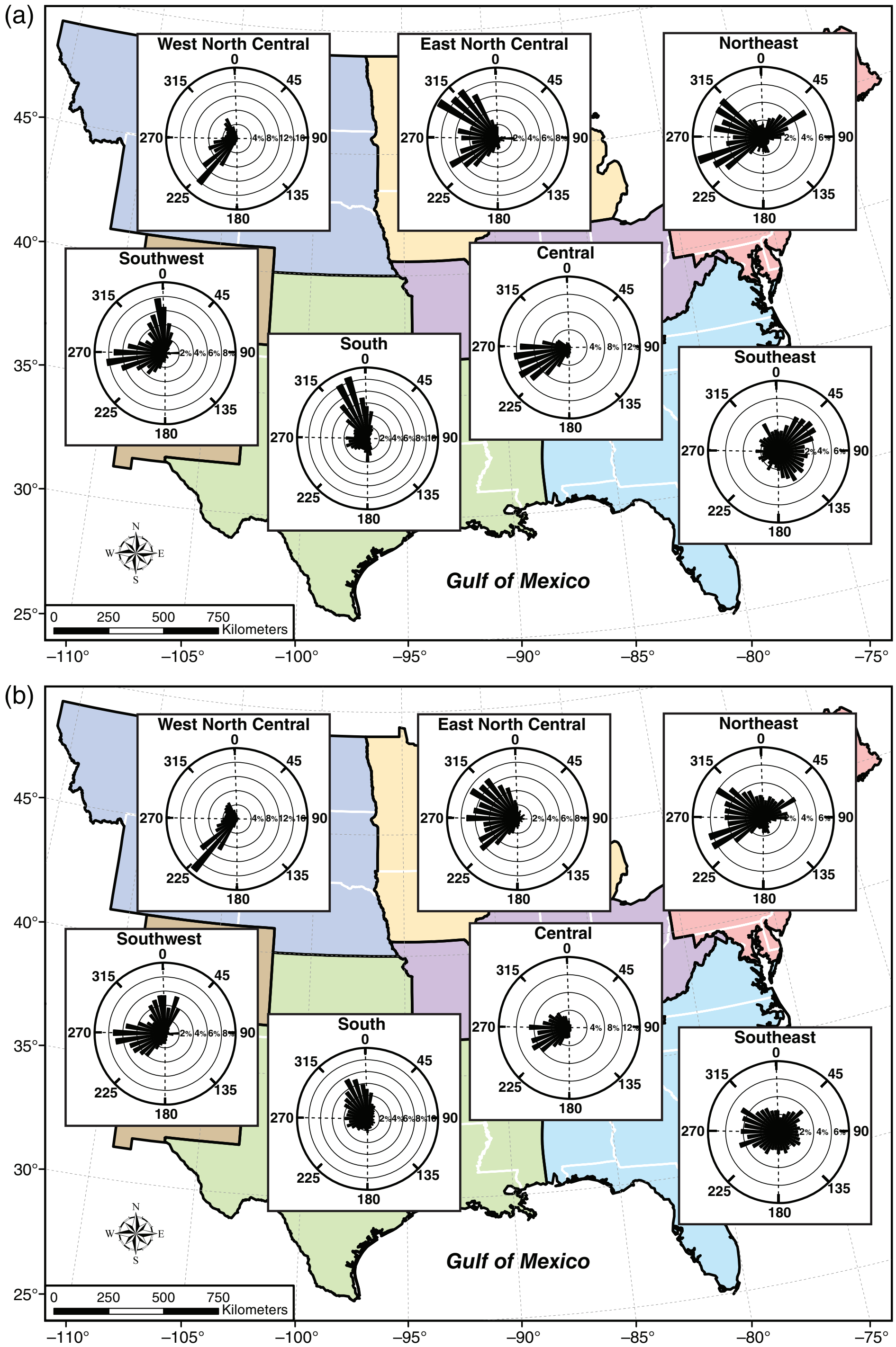

FIGURE 9 Wind rose frequency (%) based on direction of (a) sustained and (b) gust HWEs by NCEI climate region. NCEI climate regions outlined correspond to the colours illustrated in Figure 2 [Colour figure can be viewed at wileyonlinelibrary.com]

recorded for the southern United States was interpreted based on coastal and inland site locations. Stations found along the Gulf Coast exhibited an ocean or land breeze for sustained and gust HWEs. However, sites located inland showed a varying degree of direction for sustained HWEs but displayed a northwesterly or westerly orientation for gust observations.

Sustained and gust HWEs displayed a similar annual cycle in direction when examined by Julian day (Figure 11). For most of the year, the average wind direction observed by the stations was from the southwest or west (225–270°). However, by mid-August (Julian day 225), this begins to shift to a more southerly direction, before returning back to southwesterly by late September (Julian day 270; Figure 11a,b). This shift coincided with the climatological maximum of tropical cyclone occurrence in the Atlantic and Gulf of Mexico, where sustained and gust HWEs were typically reported from the southeast or northeast quadrant. Consequently, when tropical cyclone related HWEs (TC-HWEs) were excluded from the analysis, it all but eliminated the shift to a more southerly wind direction (Figure 11c,d). The annual mean wind direction associated

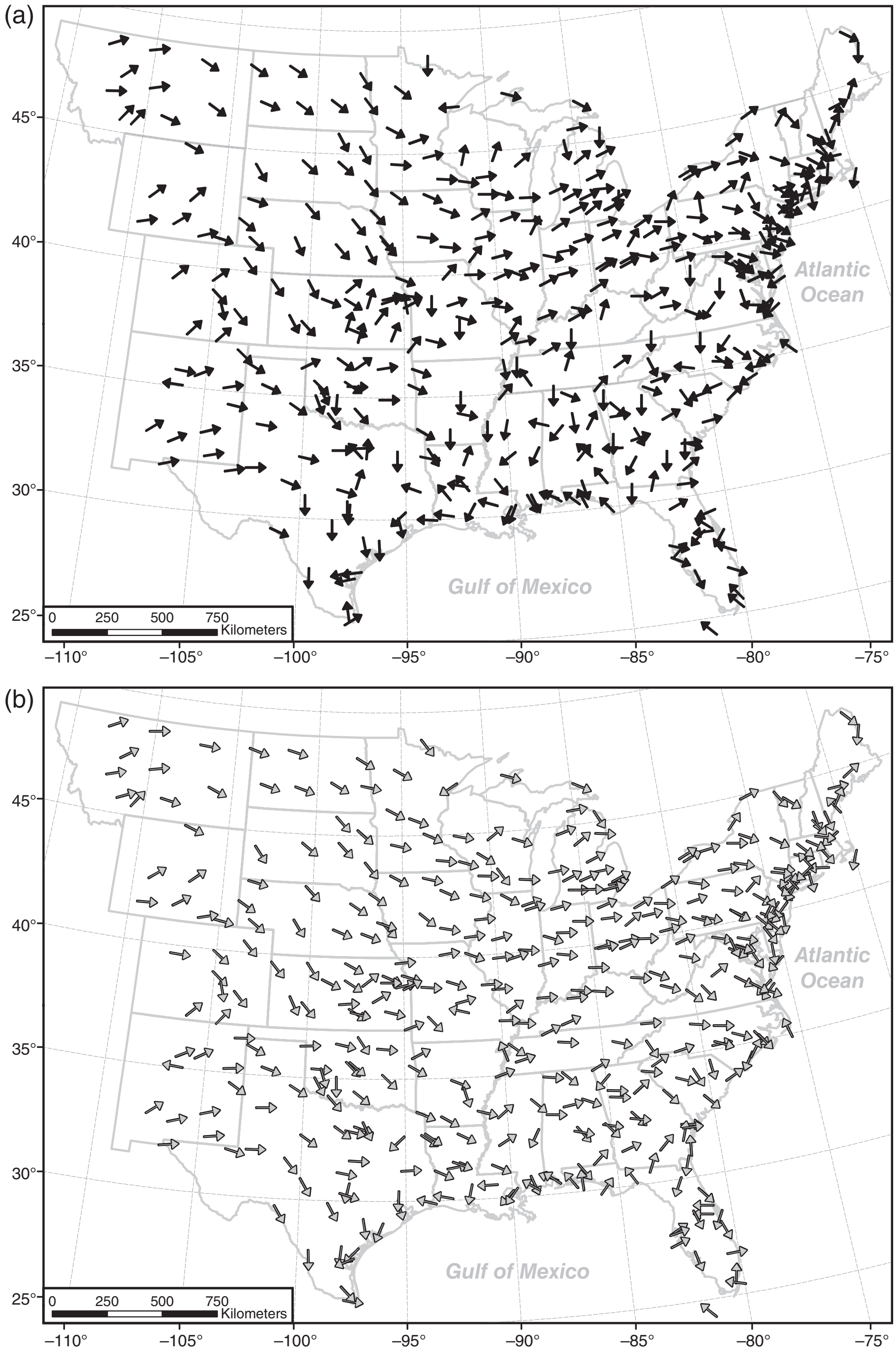

FIGURE 10 Mean wind direction of (a) sustained and (b) gust HWEs by station for the period 1973–2015

with sustained (gust) HWEs has shifted to a more southerly (northerly) direction during the 1973–2015 period of record (Figure 12). A non-significant (p = .336) shift towards a more southerly wind direction was present when considering all HWEs for sustained winds (−0.224 degrees/year), while a statistically significant (p = .005) northward change was identified for (0.548 degrees/year) gust winds in the eastern United States (Figure 12a). This southerly shift (−0.198 degrees/year) determined for sustained winds was still present after the removal of TC-HWEs but was not statistically significant (p = .368), while the northward shift observed for gust (0.502 degrees/year) winds remained statistically significant (p = .007) during the study period (Figure 12b).

4 | DISCUSSION

This study has described regional HWE patterns for the eastern United States during the period 1973–2015 (Figure 3). The frequency of sustained and gust HWEs was consistent

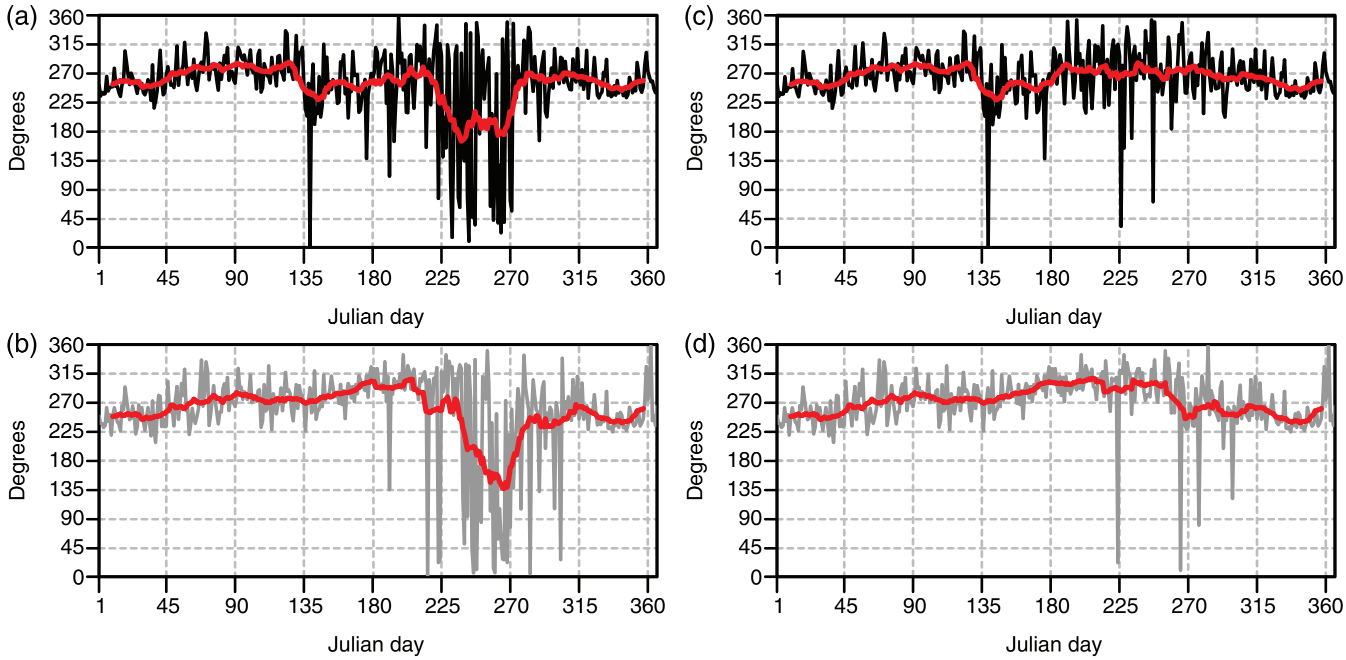

FIGURE 11 Mean wind direction by Julian day of all (a) sustained and (b) gust HWEs and when excluding (c) sustained and (d) gust TC-HWEs from the study. A simple 15-day moving average (red line) is calculated to show how the direction changes over the year for the eastern United States [Colour figure can be viewed at wileyonlinelibrary.com]

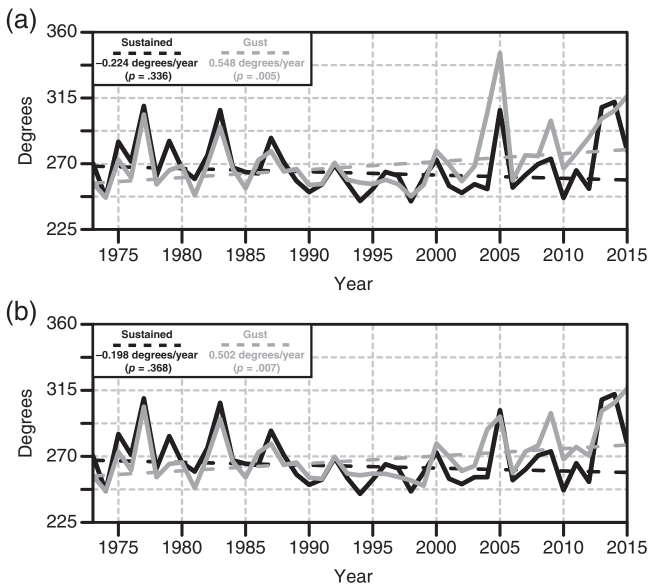

FIGURE 12 Mean wind direction and linear trend (degrees/year) that includes (a) all sustained (black) and gust (grey) HWEs and (b) excludes sustained and gust TC-HWEs for the eastern United States from 1973 to 2015

with Lacke *et al*. (2007) and Kurtz (2010), which showed that the highest number of HWEs occurred in the Great Plains and Great Lakes regions. After departing the primary axis of HWEs, a decrease was observed for the Mid-South, where a lower frequency of HWEs was described during the 43-year study period. The minimal number of HWEs was also supported by stations located in the southeastern United States. Martin and Konrad (2006) found that wind gusts greater than 17.9 m/s (~40 mph) was rarely reported in the southeastern United States during 1995–2003. The HWE regional groupings described in this study is supported by Letson *et al*. (2018), which determined that the fastest (95% percentile) gust winds were reported in the central and northern High Plains, followed by a secondary axis pertained to the Great Lakes, Mid-Atlantic, and coastal locations. That study also showed that the slowest reported wind gusts occurred in the southeast United States, which supported the low number of sustained and gust HWEs found in this study.

When HWEs were examined over a given year, a temporal pattern was identified for both sustained and gust winds (Figure 5). The highest frequency of sustained HWEs was observed during winter and spring, while gust HWEs occurred in spring and summer. The seasonal lag established between sustained and gust HWEs was most likely related to the way that these winds are produced. The patterns in HWE frequency and wind direction identified for both the Great Lakes (Niziol and Paone, 2000; Lacke *et al*., 2007) and central Great Plains (Kurtz, 2010) were related to the synoptic and dynamic factors that produced non-convective winds. McCabe *et al*. (2001) showed that the intensity and frequency of winter (November–March) extratropical cyclones has changed across the middle and high latitudes of the Northern Hemisphere between 1959 and 1997. Their work described a northward shift in the frequency of cyclones propagating across the Northern Hemisphere, with an increase in the strength of cyclones. This poleward shift in the frequency may influence the magnitude and length of HWEs being reported in the eastern United States. For example, Pryor *et al*. (2014) highlighted that cold fronts associated with mid-latitude cyclones were related to the duration of sustained and gust wind speeds reported in the eastern United States. That study analysed 35 cold front events positioned over Illinois during a 2-year period and found that 40% (50%) of those events reported sustained (gust) wind speeds over 10 m/s for at least 2 hr. This constant wind duration documented by Pryor *et al*. (2014) would support the number of sustained HWEs reported during late winter into early spring for NCEI climate regions located in the eastern United States (Figures 5a and 6).

Further, the occurrence of gust HWEs found in this study was supported by previous work that examined the spatiotemporal characteristics related to convective (thunderstorms) systems that initiated during summer (Mohee and Miller, 2010; Lock and Houston, 2015). Those studies showed that the life cycle of thunderstorms (based on radar reflectivity data) tends to be relatively short. Mohee and Miller (2010) described the mean life cycle of a thunderstorm cell observed in North Dakota was 23.6 min, with a mean gust wind speed of 16.5 m/s. However, when the NCEI thunderstorm definition (15-min minimum) was applied, the average duration of a thunderstorm cell increased to 41.3 min, with the most intense cells producing wind gusts of 31.4 m/s. This time length concurred with Lock and Houston (2015) who found that the mean life cycle of a thunderstorm was between 43 and 45 min in the Great Plains during 2005–2007. In addition, the frequency of thunderstorm derived wind-events is supported by Kelly *et al*. (1985) who identified the highest (lowest) frequency of severe thunderstorm wind events were reported between June and August (December and February) in United States during 1955–1983. Their study showed that the highest (lowest) wind gust reported (>25.8 m/s) from non-tornadic thunderstorms coincided with the peak of summer (winter). The duration and time periods identified from these studies supported the tendency for weather stations in the eastern United States to report wind gusts that satisfied the NWS high-wind criteria during late spring and summer (May–August) (Figure 5b).

Annual examination of the number of HWEs showed that the frequency of sustained and gust HWEs exhibited both increases and decreases over the 43-year study period (Figure 7). The annual occurrence of HWEs showed a positive trend until reaching the peak of anemometer height correction (1995 and 1996), before a decrease is observed during the early 2000s for sustained and gust winds (Figure 7a). Pryor *et al*. (2007) showed that annual 50 and 95% percentile surface wind speeds (5-year running average) did not largely change when ASOS instruments were deployed between 1995 and 1996 in the United States. A summary of previous high-wind studies by Knox *et al*. (2011) revealed varying temporal trends in NCWEs across the Northern Hemisphere. This temporal cycling of HWEs was noted when the long-term climatological mean was removed for sustained and gust winds (Figure 7b). A possible explanation of the HWE cycle could be attributed to the frequency and intensity of extratropical cyclones in the mid-latitudes. Vose *et al*. (2014) found a cyclical pattern in the frequency and intensity of mid-latitude cyclones (30–60°N) between 1948 and 2010. That study showed when below (above) normal extratropical activity was present in the mid-latitudes, typically associated weaker (stronger) cyclones were evident. This change in the intensity and frequency of mid-latitude cyclones may attribute to the decrease in surface wind speeds observed across the Northern Hemisphere. Recent climatological studies have suggested that modifications in macro-scale atmospheric circulations may influence the speed of surface winds being observed across Earth during the 20th century (Klink, 2002; Abhishek *et al*., 2010; Jiang *et al*., 2010; Troccoli *et al*., 2012; Jaswal and Koppar, 2013; Dadaser-Celik and Cengiz, 2014; You *et al*., 2014; Romanić *et al*., 2015; Nchaba *et al*., 2017).

While the occurrence and strength of cyclones propagating through the mid-latitudes can affect the annual count of HWEs, it was also important to discuss the role that large-scale atmospheric circulation (teleconnections) may have on the number of HWEs observed over a given time period. Klink (2007) examined the role of atmospheric circulation on mean monthly wind speeds (70 m) of 11 stations in Minnesota between 1995 and 2003. The study identified below normal monthly wind speeds when negative Arctic Oscillation (AO) and positive Pacific-North American (PNA) indices occurred with above normal sea surface temperature anomalies (positive El Niño–Southern Oscillation; ENSO) in the central Pacific from l997 to 1998. Above normal monthly winds were observed when positive AO, a fluctuating (positive and negative) PNA, and neutral to weak ENSO from late 2001 to mid-2002. While the cycle of atmospheric teleconnections (ENSO and PNA) seemed to coincide with the frequency of HWEs reported in the eastern United States, it may not represent or explain the anomaly pattern described of sustained and gust winds during the 43-year study period. Therefore, the phases of atmospheric circulations should be further investigated to understand how those circulations could potentially affect HWE occurrences in the eastern United States.

The typical wind direction reported from sustained and gust HWEs was described with a southwesterly preference followed by a secondary peak reported from the northwest (Figure 8). These two wind direction tendencies were further explained through spatial interpretation by region and station (Figures 9 and 10). First, the wind direction noted for the

High Plains followed the findings of Kurtz (2010). That study found a northwest wind direction for the north and central High Plains, which gradually shifted to a southwest direction across the state of Iowa. The findings from this study showed a similar spatial transition of wind direction from the northwest for western Iowa and southeast South Dakota to a westerly component in central Iowa, and finally a southwest direction in eastern Iowa. This southwest wind preference extended into the Great Lakes, which was consistent with Lacke *et al*. (2007). Lacke *et al*. (2007) results suggested that mid-latitude dynamics (i.e., propagation of low-pressure circulations during winter and spring) were a contributing factor to the wind direction observed across the Great Lakes region. Kurtz (2010) similarly found sites located in the central and northern High Plains (Midwest) observed a west-to-northwest (southwest) wind direction when lower-level (850 and 700 hPa) trough axes were positioned east (west) of the reporting station during a HWE.

This southwesterly wind direction was further documented into the Mid-Atlantic and New England states with the exception of coastal stations which observed a land-ocean breeze or parallel wind flow. Booth *et al*. (2015) identified that HWEs occurred when mid-latitude cyclones originated west of the Appalachian Mountains and took a southwest to northeast path over northeastern United States. With this travel path, the centre of the mid-latitude cyclone was positioned north of the Mid-Atlantic or New England states, placing both regions within the warm sector of the cyclone and along the cold front where the strongest winds are normally observed (Booth *et al*., 2015). The final wind direction grouping found for the southeastern United States was highly variable. Martin and Konrad (2006) determined a differing gust wind pattern for 20 ASOS stations located in the Appalachian Mountains, Piedmont, and coastal southeastern United States between 1995 and 2003. The study described four geographic wind patterns: (a) northeast and southwest wind direction for northeastern coast (Virginia and North Carolina), (b) westerly orientation for the southeast coast; (c) southwest direction was prevalent for Piedmont stations, with a secondary easterly component documented towards the northeast; and (d) mountainous stations observed high-wind gust related to orographic and topographic settings. This variation in the wind direction described for the southeastern United States was identified through spatial statistics, where Gulf Coast stations were found to be independent of inland locations (Figure 10).

With an understanding of the geographical wind direction across the study region, it was important to identify how the wind direction has changed over time (Figure 11). When sustained and gust HWEs were examined by Julian day, a persistent southwest to west direction was present during winter and early spring. A gradual shift in the wind direction was shown until reaching the maximum peak (September) of the Atlantic tropical cyclone season, where stations tended to report a southeasterly or northeasterly wind direction before returning to a southwesterly orientation for the reminder of the year.

A time series of the annual mean wind direction for sustained (gust) HWEs revealed that high-wind observations have shifted to a more southerly (northerly) direction across the study region (Figure 12). This directional trend of sustained (gust) winds was still noted when TC-HWEs were excluded from the analysis, a non-significant (significant) shift in the wind direction towards the south (north) during the 43-year study period. Ulbrich *et al*. (2009) summarized that the track of mid-latitude cyclones under future climate scenarios was expected to change in the Northern Hemisphere. Their analysis identified a decrease in the frequency of winter cyclone tracks over the mid-latitudes of United States and Canada. This change in cyclone activity was possibly related to changes observed in surface air temperature. Klink (1999) found that changes in near-surface winds in the United States resulted from modifications in temperature and pressure gradients for the period of 1961–1990. With atmosphere warming and weakening of the pressure gradient, it is expected that a poleward shift in mid-latitude dynamics could influence the orientation of wind direction reported at higher latitudes (Great Plains and Great Lakes) in the eastern United States. This northward shift of the mid-latitude cyclone track from a changing climate would support the gradual shift in the annual mean wind direction of sustain HWEs reported by stations from the west to southwest during the 43-year study period.

5 | CONCLUSIONS

HWEs can result in human fatalities (Ashley and Black, 2008; Schmidlin, 2009; Miller *et al*., 2016) and socioeconomic losses (Changnon, 2009; Barthel and Neumayer, 2012) in the United States. However, a limited number of studies have investigated the climatological characteristics of HWEs for the United States. The majority of the work has been concentrated on the Great Lakes (Niziol and Paone, 2000; Lacke *et al*., 2007) and Great Plains (Kurtz, 2010) regions. As a result, this study was completed to understand the HWE characteristics based on observations of 391 weather stations across the eastern United States from 1973 to 2015. HWEs were identified and classified through the NWS high-wind criteria in order to determine geographical and temporal patterns. This analysis showed regional patterns in the frequency of sustained and gust HWEs across the study region. Most of the HWEs associated with sustained winds were observed during winter and spring, while gust HWEs occurred from late spring into early summer. This temporal difference suggests that non-convective fronts are conducive with sustained winds, whereas convective conditions are identified with gust winds.

Nearly 90 and 82% all of sustained and gust HWEs occurred from the southwest and northwest quadrants. The highest (lowest) frequency of HWEs was reported from the southwest (southeast) quadrant for each wind criterion. However, when the wind direction was interpreted spatially, HWEs tended to follow the life cycle of mid-latitude and tropical cyclones that occurred in the upper and lower latitudes of the eastern United States. This variation was observed through the annual cycle, where the average wind direction was from the southwest until reaching the peak of tropical cyclone activity where sustained and gust winds were observed from the southeast or northeast. However, when TC-HWEs were excluded from the study, the southwest wind direction remained persistent throughout the entire year.

Previous research has shown that HWEs are rarely documented and reported by stations based on the current high-wind warning criteria deployed by NWS. Miller *et al.* (2016) found that 92% of all convective, tropical, and non-convective wind events reported from the NCEI Storm Events Database from 1996 to 2013 were associated with wind gust that did not exceed the NWS gust threshold (26 m/s). Letson *et al.* (2018) similarly identified that 95% percentile wind gusts observed across the United States did not satisfy the NWS high-wind criteria. That study showed that most stations located in the Great Plains (Southeast) have observed 95% percentile wind gust values that only exceeded 16.5 (14.4) m/s during the period of 2002–2009 (Letson *et al.*, 2018). Those findings revealed that in many cases the strongest wind gusts typically do not meet the present NWS high-wind definition. Future work should address the present-day sustained and gust HWE criteria by taking measures to develop wind advisory standards that are regionally focused and assess the climatology of winds that are below the current high-wind criteria. Future research should also attempt to segregate convective versus non-convective HWEs in order to identify key spatial and temporal differences for an improved climatological understanding of the various HWE-origins. Lastly, additional work should further examine the relationship between low and high-frequency circulation variability (teleconnections) for an improved longer-lead forecast potential of such events.

ACKNOWLEDGEMENTS

The authors thank the two anonymous reviewers for their feedback and critique of the manuscript.

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How to cite this article: Gilliland JM, Black AW, Durkee JD, Murley VA. A climatology of high-wind events for the eastern United States. *Int J Climatol*. 2019;1–16. https://doi.org/10.1002/joc.6233