Received: 10 July 2020 | Revised: 26 August 2020 | Accepted: 1 September 2020
DOI: 10.1002/met.1952

RESEARCH ARTICLE

Meteorological Applications RMetS

Historical incidence of mid-autumn wind storms in New England

Julia M. Simonson[1] | **Sean D. Birkel**[1] | **Kirk A. Maasch**[1] | **Paul A. Mayewski**[1] | **Bradfield Lyon**[1] | **Andrew M. Carleton**[2]

[1]Climate Change Institute and School of Earth and Climate Sciences, University of Maine, Orono, Maine

[2]Department of Geography, and the Polar Center, Pennsylvania State University, University Park, Pennsylvania

Correspondence
Julia M. Simonson, University of Maine, Orono, Maine.
Email: julia.simonson@maine.edu

Funding information
National Center for Atmospheric Research; University of Maine, Grant/Award Number: NA

Abstract

New England has seen a number of mid-autumn (October–November) wind storms—high-wind events associated with extratropical cyclones—in recent years that have produced extensive infrastructure damage, raising concerns that these events may become more common in a changing climate. Storms developing at this time of year are unique in that they can have dominant cold-season characteristics while also being fueled by warm-season moisture sources (such as the remnants of tropical cyclones) or the result of an extratropical transition. To provide insights on the behavior of such storms, we explore recent storm frequency and intensity by using reanalysis and station-based meteorological observations onward from 1979. Variables taken into consideration include 10 m wind speed, sea-level pressure and precipitation. The results do not show a statistically significant increase in the overall frequency of mid-autumn wind storms nor of their intensity with respect to central pressure or surface wind speeds. However, there is a statistically significant trend toward increasing precipitation accompanying wind storms with maximum 10 m wind gusts greater than 26 m·s^{-1} (58 mph). While stronger high-wind events tend to be associated with lower central sea-level pressure values and substantial intensification rates, other factors such as storm tracks and the pressure gradient across the New England region also affect the development and overall impact of storms. This study highlights the variety of elements, such as the background climate conditions, which could potentially increase the risk of wind damage in a warming world.

KEYWORDS

bomb cyclones, explosive cyclones, extratropical cyclones, high-wind events, wind storms

1 | INTRODUCTION

In the past 3 years, three notable mid-autumn wind storms, defined in this study as high-wind events associated with extratropical cyclones, caused extensive infrastructure damage across New England, primarily from wind gusts in excess of 20 m·s^{-1} and in some cases over 30 m·s^{-1}. The most impactful of these storms was a nor'easter (coastal storm) "bomb" cyclone (central pressure drop of at least 24 mbar in 24 hr at 60 ° latitude [Sanders and Gyakum, 1980]) that passed over eastern New York and Vermont on October 30, 2017, and resulted in over 1 million outages to the electric grid (Samenow, 2017). In Maine alone, electric utilities registered nearly 484,000 power outages, a number exceeding that resulting from the historic January 1998 ice storm, and over $69 million in damage to the State's electrical power grid (Graham, 2017; Russell, 2018). In 2019, two major wind storms occurred within 2 weeks of one another: the first occurred on 17 October with heaviest impact over eastern Massachusetts and southern Maine, and the second on 1 November with impacts from central to northern Maine. The October 17, 2019, storm was another nor'easter that underwent rapid intensification and became a bomb cyclone, setting a new record of 975.3 mbar for the lowest atmospheric pressure recorded in Boston, MA, for the month of October, and causing over 500,000 power outages (Barry, 2019). The November 1, 2019, storm was an extratropical cyclone that developed over the Ohio Valley and caused more than 800,000 power outages across 14 states in the Great Lakes, Mid-Atlantic and northeastern regions (Stanglin, 2019).

Wind storms represent a major hazard to life and property, as well as a potential mechanism for ecosystem disruption. Ashley and Black (2008) examined the number of fatalities as a result of non-convective high-wind events in the United States from 1980 to 2005 and found that these wind events can result in greater loss of life than thunderstorm or hurricane winds. More than 83% of all fatalities from these events are associated with passing extratropical cyclones, particularly in the US northeast region, and tend to occur across larger spatial and temporal scales than convective wind events. In forested regions that do not frequently experience fires, wind storms are a major disturbance to the local ecosystem. For example, a 1989 wind storm resulted in damage to 35% of the trees in an old growth forest in central New York (Marks *et al*., 1999). Also, 33% of wind storm fatalities involve felled trees (Ashley and Black, 2008) and the majority of power outages in states with extensive forest cover are the result of tree damage (Li *et al*., 2014). Autumn wind storms can potentially result in greater tree damage than those in other seasons, as the presence of foliage increases drag and wind stress on a tree and thus the risk of tree damage or uprooting from high winds (Vollsinger *et al*., 2005).

Due to the association of high-wind events with the passage of extratropical cyclones (Niziol and Paone, 2000; Lacke *et al*., 2007; Booth *et al*., 2015), most previous work examines high-wind events during the cold season (November–April). In the Great Lakes region and the northeastern United States, high-wind events during the cold season are most often associated with extratropical cyclones that travel from southwest to northeast, passing to the north and west of the northeast region. This preferred track is not necessarily associated with the strongest cyclones overall, but instead those in which the strongest winds of the cyclone (typically to the south or southeast of the storm center) pass over the region. Projecting changes to high-wind events in a warming climate will therefore depend in part on understanding how storm tracks might shift. Although winter extratropical cyclones in the western Atlantic are projected to decrease in frequency (Colle *et al*., 2013), Booth *et al*. (2015) note that projected increases in coastal storm track density over the eastern United States could result in more frequent nor'easters, which are associated with high winds as well as high storm surges.

The recent damaging wind storms in New England in 2017 and 2019 also incorporated attributes of warm-season storms. In the past two decades, heavy precipitation has increased across the northeastern United States, associated primarily with tropical cyclones and tropical moisture sources in September and October (Frei *et al*., 2015; Huang *et al*., 2017; 2018; Howarth *et al*., 2019). Major mid-latitude cites along the eastern coast of North America such as Washington, DC, New York City and Boston are threatened every 2–4 years by tropical cyclones or those that have transitioned to extratropical cyclones (Hart and Evans, 2001). Tropical cyclones that transition can re-intensify and bring heavy rainfall and strong winds farther north. One example is Hurricane Sandy in October 2012, which transitioned to a post-tropical storm prior to landfall and brought high winds and waves to New England (Galarneau *et al*., 2013). Additionally, wind storms originating over the continent can interact with offshore tropical cyclones or their remnants, thereby providing additional moisture and energy for the wind storm. This was the case for the October 30, 2017, wind storm, which absorbed the remnants of Tropical Storm Philippe (NOAA, 2017), and the October 18–22, 1996, wind storm, which tapped into moisture advected from Hurricane Lili (McNally *et al*., 2008). Model projections and analysis of empirical data indicate that a future environment of warmer sea surface temperatures and lower wind shear in the eastern North Atlantic will be more conducive to tropical cyclone development and propagation (Benestad, 2009; Liu *et al*., 2017). There could also be a greater proportion of tropical cyclones undergoing extratropical transition, resulting in extratropical cyclones of greater intensity and which produce heavier precipitation than in the current climate (Liu *et al*., 2017; Jung and Lackmann, 2019; Michaelis and Lackmann, 2019). Moreover, storm tracks for tropical and extratropical cyclones could shift poleward and closer to the eastern US coast due to a more northerly polar jet and a northward and westward expansion of the subtropical high (Jiang and Perrie, 2007; Liu *et al*., 2017). These future scenarios imply not only an increase in the number of wind storms originating from the tropics, but also that mid-autumn wind storms, in general, will probably produce more heavy rainfall.

Another question of concern is whether the frequency and intensity of wind storms have changed in response to broader circulation patterns. The three unusually strong wind storms to affect the New England region in 2017 and 2019 occurred during an interval of unprecedented autumn warmth in the Arctic (Overland *et al*., 2017; 2019). Previous studies have suggested that Arctic amplification (northern high latitude warming associated with greenhouse-gas increases and albedo, water vapor, cloud and other feedbacks [e.g. Stroeve *et al*., 2012]) affords weakened zonal flow of the westerlies and higher amplitude Rossby waves (Francis and Vavrus, 2012; 2015). A "wavier" jet stream circulation has been linked to atmospheric blocking and increased extreme weather in the middle latitudes (Screen and Simmonds, 2014). However, the underlying dynamics associated with this phenomenon are still uncertain, as other studies have indicated that an increasing wave amplitude trend is sensitive to how atmospheric waves are defined, and the trend is not replicated by climate model simulations (Screen and Simmonds, 2013; Barnes *et al*., 2014; Blackport and Screen, 2020).

This study examines storm characteristics and changes in the frequency and intensity of mid-autumn (October–November) wind storms in New England to help inform future climate projections for the region. We first develop a climatology of wind storms using reanalysis data, gridded precipitation data and surface station observations. We then identify trends in wind storm frequency and intensity (as measured by sustained wind speeds and gusts), as well as other properties of the events such as the central sea-level pressure (SLP), SLP tendency and the SLP gradient of the accompanying extratropical cyclone, and daily precipitation. In addition, we assess and compare the characteristics of stronger and weaker wind storms. These include the distribution of the SLP tendencies (i.e. intensification/deintensification rates of associated extratropical cyclones), composite analyses of SLP and maximum 10 m wind gusts for stronger and weaker wind storms, preferential storm tracks, and the prevailing wind direction of wind gusts. Section 2 details the methodology. The analysis results are described and discussed in Sections 3 and 4. A summary of our major conclusions is presented in Section 5.

2 | DATA AND METHODS

This study uses two gridded datasets and one station observation dataset. Atmospheric data were extracted from the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis version 5 (ERA5; Hersbach *et al*., 2020; ECMWF, 2019), a fifth generation reanalysis product and the successor to the ERA-Interim reanalysis. This reanalysis was chosen for its high spatial and temporal resolutions, with global variables available at 31 km grid cell resolution and hourly time outputs. Data were acquired for SLP, 10 m maximum wind gusts, 10 m zonal (u) and meridional (v) winds, and precipitation for October and November from 1979 to 2019. Maximum wind gusts in the reanalysis are derived from instantaneous model calculations within the preceding forecast integration. Precipitation data were obtained from the Parameter-Elevation Regressions on Independent Slopes Model (PRISM) (Daly *et al*., 1994; PRISM Climate Group, 2020) time series dataset, a set of spatial climate data products for temperature, dew point temperature, vapor pressure and precipitation. PRISM interpolates estimates of climate data to a 30 s 2.5 min (~4 km) resolution grid using station data, a digital elevation model and other spatial datasets. Daily precipitation totals were used from 1981 to 2018. Surface observation data were obtained from the National Oceanic and Atmospheric Administration (NOAA) Integrated Surface Database (ISD) (Smith *et al*., 2011) daily summaries database. The ISD consists of hourly and synoptic weather observations from more than 35,000 stations worldwide, with some locations having data as far back as 1901. The daily summaries subset includes various daily mean and maximum values (based on Greenwich Mean Time), such as sea-level and station pressures, 10 m sustained wind and gusts, temperature and precipitation. Station data for daily maximum wind gusts, maximum sustained winds and total accumulated precipitation were obtained for 15 stations in the states of Maine, New Hampshire, Vermont, Massachusetts, Rhode Island and Connecticut (Figure 1).

For this study, we identify wind storms using wind gust and sustained wind speed thresholds corresponding to the National Weather Service (NWS) Wind Advisory and High Wind Warning criteria (https://www.weather.gov/box/criteria). Wind storms were defined using the Wind Advisory criteria as when the daily maximum wind gust was at or above 21 $m{\cdot}s^{-1}$ (46 mph) or the daily maximum sustained wind speed (maximum observed 2 min average wind speed) was at or above 14 $m{\cdot}s^{-1}$ (31 mph). For observation-based wind storms, the criteria must be met at three or more stations. A subset of strong wind storms was defined using the NWS High Wind Warning criteria as days with maximum wind gusts of at least

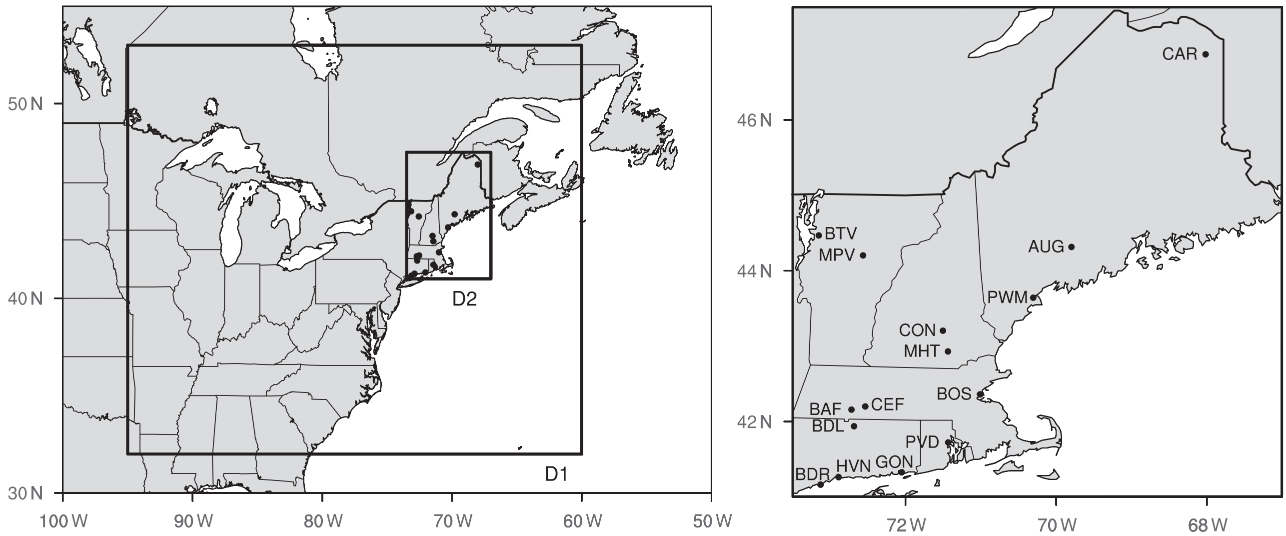

FIGURE 1 Domains for sea-level pressure (D1, left) and 10 m wind gusts (D2, right) with the locations of observation stations. Surface stations include Augusta, ME (AUG); Barnes, MA (BAF), Hartford-Bradley, CT (BDL); Bridgeport, CT (BDR); Boston, MA (BOS); Burlington, VT (BTV); Caribou, ME (CAR); Chicopee Falls, MA (CEF); Concord, NH (CON); Groton-New London, CT (GON); New Haven, CT (HVN); Manchester, NH (MHT); Montpelier, VT (MPV); Providence, RI (PVD); and Portland, ME (PWM)

26 m·s^{-1} (58 mph) or maximum 2 min sustained winds of at least 18 m·s^{-1} (40 mph). Both the wind gust and sustained wind speed criteria were used for observations in order to produce a more complete climatology of events, as wind gusts are only recorded when wind speeds rapidly fluctuate by 10 kn (5.1 m·s^{-1}) or more, but a wind storm event only needs to satisfy the threshold for at least one of the wind variables.

Two wind storm climatologies were created using the ERA5 reanalysis and PRISM precipitation datasets. For the first climatology, wind storms were identified using 3 hourly SLP and maximum wind gust fields over two domains (D1 and D2, Figure 1). Within the larger domain, low-pressure centers were isolated by comparing the SLP of a given grid cell with the eight grid cells surrounding it to see if the pressure of the central cell was lower than its neighbors, a commonly used approach (Ulbrich *et al.*, 2009; Neu *et al.*, 2013). Additional criteria were applied in order to isolate high-wind events over land that are associated with synoptic-scale features, as opposed to short-lived events or high winds confined to elevated terrain. A low center was designated as a wind storm if the maximum wind gusts for more than 20 grid cells within the inner domain were at or above the advisory or warning criteria. A land–sea mask was used to exclude wind values over water, and wind storms lasting <12 hr were also excluded. Although these restrictions produce a smaller sample of wind storms (the number identified approximately doubles using a 10 grid cell criterion), the additional "events" typically involve a few grid cells, often localized over mountain peaks, with maximum wind gusts just above the minimum criterion, and would be unlikely to result in substantial wind damage in the region. A second reanalysis climatology was created by applying the wind gust criteria to the grid cells corresponding to the approximate locations of the ISD surface stations. As with the observation-based climatology, the wind criteria must be met at three or more station locations.

The statistical analysis for the reanalysis- and observation-based wind storm climatologies consisted of assessing the frequency and intensity of wind storms for the period October 1 to November 30 inclusive, as well as the 2 months separately. Wind storm frequency was determined by counting the number of storms that occurred during the specified time period. Although wind storm intensity was defined by sustained winds and gusts, other storm characteristics were also assessed, including the central SLP of the low-pressure center, the 24 hr normalized SLP tendency, the SLP gradient, the average daily accumulated precipitation within the inner domain for the domain-level reanalysis-based climatology, and the daily total precipitation for the two station-level climatologies. SLP tendencies were calculated over a 24 hr period centered on the time of maximum wind gusts (T_0) and then normalized to a reference latitude of 46 ° N following Roebber (1989):

$$\Delta P_{46} = \frac{\Delta P_{\phi} \sin 46^{\circ}}{\sin \phi}$$

where ΔP_{46} is the normalized 24 hr SLP tendency, ΔP_{ϕ} is the SLP tendency and ϕ is the mean latitude of the low during the 24 hr period. At 46 ° N, the threshold for a bomb cyclone is a drop in central pressure of at least 20 mbar over 24 hr. SLP gradients were calculated by choosing the maximum difference between the central SLP value from the SLP 10 grid squares from the low in the four cardinal directions, which are normalized to 1,000 km. The trends in these individual variables were identified using the ordinary linear regression slope and the Theil–Sen slope estimator (Theil, 1950; Sen, 1968), and the statistical significance of the trends was assessed at the 95% level using Student's t test and the Mann–Kendall trend test (Mann, 1945; Kendall, 1948). The Theil–Sen slope estimator represents how the median of the data changes linearly with time. This method is a non-parametric alternative to least squares regression, which represents how the mean of the data changes with time. The Mann–Kendall test is a commonly used non-parametric test for detecting statistically significant linear or non-linear trends in hydrological and meteorological time series (Tabari *et al.*, 2011; Romanić *et al.*, 2015). The null hypothesis is that there is no trend, while the alternative hypotheses are that there is a negative, positive or non-null trend. This test is based on the ranks of observations and compares the relative magnitudes of data points as opposed to the data values themselves (Gilbert, 1987). The advantage of the Mann–Kendall test is that it is not affected by the distribution of the data and is less sensitive to outliers. The statistical analysis was performed using the NCAR Command Language (NCL) functions for linear regression and Mann–Kendall/Theil–Sen (NCAR, 2019).

3 | RESULTS

3.1 | Trends

For the 1979–2019 study period, 44 wind storms were identified from the reanalysis in connection with a low-pressure system in proximity to New England. Wind storms more often occur in November, and the majority of October wind storms occur near the end of the month (Figure 2). A greater number of wind storms are identified at the station level from the reanalysis (82) and a smaller number from observations (35), probably due to stronger reanalysis wind gusts at surface stations along the coast. As a result, the number of strong storms, which correspond to the NWS's High Wind Warning criteria

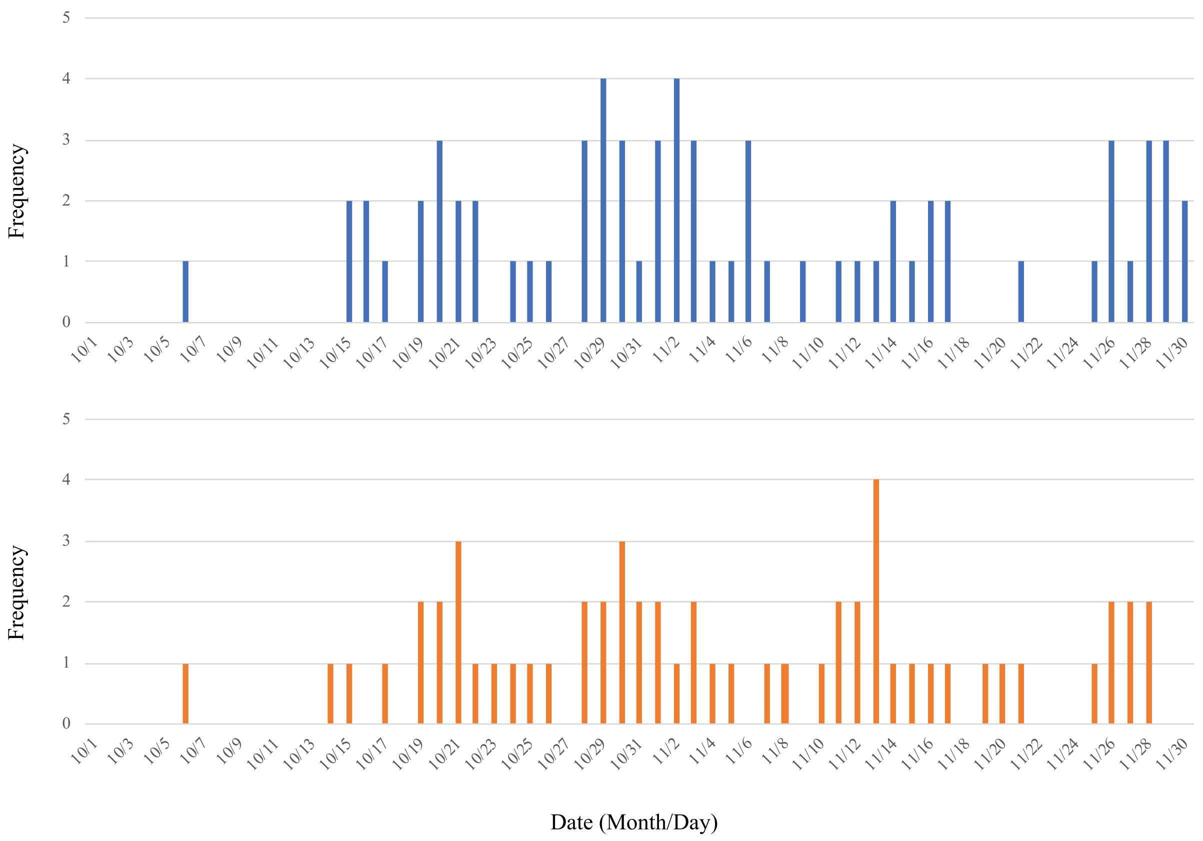

FIGURE 2 Distribution of all wind storms from the domain-level reanalysis-based climatology (top) and the station-level observation-based climatology (bottom)

(wind gusts greater than 26 m·s^{-1} or sustained winds greater than 18 m·s^{-1}), constitute less than half (45%) of all wind storms included in the station-level reanalysis-based climatology, while the number of strong storms are similarly dispersed among the domain-level reanalysis-based (61%) and the station-level observation-based (54%) climatologies (Table 1). Thirteen wind storms from the domain-level climatology are associated with extratropical cyclones that meet the criteria for a bomb cyclone (normalized 24 hr SLP tendency ≤ −20 hPa), with 10 of those storms resulting in wind gusts greater than 26 m·s^{-1} over New England. This indicates that while bomb cyclones are linked to strong wind storms more often than weak ones, the majority of wind storms in the region are not associated with bomb cyclones.

For the reanalysis- and observation-based climatologies, there are no significant positive or negative trends in overall wind storm frequency (Table 1). The lack of a significant positive or negative trend in the number of wind storms over time is partly reflective of the relatively small sample of events for the 41 year study period, with the number of storms generally ranging between zero and two during the 2 month period (Figure 3). In examining the full length of the record, there appears to be greater year-to-year variability in the number of wind storms in the past two decades compared to the two decades prior. However, there is not a similarly marked difference in the frequency of bomb cyclones between the first half of the study period compared to the latter half.

The results of the storm intensity (sustained winds and wind gusts) and storm characteristic metrics (SLP, normalized SLP tendency, SLP gradient, precipitation) indicate that there are few statistically significant trends present in more than one of the climatologies. There are no statistically significant trends in the domain-level reanalysis-based climatology (Table 2). However, there are statistically significant trends in precipitation identified from the two station-level climatologies. For the station-level reanalysis-based climatology, statistically significant positive trends are present for daily precipitation from strong October wind storms (Table 3). From the observation-based climatology, there are statistically significant positive precipitation trends for both categories of October wind storms as well as for the 2 month period overall for strong wind storms (Table 4).

TABLE 1 Statistical analysis of wind-storm frequency (storms·year^{-1}) for the reanalysis-based and station-based wind storm climatologies

			Total	Linear slope	Theil–Sen slope
ERA5	All	2 month	44	0.02	0.00
Domain level		October	18	0.02	0.00
		November	26	0.00	0.00
		BC	13	0.00	0.00
	Strong	2 month	27	0.01	0.00
		October	10	0.02	0.00
		November	17	0.00	0.00
		BC	10	0.00	0.00
ERA5	All	2 month	82	0.01	0.00
Station level		October	35	0.02	0.00
		November	47	−0.01	0.00
	Strong	2 month	37	0.00	0.00
		October	16	0.01	0.00
		November	21	−0.01	0.00
ISD	All	2 month	35	0.00	0.00
Station level		October	15	0.00	0.00
		November	20	0.00	0.00
	Strong	2 month	19	−0.01	0.00
		October	11	0.00	0.00
		November	8	0.00	0.00

Strong storms are those in which maximum wind gusts greater than 21 m·s^{-1} (58 mph) or maximum sustained winds greater than 18 m·s^{-1} (40 mph) are present. Bomb cyclones (BC) are wind storms where the 24 hr SLP tendency is −20 hPa or lower.

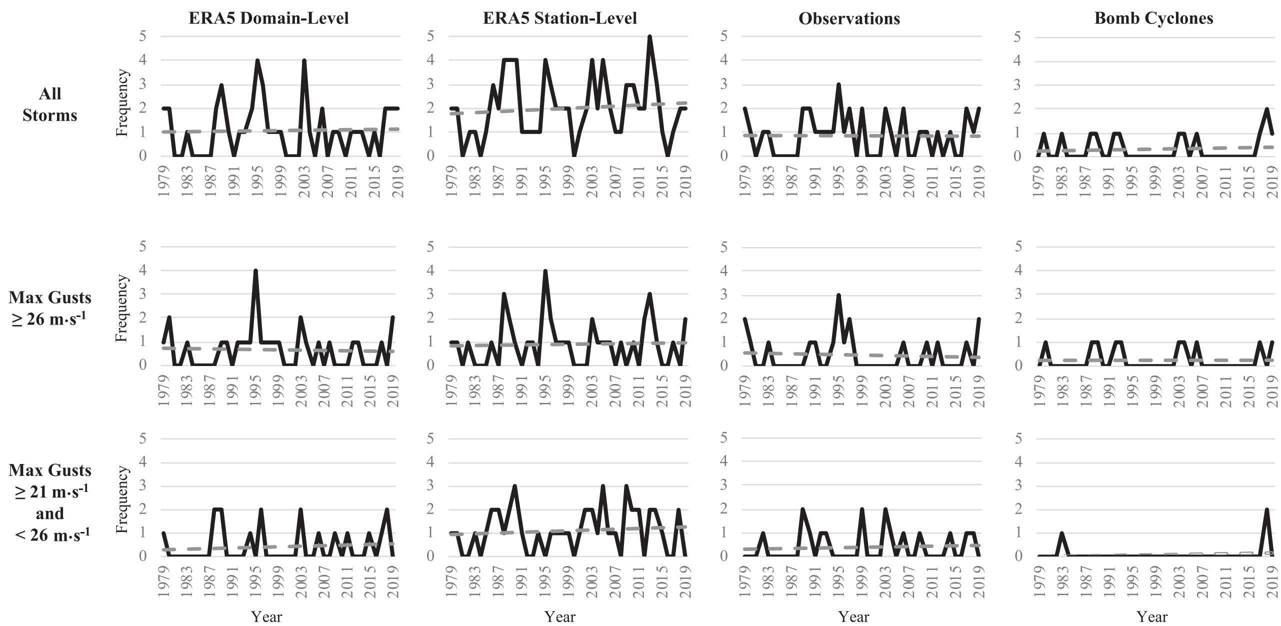

FIGURE 3 The frequency of wind storms over time for 1979–2019 from the domain-level reanalysis-based climatology (far left), the station-level reanalysis-based climatology (center left), the observation-based climatology (center right), and the number of wind storms classified as bomb cyclones from the domain-level reanalysis-based climatology (far right). The linear regression line is indicated in gray in each plot

3.2 | Storm characteristics

In this section, the characteristics of wind storms included in the domain-level reanalysis-based climatology are examined, as well as how storm characteristics differ between the first half of the study period (1979–1999) and the second half (2000–2019), and between weak and strong wind storms. These characteristics include the intensification/deintensification rates of the extratropical cyclones, the composite SLP and wind gust fields for weak and strong wind storms, the spatial distribution of storm tracks, and the prevailing direction of high winds.

The first storm characteristic is the intensification (and deintensification) rates for the extratropical cyclones associated with wind storms. The normalized 24 hr SLP tendency, which is calculated over a 24 hr period centered on the time of maximum wind gusts, indicates whether the accompanying low-pressure systems are strengthening (deepening) or weakening (filling) during the wind event. The normalized 24 hr SLP tendencies for all wind storms, as well as strong and weak wind storms separately, are shown in Figure 4. Overall, the low-pressure systems tend to deepen during high-wind events in New England. The distribution for SLP tendencies for all wind storms has two peaks, with a higher peak at weakly negative or zero tendencies and a lower peak at negative tendencies falling within the criteria for bomb cyclones. The average 24 hr SLP tendency for the sample of strong wind storms is −13.6 hPa and −8.3 hPa for the sample of weaker wind storms. The peak SLP tendency for strong wind storms is towards slightly more negative values (greater deepening rates) than weaker storms. However, the SLP tendencies for weak wind storms are concentrated towards less negative and more positive values while SLP tendencies for strong storms are more evenly distributed across highly negative, less negative and positive tendencies. When examining the SLP tendency distributions for the first and second half of the study period (Figure 5), the general pattern is a shift towards lower SLP tendencies, and thus higher deepening rates, for all wind storms. Also, the number of bomb cyclones stays the same or slightly increases for both weak and strong wind storms, despite a decrease in the overall number of wind storms between the first and second half of the study period.

The second storm characteristic is the average, or composite, SLP and wind fields associated with stronger and weaker wind storms. A region-specific composite approach on a fixed grid (D1) is used, as opposed to a storm-relative approach on a movable grid, to examine the variable fields with respect to New England. Figure 6 shows the composites for strong and all other wind storms, respectively, at the time of maximum wind gusts, as well as 12 hr before and after. The average storm track for both wind storm categories is similar, with the center of the low approaching New England from the southwest and then passing to the north of the region, which is

TABLE 2 Statistical analysis of wind storm intensity for the domain-level reanalysis-based climatology

		Variable	Linear slope	Theil–Sen slope
All	2 month	SLP	0.02	0.07
		SLPtend	0.02	0.02
		SLPgrad	0.02	−0.15
		Max gust	−0.01	−0.02
		PRE	0.03	0.00
	October	SLP	−0.16	−0.20
		SLPtend	−0.01	0.00
		SLPgrad	0.14	0.00
		Max gust	0.04	0.17
		PRE	0.01	−0.30
	November	SLP	0.15	0.21
		SLPtend	0.10	0.07
		SLPgrad	−0.01	0.35
		Max gust	−0.05	−0.08
		PRE	0.01	−0.08
Strong	2 month	SLP	−0.34	0.00
		SLPtend	0.02	0.04
		SLPgrad	0.04	−0.27
		Max gust	−0.02	0.00
		PRE	−0.17	0.00
	October	SLP	−0.14	−0.33
		SLPtend	0.00	0.00
		SLPgrad	0.02	0.00
		Max gust	−0.04	−0.03
		PRE	0.20	−0.57
	November	SLP	0.04	0.23
		SLPtend	0.03	0.01
		SLPgrad	−0.04	0.63
		Max gust	−0.02	0.02
		PRE	−0.21	−0.24

Units are hPa·year^{-1} for sea-level pressure, hPa·(24 hr)$^{-1}$·year^{-1} for normalized sea-level pressure tendency, hPa·(1,000 km)$^{-1}$·year^{-1} for pressure gradient, m·s^{-1}·year^{-1} for 10 m wind gusts and mm·year^{-1} for precipitation.

consistent with previous studies (e.g. Niziol and Paone, 2000; Booth *et al.*, 2015). The strongest surface winds across New England tend to be out of the south or southeast, and the strongest wind gusts occur to the southeast of the low center. Notable differences between the two sets of composites are that the average low pressure system associated with strong wind storms tends to be more compact and have a lower central SLP value.

The third storm characteristic is the preferred storm tracks of wind storms. Although the composites indicate a prevalent southwest-to-northeast path over the Great Lakes, it is also important to consider other major storm tracks. From the domain-level climatology, we identify three categories of storm tracks. The first category is the southwest-to-northeast track over the Great Lakes previously shown in the composites (Figure 7a), the second category includes lows originating in closer proximity to the East Coast, such as nor'easters (Figure 7b), and the third category includes tracks over the western Great Lakes with more south-to-north trajectories towards Hudson Bay (Figure 7c). The first two categories each account for approximately a third (15 and 14 wind storms, respectively) of all wind storms, while the third category accounts for 22% (10) of wind storms. Four

TABLE 3 As in Table 2 but for the station-level reanalysis-based climatology

	Duration	Variable	Linear slope	Theil–Sen slope
All	2 month	Max gust	0.00	−0.02
		Max wind	0.00	0.01
		PRE	−0.06	−0.14
	October	Max gust	0.00	0.00
		Max wind	0.01	0.04
		PRE	0.22	0.32
	November	Max gust	−0.01	−0.02
		Max wind	0.03	0.04
		PRE	−0.35	−0.51
Strong	2 month	Max gust	0.03	0.04
		Max wind	0.00	0.00
		PRE	0.44	−0.07
	October	Max gust	0.03	0.18
		Max wind	−0.05	0.09
		PRE	0.30	**0.25**
	November	Max gust	0.05	0.08
		Max wind	0.02	0.14
		PRE	−0.52	−0.67

Statistically significant trends at the 95% level are in bold.

TABLE 4 As in Table 2 but for the station-level observation-based climatology

	All	Variable	Linear slope	Theil–Sen slope
All	2 month	Max gust	0.01	0.00
		Max wind	−0.01	−0.01
		PRE	0.38	0.65
	October	Max gust	0.01	**0.01**
		Max wind	−0.01	−0.07
		PRE	**0.68**	2.47
	November	Max gust	0.00	0.01
		Max wind	−0.01	−0.01
		PRE	0.05	0.19
Strong	2 month	Max gust	−0.05	−0.13
		Max wind	−0.02	−0.02
		PRE	**0.65**	1.77
	October	Max gust	−0.04	−0.23
		Max wind	0.01	−0.07
		PRE	**0.71**	3.56
	November	Max gust	−0.01	−0.02
		Max wind	−0.06	−0.01
		PRE	0.24	0.00

Statistically significant trends at the 95% level are in bold.

storms had paths that did not fit any of the categories. Bomb cyclones are more common in the second (seven) and the first storm track categories (six) than the third category (two).

The last storm characteristic is the prevailing direction of maximum wind gusts in the region. Although these high-wind events are associated with an extratropical cyclone, previous studies and the composite

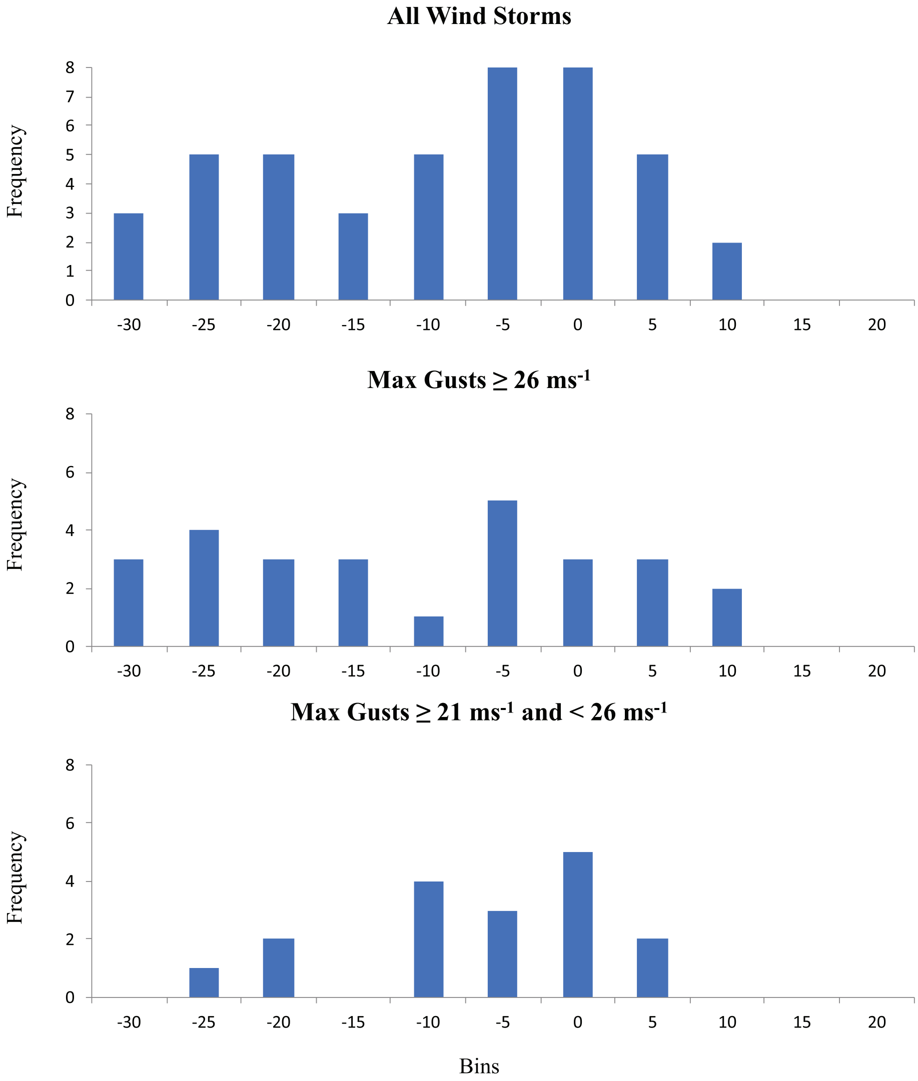

FIGURE 4 Normalized 24 hr sea-level pressure tendency distributions for wind storms from the domain-level reanalysis-based climatology. Bins are at intervals of 5 hPa·(24 hr)$^{-1}$ with the upper bounds labeled (i.e. < −30, −30 to −25, −25 to −20, etc.)

analysis show that the highest winds are more closely tied to the location of a frontal boundary (Leckebusch *et al.*, 2008; Nissen *et al.*, 2010; Booth *et al.*, 2015). To examine the prevailing wind direction during the wind storms, wind roses for several station locations are shown in Figure 8. While the direction of wind gusts varies for some stations along the southern New England coast and southern New Hampshire, the strongest wind gusts, as well as event winds overall, tend to be out of the south or southeast (wind a lesser fraction out of the east or northeast). The prevailing wind directions indicated by the wind roses and the composites are consistent with previous studies indicating that the highest winds are located in the southeast quadrant of the low ahead of a cold front.

4 | DISCUSSION

The results of this study support and expand upon the findings from previous studies on the characteristics of high-wind events associated with extratropical cyclones in the region. The composite analysis shows that high-wind events in New England associated with extratropical cyclones typically approach from the southwest and pass to the north of the region, and the wind roses indicate that the strongest winds tend to be out of the south or southeast. This storm track and prevailing wind direction are consistent with the results of previous wind storm studies (e.g. Booth *et al.*, 2015), which indicate that the southeast quadrant of a low is where the strongest winds are located. However, there are many examples of wind storms that have characteristics differing from the composite. Low-pressure systems with more coastal storm tracks (such as nor'easters) occur at an equal frequency to the Great Lakes storm track indicated by the composite, although the lows tend to pass to the north of the region as well. The majority of wind storms that fall within the third storm track category are considered strong wind storms, and yet the lows do not approach New England at all. Additionally, the strongest wind storms are not always

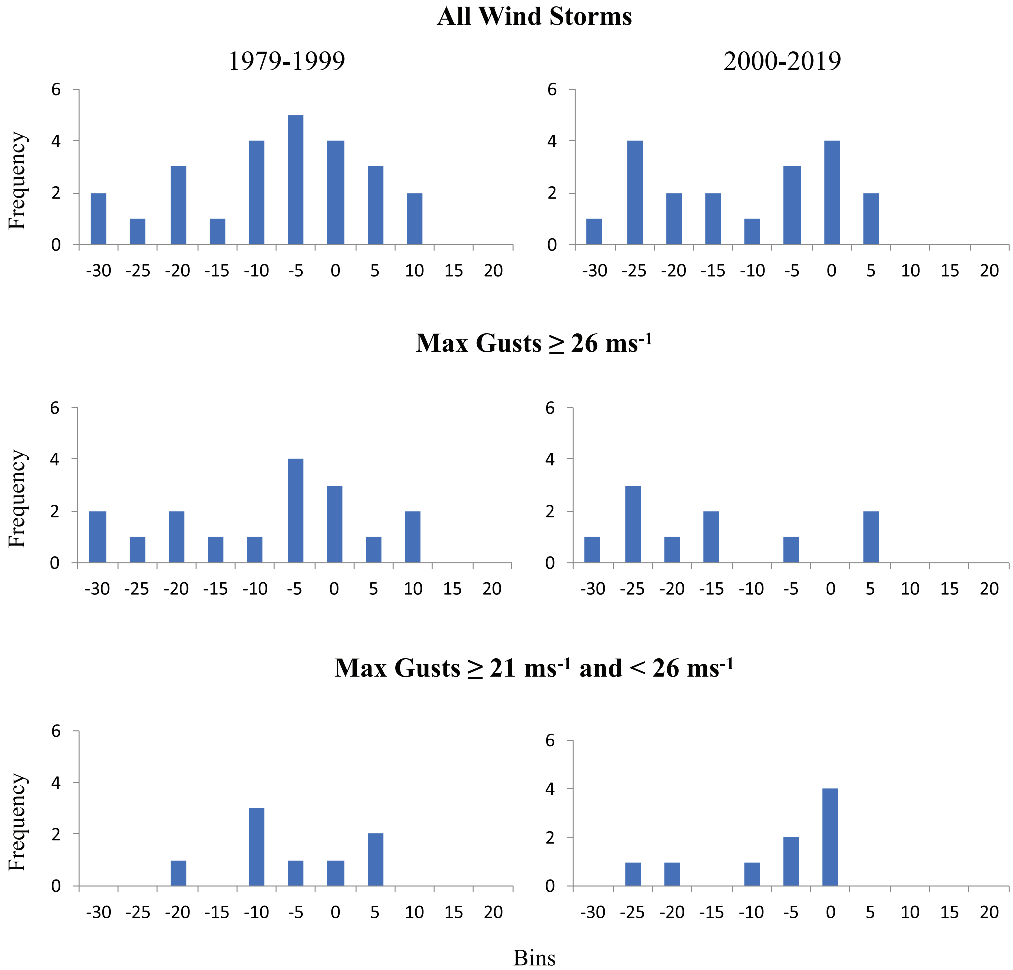

FIGURE 5 As in Figure 4 for the first half (1979–1999) and second half (2000–2019) of the study period

associated with very low central pressures or bomb cyclones. Other factors, such as the pressure gradient, are also important.

It is difficult to determine whether changes in large-scale circulation patterns have had a detectable effect on wind storms in New England, as our results overall do not indicate a statistically significant change in wind storm frequency or intensity. This outcome could relate to the relatively short 2 month sampling period, as the small sample of storms makes identifying a statistically significant trend from interannual variability less straightforward. It is also possible that other wind storm characteristics not typically examined are changing, such as the size of storm systems and the area of high winds, rather than overall wind speeds. Despite the lack of statistically significant temporal trends in overall wind storm frequency or wind intensity, this study illuminates other aspects which could be important when projecting damage from future wind storms. There are indications that, at the surface stations used in this analysis, strong wind storms (i.e. events which meet NWS High Wind Warning criteria) in October are associated with higher rainfall accumulations than at the beginning of the study period. Although high winds are the main characteristic of wind storms, heavy rainfall can also occur with these events. As previous studies (e.g. Huang *et al.*, 2018; Howarth *et al.*, 2019) have shown that tropical cyclones and their remnants have substantially contributed to a rise in extreme precipitation in the northeastern United States, we cross-referenced dates from the wind storm climatologies with the National Hurricane Center's North Atlantic hurricane database version 2 (HURDAT2; Landsea and Franklin, 2013) to identify wind storms with tropical origins. Only three wind storms from the domain-level climatology were associated with tropical cyclones which transitioned to extratropical cyclones before reaching New England: Josephine (October 8, 1996), Noel (November 3, 2007) and Sandy (October 29–30, 2012). However, tropical cyclones can also help strengthen wind storms of extratropical origin. At least two wind storms, occurring on October 30, 2017, and between October 18 and 22, 1996, interacted with

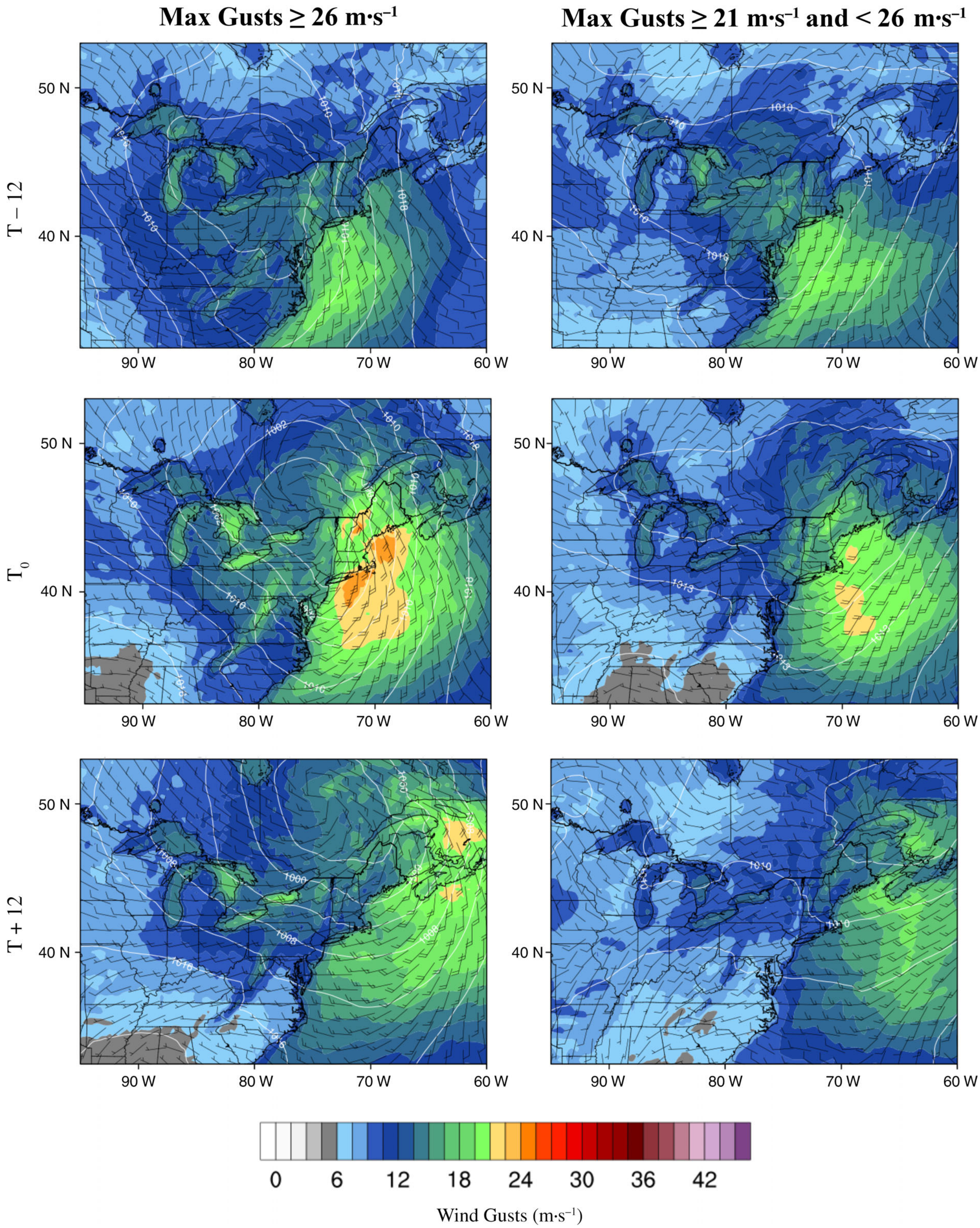

FIGURE 6 Sea-level pressure (in hPa) and maximum 10 m wind gust (in m·s^{-1}) composite analysis of strong wind storms (left, 27 total) and all other wind storms (right, 17 total) from the domain-level reanalysis-based climatology. Composites are shown for the time of the maximum wind gusts within the New England domain (T_0), and for 12 hr before (T – 12) and after (T + 12)

offshore tropical systems and resulted in heavy rainfall in New England. Additionally, future shifts in storm tracks could result in additional damage from storm surges associated with wind storms. Extratropical cyclones with coastal storm tracks, such as nor'easters, can cause substantial coastal flooding and beach erosion (Dolan and

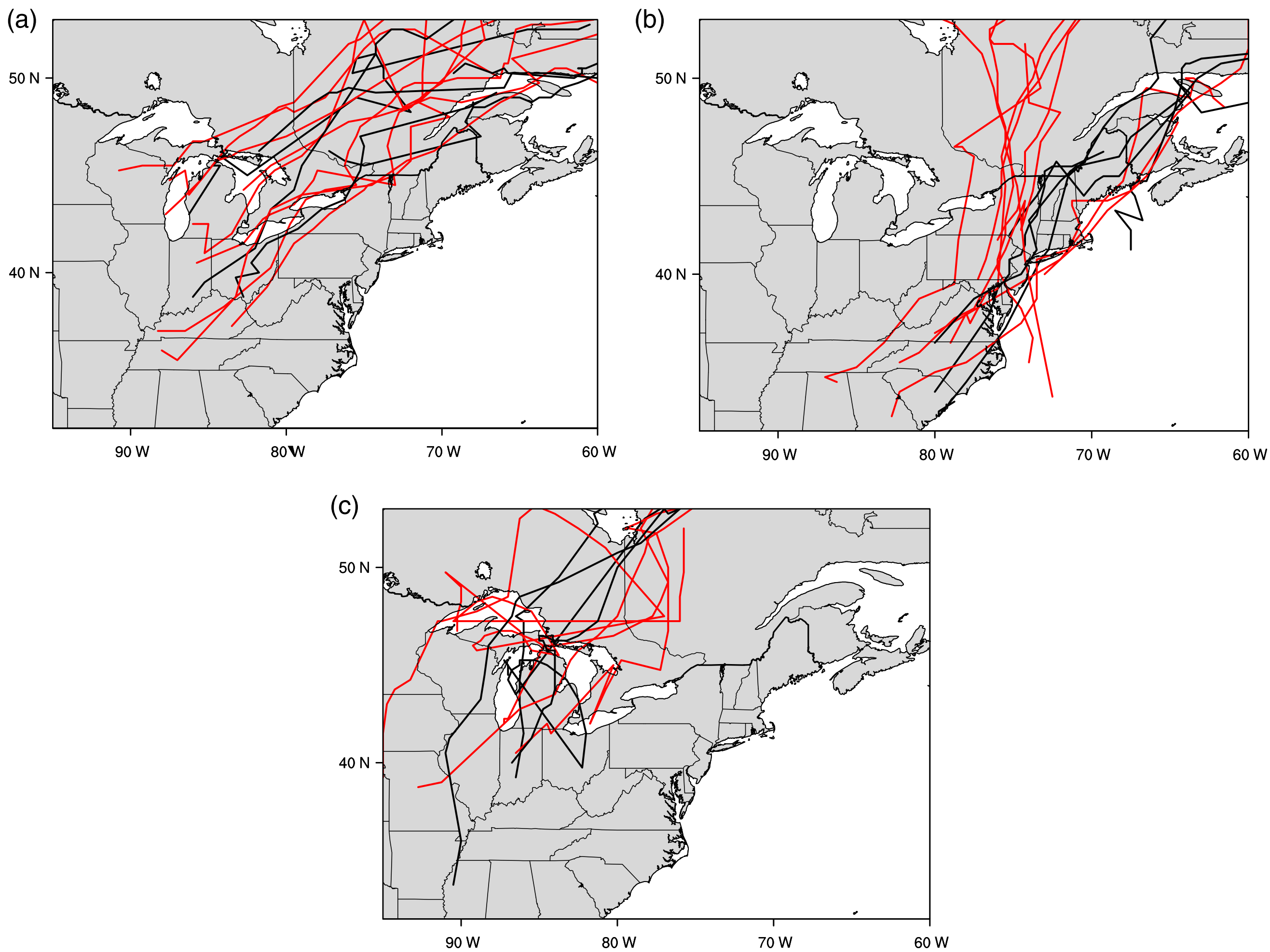

FIGURE 7 Storm tracks organized by category: (a) type 1, (b) type 2 and (c) type 3. Tracks for strong wind storms are in red; all other tracks are in black

Davis, 1992). This storm track is a common one for New England wind storms, and a projected increase in storms following this path could result not only in more high-wind events for the region but also in greater damage along the coast. Future work is suggested to examine more thoroughly the roles of tropical moisture sources and storm tracks in projections of New England wind storms.

There are challenges associated with the study of wind storms and predictions for storm damage in the future. One major difficulty is developing a single, precise definition for "wind storm." In this study we apply wind criteria used by the NWS, an approach commonly used by other studies (Niziol and Paone, 2000; Lacke *et al.*, 2007; Booth *et al.*, 2015). However, it is difficult to determine how to apply the wind criteria spatially and temporally, and to do so uniformly at both the station level and the domain level. For the domain-level reanalysis climatology, additional criteria are used in order to isolate high-wind events that are associated with synoptic-scale features and not local topographical features. Although the criteria limit the number of identified wind storms, the additional "events" often involve a few grid cells with maximum wind gusts just above the minimum criteria and would be unlikely to result in substantial wind damage in the region. Similar criteria are more difficult to apply to station observations as the values are for daily maximum values and long-term automated weather variables are available for a limited number of locations in New England. The requirement that sustained winds and gusts must meet the criteria at multiple stations has a similar effect on the sample size as the grid cell criteria, although the location and density of surface stations have a notable effect on how many and which wind storms are included in the dataset.

Another major challenge is predicting how changes in extratropical cyclone intensity translate into wind damage. Although the central pressure is a common measure of extratropical cyclone intensity, it is a combination of factors (central SLP, SLP gradient, storm track)

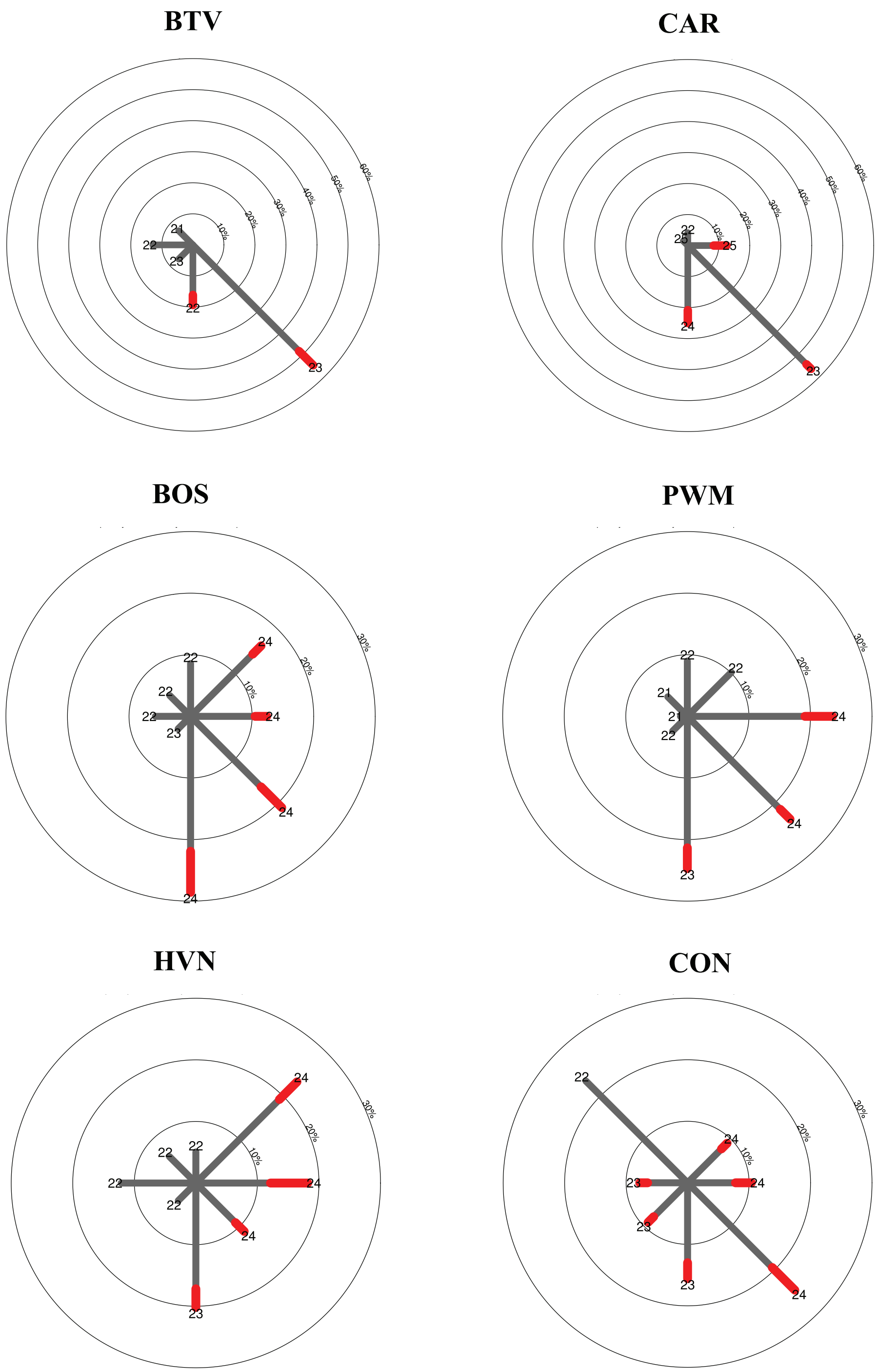

FIGURE 8 Wind roses for Burlington, VT (BTV), Caribou, ME (CAR), Boston, MA (BOS), Portland, ME (PWM), New Haven, CT (HVN) and Concord, NH (CON). Concentric circles indicate the frequency (%) of wind gusts during wind storms, with the average wind gust (in m·s^{-1}) for each direction labeled at the end of the "petal." The frequencies of wind gusts between 21 m·s^{-1} and 26 m·s^{-1} are indicated in gray, and the frequencies of wind gusts at or above 26 m·s^{-1} are indicated in red

that results in high-wind events over a given location. For example, Booth *et al.* (2015) noted that extratropical cyclones associated with the strongest winter winds in the northeastern United States are not necessarily the strongest extratropical cyclones overall. Instead, it is important to consider the location of the strongest winds associated with the low with respect to the region of interest. Furthermore, high sustained winds or wind gusts do not guarantee that wind damage will occur (although the risk of damage increases), and wind damage can occur at wind speeds below the criteria used by the NWS. Modeling studies show that forest damage can begin at wind speeds as low as 10 m·s^{-1}, with changes in wind loading (e.g. due to altered canopy and stand density) increasing the susceptibility of trees to damage (Peltola *et al.*, 1999; Gardiner *et al.*, 2000). Other studies have used wind reports to compare damaging and non-damaging extratropical cyclones (Angel and Isard, 1998) or to produce wind storm climatologies (Lacke *et al.*, 2007); however, this method has its own limitations, such as the lack of wind reports outside of population centers as well as changing reporting methods over time and among NWS offices (Doswell *et al.*, 2005). Additionally, other factors can increase the risk of wind damage that are not only attributable to wind storms. Heavy rainfall from tropical and extratropical cyclones not associated with high winds during these months increases the risk of flooding and tree damage due to windthrow. Other environmental stresses such as drought, heat, disease and insect infestations can weaken trees and increase the risk of wind damage. For example, drought conditions across Maine were a contributing factor to the large number of downed trees during the October 30, 2017, wind storm (Whittle, 2017). The combination of weather, climate and environmental factors ultimately determines the resulting damage from these events.

5 | CONCLUSIONS

This study examines the frequency and intensity of mid-autumn wind storms in New England and their characteristics. Wind storms are identified separately from the ERA5 reanalysis and Integrated Surface Database (ISD) observation dataset using the National Weather Service's Wind Advisory and High Wind Warning criteria. From the trend analysis, we find little evidence that wind storms have become stronger in terms of central surface pressure or wind speeds, although there are indications that strong October wind storms in the past two decades are associated with more precipitation than October storms from earlier in the record. The increased precipitation could be connected to the increased moisture transport associated with tropical cyclones and their remnant circulations, although to what degree is beyond the scope of this study. Our results also show that extratropical cyclones associated with mid-autumn high-wind events in New England typically travel from southwest to northeast with three preferred storm tracks. Although strong wind storms are often characterized by lower surface pressure or rapidly intensifying bomb cyclones, the intensity of an extratropical cyclone itself is not the only predictor of a high-wind event in the New England region, and the damage that they produce is a function of many factors. These include the local climatology, such as the frequency of heavy rainfall events, and the presence of environmental factors such as drought and heat stress. All such factors can increase the risk of damage from wind storms and highlight the various ways in which climate change can impact storm severity.

ACKNOWLEDGEMENTS

This study is supported by a University of Maine Signature and Emerging Area of Excellence Graduate Fellowship to the Climate Change Institute. High-performance computing support from Cheyenne (doi: 10.5065/D6RX99HX) is provided by NCAR's Computational and Information Systems Laboratory, sponsored by the National Science Foundation. The data were provided by the Research Data Archive (RDA) of the Computational and Information Systems Laboratory at the National Center for Atmospheric Research.

ORCID

Julia M. Simonson https://orcid.org/0000-0003-1393-2352

REFERENCES

Angel, J.R. and Isard, S.A. (1998) The frequency and intensity of Great Lake cyclones. *Journal of Climate*, 11(1), 61–71. https://doi.org/10.1175/1520-0442(1998)011<0061:TFAIOG>2.0.CO;2.

Ashley, W.S. and Black, A.W. (2008) Fatalities associated with non-convective high-wind events in the United States. *Journal of Applied Meteorology and Climatology*, 47(2), 717–725. https://doi.org/10.1175/2007JAMC1689.1.

Barnes, E.A., Dunn-Sigouin, E., Masato, G. and Woollings, T. (2014) Exploring recent trends in northern hemisphere blocking. *Geophysical Research Letters*, 41(2), 638–644. https://doi.org/10.1002/2013GL058745.

Barry, E. (2019) Northeast 'Bomb Cyclone': Powerful Winds Knock Out Power to 500,000, *The New York Times*, 17 October [online]. Available at: https://www.nytimes.com/2019/10/17/us/northeast-bomb-cyclone.html [Accessed 17th March 2020].

Benestad, R.E. (2009) On tropical cyclone frequency and the warm pool area. *Natural Hazards and Earth System Sciences*, 9(2), 635–645. https://doi.org/10.5194/nhess-9-635-2009.

Blackport, R. and Screen, J.A. (2020) Insignificant effect of Arctic amplification on the amplitude of midlatitude atmospheric waves. *Science Advances*, 6(8), eaay2880. https://doi.org/10.1126/sciadv.aay2880.

Booth, J.F., Rieder, H.E., Lee, D.E. and Kushnir, Y. (2015) The paths of extratropical cyclones associated with wintertime high-wind events in the northeastern United States. *Journal of Applied Meteorology and Climatology*, 54(9), 1871–1885. https://doi.org/10.1175/JAMC-D-14-0320.1.

Colle, B.A., Zhang, Z., Lombardo, K.A., Chang, E., Liu, P. and Zhang, M. (2013) Historical evaluation and future prediction of eastern north American and Western Atlantic extratropical cyclones in the CMIP5 models during the cool season. *Journal of Climate*, 26(18), 6882–6903. https://doi.org/10.1175/JCLI-D-12-00498.1.

Daly, C., Neilson, R.P. and Phillips, D.L. (1994) A statistical-topographic model for mapping climatological precipitation over mountainous terrain. *Journal of Applied Meteorology*, 33(2), 140–158. https://doi.org/10.1175/1520-0450(1994)033<0140:ASTMFM>2.0.CO;2.

Dolan, R. and Davis, R.E. (1992) An intensity scale for Atlantic Coast northeast storms. *Journal of Coastal Research*, 8(4), 840–853.

Doswell, C.A., Brooks, H.E. and Kay, M.P. (2005) Climatological estimates of daily local nontornadic severe thunderstorm probability for the United States. *Weather and Forecasting*, 20(4), 577–595. https://doi.org/10.1175/WAF866.1.

ECMWF (2019) ERA5 Reanalysis (0.25 degree latitude–longitude grid). Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory, Boulder, CO. https://doi.org/10.5065/BH6N-5N20.

Francis, J.A. and Vavrus, S.J. (2012) Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophysical Research Letters*, 39(6), L06801. https://doi.org/10.1029/2012GL051000.

Francis, J.A. and Vavrus, S.J. (2015) Evidence for a wavier jet stream in response to rapid Arctic warming. *Environmental Research Letters*, 10(1), 014005. https://doi.org/10.1088/1748-9326/10/1/014005.

Frei, A., Kunkel, K.E. and Matonse, A. (2015) The seasonal nature of extreme hydrological events in the northeastern United States. *Journal of Hydrometeorology*, 16(5), 2065–2085. https://doi.org/10.1175/JHM-D-14-0237.1.

Galarneau, T.J., Davis, C.A. and Shapiro, M.A. (2013) Intensification of Hurricane Sandy (2012) through extratropical warm core seclusion. *Monthly Weather Review*, 141(12), 4296–4321. https://doi.org/10.1175/MWR-D-13-00181.1.

Gardiner, B., Peltola, H. and Kellomäki, S. (2000) Comparison of two models for predicting the critical wind speeds required to damage coniferous trees. *Ecological Modelling*, 129(1), 1–23. https://doi.org/10.1016/S0304-3800(00)00220-9.

Gilbert, R.O. (1987) *Statistical Methods for Environmental Pollution Monitoring*. New York, NY: John Wiley & Sons.

Graham, G. (2017) Raging winds, rain leave 484,000 customers without power, *Portland Press Herald*, 31 October, A1.

Hart, R.E. and Evans, J.L. (2001) A climatology of the extratropical transition of Atlantic tropical cyclones. *Journal of Climate*, 14 (4), 546–564 https://doi.org/10.1175/1520-0442(2001)014<0546:ACOTET>2.0.CO;2.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D. and Simmons, A. (2020) The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146, 1–51. https://doi.org/10.1002/qj.3803.

Howarth, M.E., Thorncroft, C.D. and Bosart, L.F. (2019) Changes in extreme precipitation in the northeast United States: 1979–2014. *Journal of Hydrometeorology. American Meteorological Society*, 20(4), 673–689. https://doi.org/10.1175/JHM-D-18-0155.1.

Huang, H., Winter, J.M., Osterberg, E.C., Horton, R.M. and Beckage, B. (2017) Total and extreme precipitation changes over the northeastern United States. *Journal of Hydrometeorology*, 18(6), 1783–1798. https://doi.org/10.1175/JHM-D-16-0195.1.

Huang, H., Winter, J.M. and Osterberg, E.C. (2018) Mechanisms of abrupt extreme precipitation change over the northeastern United States. *Journal of Geophysical Research: Atmospheres*, 123(14), 7179–7192. https://doi.org/10.1029/2017JD028136.

Jiang, J. and Perrie, W. (2007) The impacts of climate change on autumn North Atlantic midlatitude cyclones. *Journal of Climate*, 20(7), 1174–1187. https://doi.org/10.1175/JCLI4058.1.

Jung, C. and Lackmann, G.M. (2019) Extratropical transition of Hurricane Irene (2011) in a changing climate. *Journal of Climate*, 32(15), 4847–4871. https://doi.org/10.1175/JCLI-D-18-0558.1.

Kendall, M.G. (1948) *Rank Correlation Methods*. London: Charles Griffin & Co. Ltd..

Lacke, M.C., Knox, J.A., Frye, J.D., Stewart, A.E., Durkee, J.D., Fuhrmann, C.M. and Dillingham, S.M. (2007) A climatology of cold-season nonconvective wind events in the Great Lakes region. *Journal of Climate*, 20(24), 6012–6022. https://doi.org/10.1175/2007JCLI1750.1.

Landsea, C.W. and Franklin, J.L. (2013) Atlantic hurricane database uncertainty and presentation of a new database format. *Monthly Weather Review*, 141(10), 3576–3592. https://doi.org/10.1175/MWR-D-12-00254.1.

Leckebusch, G.C., Renggli, D. and Ulbrich, U. (2008) Development and application of an objective storm severity measure for the Northeast Atlantic region. *Meteorologische Zeitschrift*, 17(5), 575–587. https://doi.org/10.1127/0941-2948/2008/0323.

Li, G., Zhang, P., Luh, P.B., Li, W., Bie, Z., Serna, C. and Zhao, Z. (2014) Risk analysis for distribution systems in the Northeast U.S. under wind storms. *IEEE Transactions on Power Systems*, 29(2), 889–898. https://doi.org/10.1109/TPWRS.2013.2286171.

Liu, M., Vecchi, G.A., Smith, J.A. and Murakami, H. (2017) The present-day simulation and twenty-first-century projection of the climatology of extratropical transition in the North Atlantic. *Journal of Climate*, 30(8), 2739–2756. https://doi.org/10.1175/JCLI-D-16-0352.1.

Mann, H.B. (1945) Nonparametric tests against trend. *Econometrica*, 13(3), 245–259. https://doi.org/10.2307/1907187.

Marks, P.L., Gardescu, S. and Hitzhusen, G.E. (1999) Windstorm damage and age structure in an old growth forest in Central New York. *Northeastern Naturalist*, 6(2), 165–176. https://doi.org/10.2307/3858347.

McNally, L.K., Maasch, K.A. and Zuill, K.A. (2008) The use of ships' protests for reconstruction of synoptic-scale weather and tropical storm identification in the late eighteenth century. *Weather*, 63(7), 208–213. https://doi.org/10.1002/wea.272.

Michaelis, A.C. and Lackmann, G.M. (2019) Climatological changes in the extratropical transition of tropical cyclones in high-resolution global simulations. *Journal of Climate*, 32(24), 8733–8753. https://doi.org/10.1175/JCLI-D-19-0259.1.

NCAR (2019) *The NCAR Command Language* (Version 6.6.2) [Software]. Boulder, Colorado: UCAR/NCAR/CISL/TDD. https://doi.org/10.5065/D6WD3XH5.

Neu, U., Akperov, M.G., Bellenbaum, N., Benestad, R., Blender, R., Caballero, R., Cocozza, A., Dacre, H.F., Feng, Y., Fraedrich, K., Grieger, J., Gulev, S., Hanley, J., Hewson, T., Inatsu, M., Keay, K., Kew, S.F., Kindem, I., Leckebusch, G.C., Liberato, M. L.R., Lionello, P., Mokhov, I.I., Pinto, J.G., Raible, C.C., Reale, M., Rudeva, I., Schuster, M., Simmonds, I., Sinclair, M., Sprenger, M., Tilinina, N.D., Trigo, I.F., Ulbrich, S., Ulbrich, U., Wang, X.L. and Wernli, H. (2013) IMILAST: a community effort to intercompare extratropical cyclone detection and tracking algorithms. *Bulletin of the American Meteorological Society*, 94 (4), 529–547. https://doi.org/10.1175/BAMS-D-11-00154.1.

Nissen, K.M., Leckebusch, G.C., Pinto, J.G., Renggli, D., Ulbrich, S. and Ulbrich, U. (2010) Cyclones causing wind storms in the Mediterranean: characteristics, trends and links to large-scale patterns. *Natural Hazards and Earth System Sciences*, 10(7), 1379–1391. https://doi.org/10.5194/nhess-10-1379-2010.

Niziol, T.A., and T.J. Paone (2000). A climatology of non-convective high wind events in western New York state. NOAA Technical Memorandum NWS ER-91, 36 pp. Available at: https://repository.library.noaa.gov/view/noaa/6402/noaa_6402_DS1.pdf.

NOAA (2017) *State of the Climate: National Climate Report for October 2017*. National Oceanic and Atmospheric Administration, National Centers for Environmental Information. Available at: https://www.ncdc.noaa.gov/sotc/national/201710 [Accessed 17th March 2020].

Overland, J.E., Hanna, E., Hanssen-Bauer, I., Kim, S-J., Walsh, J.E., Wang, M., Bhatt, U.S. and Thoman, R.L. (2017) Surface air temperature. Arctic Report Card 2017. Available at: http://www.arctic.noaa.gov/Report-Card.

Overland, J.E., Hanna, E., Hanssen-Bauer, I., Kim, S.-J., Walsh, J. E., Wang, M., Bhatt, U.S., Thoman, R.L. and Ballinger, T.J. (2019) Surface air temperature. In: Richter-Menge, J., Druckenmiller, M.L. and Jeffries, M. (Eds.) *Arctic Report Card 2019*, Available at: http://www.arctic.noaa.gov/Report-Card.

Peltola, H., Kellomäki, S., Väisänen, H. and Ikonen, V.-P. (1999) A mechanistic model for assessing the risk of wind and snow damage to single trees and stands of Scots pine, Norway spruce, and birch. *Canadian Journal of Forest Research*, 29(6), 647–661. https://doi.org/10.1139/x99-029.

PRISM Climate Group (2020) PRISM daily time series dataset. Northwest Alliance for Computational Science and Engineering, Oregon State University, Corvallis, OR. Available at: http://prism.oregonstate.edu/ [Accessed 9th March 2020].

Roebber, P.J. (1989) On the statistical analysis of cyclone deepening rates. *Monthly Weather Review*, 117(10), 2293–2298. https://doi.org/10.1175/1520-0493(1989)117<2293:OTSAOC>2.0.CO;2.

Romanić, D., Ćurić, M., Jovičić, I. and Lompar, M. (2015) Long-term trends of the 'Koshava' wind during the period 1949–2010. *International Journal of Climatology*, 35(2), 288–302. https://doi.org/10.1002/joc.3981.

Russell, E. (2018) CMP says October windstorm cost it $69 million, and customers will help pay the cost, *Portland Press Herald*, 18 January [online]. Available at: https://www.pressherald.com/2018/01/18/unprecedented-october-storm-cost-central-maine-power-69-million/ [Accessed 17th March 2020].

Samenow, J. (2017) More than 1 million power outages in the Northeast after blockbuster fall storm, *Washington Post*, 17 October [online]. Available at: https://www.washingtonpost.com/news/capital-weather-gang/wp/2017/10/30/over-one-million-power-outages-in-the-northeast-after-blockbuster-fall-storm/ [Accessed 17th March 2020].

Sanders, F. and Gyakum, J.R. (1980) Synoptic-dynamic climatology of the "Bomb". *Monthly Weather Review*, 108(10), 1589–1606. https://doi.org/10.1175/1520-0493(1980)108<1589:SDCOT>2.0.CO;2.

Screen, J.A. and Simmonds, I. (2013) Exploring links between Arctic amplification and mid-latitude weather. *Geophysical Research Letters*, 40(5), 959–964. https://doi.org/10.1002/grl.50174.

Screen, J.A. and Simmonds, I. (2014) Amplified mid-latitude planetary waves favour particular regional weather extremes. *Nature Climate Change*, 4(8), 704–709. https://doi.org/10.1038/nclimate2271.

Sen, P.K. (1968) Estimates of the regression coefficient based on Kendall's tau. *Journal of the American Statistical Association*, 63(324), 1379–1389. https://doi.org/10.1080/01621459.1968.10480934.

Smith, A., Lott, N. and Vose, R. (2011) The integrated surface database: recent developments and partnerships. *Bulletin of the American Meteorological Society*, 92(6), 704–708. https://doi.org/10.1175/2011BAMS3015.1.

Stanglin, D. (2019) Almost 1 million lose power after intense Halloween storm rolls through eastern US, *USA Today*, 1 November [online]. Available at: https://www.usatoday.com/story/news/nation/2019/11/01/power-outages-halloween-storm-maine-new-york-connecticut-vermont/4120890002/ [Accessed 17th March 2020].

Stroeve, J.C., Serreze, M.C., Holland, M.M., Kay, J.E., Maslanik, J. and Barrett, A.P. (2012) The Arctic's rapidly shrinking sea ice cover: a research synthesis. *Climate Change*, 110(3–4), 1005–1027. https://doi.org/10.1007/s10584-011-0101-1.

Tabari, H., Somee, B.S. and Zadeh, M.R. (2011) Testing for long-term trends in climatic variables in Iran. *Atmospheric Research*, 100(1), 132–140. https://doi.org/10.1016/j.atmosres.2011.01.005.

Theil, H. (1950) A rank-invariant method of linear and polynomial regression analysis, part 3. In: *Proceedings of Koninalijke Nederlandse Akademie van Weinenschatpen A*, Vol. 53 Amsterdam, Netherlands: Koninklijke Nederlandse Akademie van Wetenschappen, pp. 1397–1412.

Ulbrich, U., Leckebusch, G.C. and Pinto, J.G. (2009) Extra-tropical cyclones in the present and future climate: a review. *Theoretical and Applied Climatology*, 96(1), 117–131. https://doi.org/10.1007/s00704-008-0083-8.

Vollsinger, S., Mitchell, S.J., Byrne, K.E., Novak, M.D. and Rudnicki, M. (2005) Wind tunnel measurements of crown streamlining and drag relationships for several hardwood species. *Canadian Journal of Forest Research*, 35(5), 1238–1249. https://doi.org/10.1139/x05-051.

Whittle, P. (2017) Drought fueled wind damage from storm that walloped Maine, officials say, *Bangor Daily News*, 1 November [online]. Available at: https://bangordailynews.com/2017/11/01/news/bangor/drought-aided-wind-damage-from-storm-that-walloped-maine-officials-say/ [Accessed March 12, 2020].

How to cite this article: Simonson JM, Birkel SD, Maasch KA, Mayewski PA, Lyon B, Carleton AM. Historical incidence of mid-autumn wind storms in New England. *Meteorol Appl*. 2020; 27:e1952. https://doi.org/10.1002/met.1952