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A Climatology of Convective and Non-Convective High-Wind Events across the Eastern United States During 1973-2015

Victoria Murley
Western Kentucky University, victoria.hampton714@topper.wku.edu

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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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Master of Science

By
Victoria A. Murley

August 2018

A CLIMATOLOGY OF CONVECTIVE AND NON-CONVECTIVE HIGH-WIND EVENTS IN THE EASTERN UNITED STATES DURING 1973-2015

Date Recommended 7/9/18

Joshua Durkee, Director of Thesis

Kevin Cary

Greg Goodrich
Gregory Goodrich

Cheryl D. Davis 7/19/18
Dean, Graduate Studies and Research Date

I dedicate this thesis to my late grandmother, Helen. You were taken too soon, but your love for your family, community, and church is still felt today. You supported me throughout all my years of school and I know you would be so proud that I have made it this far. I strive to be more like you every day.

ACKNOWLEDGEMENTS

I could not have maintained my sanity in graduate school had it not been for the love and support of my husband, Jake. You stepped up and took on numerous tasks while I was working full-time, completing graduate classes, and planning our wedding. Every day is an adventure with you and I am so blessed to have such a caring, selfless life-partner. In addition, I would like to thank my mom for her support during the last 25 years. You encouraged me to pursue the sciences and excel in everything I do. You truly are a role model and I appreciate you more than words can say.

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A CLIMATOLOGY OF CONVECTIVE AND NON-CONVECTIVE HIGH-WIND EVENTS ACROSS THE EASTERN UNITED STATES DURING 1973-2015

Victoria A. Murley August 2018 99 Pages

Directed by: Dr. Joshua D. Durkee, Dr. Kevin Cary, and Dr. Gregory Goodrich

Department of Geography and Geology Western Kentucky University

High-wind events (HWE) occur across every region of the United States (U.S.) and result in hundreds of fatalities, as well as thousands of dollars in damages annually. HWEs are classified as sustained high-winds or high-wind gusts and can be generated from convective or non-convective weather systems. This study investigates high-wind observations 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 HWEs were most concentrated in the High Plains and fewer convective HWEs occurred during the study period compared to non-convective. Convective and non-convective sustained HWE frequency and mean wind-speeds declined during the study period while gust HWE frequencies and speeds increased. The purpose of this study is to develop an extensive climatological understanding of convective and non-convective high-wind events to mitigate associated damages and fatalities caused by these events.

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

Wind affects every region of the world by providing sources for alternative energy, driving the motion for weather systems, and transporting particulates through the atmosphere. Within the last few decades, interest has increased in wind climatology and variations of surface wind speeds as wind energy becomes a more viable resource. Wind energy is now a multibillion-dollar industry and continues to grow rapidly (Lackmann 2011). Wind is highly variable, both spatially and temporally, and numerous studies identify long-term changes in the wind patterns across the United States (U.S.) (Klink 1999; Klink 2002; Pryor et al. 2007; Pryor et al. 2014). Determining the overall variances in wind speeds and directions can help energy consultants make better decisions regarding the placement of wind farms. Much is known about wind from a large body of research; yet, questions remain.

Synoptic-scale weather systems, especially extratropical cyclones, are directly linked to wind patterns (Klink 1999; McCabe et al. 2001; Klink 2002; Pryor et al. 2007; Ashley and Black 2008; Changnon 2009; Knox et al. 2011; Pryor et al. 2014). Cyclonic weather systems decreased in frequency over the last four decades; yet, are becoming more intense when they do occur (McCabe et al. 2001). If the surface wind pattern and characteristics of cyclones are changing spatially and temporally, it is possible that high-wind events (HWEs) may exhibit similar changes.

HWEs resulting from cyclonic systems are known to cause property damage and fatalities. They were responsible for approximately $300 million in property losses during 1956-2006 (Changnon 2009) and resulted in almost 3,000 fatalities during 1980-2005 (Ashley and Black 2008). High-winds are associated with almost every type of severe weather event and do not always cause damage directly. Fatalities due to falling tree limbs are common during HWEs, as well as vehicular-related casualties (Ashley and Black 2008).

Convective and non-convective high-winds collectively account for 45.5% of all wind-related fatalities (Ashley and Black 2008). HWEs generated both convectively and non-convectively are severe and produce much damage across the affected regions. Both types of events are associated with different weather systems, but result in similar hazards at the surface.

The purpose of this thesis is to investigate high-wind observations across the eastern U.S. during a 43-year climatological period for spatial and temporal variations in speed and direction. The eastern U.S. encompasses many regions that experience frequent amounts of HWEs annually. Only one published study has been conducted for the entire eastern U.S. (Pryor et al. 2014), and Gilliland et al. (2018) analyzed sustained and gust HWEs during 1973-2015 for the eastern U.S. Furthermore, there is lack of research for HWEs that are specifically generated by convective and non-convective systems. This thesis will address the following research questions:

- How do HWEs vary spatially and temporally in the eastern U.S.?
- How does seasonality affect the frequency and intensity of both convective and non-convective HWEs?

- What can regional analyses tell us about the influence of synoptic and mesoscale patterns in the characteristics of HWEs?

Although Pryor et al. (2014) extensively studied HWEs recorded over a 35-year period, no study has analyzed sustained and gust HWEs across the entire eastern U.S. with consideration to both convective and non-convective systems. This thesis will provide an understanding of temporal and spatial variability in HWEs across the eastern U.S.

1.2 Literature Review

Wind is a fluid system that drives horizontal flow of air in the atmosphere and is made possible by a balance of forces in the atmosphere. Newton's Second Law of motion applies to this system and multiple forces contribute to the total acceleration of the wind (Martin 2006). The atmospheric equation of motion consists of a sum of forces that equal the net acceleration of wind:

$$\frac{D\mathrm{U}}{D\mathrm{t}} = -2\Omega \times U - \frac{1}{\rho}\nabla \mathrm{p} + g + F \qquad \textbf{Eq. 1.1}$$

where U is the wind velocity vector, Ω is the angular velocity of the earth, p is the pressure, g is the gravitational force, and F is frictional force per unit mass. Thus, the acceleration of wind is equal to the sum of the Coriolis force, the pressure gradient force, effective gravity, and frictional force (Martin 2006), though some components can be considered void if the scale of motion is small (e.g. Coriolis and frictional forces).

Pressure plays a large role in the movement of air across the globe. Differences in pressure are created by the temperature gradient that exists between the poles and equator. The difference in temperature forms a baroclinic environment in the midlatitudes, thus creating a state of instability. Thermal wind circulations in a baroclinic environment cause air to rise and sink in an attempt to restore stability to the atmosphere and subsequently create areas of low and high pressures, respectively. The direction and speed of wind is influenced greatly by the pressure gradient force (PGF), or flow of air from high to low pressure (Martin 2006).

Other types of wind also affect atmospheric motion across the globe. Geostrophic wind, or the balance of the horizontal pressure force and Coriolis acceleration, governs the approximate westward movement of synoptic-level atmospheric processes (Holton 1992; Martin 2006). The speed of geostrophic wind is given by:

$$V_g = -(\frac{g}{f})\frac{\partial z}{\partial n} \ , \qquad \textbf{Eq. 1.2}$$

where g is the acceleration of gravity, f is the Coriolis parameter, and $\frac{\partial z}{\partial n}$ is the slope of the isobaric surface.

Gradient wind is defined as the horizontal pressure gradient balanced by the Coriolis and centripetal acceleration. This type of wind determines the velocity and direction of wind vectors with consideration to curvature flow around low and high pressure systems, respectively (Holton 1992; Martin 2006). The balance of the forces is given by:

$$\frac{V_{gr}^2}{R} + fV_{gr} = -g\frac{\partial z}{\partial n}, \qquad \textbf{Eq. 1.3}$$

where V_{gr}^2 is the gradient wind speed, R is the radius of curvature, f is the Coriolis parameter, g is the acceleration of gravity, and $\frac{\partial z}{\partial n}$ is the change in elevation of a pressure surface relative to the direction perpendicular to the height contour.

As the magnitude of high and low pressure systems strengthens, the horizontal PGF increases and result in an increase of surface wind speeds. Tight temperature and pressure gradients associated with frontal systems and midlatitude cyclones are a major cause of HWEs (Ashley and Black 2008; Changnon 2009; Knox et al. 2011; Pryor et al. 2014).

Several studies on temporal and spatial surface wind climatology in the U.S. identified trends and variability in surface wind speeds and directions (Klink 1999; Klink 2002; Pryor et al. 2007). Klink (1999) investigated the monthly mean and seasonal variability of wind speed and direction in different regions of the U.S. and identified a southerly directional preference in the summer months and a northwesterly preference in the winter months. There was much variability in the wind direction during the transition seasons. The results also indicated a preference for greater wind speeds in the Midwest and Northeast during fall, winter, and spring. Additionally, the spring months were the most variable in wind speed in the Midwest and Northeast.

Pryor et al. (2007) found a decline in wind speeds in the eastern U.S. from 1973-2005 (Fig 1.1). Within the 30-year period, while there were regions of the U.S. that experienced periods with positive trends in wind speed, the overall trend was negative for the entire study area. Though wind measurement instrumentation changed during this time period, the results did not show a bias in the data. Instead, synoptic scale patterns are thought to play a role in wind speed, direction, and variance trends (Klink 1999; Klink 2002; Pryor et al. 2007). Further investigation is needed to improve the results by examining a broader study region in the U.S.

Midlatitude extratropical systems directly influence surface wind speed and direction. These systems are generated in a baroclinic environment and are represented by a low pressure system with a poleward-progressing warm front and equatorward-progressing cold front (Hoskins and Pedder 1980). Variations in midlatitude cyclones affect surface winds (McCabe et al. 2001). McCabe et al. (2001) analyzed midlatitude 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 (Fig 1.2). 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 midlatitudes. The authors hypothesized that cyclone frequency will continue to decrease, while intensity increases, as global temperatures rise. Since midlatitude cyclones affect surface winds, it can be inferred that a decrease in cyclonic activity may also influence HWEs.

a. HWEs

According to the National Weather Service criteria, a “high-wind” event is classified as a sustained wind of 18 m s^{-1} (40 mph) for at least one hour or a gust of 26 m s^{-1} (58 mph) for any length of time. HWEs have resulted in fatalities, injuries, and property damage. HWEs occur in every region of the U.S. and vary meteorologically, though these events cause similar hazards at the surface (Cairns and Corey 2003; Lynch et al. 2003; Ashley and Black 2008; Zhong et al. 2008; Changnon 2009; Pryor et al. 2014; Martin and Konrad 2006; Knox et al. 2011; Booth et al. 2015).

Changnon (2009) conducted a study on damages associated with HWEs in regions in the U.S. during 1952-2006. The average annual loss due to catastrophic HWEs is approximately $354 million. The data showed more catastrophic wind events occurring in the northeast, central, and western regions in the U.S. According to this study HWEs occur most frequently in the cold season months of November-January when cyclonic systems are strongest. While the authors of this study discovered meaningful trends in the spatiality and seasonality of HWEs, it is still unknown as to whether these events were due to sustained high-winds or high-wind gusts. Furthermore, additional analysis is needed to determine whether these events were produced from convective or non-convective weather systems.

Numerous factors influence wind direction and speed during a HWE, including topography and forcing from large-scale circulations and pressure gradient magnitude. Topographical influences are most common along the Rockies in the western U.S. (Cairns and Corey 2003; Zhong et al. 2008; Changnon 2011; Pryor et al. 2014), but can also be found in the Appalachian region as well (Martin and Konrad 2006). Cairns and Corey (2003) modeled HWE simulations for western Nevada. The results showed a large topographic factor influence in the generation and intensity of high-winds occurring in this region.

In a study by Zhong et al. (2008), HWEs in the Owens Valley of California were analyzed. Though it was determined that topography played a small role in the forcing of surface winds, synoptic-scale forcing was found to be the major influence on HWEs in the Owens Valley. The results also revealed that frontal passages affect the wind direction during HWEs in the Valley. In a separate study by Lynch et al. (2003), two cyclonic systems occurring in the years 1963 and 2000 produced record-breaking high-winds in Barrow, Alaska. Strengthened by small-scale mesoscale processes such as surface fluxes and thermal advection, these systems intensified over open water and resulted in numerous hazards once making landfall. While many factors play a role in the variability of wind speed and direction, research indicates that synoptic forcing is most influential. For example, high-winds resulting from synoptic systems accounted for nearly 70% of all HWEs in the U.S. during the last 50 years (Changnon 2011, Pryor et al. 2014).

The synoptic forcing mechanism affecting HWEs across the U.S. is related to cold front passages and extratropical cyclones (Changnon 2011, Pryor et al. 2014). Pryor et al. (2014) conducted a recent study on extreme wind speeds across the eastern U.S. and found an increase in wind speeds and gusts with strengthening frontal boundaries.

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 northwesterly or southwesterly projected track; thus, high-winds resulting from cyclonic activity tend to have westerly, southwesterly, and northwesterly directions (Niziol and Paone 2000; Martin and Konrad 2006; Lacke et al. 2007; Booth et al. 2015). Likewise, HWEs are most common in the winter and spring months when cyclonic activity is most frequent (Lacke et al. 2007; Changnon 2009; Booth, et al. 2015).

Booth et al. (2015) compared HWEs in the northeastern U.S. to results from European high-wind studies. Booth et al. (2015) found a relationship between cyclone tracks and location of HWEs that are in agreement with European studies (Nissen et al. 2010). The results also indicate a southwest to northeast track for cyclones and high-winds occurring to the south and west of the cyclone center (Fig 1.3). The results from both Booth et al. (2015) and Nissen et al. (2010) support the placement of HWEs within the warm sector near the cold frontal boundary. These results agree with Changnon (2011) in that numerous HWEs occur with the passage of a cold front. Given preferred wind directions and proximity to cold fronts, HWEs should be explored by pre- and post-frontal position, thus analyzing convective and non-convective system contributions.

b. Convective HWEs

HWEs can be classified into two categories: those caused by convective systems and non-convective systems. A convective high-wind simply describes any high-wind that is the result of a convective weather system. This includes the typical spectrum of thunderstorms ranging from disorganized air-mass storms to organized mesoscale convective systems (MCSs) and supercell systems (Klimowski et al. 2003). Embedded within these systems are common HWE-producing phenomena such as derechos, microbursts, and bow echoes, among others.

Schoen and Ashley (2011) showed that convective HWEs result in an average of 84 fatalities annually in the U.S. In a 26-year study on HWE-related fatalities, 78.6% of all fatalities were caused by convective wind events (Ashley and Black 2008). Convective high-winds are the most deadly and occur across the majority of the eastern U.S. High-winds produced from tornadoes resulted in twice as many fatalities as thunderstorm-related high-winds during the period 1980-2005 (Ashley and Black 2008) (Fig. 2.4). In a separate study by Schoen and Ashley (2011), 77% of convective high-wind fatalities ensued from tornadoes during 1998-2007. Nontornadic HWEs, due to convective systems such as thunderstorms and straight-line winds, have also led to numerous fatalities and damage.

Kelly and Schaefer (1985) found a uniform distribution of nontornadic severe thunderstorm events across the eastern U.S. during the summer months. The northern, central, and southern plains experienced the most damaging wind reports in the summertime for this period. June was the most active month for thunderstorm activity, resulting in wind gusts greater than 28.5 m s^{-1}. In a similar study, fatal nontornadic convective wind events occurred most frequently in the warm season during 1998-2007 (Schoen and Ashley 2011).

Following tornadic storms, organized linear convective systems are the second largest cause of fatalities due to high-winds (Klimowski et al. 2003; Schoen and Ashley 2011). Organized linear systems (e.g. squall lines) often produce areas of intense straight-line winds. Bow echoes alone make up one quarter of nontornadic convective wind fatalities (Schoen and Ashley 2011). Bow echoes affect small regions and are embedded within a much larger convective system. Long-lived bow echoes or several bow echoes within the same linear system can lead to the formation of a derecho. A derecho is a large bowing region of a MCS and often results in widespread damaging straight-line winds at the surface (John and Hirt 1987; Coniglio et al. 2004).

In a study by Coniglio et al. (2004), results indicated a synoptic influence on the formation of derecho convective systems. Over 70% of all derecho convective systems (DCSs) fall into three upper-level synoptic patterns with the most prominent pattern involving a well-defined trough upstream of the convective system. In a case study by Van Den Broeke et al. (2005), two separate squall lines resulted in numerous damaging wind reports during the span of each event. Both squall lines were associated with an upper-level trough upstream of the reports and a cold frontal boundary.

Derechos are often associated with clusters of downbursts located within a MCS (Fujita and Wakimoto 1981; John and Hirt 1987). A downburst is defined by Wakimoto (1985, pp. 1131) as a “strong downdraft which induces an outburst of damaging winds on or near the ground”. Downbursts, depending on the size and time scale, can be categorized as either macrobursts or microbursts (Rose 1996). Macrobursts are the larger of the two categories with outflow diameters extending beyond 4 km and damaging winds lasting for 5 to 20 minutes. Microbursts are less than 4 km in outflow diameter with damaging winds that last for 2 to 5 minutes (Wakimoto 1985; Rose 1996). Microbursts can be further categorized as dry or wet. Dry microbursts exist with little-to-no precipitation whereas wet microbursts occur alongside heavy precipitation from a storm system (Wakimoto 1985). Downbursts have been hypothesized to cause smaller areas of wind damage near the convective linear system that is comparable to damage created by some tornadoes (Wakimoto 1985). Downburst-related damages are not limited to the surface; they have also been speculated to cause aircraft delays and accidents (Wakimoto 1985; Peterson 2000).

Peterson (2000) detailed the damage caused by downbursts and tornadoes to North American forests during the 20th century. According to this study, downbursts caused the most damage in the Great Lakes region of the U.S. during the study period and resulted in both negative and positive changes in the forest biology and vegetation.

While convective linear systems have been shown to produce areas of widespread damage, supercellular systems can result in comparable damages as well. A supercell is a convective storm with a rotating updraft that can last for several hours. Supercells are one of the least common storm types in the world, however these systems can be extremely severe due to the associated large hail, lightning, damaging winds, and tornadic activity (Markowski and Richardson 2010).

Though supercells are most dangerous when tornadic, there are other features within a supercellular system that can produce hazards. Gust fronts, for example, are common ahead of supercell storms and sometimes produce damaging winds (Kuchera and Parker 2006). Areas of heavy precipitation, evaporative cooling, and ice melting generate negative buoyancy in a convective cloud, which can lead to downdrafts of high-momentum air that can cause severe high-wind gusts and wind damage at the surface (Kuchera and Parker 2006). A rear-flanking downdraft, or RFD, occurs near the rear of a supercellular storm and has been linked to tornado formation due to proximity to the classic “hook echo” feature of a supercell (Markowski 2002). RFDs may intensify with an increase in low-level cyclonic vorticity and a rapidly occluding gust front, leading to stronger wind gusts in this area of the storm (Klemp and Rotunno 1983; Markowski 2002). These features are not widely known to the general public, yet are conducive to convective high-wind events and severe wind damage.

c. Non-convective HWEs

A non-convective high-wind is defined as a high-wind that is produced without the presence of a thunderstorm, tornado, or tropical cyclone (Niziol and Paone 2000; Lacke et al. 2007; Ashley and Black 2008; Knox et al. 2011; Durkee et al. 2012). Research shows that non-convective HWEs and fatalities are most commonly associated with extratropical cyclones (Kapela et al. 1995; Niziol and Paone 2000; Ashley and Black 2008; Knox et al. 2011). Non-convective high-winds are responsible for almost as many fatalities as nontornadic convective high-winds, as well as over three times the amount of fatalities due to hurricanes and tropical systems (Fig. 1.4) (Ashley and Black 2008). This is possibly due to a lack in awareness in the severity of non-convective HWEs. Additionally, tropical systems have advanced warning systems to aid in evacuation whereas non-convective HWEs do not. Ashley and Black (2008) found that non-convective HWE-related fatalities represented 21.4% of all wind fatalities over a 26-year period. 68% of the non-convective high-wind fatalities related to vehicle or boat incidents.

The Great Lakes region has been a common area of interest in several high-wind studies (Niziol and Paone 2000; Crupi 2004; Hultquist et al. 2006; Lacke et al. 2007; Knox et al. 2011; Durkee et al. 2012). In a study by Niziol and Paone (2000), climatologies of HWEs in the Great Lakes and western New York regions were analyzed. Results indicated that all recorded high-winds occurred to the south and west of the surface low, which were later supported by other HWE studies, both in the U.S. and Europe (Nissen et al. 2010; Booth et al. 2015). Results from several studies suggest that the majority of HWEs in the Great Lakes region occur during the cool-season with a prevailing southwesterly wind direction (Niziol and Paone 2000; Lacke et al. 2007; Durkee et al. 2012). Lacke et al. (2007) found that approximately 70% of non-convective HWEs had a southwesterly directional preference during the period from 1951-1995, especially in January, March, and April. Durkee et al. (2012) analyzed a non-convective HWE that occurred on 12-13 November 2003 in the Great Lakes region. The results from this study indicated a southwesterly directional preference and ageostrophic contributions, specifically the isallobaric wind, as the primary influence on the event. Analysis of the wind data in the Niziol and Paone (2000) study also showed stronger isallobaric wind speeds with greater differences between height rises and falls.

In September 2008, Hurricane Ike transitioned into an extratropical cyclone and produced high-winds over the Ohio Valley (Stoppkotte et al. 2009). The low pressure system strengthened unexpectedly and the associated low-level jet increased rapidly.

The difference in the pressure rise/fall couplet became greater, thus strengthening the isallobaric wind. The event resulted in billions of dollars of damages, millions of power outages, closed roads due to fallen trees, and 12 fatalities. The results from this study are in agreement with other studies that conclude a positive relationship between the pressure gradient and strength of high-winds (Ashley and Black 2008; Changnon 2009; Knox et al. 2011; Pryor et al. 2014).

Kapela et al. (1995) defined the ingredients for post-cold front HWEs associated with wintertime extratropical cyclones. A tight pressure gradient, strong 500 hPa vorticity maximum, isallobaric wind gradient, subsidence, cold air advection, steep lapse rates, the presence of an upper-level jet streak, and directional wind shear all contribute to non-convective HWEs behind cold fronts. There are several other features associated with extratropical cyclones that contribute to non-convective HWEs. Such features include topography, 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).

Crupi (2004) and Hultquist et al. (2006) indicated a topographic influence on non-convective HWEs occurs within the Great Lakes region. These influences included channeling of air and coastal convergence along Lake Superior. Other studies have found topography to have little-to-no influence on the development of non-convective HWEs in regions across the globe (Pauley et al. 1996; Homar et al. 2002; Tripoli et al. 2005; Mass and Dotson 2010; Knox et al. 2011). In the United States, Pauley et al. (1996) and Mass and Dotson (2010) have determined the minor role that topography plays on non-convective HWEs in both California and the Pacific Northwest, respectively. In Europe and Africa, Homar et al. (2002) and Tripoli et al. (2005) also found very little topographic influence on the development of HWE-inducing cyclones

With the development of a strong extratropical cyclone, a “dry slot” can often be found on satellite imagery behind a cold front. A dry slot, or dry air intrusion, is an area of strong subsidence that transports air from the upper levels of the troposphere and lower levels of stratosphere toward the surface behind a cold front boundary (Kapela et al. 1995; Pauley et al. 1996; Browning 1997; Tripoli et al. 2005; Knox et al. 2011). Dry slots often result in tropopause folds, which transfer high-momentum air to near-surface heights (Kapela et al. 1995; Knox et al. 2011). In several Midwest case studies, tropopause folds have been linked to severe wind-related hazards at the surface (Goering et al. 2001; Iacopelli and Knox 2001; Schultz and Meisner 2009).

Goering et al. (2001) found a link between tropopause folds and damaging surface winds during a severe weather event in the Midwest on 8 April 1999. A year prior to this event, the well-known “Witch of November” storm occurred in Wisconsin and resulted in damaging winds gusts at the surface (Iacopelli and Knox 2001). This storm was directly linked to a tropopause fold on the backside of the associated cold front. In another case study by Schultz and Meisner (2009) a dust storm in north Texas on 24 February 2007 produced similar damaging winds at the surface. This event stemmed from a strong midlatitude cyclone and co-located with a broad dry slot behind the cold frontal boundary. Over 500 flights were cancelled at local airports, thousands of Texas residents lost power, strong winds caused damage to structures, and two high school students were injured due to high-winds.

Lastly, one distinct feature has been noted as influential in the generation of non-convective HWEs in the United Kingdom. The “sting jet” is a phenomenon involving banded structures within a hooked cloud tip that can lead to damaging wind gusts at the surface (Knox et al. 2011). This feature is often associated with a hook of the cold conveyor belt around the center of low pressure. Slantwise convective circulations form with the intrusion of dry-air at the tip of the cloud head and transfer high-momentum winds to the surface. Sting-jet winds have been observed in many areas of Europe; however, not much has been discussed with regard to sting-jets in the U.S. (Browning 2004; Clark et al. 2005; Baker et al. 2009; Parton et al. 2009).

1.3 Summary

HWEs are one of the most severe types of weather that produce many fatalities and thousands of dollars in damage per year. These events can occur year-round and in every region of the U.S. With documented negative (positive) trends in the frequency (intensity) of cyclonic activity across the northern hemisphere, it is plausible to consider that HWEs are likely to exhibit similar patterns. Convective HWEs tend to occur in the summer and transitional months, are often associated with extratropical cyclones, and collectively produce more fatalities and damage than non-convective high-winds; however, this is mostly due to tornado-related high-winds.

Non-convective HWEs are prevalent throughout the cool-season in the U.S. and have hazards comparable to those generated by convective HWEs. Although many studies have speculated the influences of topography and meteorological phenomena on the severity of non-convective HWEs occurring in both the U.S. and Europe, no study has analyzed the spatial and temporal changes of these events across the eastern U.S., specifically. Climatological studies have been conducted for regions (e.g. Great Lakes), yet not much is known about non-convective HWEs for the eastern U.S. as a comprehensive area.

Furthermore, no studies have compared both convective and non-convective HWEs spatially and temporally. A comprehensive analysis of these events is necessary to build upon the results of other regional studies. This thesis will construct a high-wind climatology across the eastern U.S. during 1973-2015 in order to determine trends for HWEs and how they differ in both convective and non-convective events.

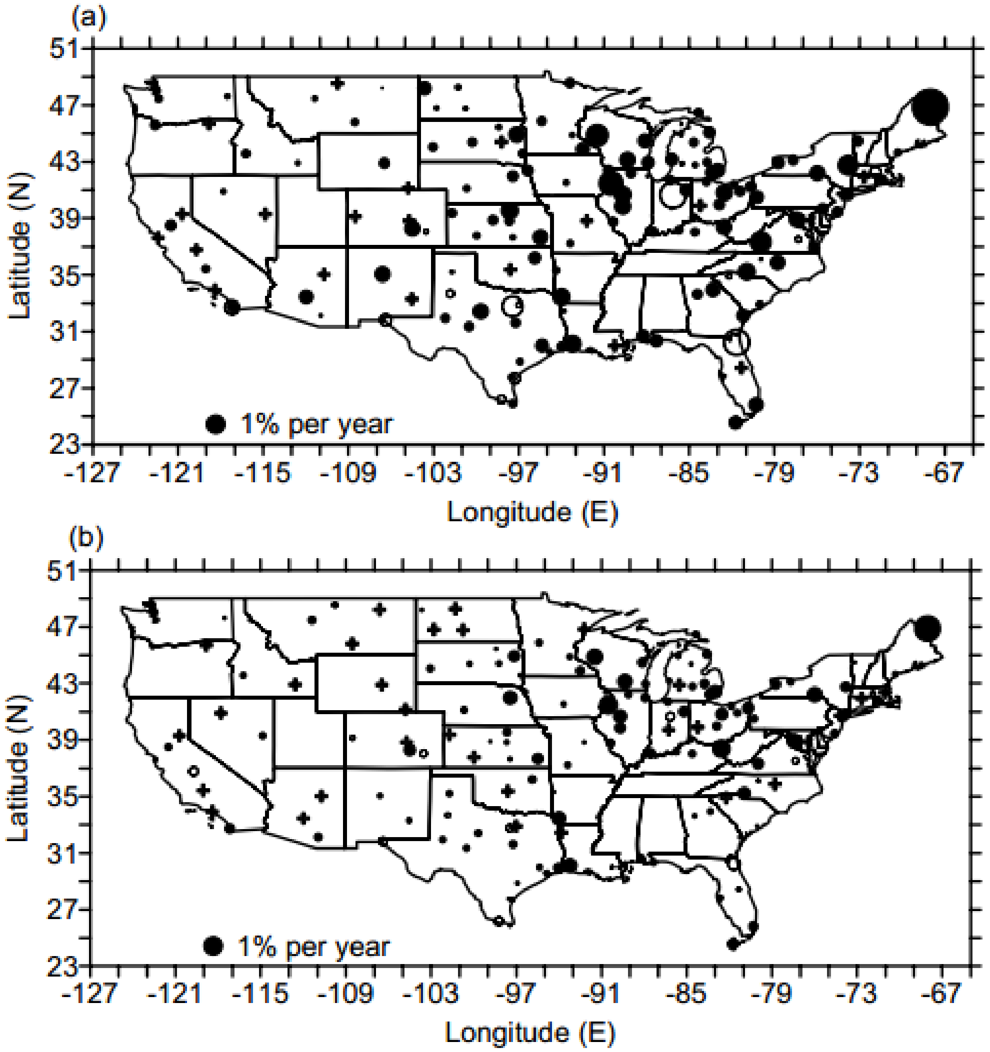


Fig 1.1. Linear trends in the annual 50th and 90th percentile wind speeds at each site as determined using the robust trend analysis methodology. If an open circle denotes the site, the trend is significant and positive (indicating increased values through time). If a filled circle denotes the site, the trend is significant and negative. If the station is denoted by a + then the trend is not significant. The trends depicted are computed using wind speed percentiles computed at the annual time scale from 1973-2005. Source: Pryor et al. (2007).

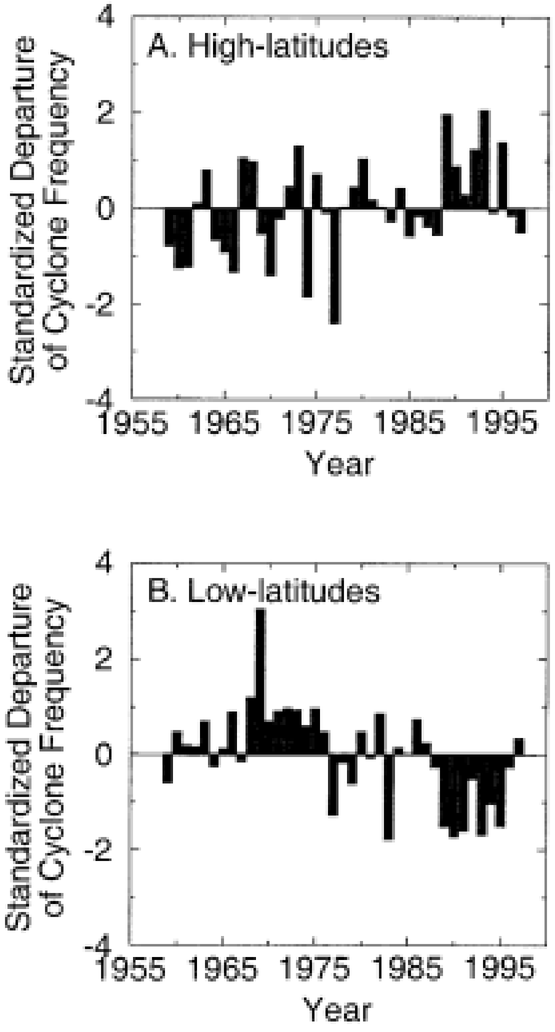


Fig 1.2 Standardized departures of winter (Nov–Mar) cyclone counts in the Northern Hemisphere, 1959–97, for (a) high latitudes (608–908N), and (b) midlatitudes (308–608N). Source: McCabe et al. (2001).

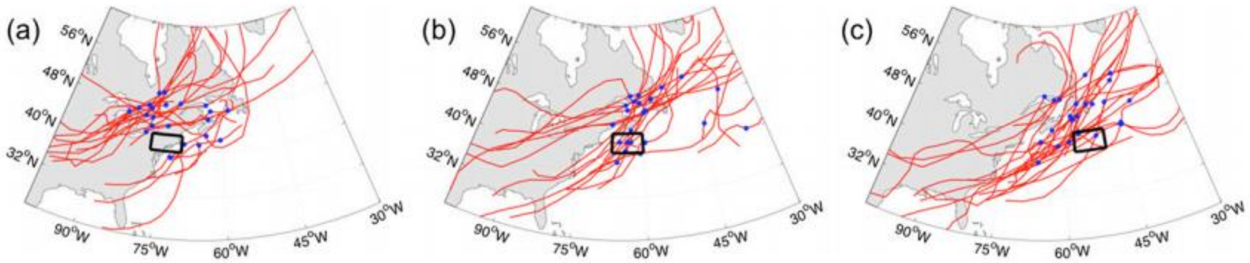


Fig 1.3. Cyclone track association for area average of 925-hPa reanalysis winds in the black rectangles. Latitude range for all boxes: 408–438N. Longitude ranges: (a) 77.58–708W, (b) 67.58–608W, and (c) 57.58–508W. Red lines indicate the cyclone tracks, and blue dots mark the location of the cyclone at the time of association with a high-wind event for the area-averaged wind in the box. Source: Booth et al. (2015).

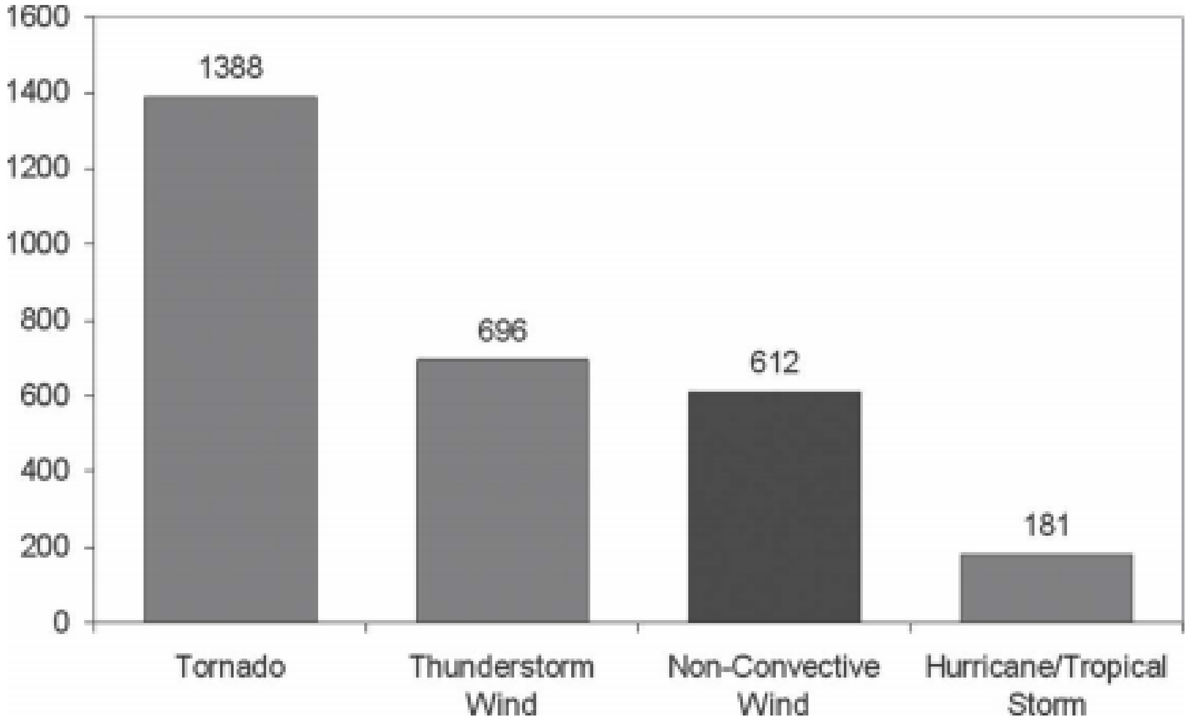


Fig 1.4. Fatalities due to various wind-related hazards, 1980–2005. Tropical system fatalities only include those deaths due to wind. Source: Ashley and Black (2008).

CHAPTER 2

A CLIMATOLOGY OF CONVECTIVE AND NON-CONVECTIVE HIGH-WIND EVENTS ACROSS THE EASTERN UNITED STATES DURING 1973-2015

2.1 Introduction

Surface wind patterns are directly influenced by synoptic-scale weather systems, especially extratropical cyclones (ETCs) (Klink 1999; McCabe et al. 2001; Klink 2002; Pryor et al. 2007; Ashley and Black 2008; Changnon 2009; Knox et al. 2011; Pryor et al. 2014). McCabe et al. (2001) indicated a decrease in the frequency of ETCs across the U.S. during 1959 to 1997; however, those cyclonic systems exhibited stronger magnitudes throughout the study period. Surface winds are influenced by cyclonic behavior; therefore, high-winds may also be affected by these changes.

High-wind events (HWEs) have resulted in approximately $300 million in property losses during the last six decades and 3,000 fatalities from 1980-2005 (Ashley and Black 2008; Changnon 2009). High-winds 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 and non-convective HWEs 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).

While convective and non-convective HWEs have been studied separately and on a regional scale, there is currently no climatological comparison of these HWE types for the eastern United States. The purpose of this study is to 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 convective and non-convective HWEs.

2.2 Background

a. High-winds

High-winds are classified by two categories: sustained high-winds and high-wind gusts, as defined by the National Weather Service (NWS). The NWS classifies high-winds as sustained when wind speeds are at least 18 m s^{-1} for an hour or longer. High-winds are classified as gusts when wind speeds are greater than 26 m s^{-1} for any length of time (Table 2.1). HWEs occur during every season and in every region of the U.S., yet much is still unknown about the long-term trends and hazards.

Numerous hazards are associated with all types of HWEs, such as property damage, injuries, and fatalities (Ashley and Black 2008; Changnon 2009; Changnon 2011; Knox et al. 2011). HWEs contributed to approximately $354 million in annual property losses during 1956-2006 (Changnon 2009). These losses were more prevalent in the northeast, central, and western regions in the U.S., specifically during the winter months of November-January.

HWEs are most common in the winter and spring season when ETC activity is most frequent (Lacke et al. 2007; Changnon 2009; Booth et al. 2015). Synoptic forcing directly influences ETC storm-track patterns and placement of frontal boundaries (Changnon 2011; Pryor et al. 2014.) Previous research has shown an increase in wind speeds and gusts with strengthening frontal boundaries that move from west to east (Pryor et al. 2014). ETCs are typically associated with upper-level troughs and have a northwesterly or southwesterly projected track. As a result, HWEs usually have westerly, southwesterly, and northwesterly wind directions (Niziol and Paone 2000; Martin and Konrad 2006; Lacke et al. 2007; Booth et al. 2015).

b. Convective HWEs

HWEs can also be categorized by weather type: convective, meaning a thunderstorm is present, or non-convective, meaning a thunderstorm is not present. Convective and non-convective HWEs produce similar hazards at the surface, but occur during different atmospheric conditions. Convective HWEs 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, convective HWEs result in an average of 84 fatalities in the U.S. (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).

Squall lines are a common type of organized linear convective system that frequently produces widespread areas of damaging straight-line winds. Other features, namely bow echoes, derechos, and downbursts, are embedded within larger convective systems and typically result in damaging straight-line winds, some comparable to the damage caused by a tornado (Fujita and Wakimoto 1981; Wakimoto 1985; John and Hirt 1987; Coniglio et al. 2004). Supercells are most dangerous when a tornado is present; however, gust fronts and rear-flanking downdrafts (RFDs) are often associated with supercell formation and linked to damaging winds.

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 in the summer months, 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 also tend to increase in the summer (Schoen and Ashley 2011).

c. Non-convective HWEs

Non-convective high-winds occur without the presence of a thunderstorm or tornado (Kapela et al. 1995; Niziol and Paone 2000; Lacke et al. 2007; Ashley and Black 2008; 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).

Non-convective high-winds are most commonly associated with 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).

Topography affects wind flow in areas such as the Great Lakes and mountainous regions where air is channeled along the coasts and mountain ranges, respectively (Crupi 2004; Hultquist et al. 2006; Martin and Konrad 2006). Dry slots occur when a strong ETC creates an area of subsidence behind a cold front boundary and transports upper-tropospheric/lower-stratospheric air to the surface, sometimes leading to a tropopause fold (Kapela et al. 1995; Knox et al. 2011). Lastly, sting-jets are not widely studied in the U.S., but several European studies have associated this feature with the transfer of high-momentum air from the tip of the cloud head in an ETC.

In several studies analyzing non-convective winds in the Great Lakes and northeastern United States regions, the majority of non-convective HWEs indicated a southwesterly prevailing wind direction (Niziol and Paone 2000; Lacke et al. 2007, Durkee et al. 2012). Additionally, non-convective HWEs occur most frequently during winter and transitional seasons when ETC frequency is greatest (Lacke et al. 2007; Changnon 2009; Booth et al. 2015).

Numerous studies have analyzed convective and non-convective-related HWEs across various regions of the U.S., yet none have analyzed on a scale as large as the continental U.S. One study does span the extent of the eastern U.S. and analyzes high-wind gusts in association with cold-season cyclones and frontal intensity (Pryor et al. 2014). Still, a comprehensive analysis of high-wind events on a spatial and temporal scale does not exist for the eastern U.S. during a multi-decadal study period.

The purpose of this study is to provide a thorough climatological analysis of sustained and gust HWEs in convective and non-convective environments during 1973-2015. This 43-year period was chosen due to the lack of high-wind data in the NCEI-

ISD database prior to 1973 (Lacke et al. 2007). The western U.S. and majority of the Rocky Mountain region was excluded from the study due to potential topographical biases as mentioned in other studies (Cairns and Corey 2003; Zhong et al. 2008; Changnon 2011; Pryor et al. 2014). Results from this study offer a more broad understanding of the different types of HWEs and their characteristics, both spatially and temporally.

2.3 Data & Methodology

The 43-year period between 1973 and 2015 was chosen based on the quality and completeness of high-wind observations via the National Centers for Environmental Information Data Center Integrated Surface database (NCEI-ISD) [available at: https://www.ncdc.noaa.gov/isd] (Fig. 2.1). Lacke et al. (2007) mentioned the presence of missing data in the NCEI-ISD database prior to 1972; thus, stations with numerous missing records and observations prior to 1973 were excluded from this study. NCEI-ISD sustained wind observations are recorded as two-minute averages per the Federal Meteorology Handbook [available at: www.ofcm.gov/publications/fmh/FMH1/FMH1.pdf]; however, Lacke et al. (2007) discussed the challenges of locating hourly-average wind observations that meet the NWS criteria of a sustained high-wind. Additionally, the NWS criteria is not consistent and can vary between local offices; therefore, this study follows guidelines for high-wind observations set forth by Lacke et al. (2007), Kurtz (2010), and Gilliland et al. (2018) (Fig. 2.2).

Automated surface wind observations from 391 first-order weather stations were gathered from the NCEI-ISD database. Observations occurring west of the Rockies were excluded due to high-wind variability from topographical influence. Additionally, extratropical cyclogenesis most frequently occurs on the leeward side of the Rockies, specifically the Colorado region (Whittaker and Horn 1982). After formation, ETCs propagate eastward via synoptic forcing and strengthen as they reach larger latitudes.

High-wind observations in the dataset were quality-controlled by using online resources such as the NCEI Climate Database Modernization Program (CDMP), Quality Controlled Local Climatological Data (QCLCD) and Unedited Local Climatological Data (ULCD). DeGaetano (1997) analyzed 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. For the first-order weather stations used in this study, high-wind records that had questionable or invalid observations were removed from the dataset.

Lastly, 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. In the 1960s, rooftop anemometers were repositioned to approximately 6.1 meters above the ground (Klink 1999; Lacke et al. 2007; Pryor et al. 2007). The World Meteorological Organization (WMO) standardized anemometer heights to 10 meters above the ground in the 1980s, thus changing anemometer heights once more. Due to this potential discrepancy in the data, the wind profile power law was used to adjust all wind observations to the 10 meter height:

$$V(z) = V(z_{ref}) \times \left(\frac{z}{z_{ref}}\right)^{\alpha} \quad , \qquad \textbf{Eq. 2.1}$$

where V(z) is equal to the observed wind velocity, z_{ref} is equal to the reference height, and z is equal to the new height, assuming neutral stability ($\alpha = 1/7$) (Klink 1999; Pryor et al. 2007).

The wind observation dataset was 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 s^{-1} for an hour or longer and *gust* when wind speeds are greater than 26 m s^{-1} for any length of time (Table 2.1). The date, time, wind speed, and wind direction for recorded HWEs at each station were included in the dataset. An automated weather code was assigned to each HWE stating what current weather conditions were present during each event. High-wind data were further classified by using the provided weather codes to disseminate convective versus non-convective HWEs, following Lacke et al. (2007). Specifically, weather codes associated with lightning, thunderstorms, or tornadoes were classified as convective HWEs. All other weather codes were classified as non-convective HWEs. Each HWE category was averaged regionally, annually, seasonally, and by station. To avoid discrepancies in averaging on a 360° scale, wind directions were converted to u/v vector form, averaged, and converted back into degrees.

The dataset was then spatially considered by climate regions according to the NCEI climate classification scheme (based on temperature similarities) (Fig. 2.3). These regions include the Northeast (Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, Delaware, Pennsylvania, and Maryland), the Southeast (Virginia, North Carolina, South Carolina, Georgia, Alabama and Florida), the Ohio Valley (West Virginia, Ohio, Kentucky, Tennessee, Indiana, Illinois, and Missouri), the South (Mississippi, Arkansas, Louisiana, Kansas, Oklahoma, and Texas), a portion of the Northern Rockies and Plains (North Dakota, South Dakota, Nebraska, Montana, and Wyoming), and a portion of the Southwest (Colorado and New Mexico).

2.4 Results

a. High-wind Days versus High-wind Events

A sustained or gust high-wind, as defined by the NWS, that is recorded at a first-order station is known as a HWE. A HWD is a day where one or more HWEs occur. This includes observations recorded on the same day at neighboring weather stations. There were 59,123 HWE observations recorded during the study period. During 1973-2015, a total of 8,078 high-wind days (HWD) were recorded. HWDs with 50 or more HWE observations accounted for less than 2% of the total dataset. Though not common occurrences, these widespread HWDs included devastating weather systems such as the Great Storm of 1975 and the 1993 Storm of the Century.

Local Moran's I analysis indicated a hot spot of HWDs in the High Plains (Fig. 2.4a). The analysis also highlighted a low outlier, or station with much fewer HWDs compared to neighboring stations, in southwestern Montana. This outlier accounted for less than 0.3% of the total HWD population. Although some stations were located in regions that were more mountainous and at higher elevations, it did not seem to bias the overall HWD dataset. Meanwhile, Local Moran's I analysis indicated more potential outliers with regard to HWE spatial autocorrelation. Two low outliers and one high outlier (station with more frequent HWEs compared to neighboring stations) were highlighted inside and near the base of the Rocky Mountains (Fig. 2.4b). These outliers accounted for only 0.7% of the HWE dataset.

1. *Observational Analysis: HWDs versus HWEs*

The majority of HWDs occurred across the High Plains, with localized areas of frequent HWDs in the Ohio Valley and along the Northeast coast, in agreement with the results of Gilliland et al. (2018) (Fig. 2.5). These results are also in alignment with the results of Changnon (2009), which show the central and northeastern regions of the U.S. as having the greatest frequency of damaging wind events during 1952-2006. Proportional symbols were assigned to HWD frequencies at each station. Stations in the High Plains, Midwest, and along the Northeast coast experienced the highest frequency of HWDs (Fig. 2.6). Although the proportional symbol map portrays HWD distribution more appropriately compared to Local Moran's I, the High Plains hotspot is visible in both maps.

2. *Regional Analysis: HWDs versus HWEs*

In this study, statistical methods were used to see if any naturally occurring regions could be determined within the U.S. with respect to wind direction patterns. These methods include the Grouping Analysis tool in ArcMap, ANOVA test, and two-sample difference of means test. The Grouping Analysis tool yielded three distinct regions – continental (stations in the Midwest and northeast), Gulf Coast (stations along the coastlines and extending partially into the southern states), and Northeast Coast (Fig.

2.7). Two of the three groups included only coastal stations, indicating a coastal bias; however, excluding the coastal regions did not produce any additional inland regions.

The regions were analyzed using the ANOVA and two-sample t-tests. The ANOVA test verified that the stations in each group were different ($p = 0.000$) with regard to wind direction. A two-sample t-test was performed for every combination of groupings for both sustained and gust wind direction. The results showed statistically similar high-wind direction characteristics for high-wind gusts in groups 1 and 2 ($p = 0.784$), or the coastal groups (Table 2.2). The other groups were different ($p < 0.05$) from one another with regard to both sustained and gust high-wind directions.

Due to the large, homogenous regions produced by grouping analyses, this study also utilized existing climate regions from the National Centers for Environmental Information (NCEI). Stations were grouped by these regions and analyzed by high-wind direction.

b. Sustained versus Gust

Sustained HWDs accounted for approximately 44% of the total dataset and gust HWDs for 56%. Sustained HWDs trended negatively during the 43-year period; however, a weak linear correlation was indicated via annual variability in both datasets (Fig. 2.8). Gust HWDs trended positively during the 43-year period, but also displayed a weak linear correlation. Likewise, Gilliland et al. (2018) found a significant decrease of -0.579 sustained HWDs per year ($p = 0.04$) and increase of 0.943 gust HWD per year ($p = 0.007$).

Average wind direction and speed was plotted per year for sustained and gust HWEs. Sustained HWEs preferred a southwesterly direction that was variable during the study period, but did not change overall (Fig. 2.9a). Wind speeds, however, declined with a moderate linear correlation. Gust HWEs recorded an average southwesterly directional preference as well, but directions trended more northerly with time (Fig. 2.9b). Gilliland et al. (2018) also indicated a southwesterly preference for both sustained and gust high-winds. Average wind speeds increased, but with a weak linear correlation. An increase in speeds can be noted between the late 1980s and early 2000s.

1. *Observational Analysis: Sustained versus Gust*

Proportional symbols were assigned to HWD frequencies at each station in the study area. Sustained HWDs occurred most frequently in the High Plains, similarly to the overall HWD distribution. HWDs were less common in the southeastern United States (Fig. 2.10a). Gust HWDs were more dispersed compared to sustained, although a similar lack of frequency in the southeast can also be noted. (Fig. 2.10b).

Sustained and gust HWEs were plotted by station with regard to wind direction and wind speed. The mean wind direction for sustained and gust HWEs indicated northwesterly to southwesterly motion from west to east in the northern half of the study area. Winds were more variable in the south and southeast, as well as along coastlines. Areas along the coast and in the southeast experienced greater mean sustained wind speeds during the 43-year period (Fig. 2.11a).

Gust HWEs produced similar results. On average, gust HWEs with greater mean wind speeds occurred through the Midwest, as well as the south, southeast, and along the coastlines (Fig. 2.11b). The spatial shift in southwesterly-to-northwesterly wind direction from west to east could be attributed to storm track patterns following synoptic-level forcing. Additionally, variability along the coastlines may be influenced by tropical and post-tropical cyclones. This influence, if present, would be minimal on the high-wind dataset used in this study. Post-tropical cyclones accounted for less than 1% of all HWE observations during 1951-2009 (Gilliland 2011).

2. *Regional: Sustained versus Gust*

For sustained HWEs, five of the seven climate regions most frequently recorded southwesterly high-wind directions (Fig. 2.12). These regions include West North Central, East North Central, Northeast, Central, and Southwest. Both East North Central and Northeast regions recorded frequent northwesterly high-wind directions. The Southwest and South regions had a prevalent northerly high-wind direction, and the Southeast region observed a variety of preferred high-wind directions.

Gust HWEs resulted in similar patterns. The West North Central, Central, and Northeast regions commonly experienced southwesterly winds (Fig 2.13). The East North Central region recorded both northwesterly and southwesterly high-wind directions more frequently. The Southwest and South regions recorded northerly mean high-wind directions. The Southeast region displayed variable high-wind directions for this category as well.

3. *Seasonal: Sustained versus Gust*

Sustained and gust HWDs were analyzed and plotted by meteorological season to determine whether seasonality affects frequency. NCEI defines meteorological seasons as follows: spring – March, April, May (MAM); summer – June, July, August (JJA); fall – September, October, November (SON); and winter – December, January, February (DJF).

Several studies have found that seasonality affects fatality rates and property damage totals (Ashley and Black 2008; Changnon 2009; Changnon 2011; Schoen and Ashley 2011). Sustained HWDs varied in frequency across each region (Fig. 2.14). In the East North Central, Southwest, Central, and South regions, sustained HWDs occurred mostly in the spring. In the West North Central and Northeast regions, the majority of sustained HWDs occurred in the winter months, supporting the findings of Gilliland et al. (2018). The Southeast was the only region to experience numerous sustained HWDs in the fall. Overall, sustained HWDs most frequently occurred in the West North Central region and less frequently in the Southeast region.

Similar to Gilliland et al. (2018), gust HWDs were most prevalent during the spring and summer months for the East North Central, Southwest, Central, South, and Southeast regions (Fig. 2.15). In the West North Central and Northeast regions, there was also a noticeable winter tendency in gust HWD seasonal preferences, in addition to spring and summer. Gust HWDs were most concentrated in the West North Central region and sparser in the East North Central region.

Average wind direction and speed were plotted per Julian Day to analyze a potential seasonal influence. Sustained HWEs were more variable during the summer and fall seasons where a shift in direction from southwesterly to easterly winds was observed (Fig. 2.16a). During this same period, wind speeds increased and reached a peak of 26 m s^{-1} near day 230. Gust HWEs displayed the same southwesterly-to-easterly directional shift in average wind direction during the summer and fall seasons (Fig. 2.16b. Average wind speeds also peaked to approximately 32 m s^{-1} during this period.

c. Convective Sustained versus Gust

A total of 2,428 convective HWDs existed in the dataset. Convective HWDs accounted for 18% of the total. Of those, 11% were convective sustained HWDs and 89% were convective gust HWDs. Convective sustained HWDs trended negatively during the 43-year period and displayed a weak linear correlation (Fig. 2.17). Convective gust HWDs displayed a moderately positive linear and a greater annual variation than sustained.

Convective sustained mean high-wind directions displayed much variability during the study period with alternating southerly and northerly directional preferences, but remaining in the southwest quadrant (Fig. 2.18a). 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. Convective gust mean high-wind directions remained within the southwest quadrant for the study period (Fig. 2.18b). Mean wind speeds decreased with time with a weak linear correlation.

1. *Observational Analysis: Convective Sustained versus Gust*

Convective sustained HWDs were few in number, with only 271 observations in the dataset. The majority of these events occurred in the High Plains (Fig. 2.19a). Similar to total gust HWD observations, convective gust HWDs were more dispersed across the U.S. with the greatest frequency occurring in the High Plains and Ohio Valley (Fig. 2.19b). Edwards et al. (2018) found similar results in a study comparing measured versus estimated convective gust reports in the U.S. In this study, the most concentrated areas of mean annual convective gusts included the southern High Plains and Ohio Valley.

Convective sustained high-wind speeds did not indicate any pattern, as the greatest values were scattered across the study area (Fig. 2.20a). Mean convective gust HWD directions and speeds displayed similar directional patterns as the other categories. The mid-range of mean wind speeds were variable throughout the study area and the greatest range of mean wind speeds occurred along the east coast, with few greater wind speed values in isolated areas (Fig. 2.20b).

2. *Regional: Convective Sustained versus Gust*

Due to fewer observations in the convective sustained HWE category, any distinguishable spatial and velocity patterns were not evident. Nevertheless, more than half of the regions displayed southwesterly directions as the most prevalent (Fig. 2.21). Further, while convective gust HWE observations were more numerous than sustained convective, there were still fewer observations than non-convective gust HWEs. Regardless, similar high-wind patterns are evident in the regional wind roses.

Southwesterly directions were not as prominent for convective gust HWEs. Specifically, five of the seven regions experienced north or northwesterly high-wind directions more frequently (Fig. 2.22). Both the East North Central and Southeast regions were divided between northwesterly and southwesterly directions, while the Central region recorded southwesterly directions more frequently.

3. *Seasonal: Convective Sustained versus Gust*

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). As expected, the majority of convective sustained HWDs occurred during the spring and summer months in every region (2.23). This is typically when convective systems are most prevalent, due to an increase in daytime heating and instability. The West North Central region recorded the greatest number of convective sustained HWDs, while the Northeast region recorded the least. Convective gust HWDs displayed similar results and were most frequent in the summer months, followed by spring (Fig. 2.24). The South recorded the greatest number of convective gust HWDs, while the East North Central region recorded the least.

Average convective sustained HWE direction and speed were plotted per Julian Day and displayed much variability throughout the year. Mean convective sustained wind directions fluctuated seasonally, with an easterly shift observed in late winter/early spring, as well as the summer season (Fig. 2.25a). Mean convective sustained wind speeds displayed a peak in the warm season. Average convective gust wind speeds were variable with a shift from southwesterly to easterly during late summer, fall, and early winter (Fig. 2.25b). Additionally, mean convective sustained wind speeds increased during this period.

d. Non-convective Sustained versus Gust

A total of 10,719 non-convective HWDs existed in the dataset, which accounted for 82% of the total HWDs. 47% of the non-convective HWDs were sustained and 53% were gust. Non-convective sustained HWDs trended negatively during the 43-year period, but with a weak linear correlation (Fig. 2.26). Non-convective gust HWDs trended positively, but also with a weak linear correlation.

Non-convective sustained high-wind directions displayed variability but remained in the southwest quadrant during the study period (Fig. 2.27a). Mean wind speeds decreased with a weak linear correlation. Non-convective gust high-wind directions remained in the southwest quadrant as well (Fig. 2.27b), with the exception of a northerly mean wind direction in 2005. Mean wind speeds displayed an oscillating pattern similar to overall gust HWEs.

1. Observational Analysis: Non-convective Sustained versus Gust

Non-convective sustained HWDs occurred more frequently in the High Plains and coastal areas (Fig 2.28a). There were more widespread non-convective gust HWD observations than sustained. This is reflected in the proportional symbol map in Fig. 2.28b, with events that occurred more frequently throughout a large portion of the study area.

Non-convective sustained HWEs accounted for approximately 99% of the total sustained HWE observations. Therefore, the wind direction and speed patterns for non-convective sustained HWEs nearly matched the wind direction and speed values of total sustained HWEs (Fig. 2.29a). Mean wind speeds for non-convective gust HWEs were mostly between 26-29 ms^{-1} with the majority of greater mean wind speeds having occurred in the southeast (Fig. 2.29b).

2. *Regional: Non-convective Sustained versus Gust*

Non-convective sustained HWEs accounted for the majority of observations in the sustained HWE dataset. 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 (Fig. 2.30). Once again, the Southeast region experienced greater directional variability.

Non-convective gust HWEs also accounted for 85% of observations in the gust HWE dataset. 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 (Fig. 2.31). 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.

3. Seasonal: Non-convective Sustained versus Gust

The results from this thesis are 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; Knox et al. 2011; Durkee et al. 2012; Booth et al. 2015). Non-convective sustained HWDs occurred most frequently in the spring and winter months in every region, with the exception of the Southeast (Fig. 2.32). A distinct minimum existed in the summer months for every region. The West North Central region recorded the greatest number of non-convective sustained HWDs and the Southeast region recorded the least.

Non-convective gust HWDs displayed slightly different results. For the West North Central and Northeast regions, non-convective gust HWDs occurred most frequently in the winter months (Fig. 2.33). In the East North Central, Central, and Southeast regions, a summertime maximum was observed. The Southwest and South regions displayed a springtime maximum. The West North Central region recorded the greatest number of non-convective gust HWDs and the East North Central region recorded the least.

Average non-convective sustained and gust HWE direction and speed were plotted per Julian Day. Non-convective sustained HWEs displayed southwesterly and northwesterly preferences throughout the year with a directional shift to east/northeasterly in summer and fall (Fig. 2.34a). Mean non-convective sustained wind speeds increased to approximately 27 m s^{-1} near day 230. Non-convective gust HWEs displayed similar mean wind directions and speed with a shift to east/northeasterly in summer and fall, as well (Fig. 2.34b). Peak non-convective gust mean wind speeds were approximately 32 m s^{-1} near day 300.

2.5 Conclusions

Damaging high-winds occur in every region and during every season in the U.S. In the last few decades, interest has grown for high-wind research and numerous studies analyzed regional high-wind characteristics. 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 an extensive analysis of sustained, gust, convective, and non-convective HWEs across the entire eastern U.S. during the last 43 years.

NCEI-ISD wind observation data was used to sort and analyze high-winds for 391 first-order stations in the eastern U.S. from 1973-2015. There were 59,123 HWEs recorded during this period; 49% (28,793) were sustained HWEs and 51% (30,331) were gust. Convective HWEs accounted for approximately 1% (284) of all sustained events and 99% (28,509) were non-convective. 15% (4,496) of all gust events were convective and 85% (25,835) were non-convective.

Sustained HWD frequencies indicated an oscillating pattern during the 43-year period, but with an overall weak linear decrease. Coincidently, sustained high-wind speeds also decreased with a moderately significant linear fit. Gust HWDs, on the other hand, tended to increase over time while also indicating an oscillating pattern. Gust high-wind speeds increased with time, but in an oscillating, non-linear pattern. Peak speeds occurred during a 20-year span from the late 1980s to the early 2000s. Both convective and non-convective sustained HWDs decreased during the study period while convective and non-convective gust HWDs increased. It is plausible that high-wind frequency and intensity may be increasing with time. Further research is needed to quantify the magnitude of a HWE and whether or not these magnitudes have strengthened over the last few decades.

HWDs occurred most frequently in the High Plains, specifically the West North Central region. The lowest concentrations of HWDs were in the East North Central and Southeast regions. Average high-wind directions indicated a southwesterly and northwesterly directional preference for almost every high-wind category and region, which is in alignment with other high-wind studies. Annually, high-wind directions displayed an oscillating pattern every few years with shifts from southwesterly to northwesterly. Convective sustained HWEs recorded northerly mean wind directions in 1983 and 2009 and southerly mean wind directions in 1985 and 1995. Non-convective gusts also recorded an annual average northerly direction in 2005; otherwise, average directions remained in the southwest and northwest quadrants.

Sustained high-winds were most common during the winter and transitional seasons while gust high-winds tended to occur in the spring and summer seasons. Convective high-winds – both sustained and gust – were mostly recorded during summer. Inversely, 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 from this study support the hypothesis that high-winds are directly influenced by synoptic and meso-scale atmospheric patterns.

When analyzed by Julian Day, the majority of HWEs displayed a shift in mean wind direction from westerly to east/northeasterly in the summer and fall seasons. This could be caused by PTC influence, as hurricane season stretches from May to June. Other explanations could include high-winds due to convective storm outflow (RFDs, downbursts, etc.), especially during the warm season. 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.

In conclusion, this thesis analyzed spatial and temporal characteristics of sustained, gust, convective, and non-convective HWEs during 1973-2015. Results from this study mirror the findings of Gilliland et al. (2018). 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.

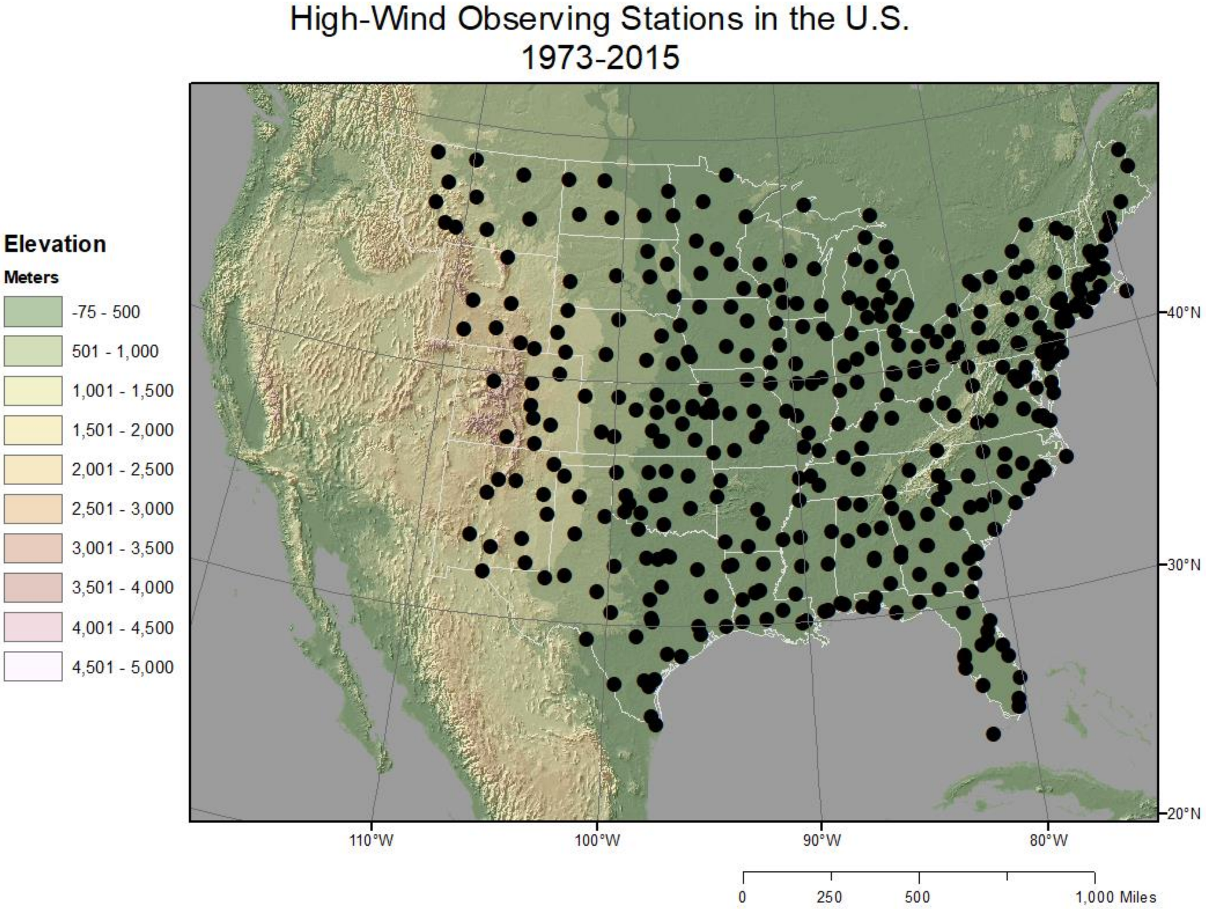


Fig 2.1. 391 first-order weather stations in the eastern U.S with plotted elevation.

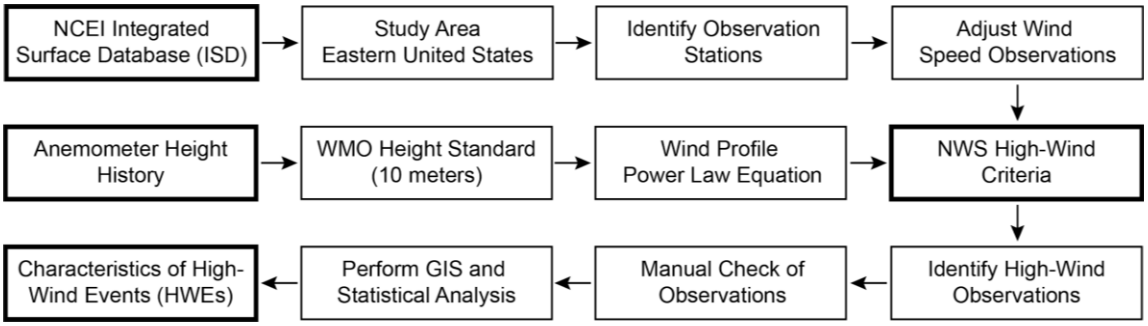


Fig 2.2. A flow diagram showing the data and methods used to characterize sustained and gust HWEs for the eastern United States. Source: Gilliland et al. (2018).

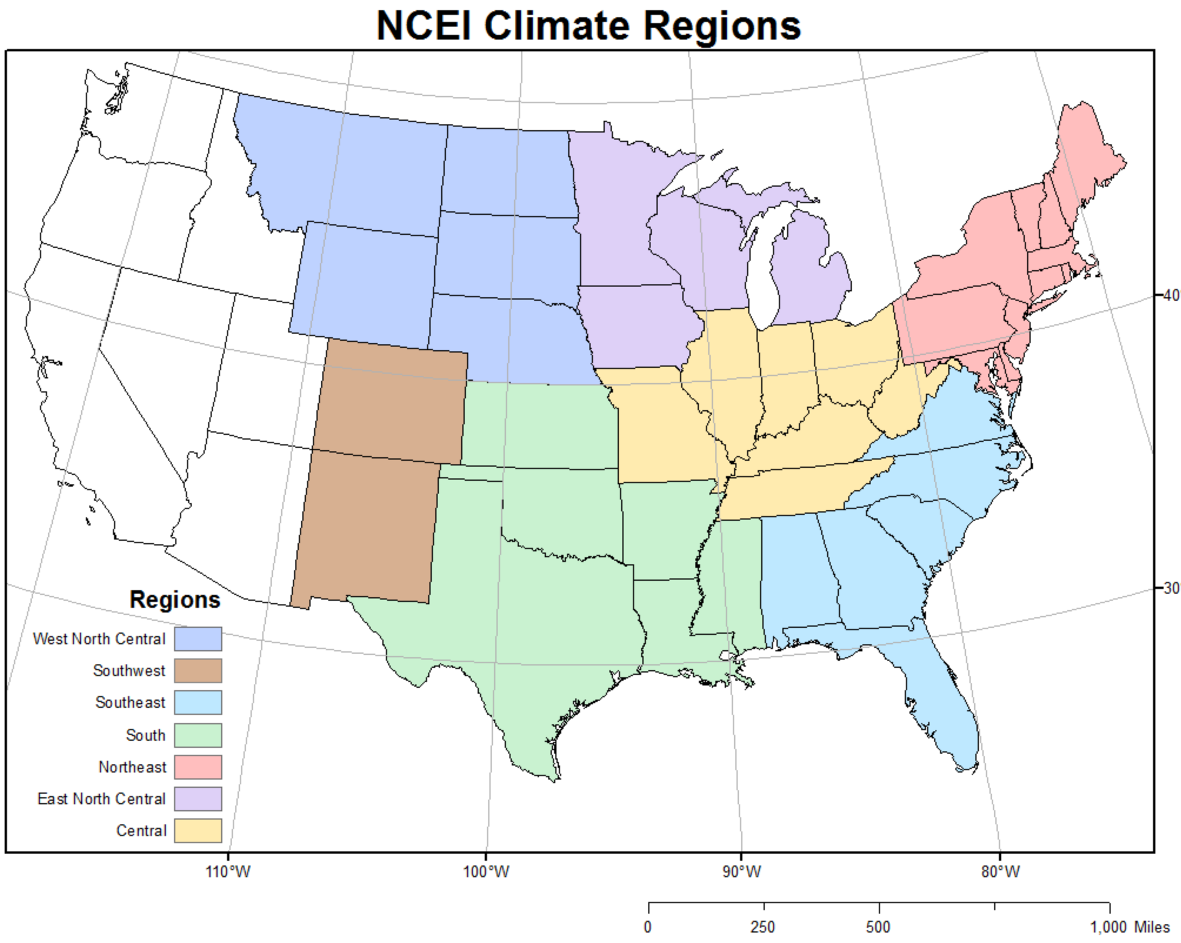


Fig. 2.3. United States Climate Regions as defined by NCEI.

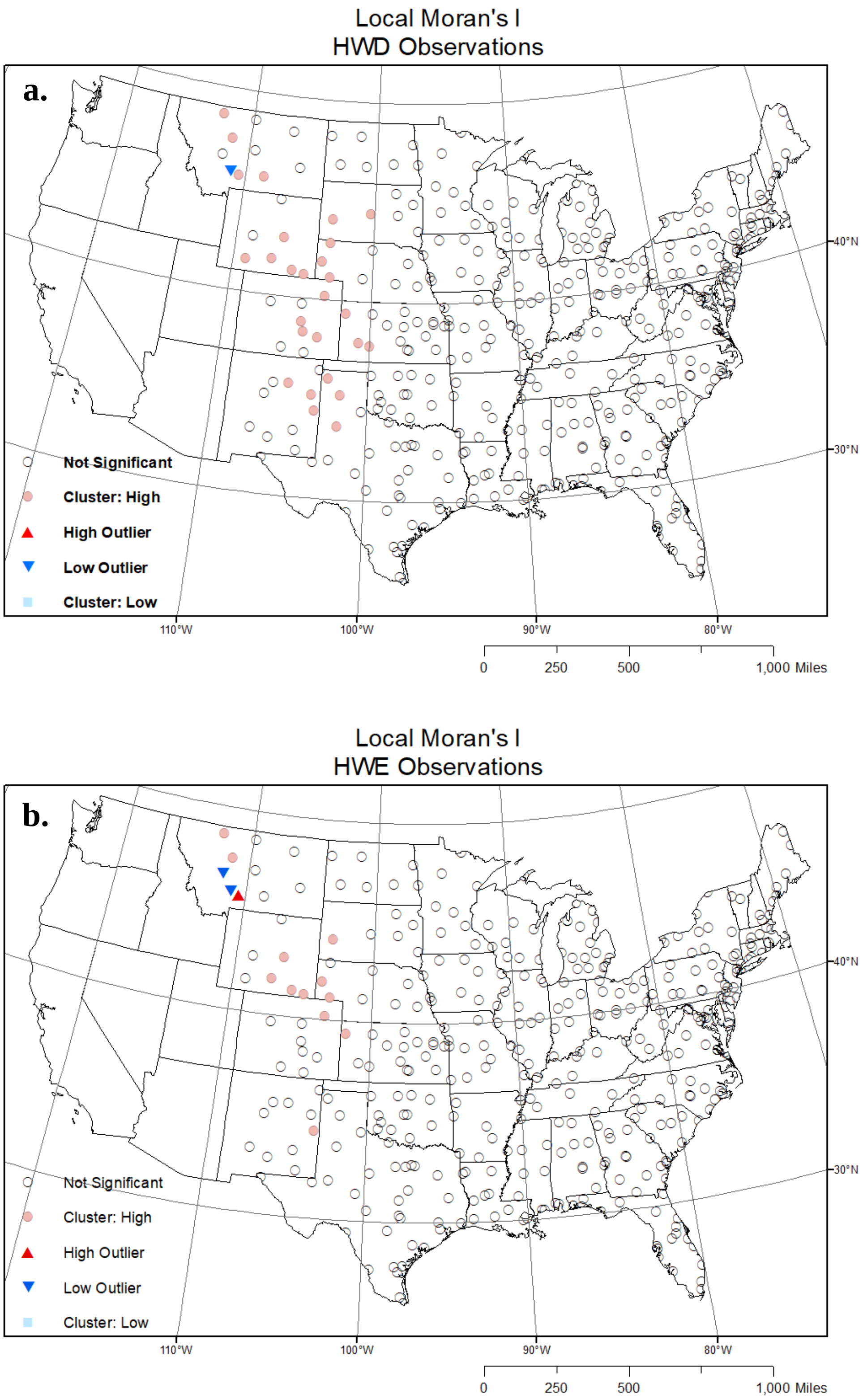


Fig. 2.4. Local Moran's I Analysis for (a.) HWDs and (b.) HWEs.

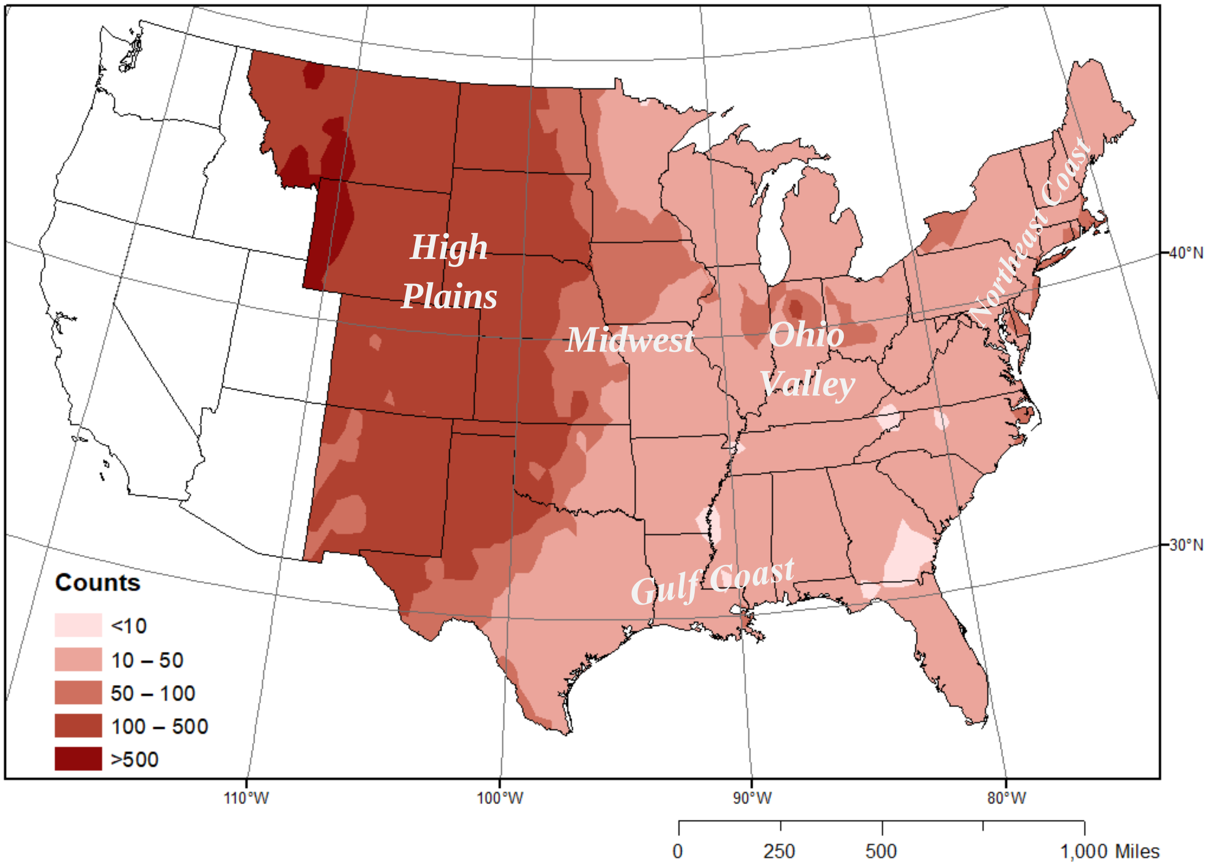


Fig. 2.5. Interpolation of total HWDs in the eastern United States during 1973-2015 using the Kriging method.

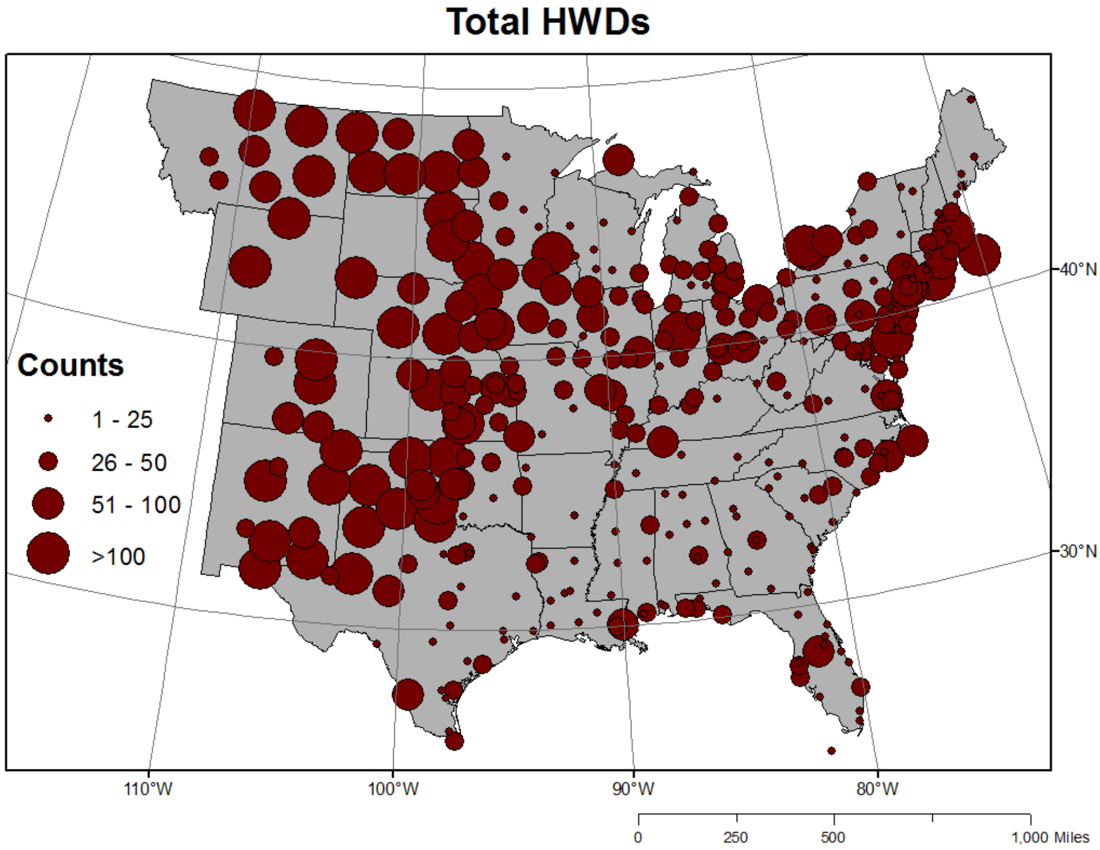


Fig 2.6. Distribution of total HWDs.

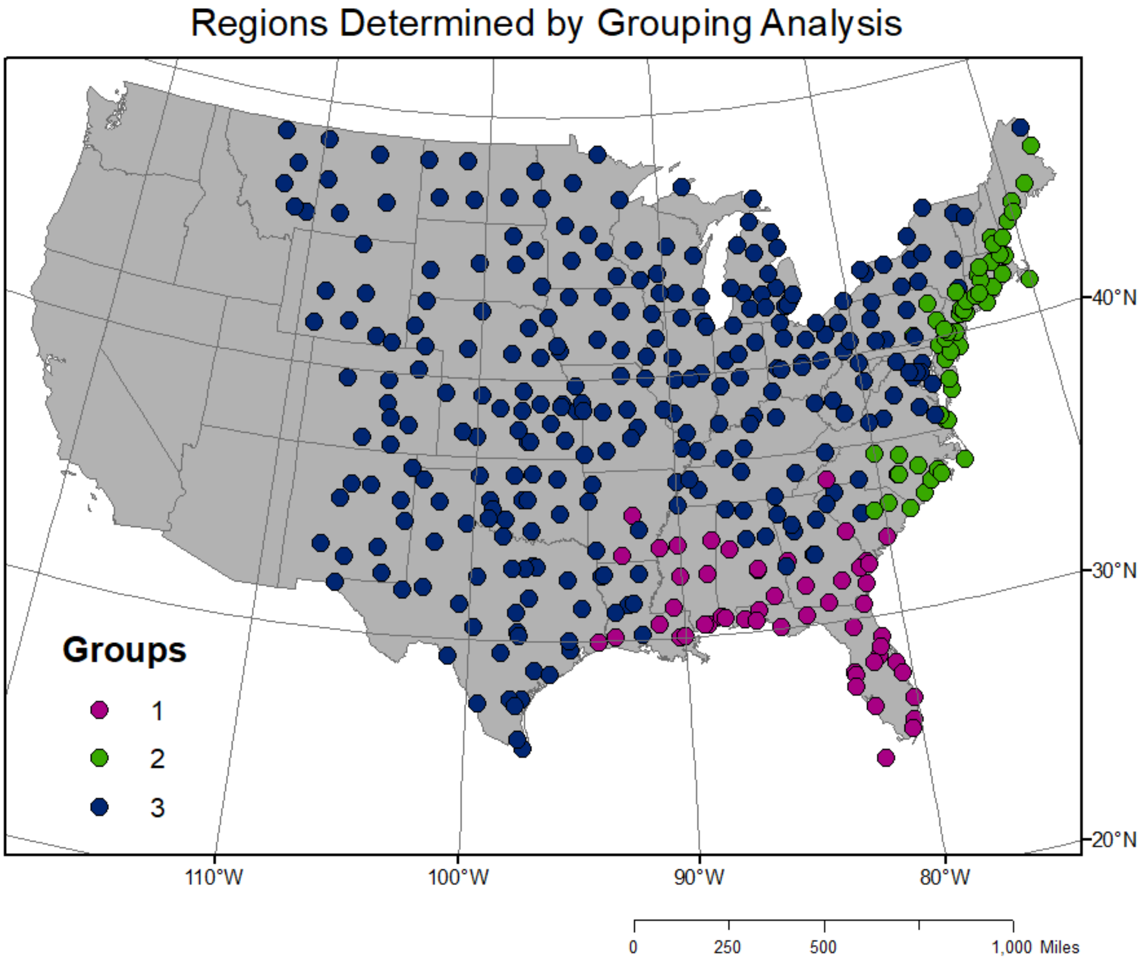


Fig. 2.7. Regions determined by Grouping Analysis.

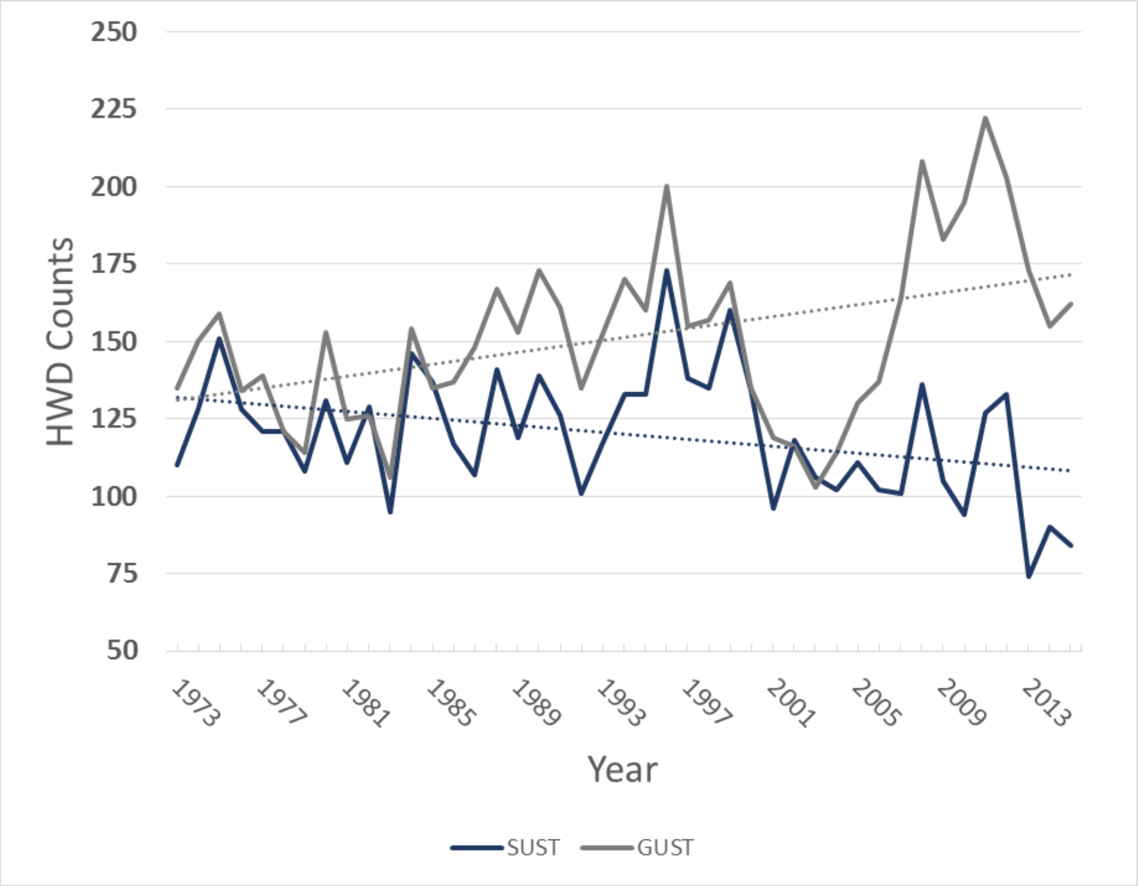


Fig. 2.8. Sustained and gust HWD frequency per year.

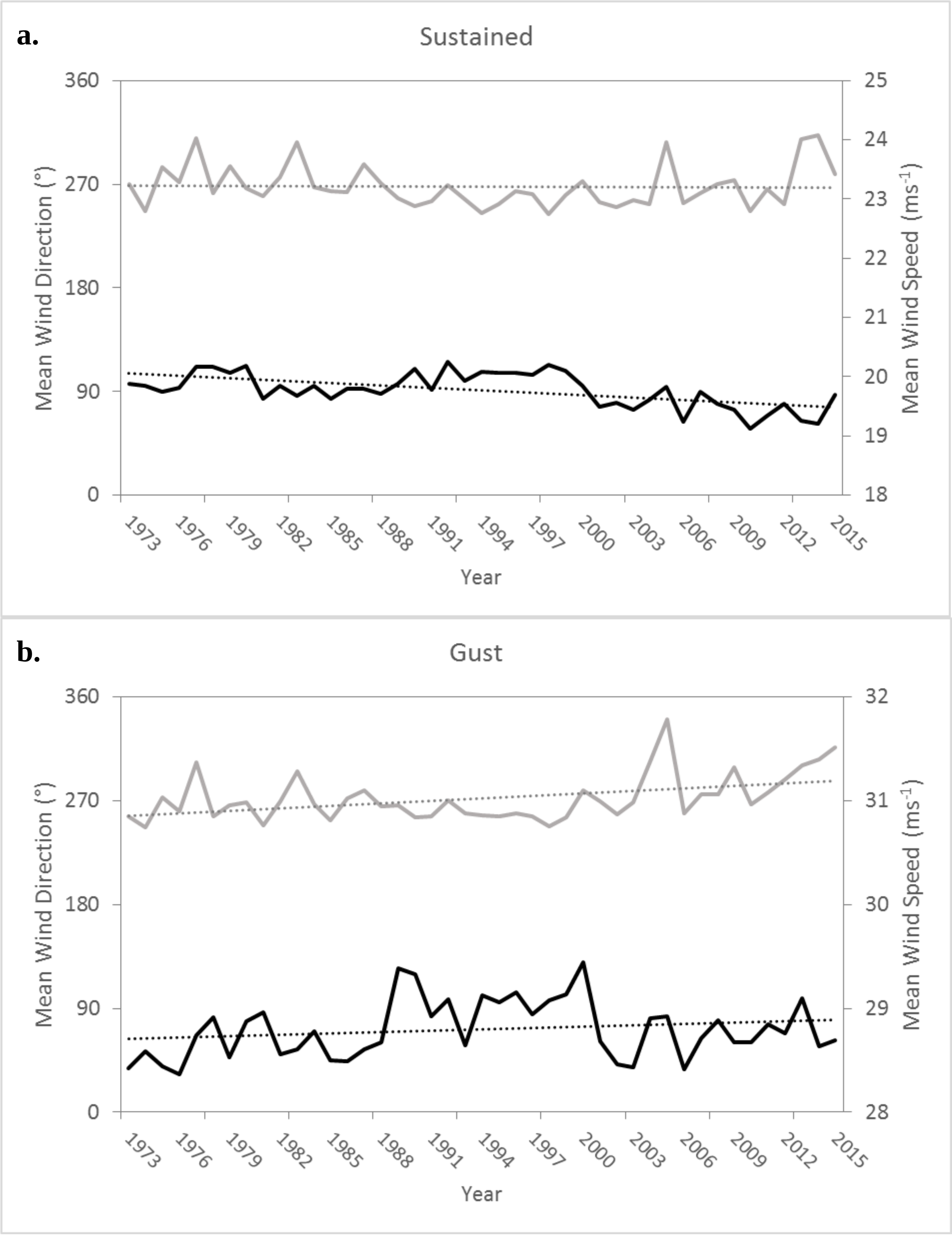


Fig. 2.9. Mean (a.) sustained and (b.) gust high-wind direction (gray line) and speed (black line) per year.

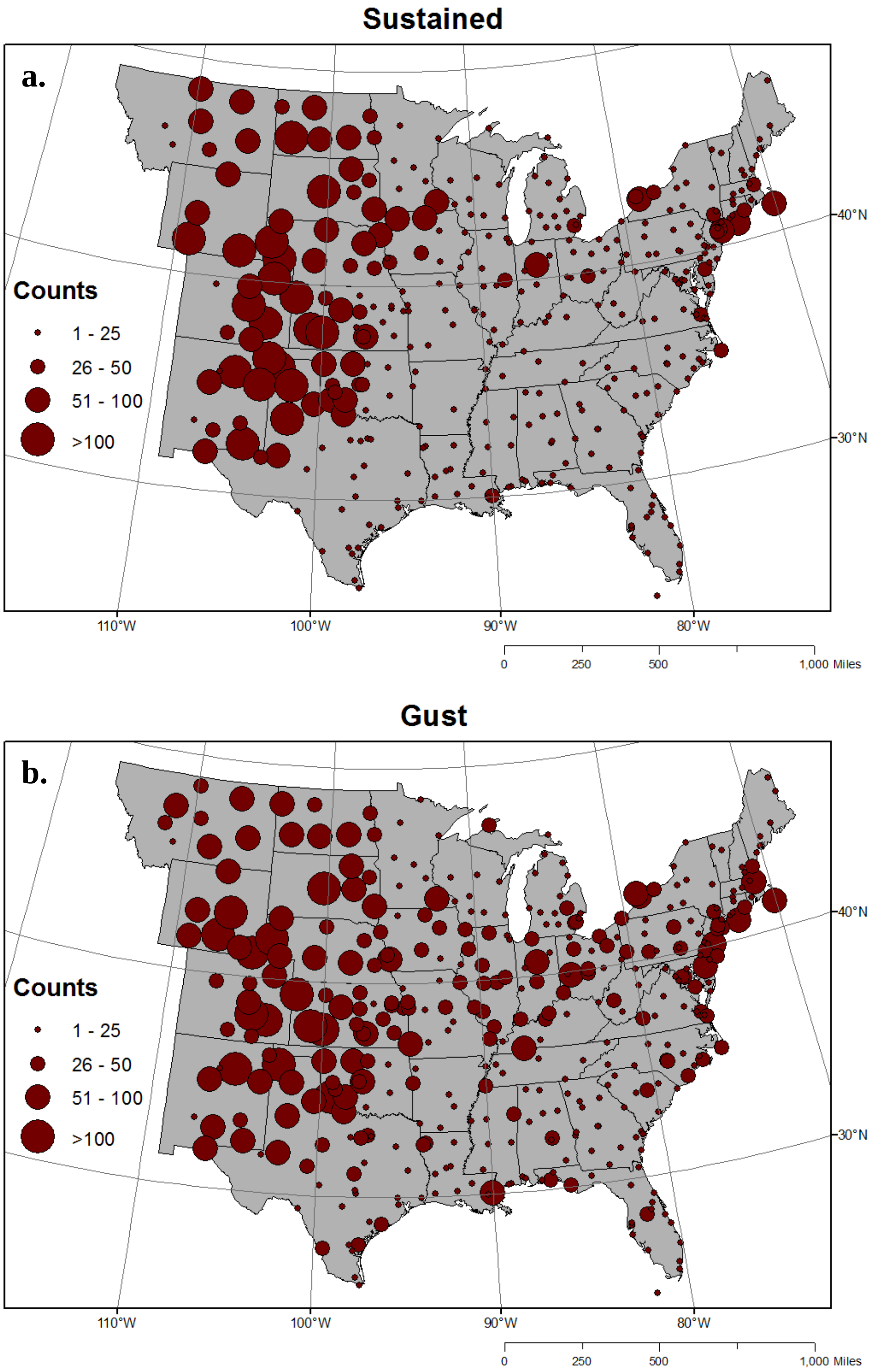


Fig. 2.10. Distribution of (a.) sustained and (b.) gust HWD observations in the eastern U.S. during 1973-2015.

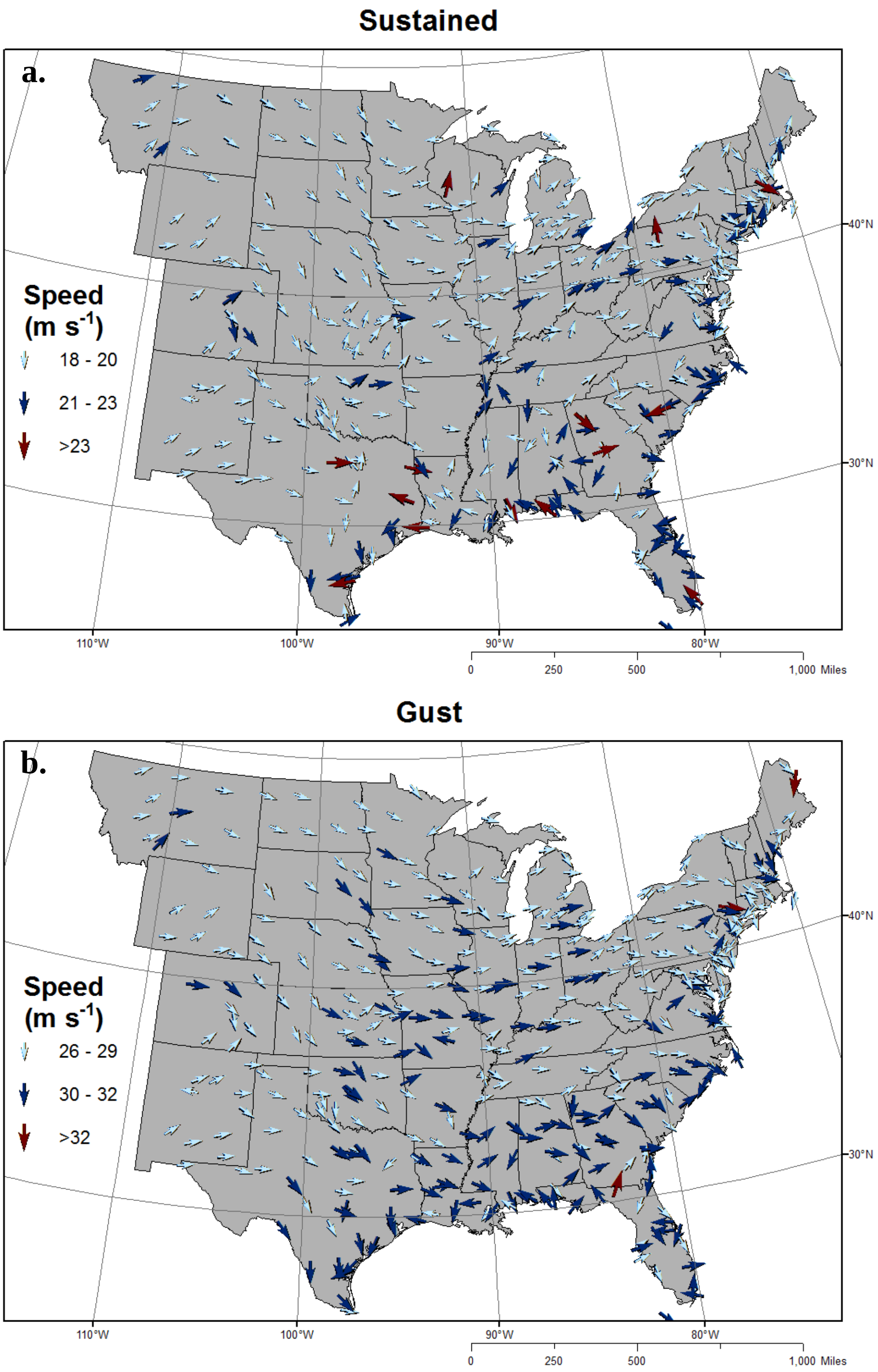


Fig. 2.11. Average (a.) sustained and (b.) gust HWE wind speed and direction in the eastern U.S. during 1973-2015.

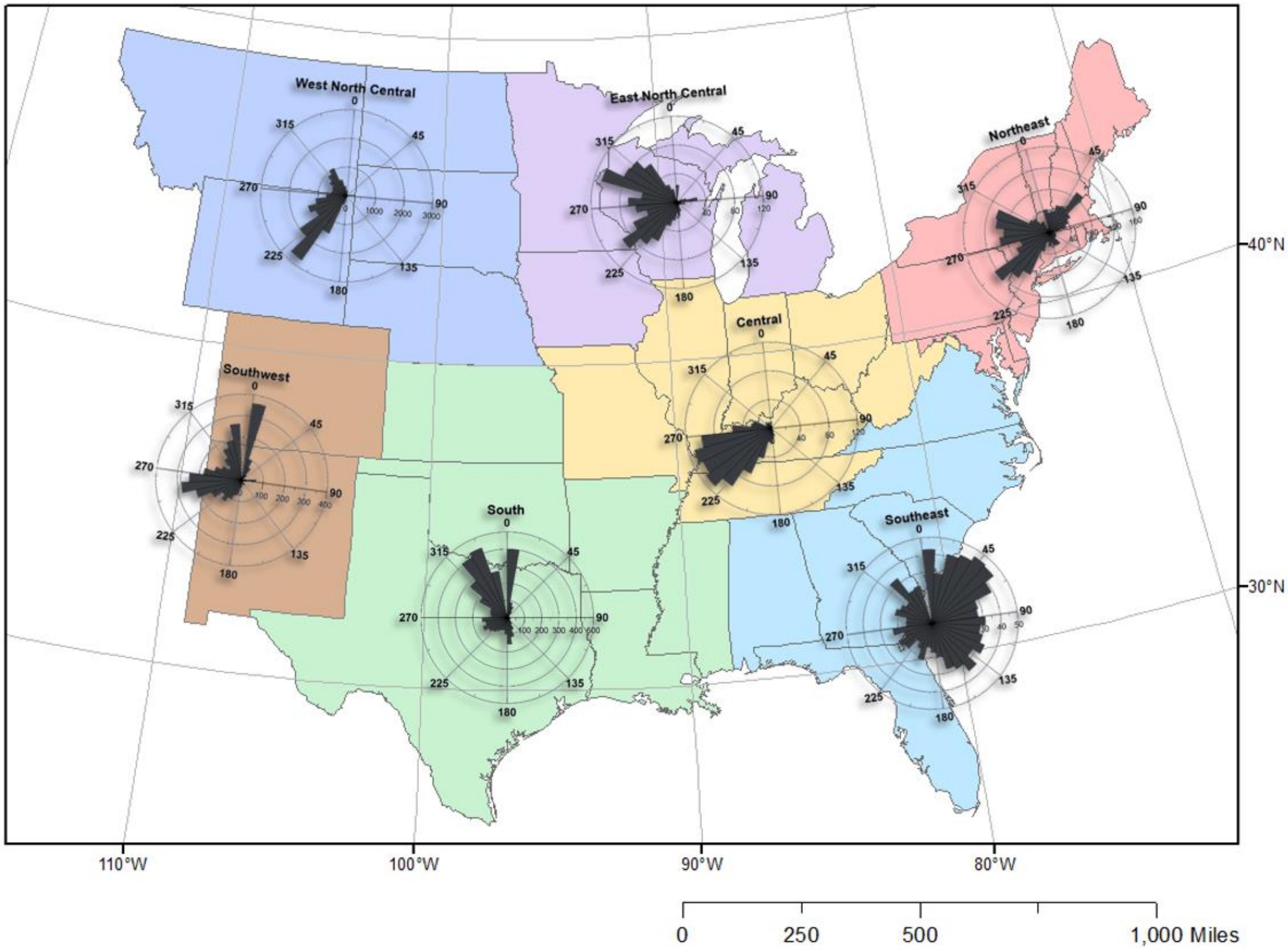


Fig. 2.12. Average sustained high-wind direction per region.

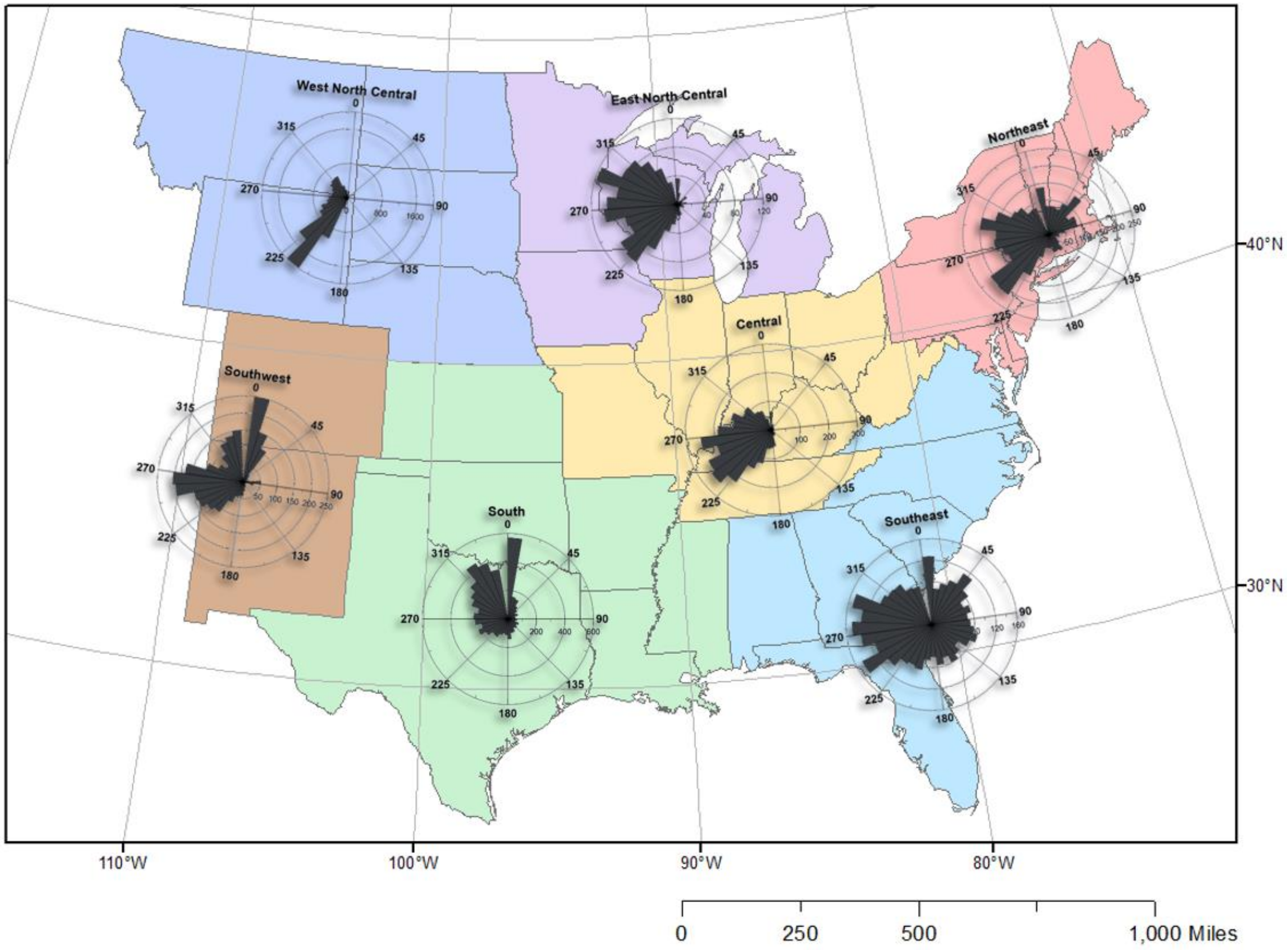


Fig. 2.13. Average gust high-wind direction per region.

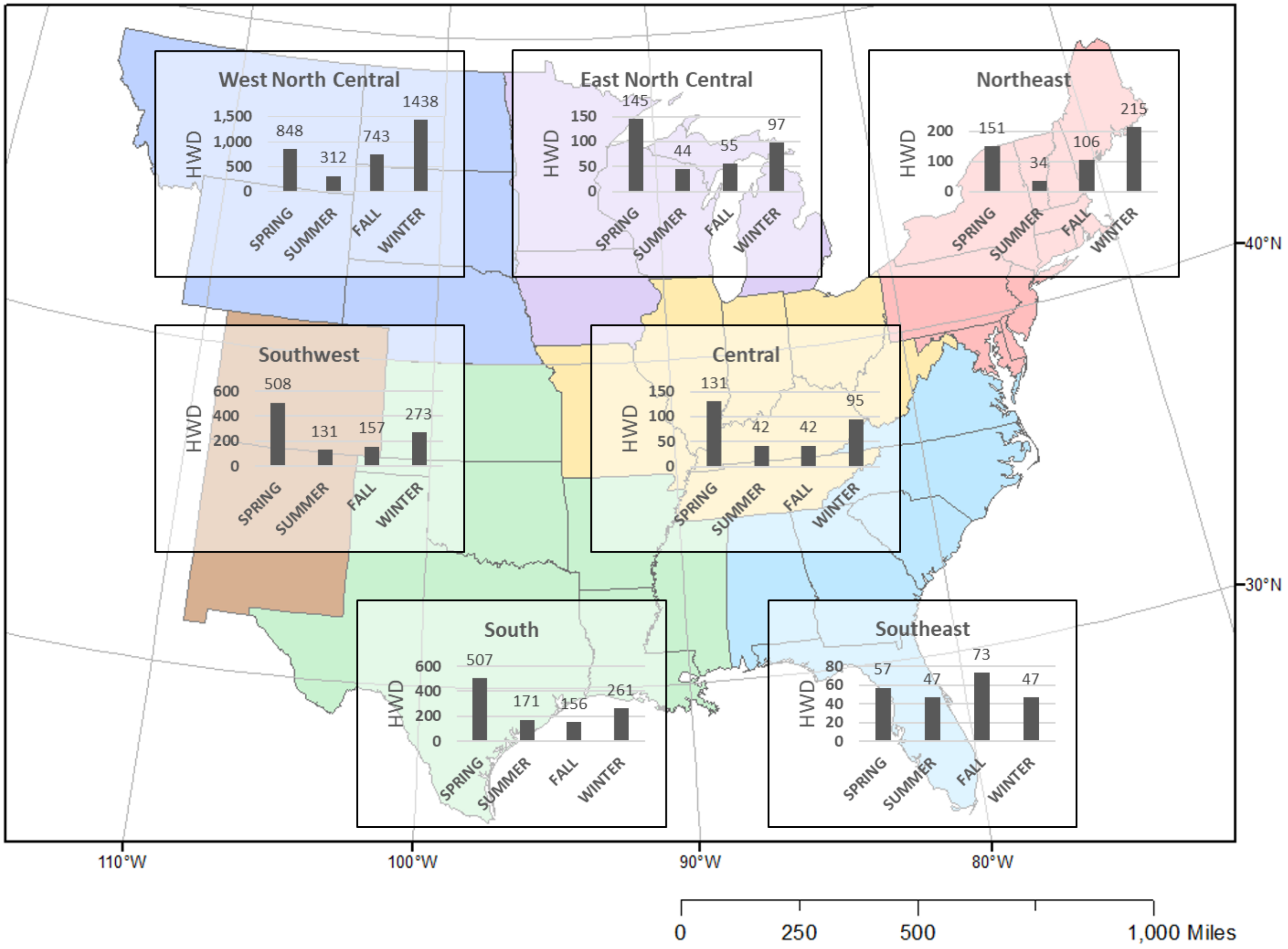


Fig. 2.14. Sustained HWD frequency per region and season.

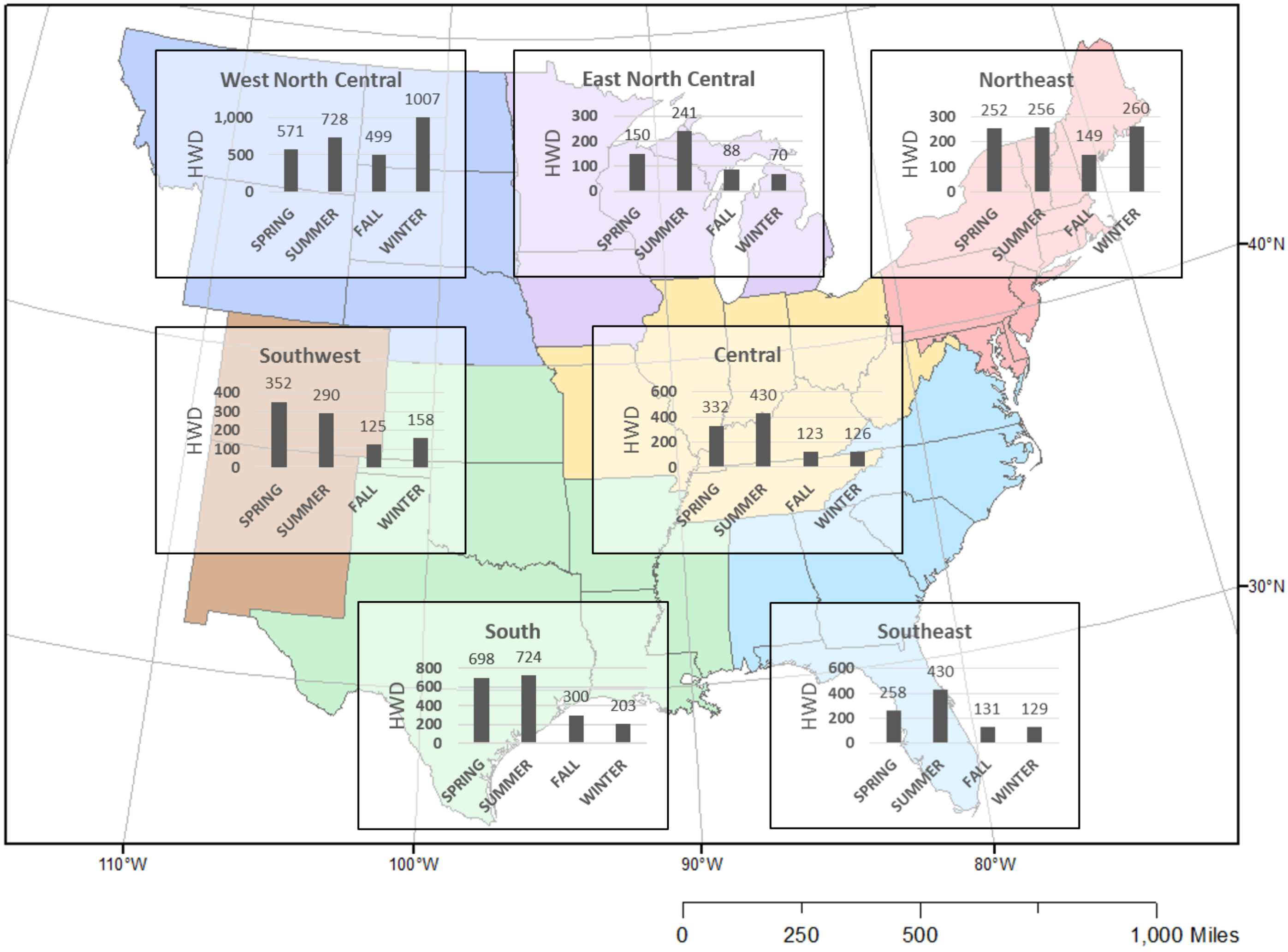


Fig. 2.15. Gust HWD frequency per region and season.

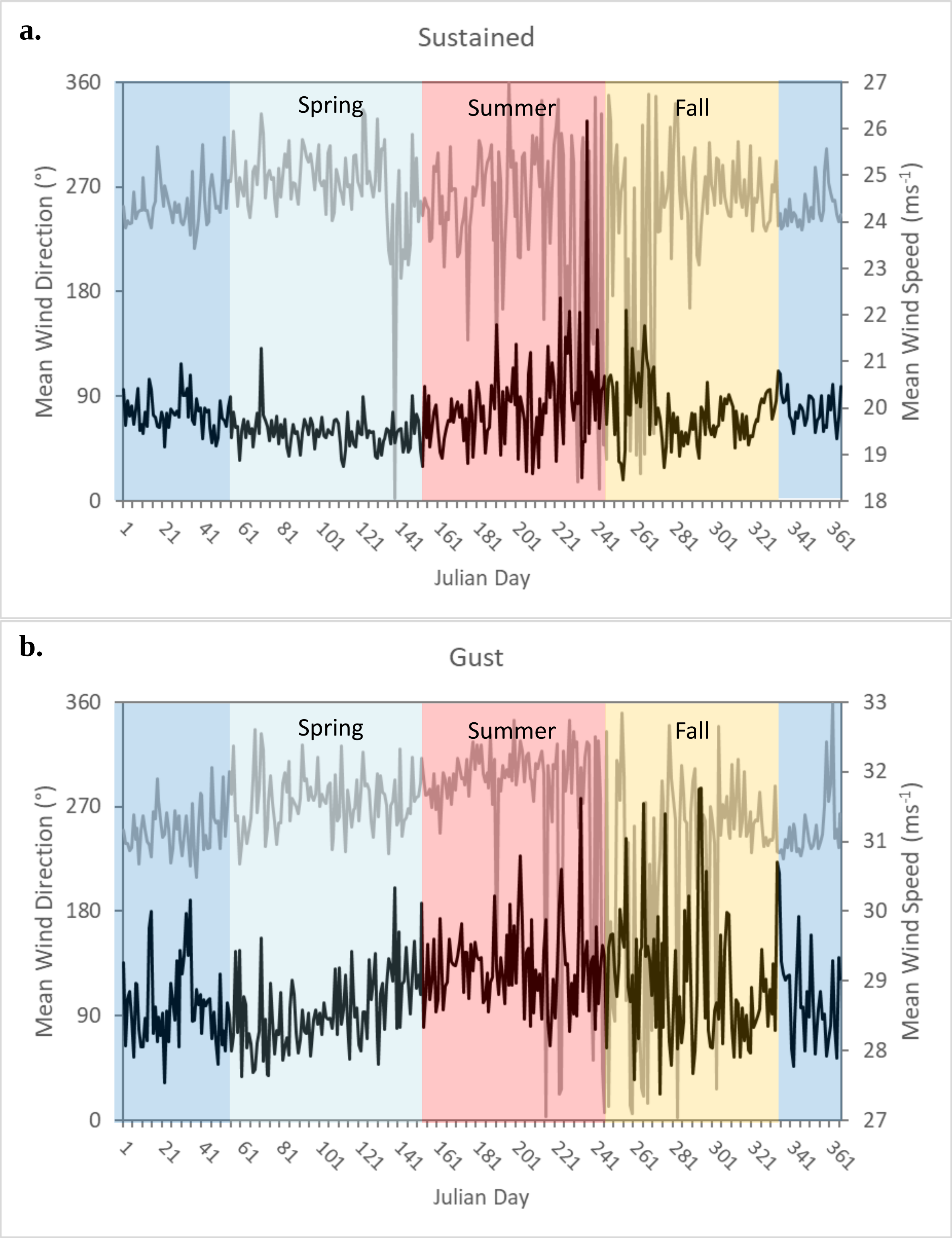


Fig. 2.16. Mean (a.) sustained and (b.) gust high-wind direction (gray line) and speed (black line) per Julian Day.

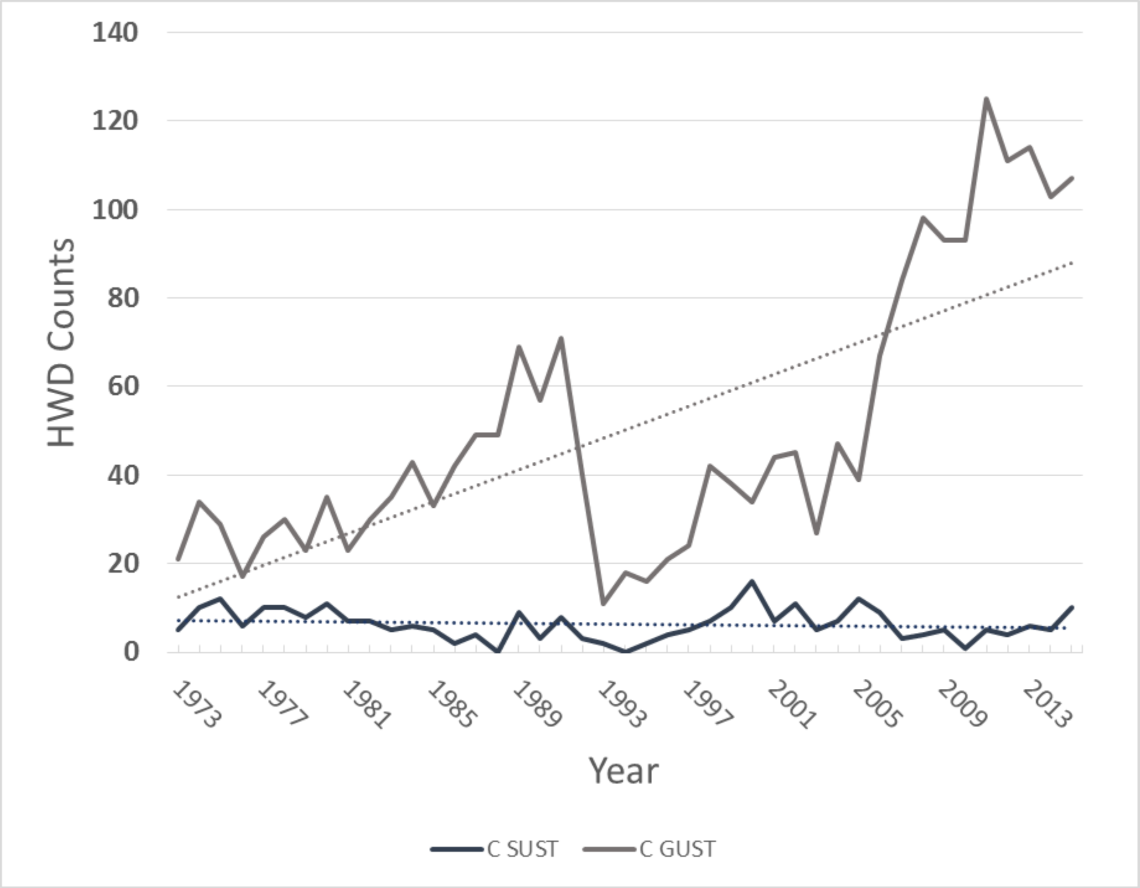


Fig. 2.17. Convective sustained and gust HWD frequency per year.

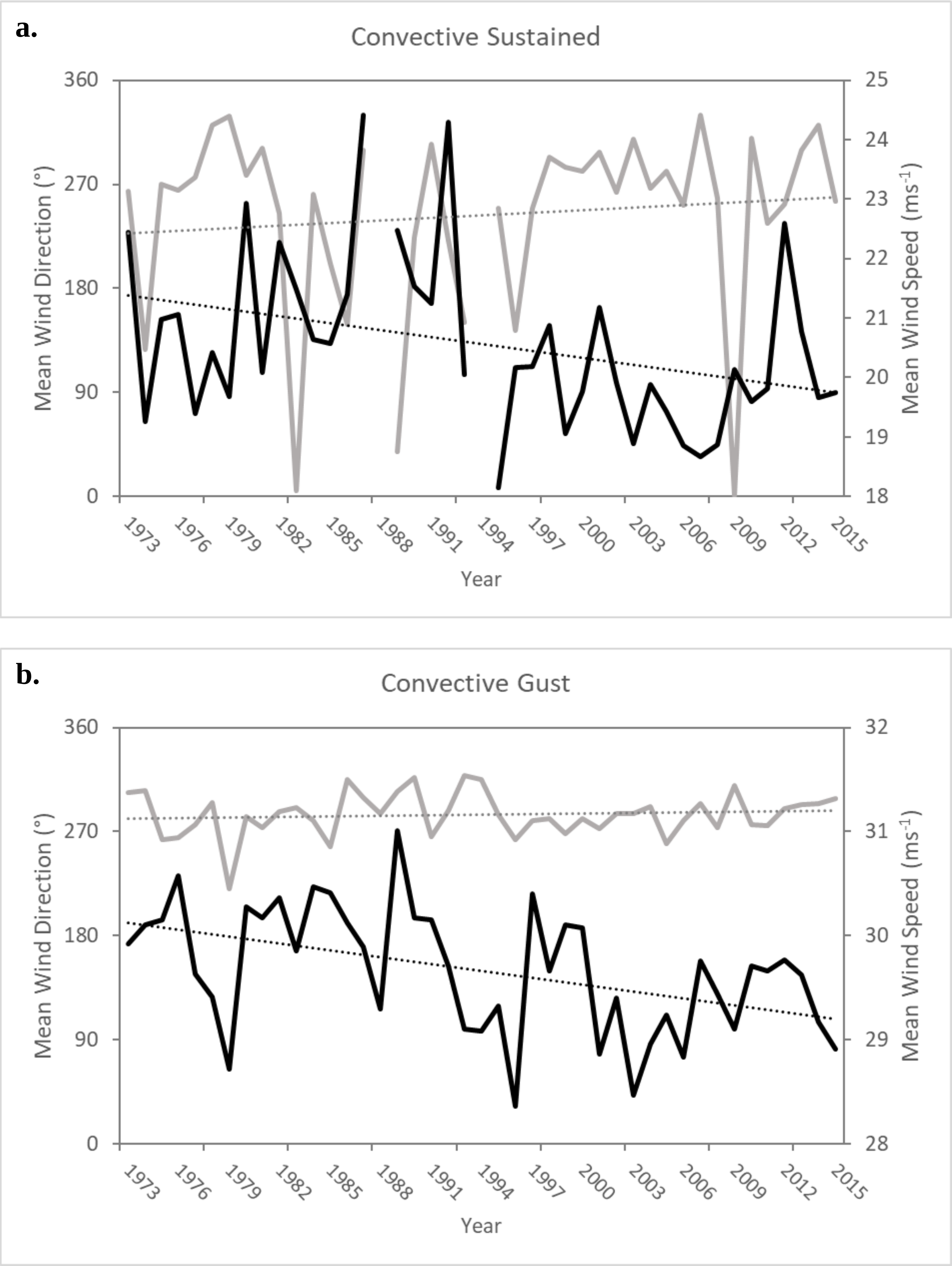


Fig. 2.18. Mean convective (a.) sustained and (b.) gust high-wind direction (gray line) and speed (black line) per year.

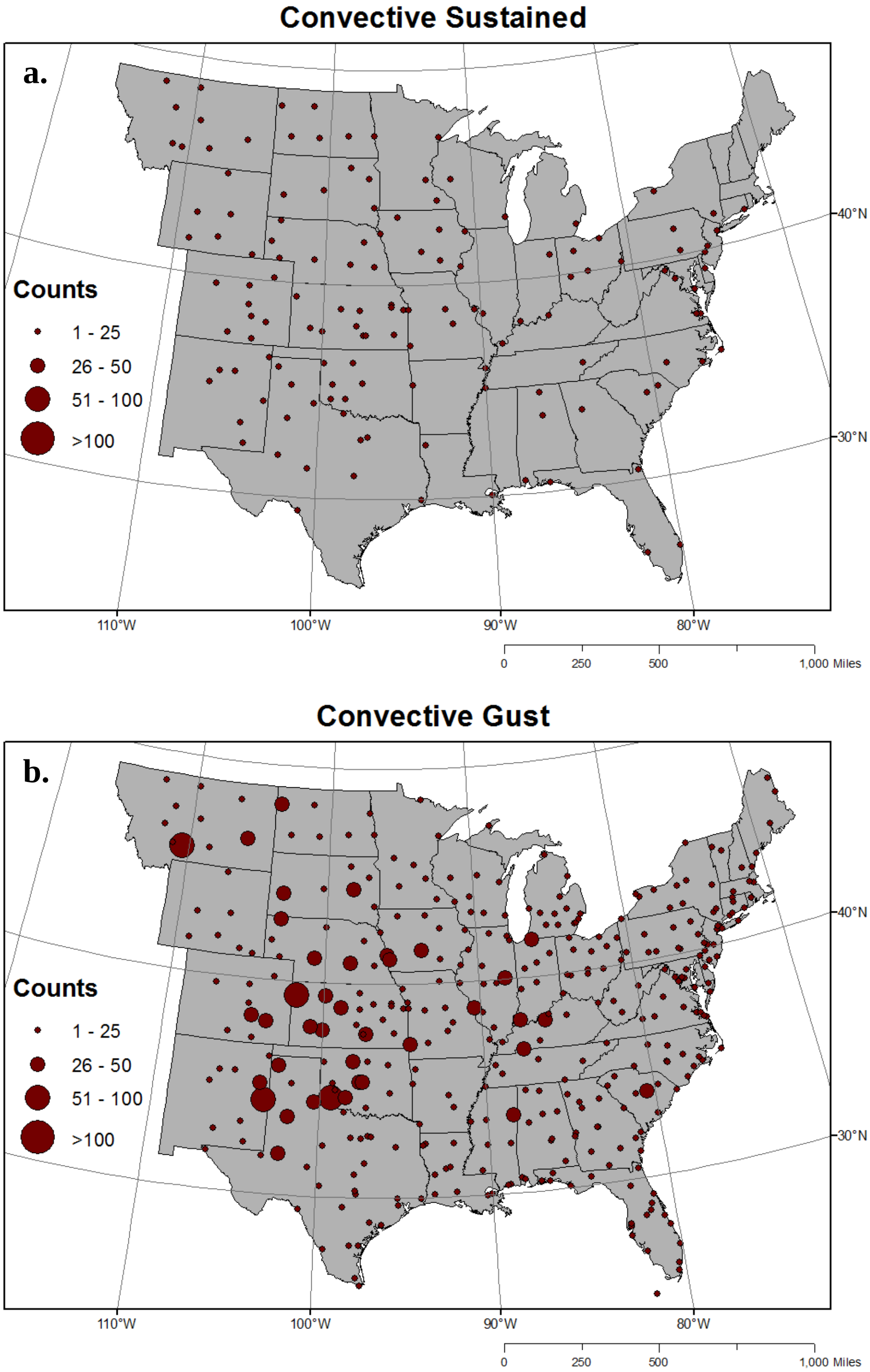


Fig. 2.19. Distribution of convective (a.) sustained and (b.) gust HWD observations during 1973-2015.

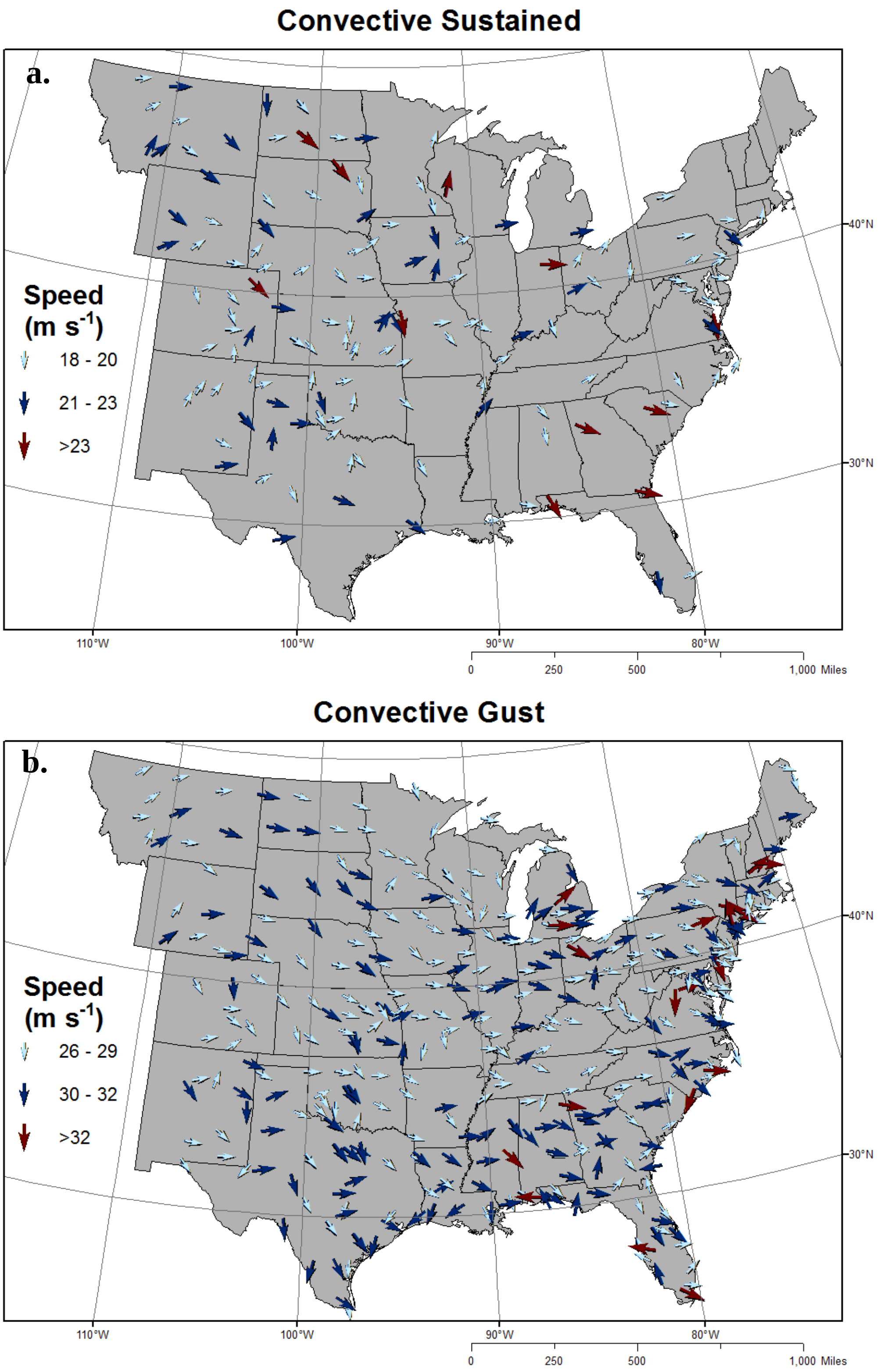


Fig. 2.20. Average convective (a.) sustained and (b.) gust HWE wind speed and direction during 1973-2015.

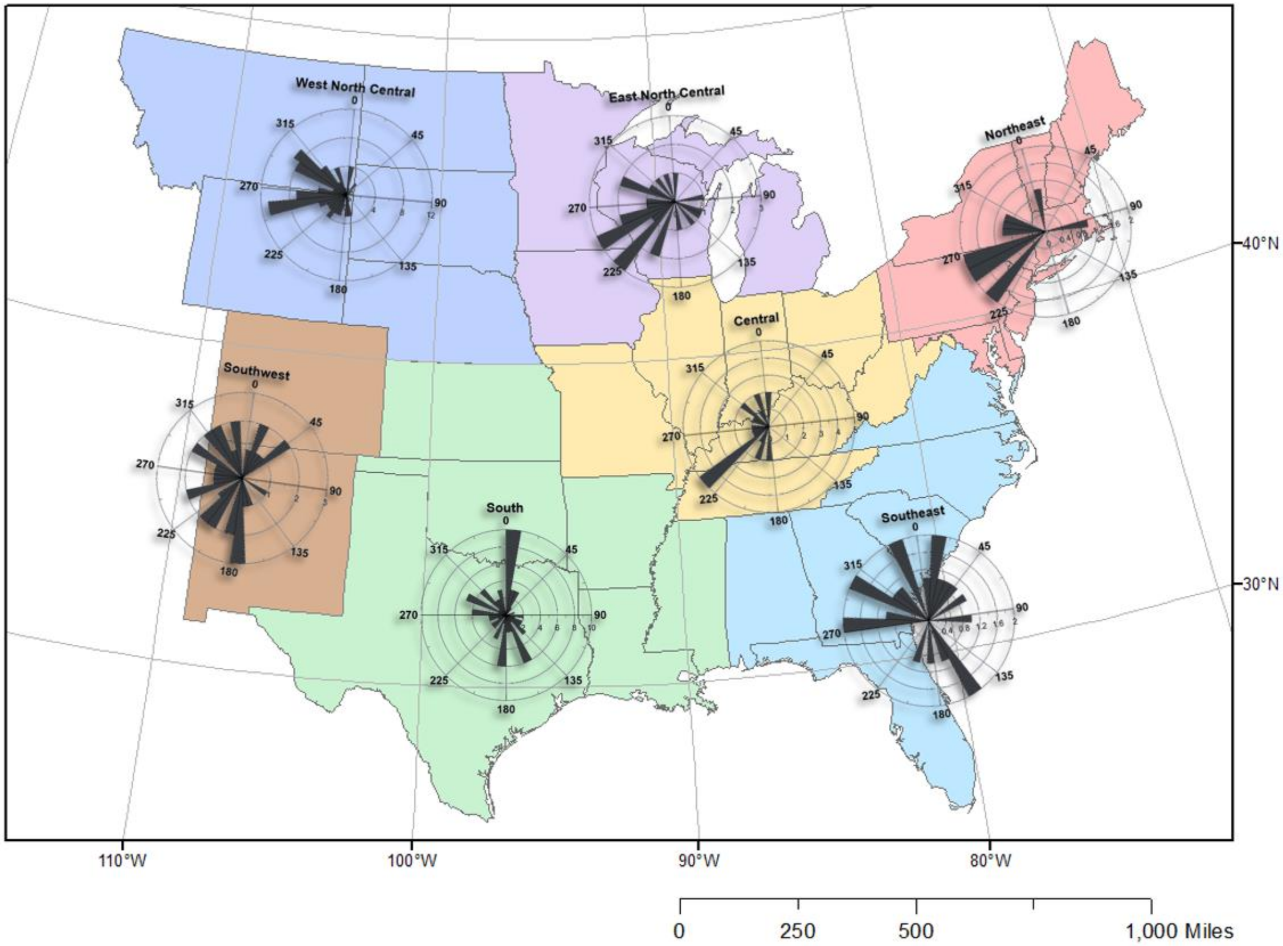


Fig. 2.21. Average convective sustained high-wind direction per region.

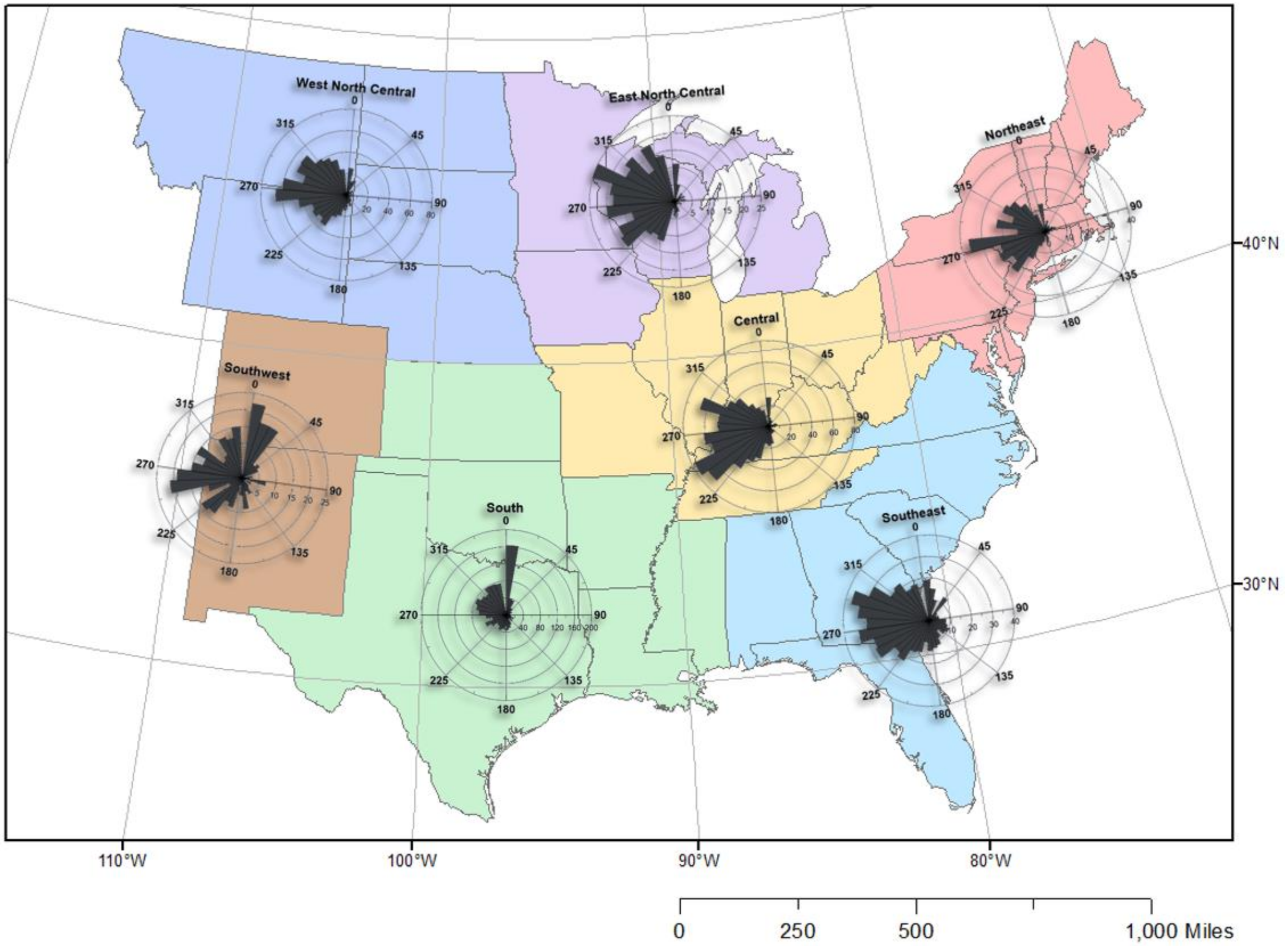


Fig. 2.22. Average convective gust high-wind direction per region.

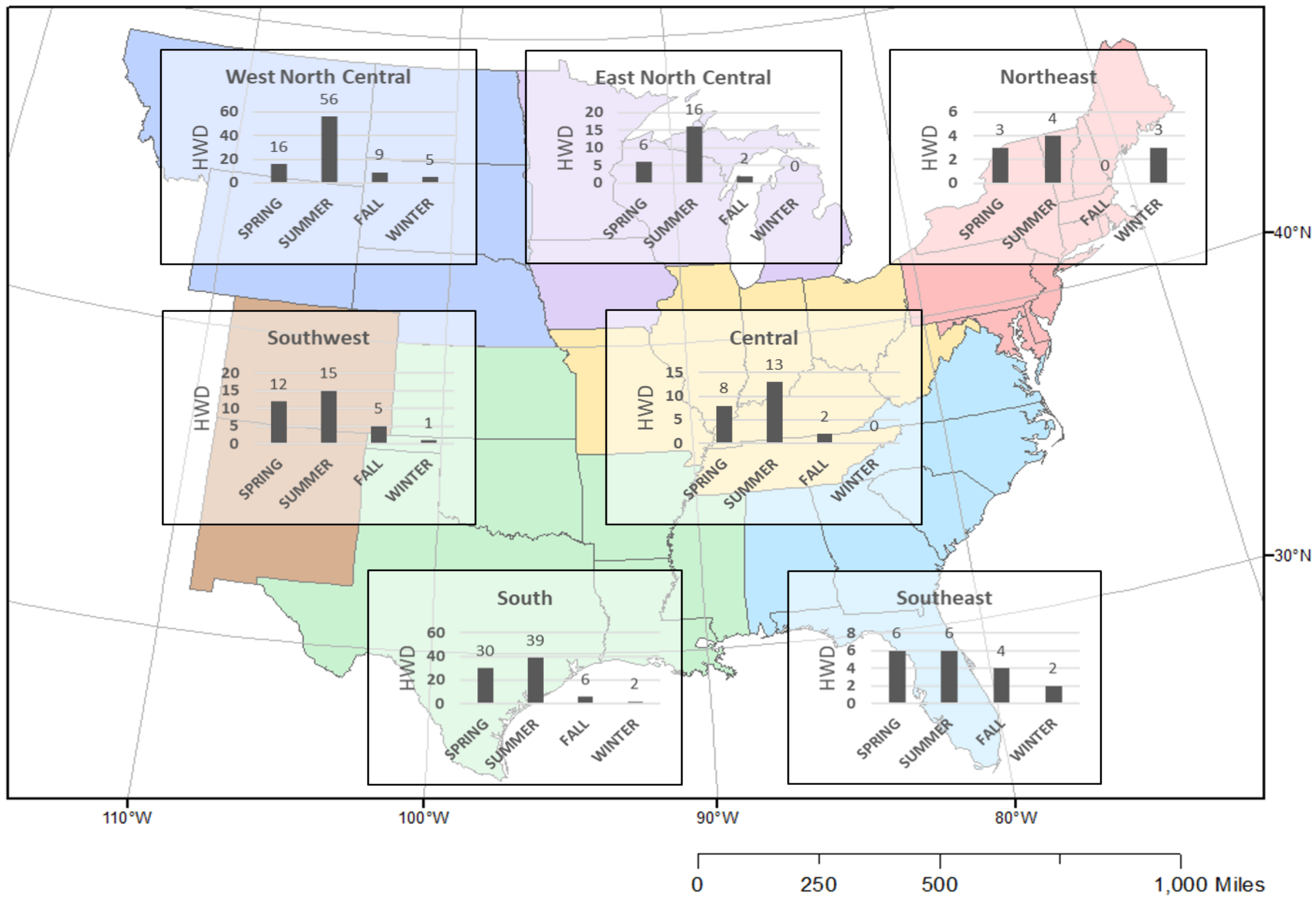


Fig. 2.23. Convective sustained HWD frequency per region and season.

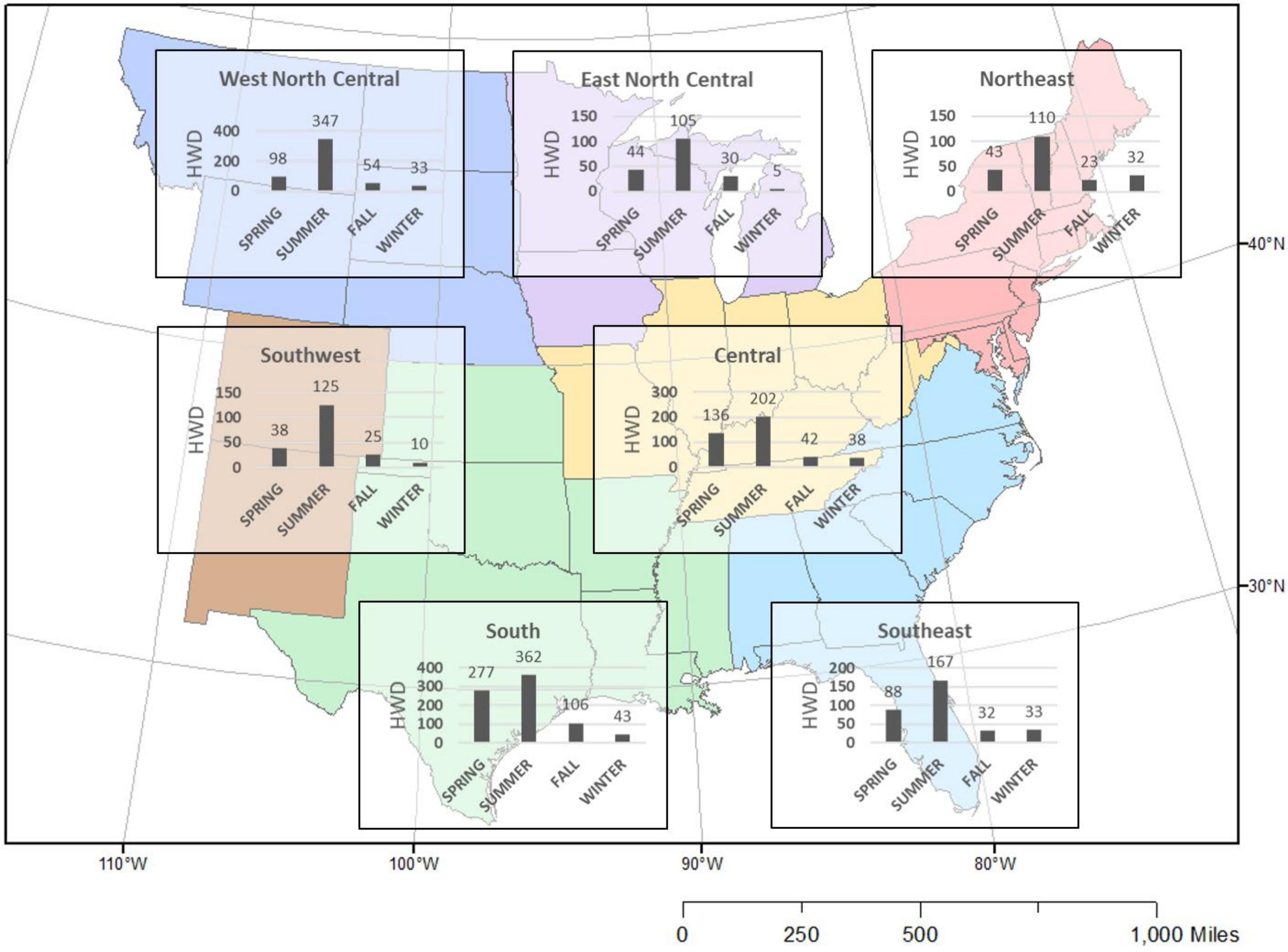


Fig. 2.24. Convective gust HWD frequency per region and season.

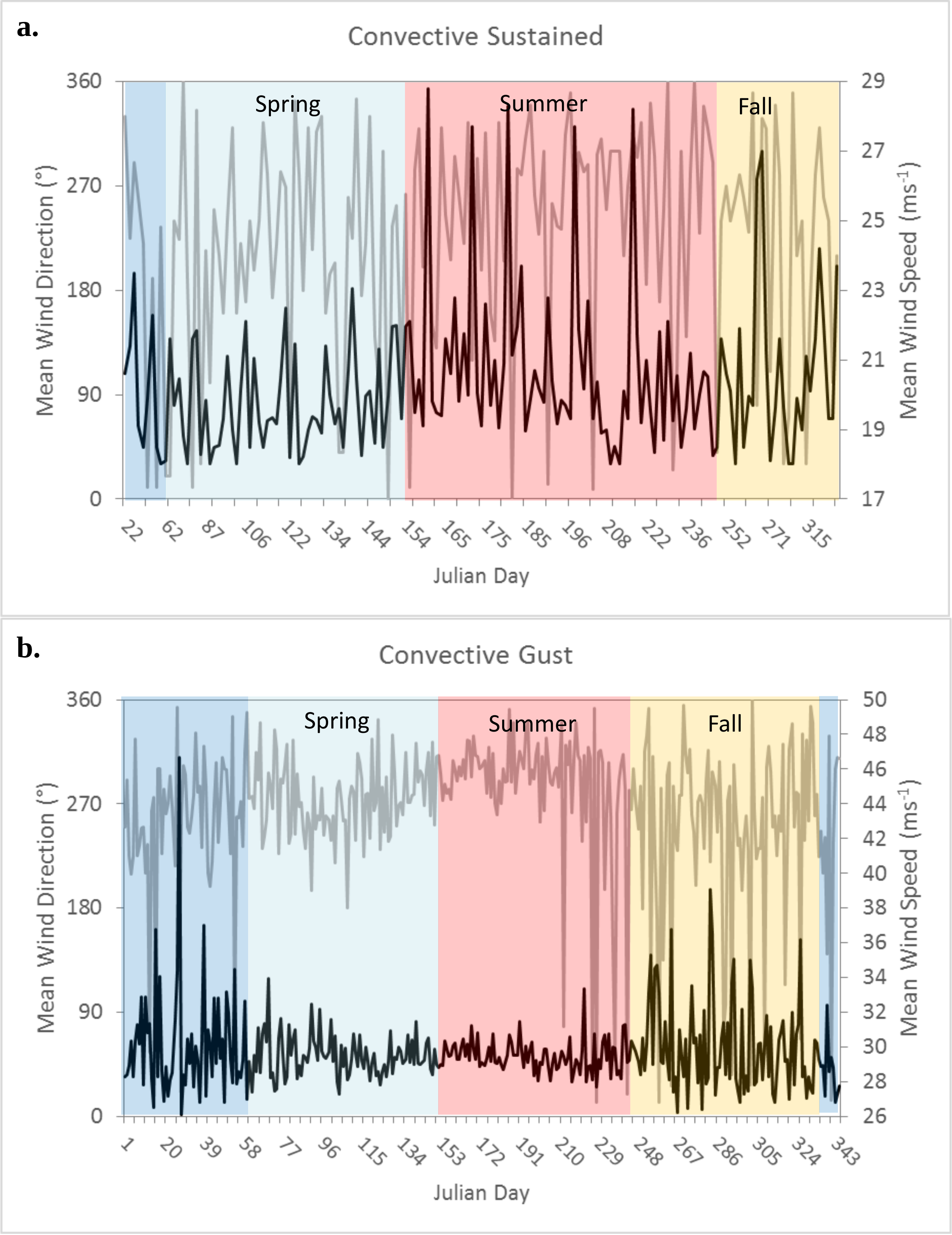


Fig. 2.25. Mean convective (a.) sustained and (b.) gust high-wind direction (gray line) and speed (black line) per Julian Day.

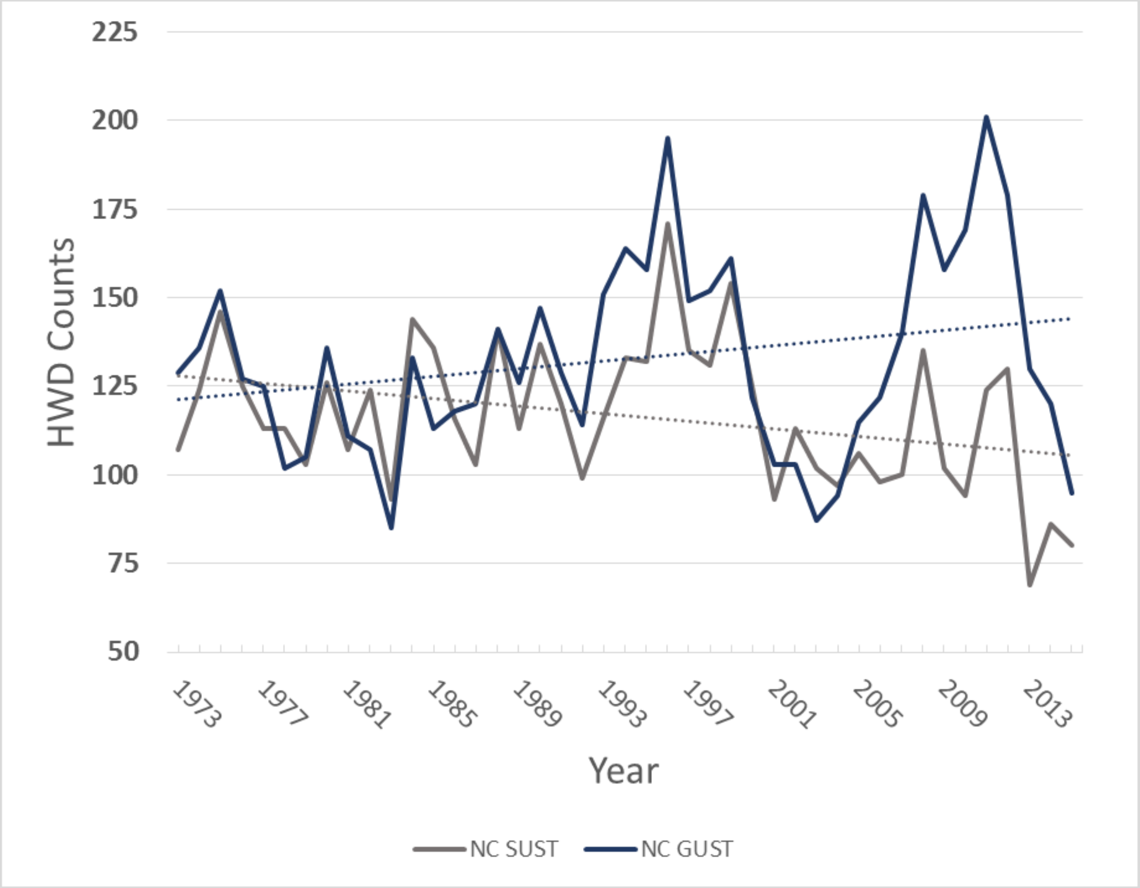


Fig. 2.26. Non-convective sustained and gust HWD frequency per year.

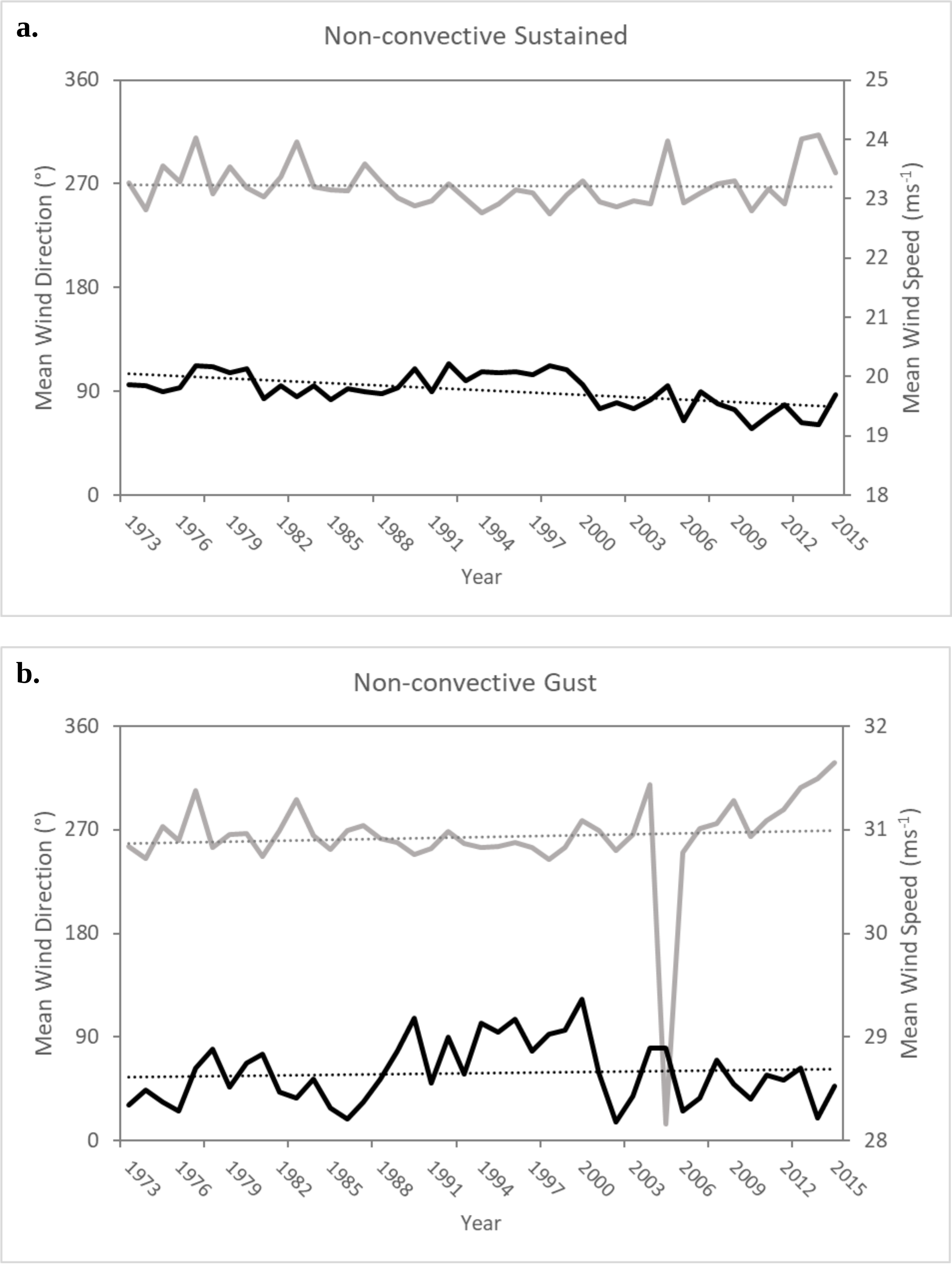


Fig. 2.27. Mean non-convective (a.) sustained and (b.) gust high-wind direction (gray line) and speed (black line) per year.

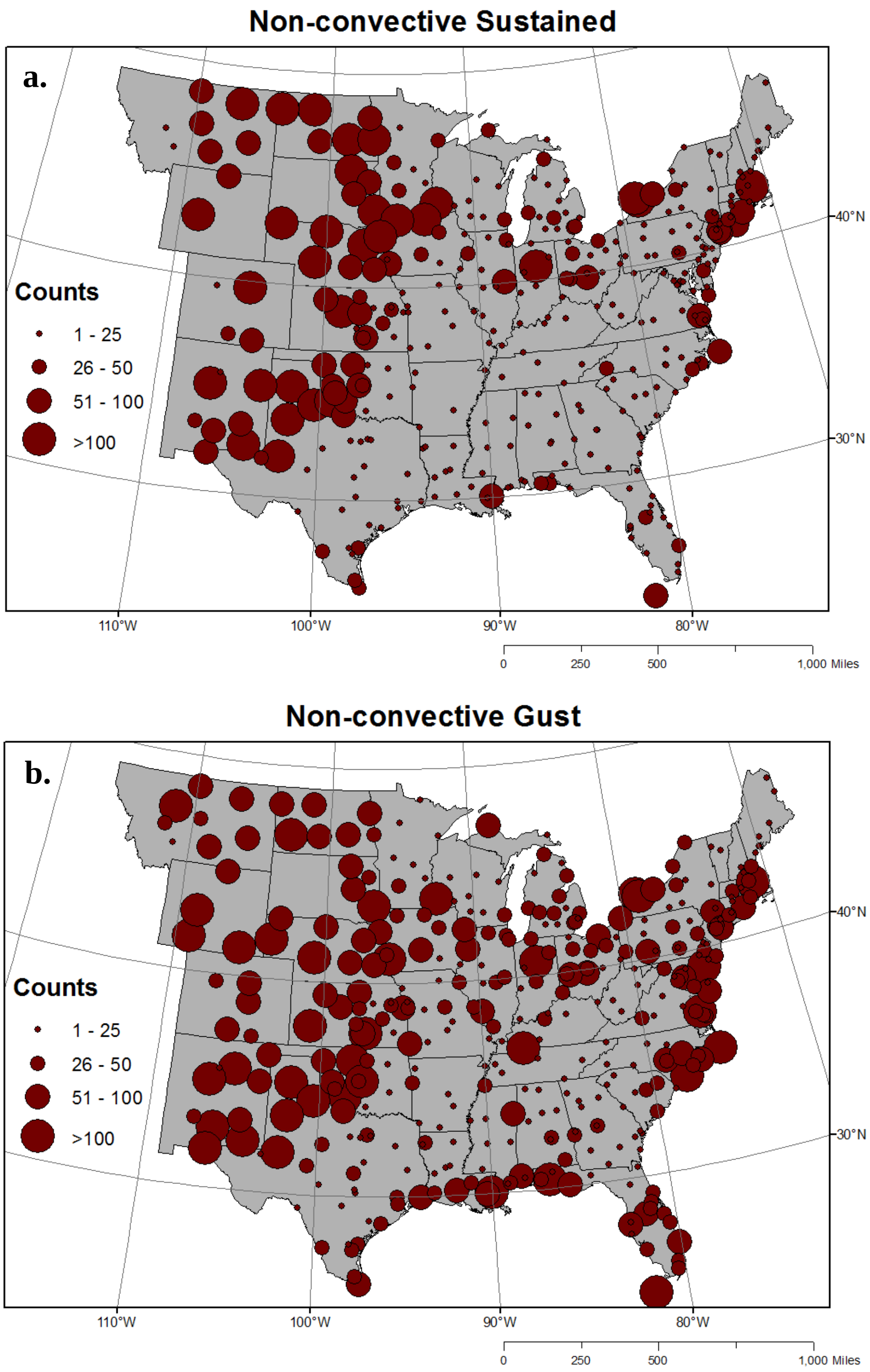


Fig. 2.28. Distribution of non-convective (a.) sustained and (b.) gust HWD observations during 1973-2015.

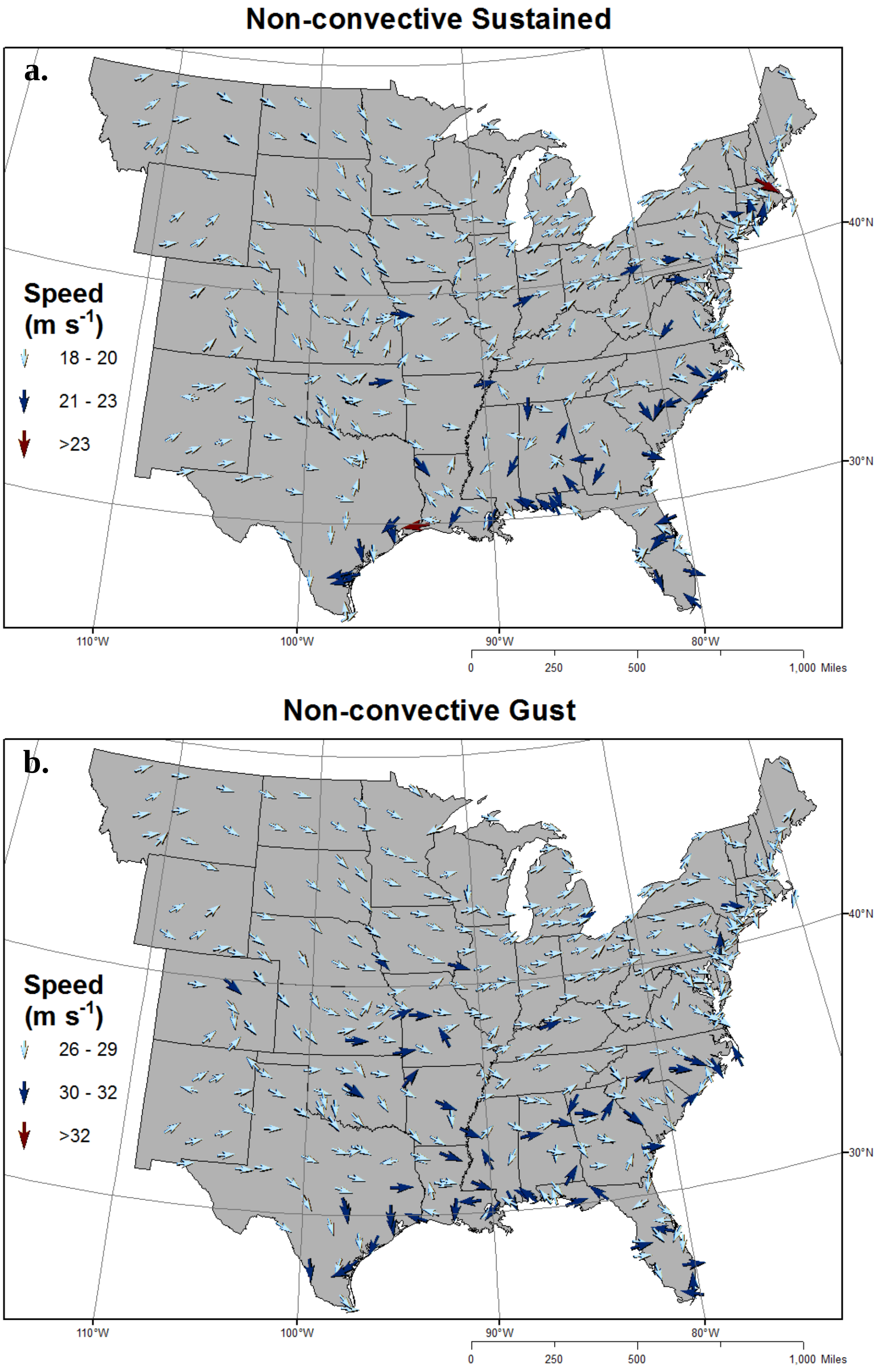


Fig. 2.29. Average non-convective (a.) sustained and (b.) gust HWE wind speed and direction during 1973-2015.

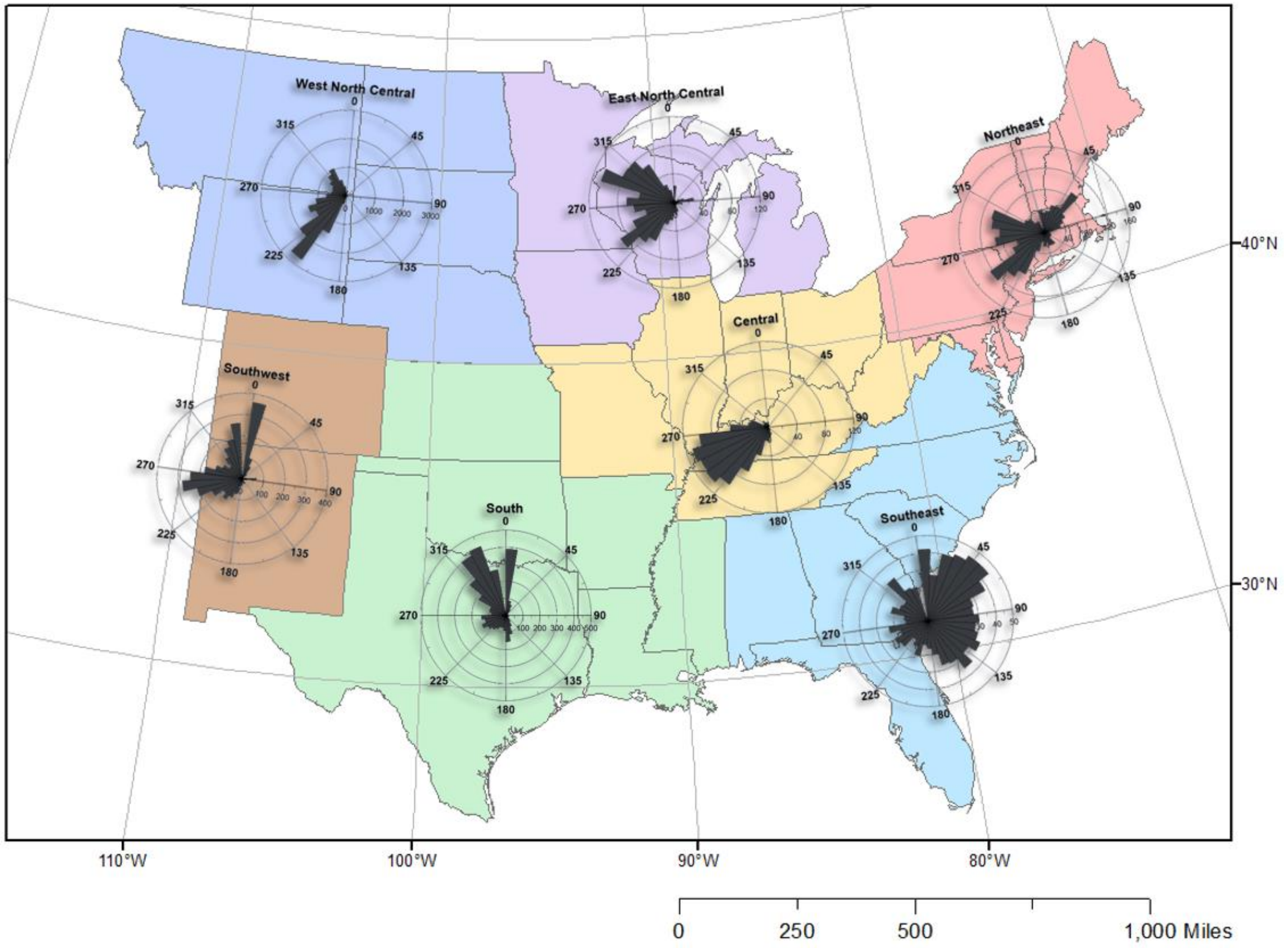


Fig. 2.30. Average non-convective sustained high-wind direction per region.

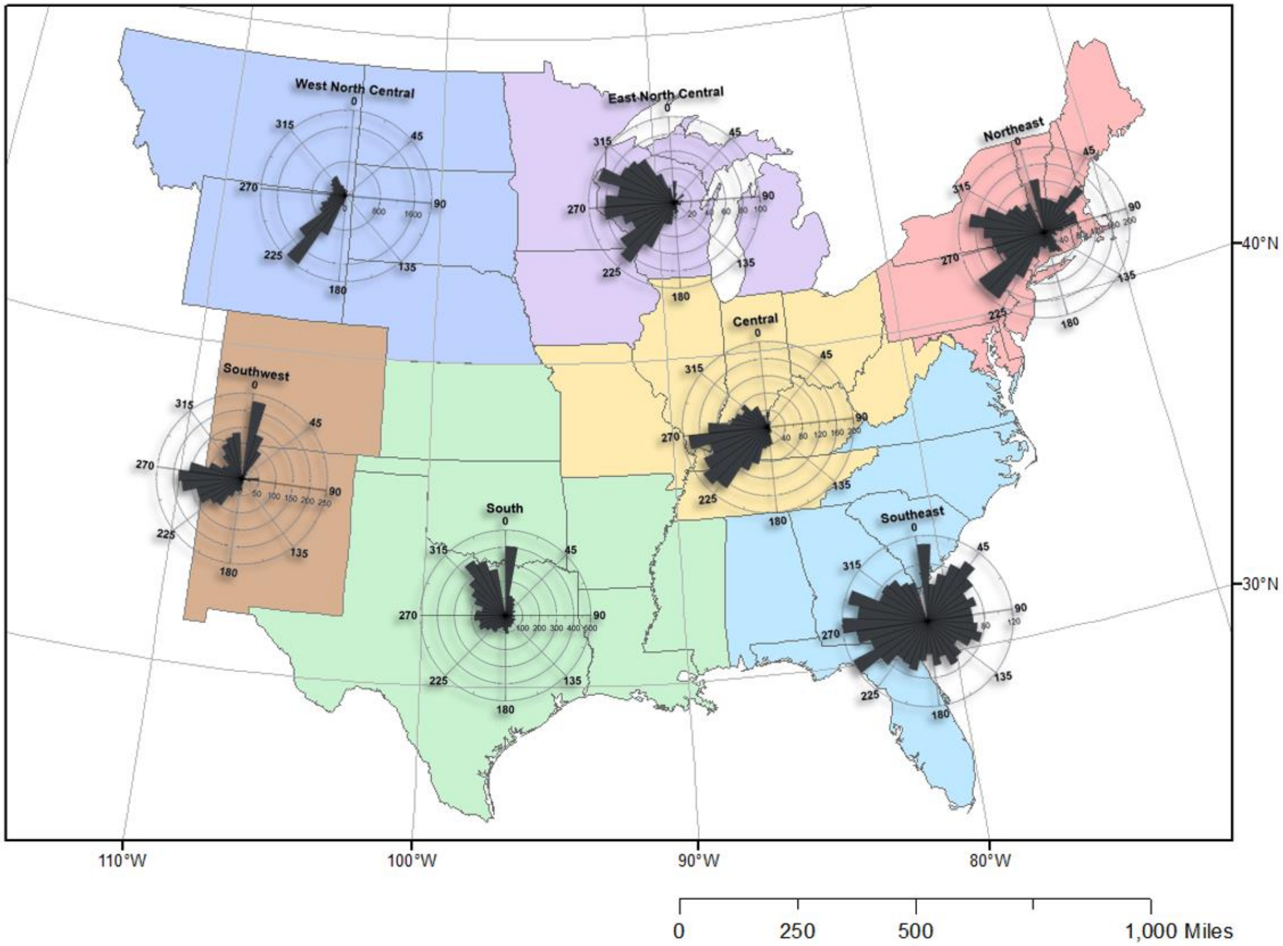


Fig. 2.31. Average non-convective gust high-wind direction per region.

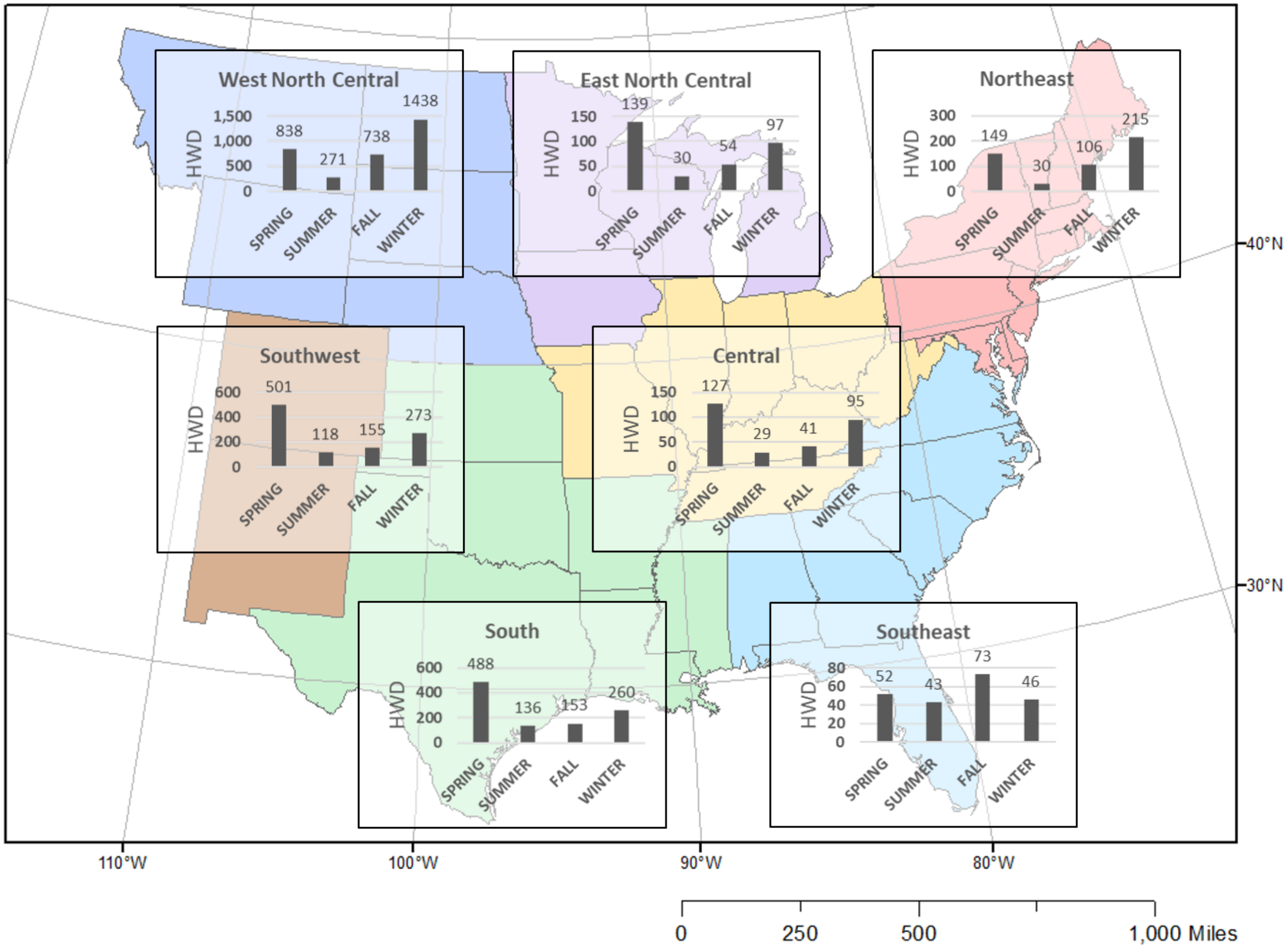


Fig. 2.32. Non-convective sustained HWD frequency per region and season.

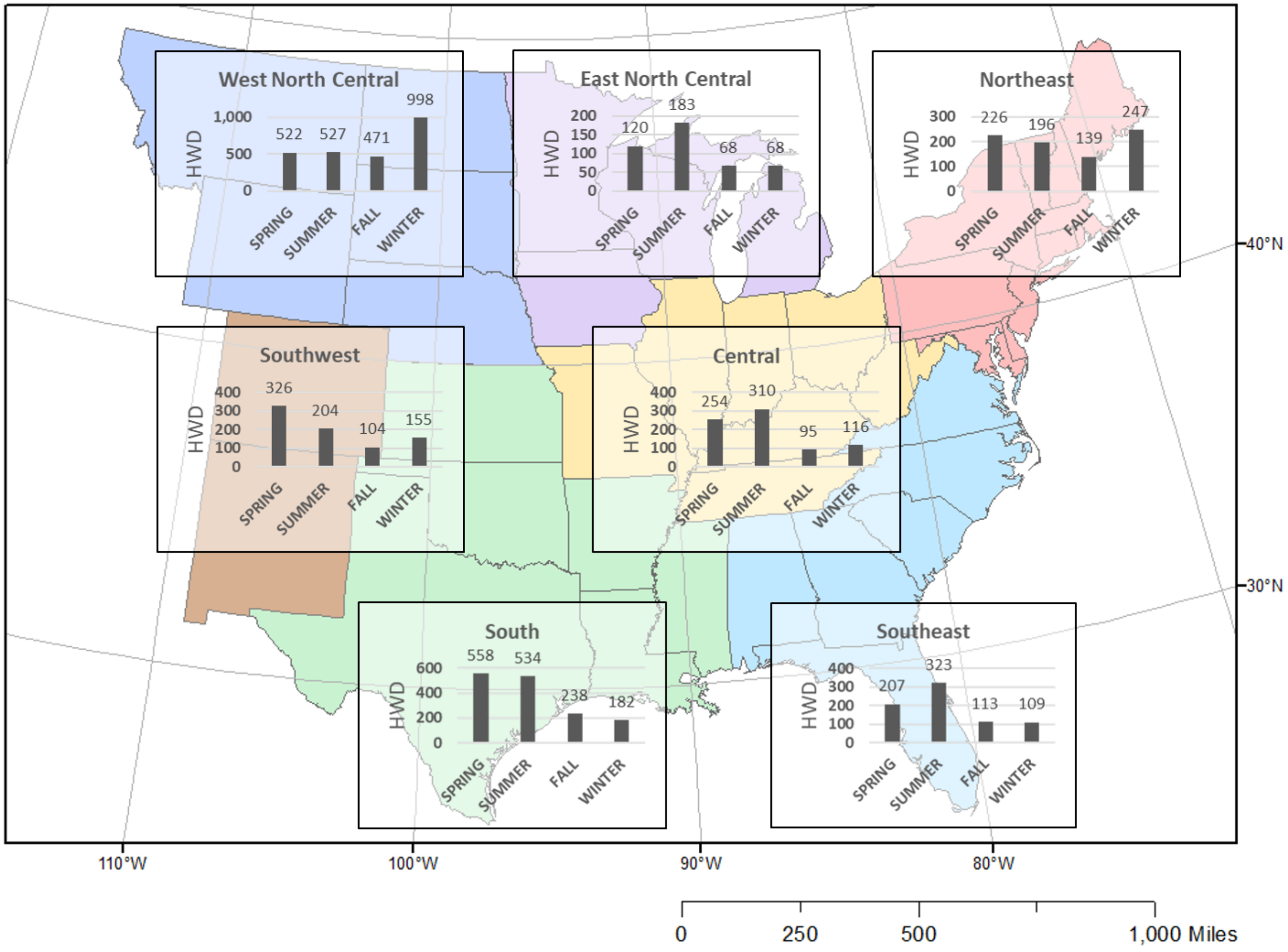


Fig. 2.33. Non-convective gust HWD frequency per region and season.

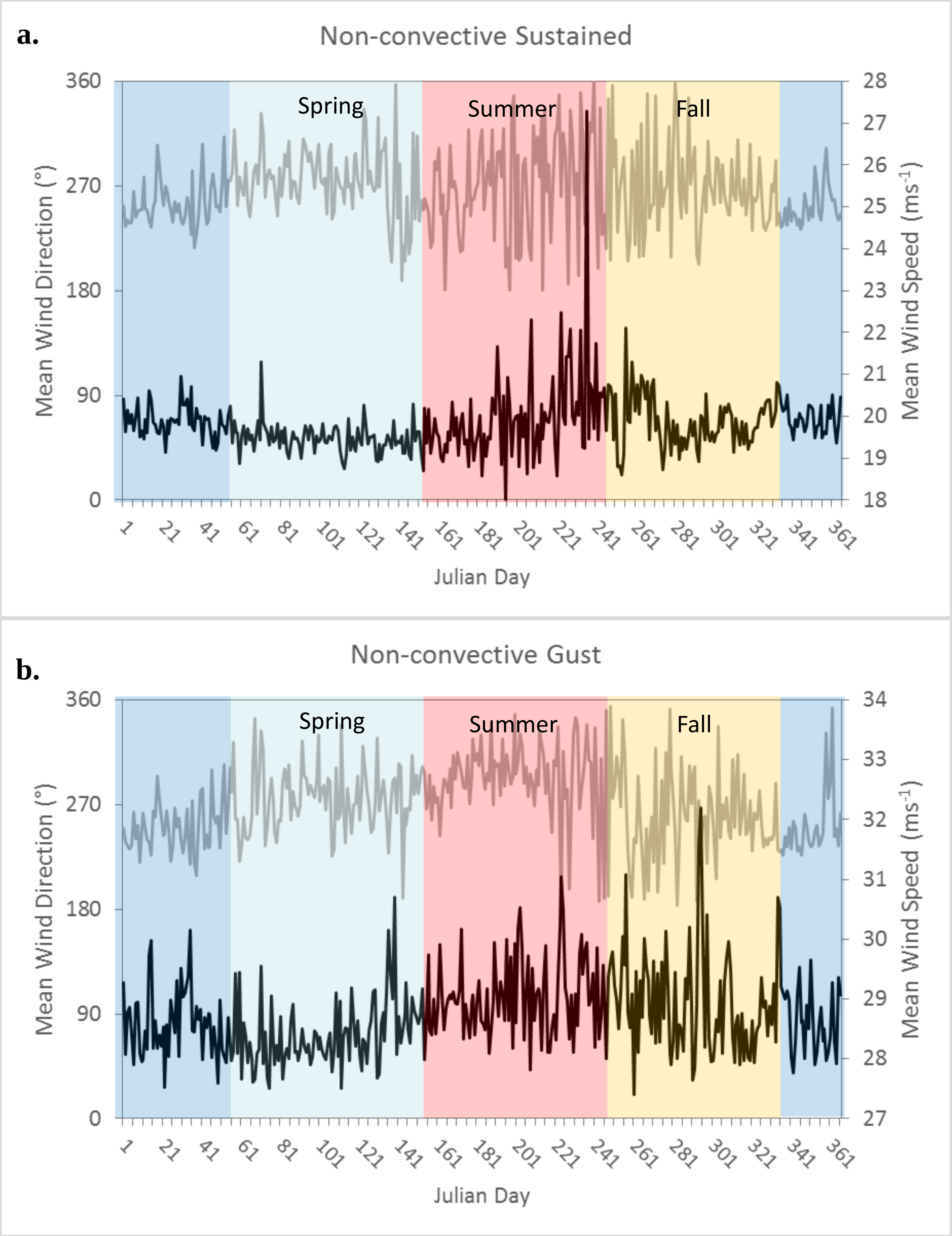
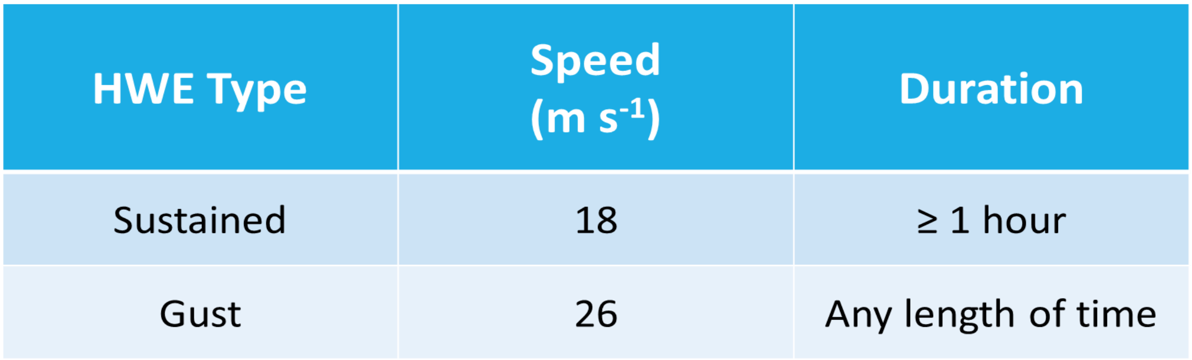


Fig. 2.34. Mean non-convective (a.) sustained and (b.) gust high-wind direction (gray line) and speed (black line) per year.

Table 2.1. NWS classification of sustained and gust high-winds.



HWE Type	Speed ($m\ s^{-1}$)	Duration
Sustained	18	≥ 1 hour
Gust	26	Any length of time

Table 2.2. P-values from two-sample T-test.

Groups	Sustained	Gust
1, 2	0.059	0.784
1, 3	0.000	0.000
2, 3	0.000	0.000

CHAPTER 3

SUMMARY AND CONCLUSIONS

3.1 Overview

HWEs are costly, sometimes deadly, events that can result in damages comparable to that of a tornado. Atmospheric processes such as the progression of extratropical cyclones, frontal boundaries, and meso-scale convective systems directly influence high-winds, yet little is known of the exact role these systems play. McCabe et al. (2001) found that extratropical cyclone activity in the midlatitudes decreased in frequency and increased in intensity during 1959 – 1997. Pryor et al. (2007) claimed an association with synoptic-level forcing and surface wind speeds, while also indicating an overall decline in wind speeds during 1973-2005. It is possible that these trends may crossover to HWEs as well.

High-winds may be defined as either sustained or gust, depending on the recorded wind speed and duration. Further, high-winds can occur in convective and non-convective environments most usually in the warm and cool season, respectively. Though numerous studies have analyzed regional characteristics of specific types of HWEs, a lack of information exists with regard to a complete HWE climatology in the U.S. The primary goal of this thesis is to provide an extensive spatial and temporal understanding of HWE behavior and activity during 1973-2015.

Several studies have analyzed convective and non-convective weather systems and their direct influence on property damage and wind-related fatalities (Peterson 2000; Martin and Konrad 2006; Ashley and Mote 2005; Ashley and Black 2008; Changnon 2009; Changnon 2011; Schoen and Ashley 2011). Other studies have produced case studies, reviews, and climatologies on non-convective HWEs alone (Niziol and Paone 2000; Crupi 2004; Lacke et al. 2007 Kurtz 2010; Knox et al. 2011; Durkee et al. 2012). Similar studies are limited to small regional scales, such as Martin and Konrad's (2006) study on HWEs in the southeast, or Li et al.'s (2008) study on HWEs in Owen's Valley California. Despite the plethora of high-wind research, there is not robust climatological convective and non-convective high-wind study that includes multiple regions of the U.S.

3.2 Summary

The purpose of this thesis was to provide a spatial and temporal understanding of convective and non-convective HWEs in the eastern U.S. During 1973-2015 there were 59,123 HWEs recorded at 391 first-order weather stations. 49% (28,793) were sustained and 51% (30,331) were gust (Fig. 3.1). Of sustained HWEs, approximately 1% (284) were convective and 99% (28,509) were non-convective. 15% (4,496) of total gust HWEs were convective and 85% (25,835) were non-convective. There were 8,078 HWDs recorded during the study period. Sustained HWEs were present for 65% (5,287) of the total HWDs and gust HWEs were present for 97% (7,860) of the total HWDs.

According to Changnon (2009), the most catastrophic wind-related loss occurred in the northeast, central, and western regions of the U.S. These regions are more populated, thus the damage risk is potentially greater in these areas. In this thesis, the West North Central region recorded the most HWDs of the seven regions with 3,341 sustained and 2,805 gust high-wind days (Fig. 3.2). This area includes the states of Nebraska, Montana, North and South Dakota, all of which fall into the lowest 25th percentile for state population according to 2010 U.S. Census data. The East North Central region recorded the least HWDs with 341 sustained and 549 gust. The most convective sustained and gust HWDs were recorded in the South whereas the West North Central region recorded the most non-convective sustained and gust HWDs. Although these results do not completely align with Changnon (2009), it is supportive when population is considered.

On any given HWD, 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 HWDs occurred in almost every season and region. Figure 3.3 displays these HWDs for both sustained and gust high-wind categories. As expected, the majority of concurrent HWDs occurred during the warm season months. The South recorded the greatest number of concurrent HWDs (N = 394, Gust = 95%). There were many more concurrent gust HWDs than sustained, which may be attributed to the correlation between strong cold fronts and wind gusts discussed in Pryor et al. (2014).

For all high-wind categories, southwesterly wind directions were most common, followed by north-to-northwesterly (Fig. 3.4). Lacke et al. (2007) also found a southwesterly preference in a study on non-convective high-winds in the Great Lakes, supporting other studies' findings (Niziol and Paone 2000; Knox et al. 2004; Durkee et al. 2012; Gilliland et al. 2018). Niziol and Paone (2000) suggested that high-winds 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.

In this study, the overall average high-wind direction displayed a trough-like pattern comparable to synoptic-level flow, supporting the hypotheses made by Pryor et al. (2014). Directions moved from northwesterly to southwesterly in a west-to-east orientation. This was seen regionally, as well – especially in the East North Central, Central, and Northeast regions. Average wind speeds indicated localized maximum speeds along the northeast and Gulf coasts for sustained, gust, and gust convective high-winds. Sustained convective high-wind speeds did not indicate any pattern, but interestingly recorded maximum speeds in the High Plains, Ohio Valley, and along the coasts as well.

Sustained high-winds occurred primarily in the winter and transitional months in every region. A noticeable springtime maximum existed for sustained HWDs in four of the seven regions. Gust high-winds were common in the spring and summer months for every region except the West North Central and Northeast regions where a wintertime maximum was observed. Convective high-winds were most frequent in the summer months, as previous studies had found (Kelly et al. 1985; Klimowski et al. 2003; Coniglio et al. 2004; Ashley and Mote 2005; Changnon 2011). Non-convective high-winds were prevalent in the winter and transitional months for every high-wind category, also in agreement with other high-wind studies (Niziol and Paone 2000; Lacke et al. 2007; Kurtz 2010; Knox et al. 2011; Durkee et al. 2012; Booth et al. 2015). Sustained and gust convective high-winds favored summer months in every region. Sustained and gust non-convective high-winds occurred more variably throughout the year, but mostly in the cool and transitional months.

Seasonally, HWEs displayed variable mean wind directions and speeds. A noticeable directional shift from westerly to easterly occurred during the summer and fall seasons, possibly due to PTC influence (Gilliland et al. 2018). Convective sustained HWEs experienced peak wind speeds in the summer months while convective gust wind speeds increased during the fall and winter. Non-convective sustained wind speeds increased during the summer season and non-convective gust wind speeds increased in the summer and fall seasons.

3.3 Conclusions

This thesis provides a thorough 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 U.S. from 1973-2015. It was found that every region in the study area was affected by HWEs and that certain types, namely convective gust HWEs, may be increasing with time.

Future work would ideally analyze 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 increase in gust HWEs and how it may affect the magnitude of catastrophic HWEs as discussed by

Changnon (2009). In closing, the results from this thesis may help to raise more awareness of the risks associated with high-winds and mitigate the hazards that ensue.

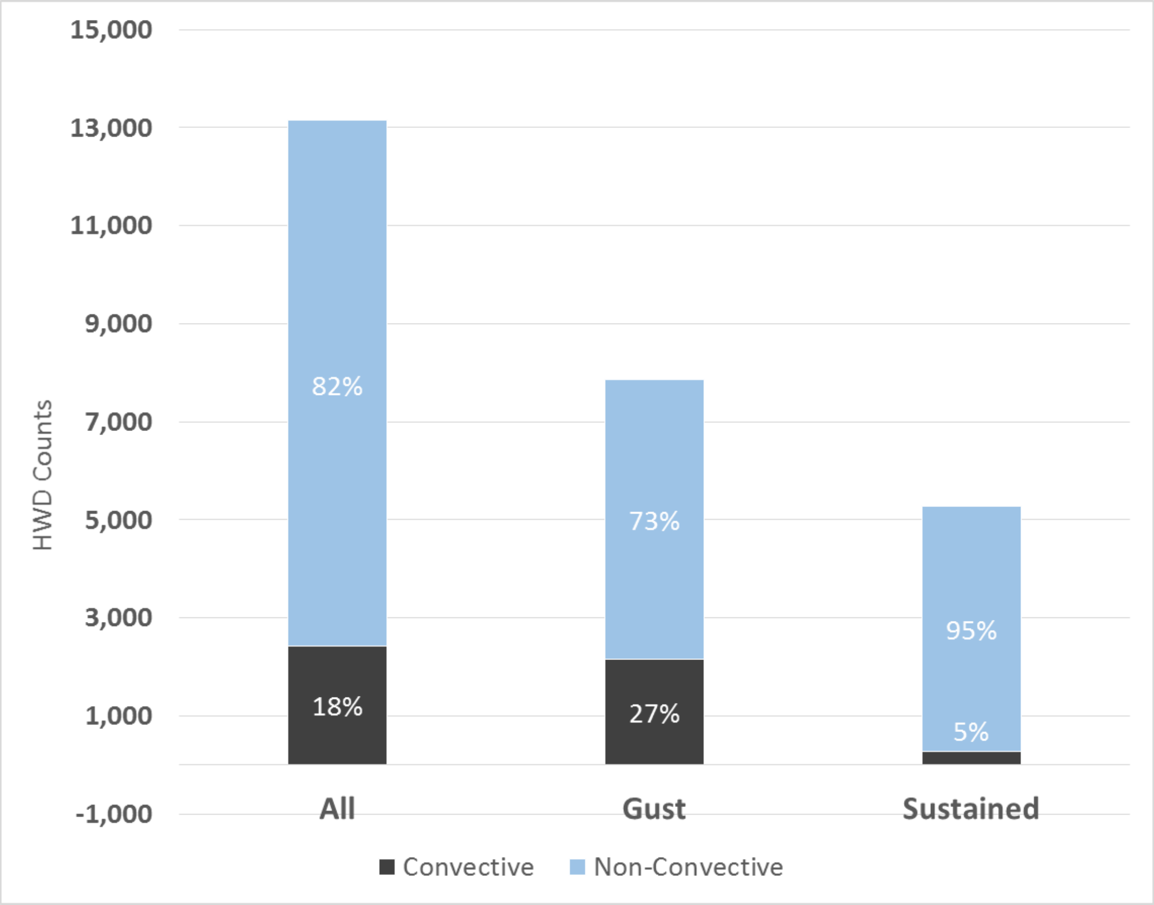


Fig. 3.1. HWD distribution by category.

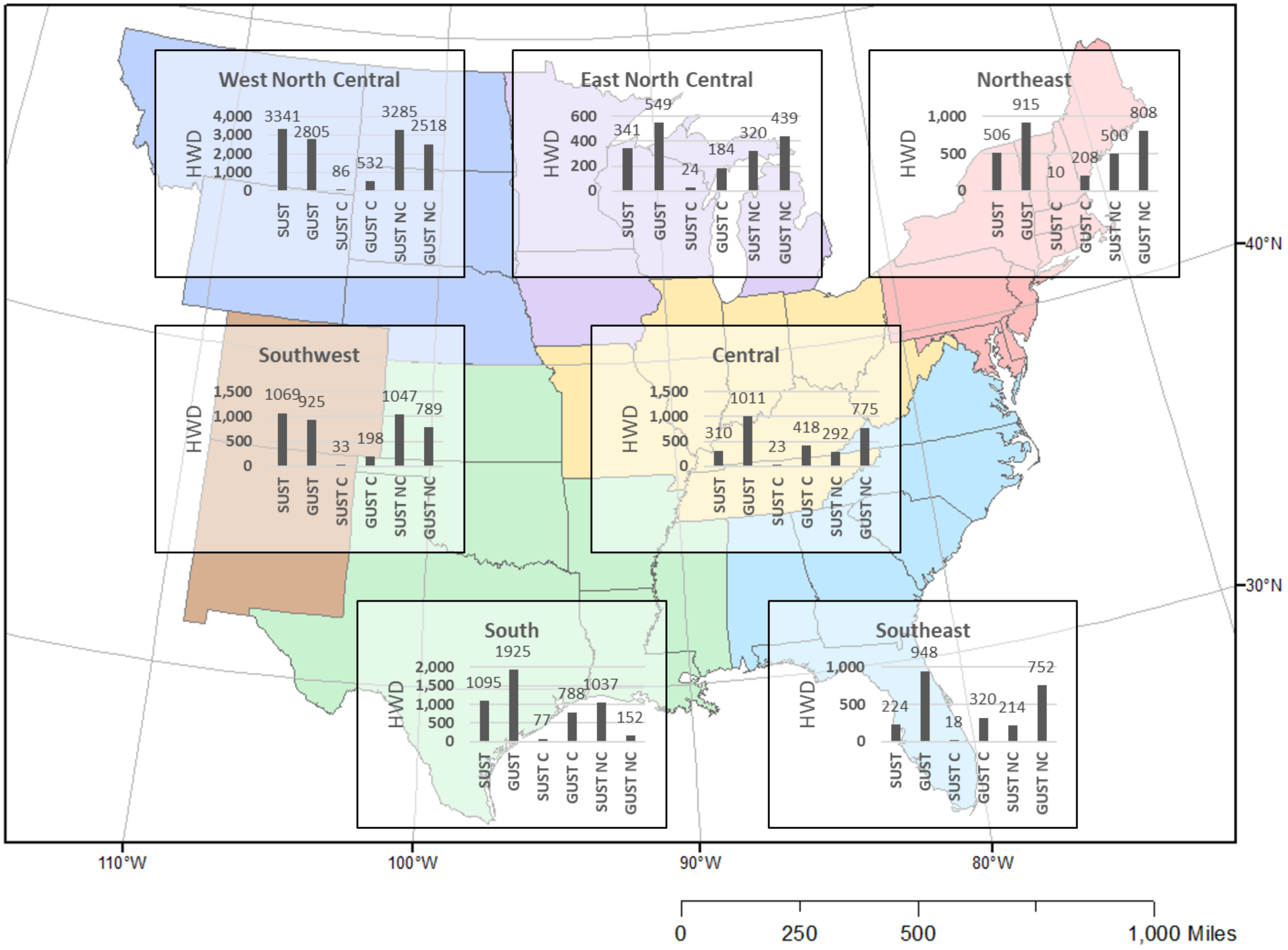
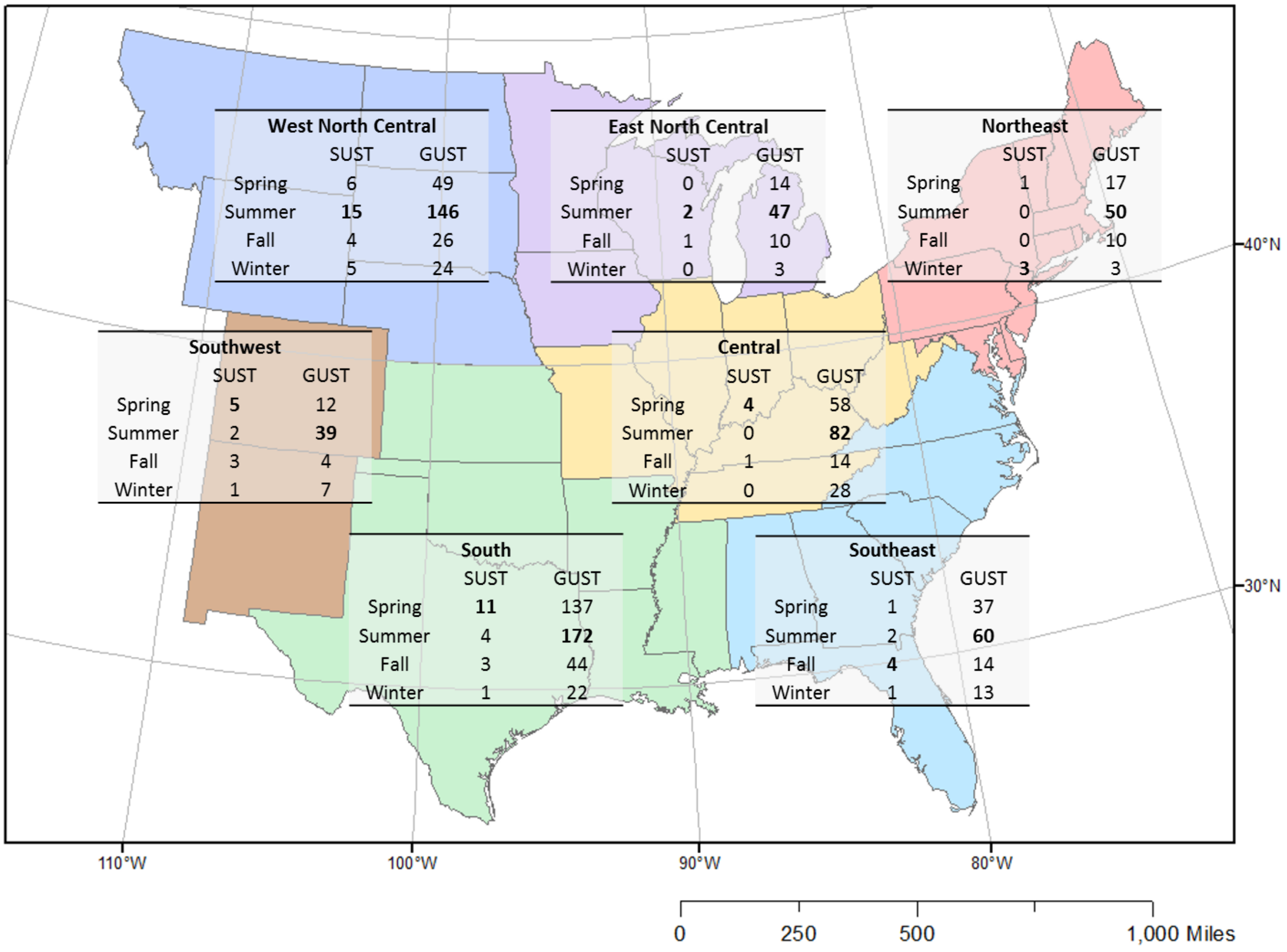


Fig. 3.2. HWD frequency per region and high-wind category.



West North Central

	SUST	GUST
Spring	6	49
Summer	**15**	**146**
Fall	4	26
Winter	5	24

East North Central

	SUST	GUST
Spring	0	14
Summer	**2**	**47**
Fall	1	10
Winter	0	3

Northeast

	SUST	GUST
Spring	1	17
Summer	0	**50**
Fall	0	10
Winter	**3**	3

Southwest

	SUST	GUST
Spring	**5**	12
Summer	2	**39**
Fall	3	4
Winter	1	7

Central

	SUST	GUST
Spring	**4**	58
Summer	0	**82**
Fall	1	14
Winter	0	28

South

	SUST	GUST
Spring	**11**	137
Summer	4	**172**
Fall	3	44
Winter	1	22

Southeast

	SUST	GUST
Spring	1	37
Summer	2	**60**
Fall	**4**	14
Winter	1	13

Fig. 3.3. Concurrent convective and non-convective HWDs per season and region (bold indicates maxima).

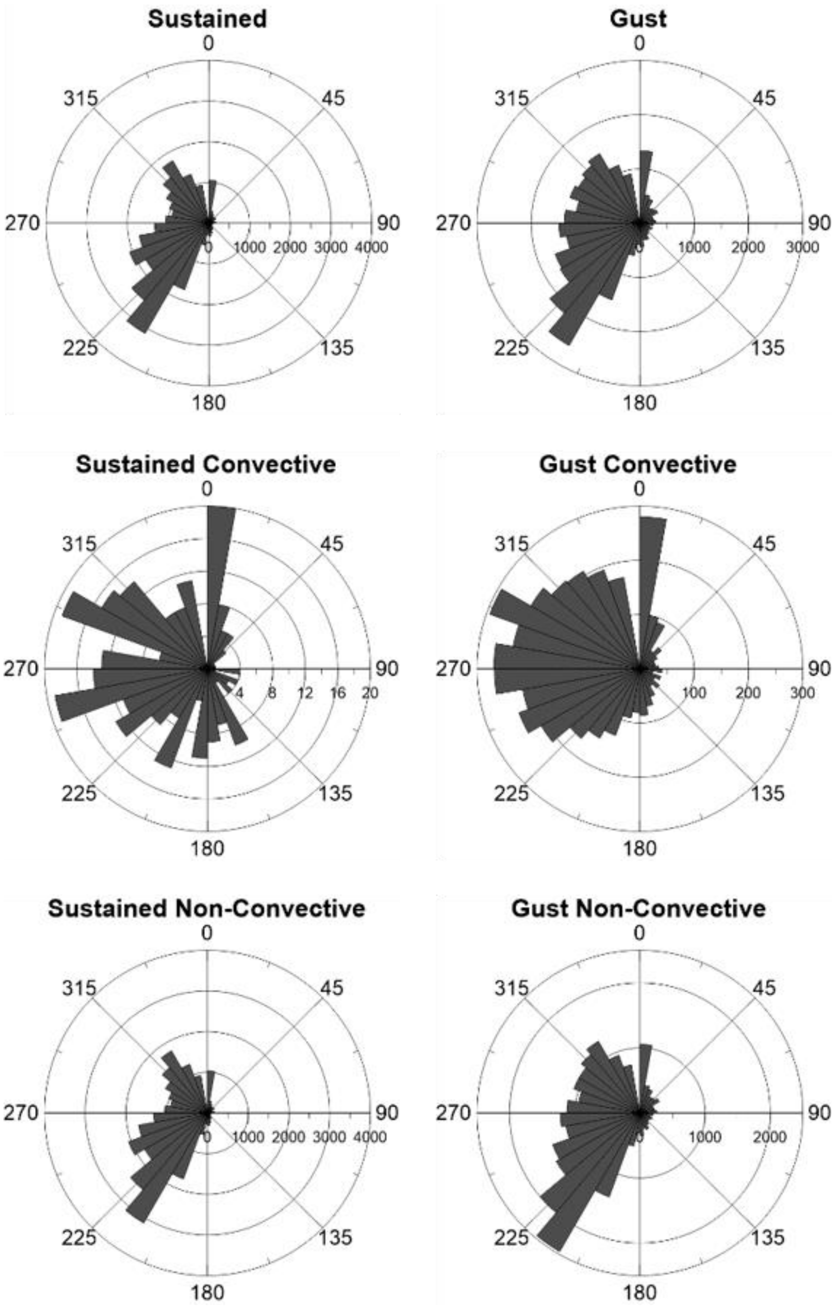


Fig. 3.4. Average high-wind direction (0°-360°) per category.

REFERENCES

Ashley, W.S. and A.W. Black, 2008: Fatalities Associated with Nonconvective High-Wind Events in the United States. *Journal of Applied Meteorology and Climatology,* **47**, 717-725.

Baker, L., 2009: Sting jets in severe northern European wind storms. *Weather,* **64**, 143-148.

Booth, J.F., H.E. Rieder, D. Lee, and Y. Kushnir, 2015: The paths of extratropical cyclones associated with wintertime high-wind events in the northeastern United States. *Journal of Applied Meteorology and Climatology*, **54**, 1871-1885.

Browning, K.A., 1997: The dry intrusion perspective of extra-tropical cyclone development. *Meteorological Applications,* **4**, 317-324.

Browning, K.A., 2004: The sting at the end of the tail: damaging winds associated with extratropical cyclones. *Quarterly Journal of the Royal Meteorological Society,* **130**, 375-399.

Browning, K.A., and B.W. Golding, 1995: Mesoscale aspects of a dry intrusion within a vigorous cyclone. *Quarterly Journal of the Royal Meteorological Society,* **121**, 463-493.

Cairns, M.M., and J. Corey, 2003: Mesoscale model simulations of high-wind events in the complex terrain of western Nevada. *Weather and Forecasting,* **18**, 249-263.

Changnon, S.A., 2009: Temporal and spatial distributions of wind storm damages in the United States. *Climatic Change,* **94**, 473-482.

Changnon, S.A., 2011: Windstorms in the United States. *Natural Hazards,* **59**, 1175-1187.

Clark, P.A., K.A. Browning, and C. Wang, 2005: The sting at the end of the tail: model diagnostics of the fine-scale 3D structure of the cloud head. *Quarterly Journal of the Royal Meteorological Society,* **131**, 2263-2292.

Coniglio, M.C., D.J. Stensrud, and M.B. Richman, 2004: An observational study of derecho-producing convective systems. *Weather and Forecasting,* **19**, 320-337.

Crupi, K.M., 2004: An anomalous non-convective high wind episode over upper Michigan. *National Weather Digest,* **28**, 3-12.

Durkee, J.D., C.M. Fuhrmann, J.A. Knox, and J.D. Frye, 2012: Ageostrophic Contributions to a Non-convective High Wind Event in the Great Lakes Region. *National Weather Digest,* **36**, 27-41.

Edwards, R., J.T. Allen, and G.W. Carbin, 2018: Reliability and Climatological Impacts of Convective Wind Estimations. *Journal of Applied Meteorology and Climatology,* Early Online Releases [available online at: https://journals.ametsoc.org/doi/abs/10.1175/JAMC-D-17-0306.1].

Fujita, T.T., and R.M. Wakimoto, 1981: Five scales of airflow associated with a series of downbursts on 16 July 1980. *Monthly Weather Review,* **109**, 1438-1456.

Gilliland, J.M., 2011: A Climatology of High-Wind Events Associated with Post-Tropical Cyclones in the United States. *Masters Theses & Special Projects*, **Paper 1074**, [available online at http://digitalcommons.wku.edu/theses/1074].

Gilliland, J.M., A.W. Black, J.D. Durkee, and V.A. Murley, 2018: A climatology of high-wind events for the eastern United States. *International Journal of Climatology (submitted).*

Goering, M.A., W.A. Wallus, M.A. Olsen, and J.L. Stanford, 2001: Role of stratospheric air in a severe weather event: analysis of potential vorticity and total ozone. *Journal of Geophysical Research*, **106**, 11813-11823.

Holton, J. R., 1992: An Introduction to Dynamic Meteorology. *Academic Press*, **3**, 67–69.

Homar, V., C. Ramis, and S. Alonso, 2002: A deep cyclone of African origin over the western Mediterranean: diagnosis and numerical simulation. *Annales Geophysicae,* **20**, 93-106.

Hoskins, B., and M. Pedder, 1980: The diagnosis of middle latitude synoptic development. *Quarterly Journal of the Royal Meteorological Society,* **106**, 707–719.

Hultquist, T.R., M.R. Dutter, and D.J. Schwab, 2006: A re-examination of the 9-10 November 1975 “Edmund Fitzgerald” storm using today’s technology. *Bulletin of the American Meteorological Society,* **87**, 607-622.

Iacopelli, A.J., and J.A. Knox, 2001: Mesoscale dynamics of the record-breaking 10 November 1998 mid-latitude cyclone: a satellite-based case study. *National Weather Digest,* **25**, 33-42.

Johns, R.H., and W.D. Hirt, 1987: Derechos: widespread convectively induced windstorms. *Weather and Forecasting,* **2**, 32-49.

Kapela, A.F., P.W. Leftwich, and R. Van Ess, 1995: Forecasting the impacts of strong wintertime post-cold front winds in the northern plains. *Weather and Forecasting,* **10**, 229-244.

Kelly, D.L., J.T. Schaefer, and C.A. Doswell III, 1985: Climatology of nontornadic severe thunderstorm events in the United States. *Monthly Weather Review,* **113**, 1997-2014.

Klemp, J.B., and R. Rotunno, 1983: A study of the tornadic region within a supercell thunderstorm. *Journal of Atmospheric Science,* **35**, 1070-1096.

Klimowski, B.A., M.J. Bunkers, M.R. Hjelmfelt, and J.N. Covert, 2003: Severe convective windstorms over the Northern High Plains of the United States. *Weather and Forecasting,* **18**, 502-519.

Klink, K., 1999: Climatological Mean and Interannual Variance of United States Surface Wind Speed, Direction and Velocity. *International Journal of Climatology,* **19**, 471–488.

Klink, K., 2002: Trends and interannual variability of wind speed distributions in Minnesota. *Journal of Climate,* **15**, 3311–3317.

Knox, J.A., J.D. Frye, J.D. Durkee, and C.M. Fuhrmann, 2011: Nonconvective high winds associated with extratropical cyclones. *Geography Compass,* **5**, 63-89.

Kuchera, E.L., and M.D. Parker, 2006: Severe convective wind environments. *Weather and Forecasting,* **21**, 595-612.

Kurtz, J., 2010: A climatology of cold season nonconvective wind events across the north central Plains, *M.S. Thesis*, Creighton University, 95 pp.

Lacke, M.C., J.A. Knox, J.D. Frye, A.E. Stewart, J.D. Durkee, C.M. Fuhrmann, and S.M. Dillingham, 2007: Climatology of Cold-season Non-convective Wind Events in the Great Lakes region. *Journal of Climate,* **20**, 6012-6222.

Lackmann, G., 2011: Midlatitude Synoptic Meteorology: Dynamics, Analysis, and Forecasting. *American Meteorological Society,* 318.

Lynch, A., E. Cassano, J. Cassano, and L. Lestak, 2003: Case studies of high wind events in Barrow, Alaska: climatological context and development processes. *Monthly Weather Review,* **131**, 719–732.

Martin, J., 2006: Midlatitude Atmospheric Dynamics: A First Course. *John Wiley & Sons, Ltd. West Sussex, England*.

Martin, J., and C. Konrad, 2006: Directional characteristics of potentially damaging wind gusts in the Southeast United States. *Physical Geography,* **27**, 155–169.

Markowski, P.M., 2002: Hook echoes and rear-flank downdrafts: a review. *Monthly Weather Review*, **130**, 852-876.

Markowski, P., and Y. Richardson, 2010: Mesoscale Meteorology in Midlatitudes. *John Wiley & Sons, Ltd. West Sussex, England.*

Mass, C., and B. Dotson, 2010: Major extratropical cyclones of the Northwest United States. Part I: historical review, climatology, and synoptic environment. *Monthly Weather Review*, **138**, 2499-2527.

McCabe, G., M. Clark, and M. Serreze, 2001: Trends in Northern Hemisphere surface cyclone frequency and intensity. *Journal of Climate,* **14**, 2763–2768.

Nissen, K.M., G.C. Leckebusch, J.G. Pinto, D. Renggli, S. Ulbrich, and U. Ulbrich 2010: Cyclones causing wind storms in the Mediterranean: Characteristics, trends and links to large-scale patterns. *Natural Hazards and Earth Systems Sciences*, **10**, 1379-1391.

Niziol, T., and T. Paone, 2000: A climatology of non-convective high wind events in western New York state. *NOAA Technical Memorandum, NWS ER-91* [available online at: http://www.erh.noaa.gov/er/hq/ssd/erps/tm/tm91.pdf].

Parton, G.A., G. Vaughan, E.G. Norton, K.A. Browning, and P.A. Clark, 2009: Wind profiler observations of a sting jet. *Quarterly Journal of the Royal Meteorological Society,* **135**, 663-680.

Pauley, P.M., N.L. Baker, and E.H. Barker, 1996: An observational study of the "Interstate 5" dust storm case. *Bulletin of the American Meteorological Society,* **77**, 693-720.

Peterson, C.J., 2000: Catastrophic wind damage to North American forests and the potential impact of climate change. *The Science of the Total Environment,* **262**, 287-311.

Pryor, S.C., R.J. Barthelmie, and E.S. Riley, 2007: Historical Evolution of Wind Climates in the USA. *Journal of Physics: Conference Series,* **75**, 012065.

Pryor, S.C., R. Conrick, C. Miller, J. Tytell, and R.J. Barthelmie, 2014: Intense and extreme wind speeds observed by anemometer and seismic networks: an eastern U.S. case study. *Journal of Applied Meteorology and Climatology,* **53**, 2417-2429.

Rose, M., 1996: Downbursts. *National Weather Digest,* **21**(1), 11-17.

Schoen, J.M. and W.S. Ashley, 2011: A climatology of fatal convective wind events by storm type. *Weather and Forecasting,* **26**, 109-121.

Schultz, J., and B. Meisner, 2009: The 24 February 2007 north Texas dust storm: an impact weather event. *National Weather Digest,* **33**, 165–184.

Stoppkotte, E., A. Lese, S. Pavlow, and R. Baker, 2009: 14 September 2008 Ohio Valley high wind event associated with the remnants of Hurricane Ike. Paper presented at the 23rd Conference on Weather Analysis and Forecasting⁄19th Conference on Numerical Weather Prediction, American Meteorological Society, Omaha, NE, 4 June 2009.

Tripoli, G.J., C.M. Medaglia, S. Dietrich, A. Mugnai, G. Panegrossi, S. Pinori, and E.A. Smith, 2005: The 9-10 November 2001 Algerian Flood: a numerical study. *Bulletin of the American Meteorological Society,* **86**, 1229-1235.

Van Den Broeke, M.S., D.M. Schultz, R.H. Johns, J.S. Evans, and J.E. Hales, 2005: Cloud-to-ground lightning production in strongly forced, low-instability convective lines associated with damaging wind. *Weather and Forecasting,* **20**, 517-530.

Vautard, R., J., Cattiaux, P. Yiou, J.N. Thepaut, and P. Ciais, 2010: Northern Hemisphere atmospheric stilling partly attributed to an increase in surface roughness. *Natural Geoscience,* **3**, 756-761.

Wakimoto, R.M., 1985: Forecasting dry microburst activity over the high plains. *Monthly Weather Review,* **113**, 1131-1143.

Zhong, S., J. Li, C.D. Whiteman, X. Bian, and W. Yao, 2008. Climatology of high wind events in the Owens Valley, California. *Monthly Weather Review,* **136**, 3536-3552.