Proceedings of the Nova Scotian Institute of Science (2025)
Volume 54, Part 1, pp. 305-335

WHO HAS SEEN THE WIND? A NATURAL HISTORY OF STORM WINDS IN NOVA SCOTIA, 1957-2024

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ABSTRACT

The natural history of storm winds is described for Nova Scotia from the late 1950s to 2024. The overall pattern was a decline from greater storm frequency and intensity in the 1960s to minimal levels 2000-2011, and a subsequent return to levels experienced in the 1970s and 1980s. Patterns were consistent in five wind metrics: (1) maximum provincial wind gust; (2) mean of annual wind maximum from the five sites; (3) annual mean of monthly maxima; (4) number of storm days (i.e., wind $\geq$ 75 km h^{-1}); and (5) number of months per year with maximum wind $\geq$ 75 km h^{-1}). Linear regression equations were significant in both the declining and increasing years. These results are consistent with continent-wide wind stilling and recovery. Despite significant temperature increases since 1998 and an increase in wind metrics since the early 2000s, the overall relationship between wind and temperature since the 1950s has been negative. These results are discussed in light of oceanographic events including periods of La Niña, Atlantic Multidecadal Oscillation, and the development of ocean hotspots. Increasing winter temperatures and winds are predicted to have a negative effect on plant communities along the Atlantic coast of Nova Scotia.

Keywords: Atlantic Multidecadal Oscillation, climate change, ocean hotspots, storms, wind stilling

INTRODUCTION

Studies of climate change have focussed primarily on temperature and precipitation, and the effects of global warming on both terrestrial and aquatic realms (IPCC 2013, 2022). Wind has received less attention, yet the importance of its consequences for the biota and human

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infrastructure is undeniable. While the causes of wind in terms of major air circulation patterns is understood to result from changes in air pressure and temperature, long-term patterns of change in wind intensity and their causes are not well understood, nor do they fit neatly into the context of human-induced climate change. An exception is the increase in ocean water temperature and its association with the increasing intensity of tropical cyclones (Goldenberg *et al.* 2001, Young *et al.* 2011, Walsh *et al.* 2019).

Long-term changes in storm frequency and intensity are important components of understanding weather as a component of overall climate change. In addition, wind impacts the physiology of plants and selects among growth forms based on height, elasticity, and strength. In eastern North America, wind sculpts the ericaceous balds of the Appalachians (Cain 1930, Bliss 1963), as it does the tuckamore (stunted trees, mainly spruce and fir) of coastal Nova Scotia and Newfoundland and Labrador. The stress of wind on tree physiology, particularly in concert with other stresses, such as soil infertility, means that changes in wind strength and timing can have major economic and ecological impacts on forestry and plant communities (e.g., Robichaud and Bégin 1997, Steenberg *et al.* 2011, Mitchell 2012, Taylor *et al.* 2020, Gardiner 2021). In addition, as Nova Scotia converts from coal and petroleum to more wind (and solar) to generate electricity, trends in wind become economically significant (Murthy and Rahi 2017).

Given the significance of changes in wind and the lack of understanding of this aspect of climate in Nova Scotia, we take two approaches to wind. First, we test the logical connection between climate change in the form of increasing heat in the system and climate change represented by shifting patterns in the wind regime. If differences in heat make wind, we should expect a relationship between these two elements of weather. We evaluate this hypothesis for Nova Scotia over the last 65 years using the temperature record where an increase in temperature of about a 1°C has occurred over this period (Garbary and Hill 2021, 2025). Second, we explore the patterns of change in 'wind' as viewed primarily from the perspective of storm winds and their change over time and with season. Long-term declines in wind velocity have been described associated with continental land masses; this phenomenon is termed 'wind stilling' and has been characterized from the late 1950s to the early 2000s (e.g., Klink 1999, Smits *et al.* 2005, Xu *et al.* 2006, Roderick *et al.* 2007, McVicar *et al.* 2008, 2012, Vautard *et al.* 2010, Azorin-Molina 2021). More recent accounts describe a reversal of the stilling process (Pirazzoli and Tomasin 2003, Azorin-Molina *et al.* 2016, Yang *et al.* 2021, Ultrabo-Carazo *et al.* 2022). Wind stilling and its reversal may be part of inherent climate variability rather than human-induced climate change (Wohland *et al.* 2021). Regardless of its cause, the wind record from Nova Scotia allows us to assess wind stilling and its reversal on a local scale. Our approach to understanding wind is to describe the pattern of change in a context that could be understood by non-climatologists. Our focus is on natural history (e.g., De Villiers 2006), especially of the terrestrial vegetation, rather than the underlying climatic mechanisms (e.g., Bichet *et al.* 2012, Lucio-Eceiza *et al.* 2020, Wohland *et al.* 2021).

We address the following questions with respect to climate in Nova Scotia over the past 65 years:

1. Is there a relationship between changing patterns of temperature and wind?
2. Have storm winds changed in frequency and intensity over this period?
3. Have there been seasonal changes in storm frequency and intensity?
4. To what extent has the phenomenon of wind stilling occurred regionally, and has the reversal of this process occurred?
5. Will changes in wind impact terrestrial plant communities in Nova Scotia?

MATERIAL AND METHODS

Selection of climate data

Data reflecting strong winds (i.e., gale force and higher) and monthly maxima were selected to avoid the complications raised in previous studies associated with much larger geographic areas and with average wind velocity (Klink 1999, Wan *et al.* 2010, Dunn *et al.* 2022). Maximum monthly gust strength throughout the year and number days per month and year with gusts ≥ 75 km h^{-1} were selected to evaluate changes in storm variables from the late 1950s to 2024. Wind data were extracted manually from the Government of Canada webpage titled Historical Climate Data (2025). Five Nova Scotia sites

(Table 1) were used that had relatively complete datasets from the late 1950s to 2024. Whereas instrumentation height for monitoring wind speed has changed at some Canadian weather stations, none of those used here were impacted by these changes (Richards and Abuamer 2007).

Table 1 **Weather stations in Nova Scotia used for analysis of storm intensity and frequency. These are domestic or military airports. Abbreviation: A, airport. climate.weather.gc.ca/historical_data/search_historic_data_e.html**

Site (weather station number)	Years	Latitude	Longitude	Elevation
Greenwood A (8202000)	1957-2024	44°59’00”	64°55’0”	28 m
Halifax Stanfield International A (8202249, 8202251)	1961-2024	44°52’5”	63°30’3”	145 m
Shearwater A and Shearwater RCS (8205090, 8205092)	1956-2024	44°38’0”	63°30’0”	44 m
Sydney A (8205700, 8205701)	1958-2024	46°09’4”	60°02’5”	61 m
Yarmouth A (8206495, 8206496)	1958-2024	43°49’3”	66°05’1”	43 m

These sites are either military or domestic airports. While multiple station numbers were used for four sites, these were in the same location except for the two Shearwater sites where wind data stopped at Shearwater A in 2004, and resumed at Shearwater RCS in 2008. For each month, we extracted the maximum wind gust speed and the number of days per month with gusts ≥ 75 km $h^{-1.}$ These we term ‘storm days’, and this threshold wind velocity corresponds to a strong gale and wind category 9 on the Beaufort scale. This wind velocity is sufficient to break branches on trees. These data were then organized for each site to evaluate annual and monthly changes in: (1) annual maximum wind gust (AM) for the province as a whole, as represented by the five stations with discrete locations, (2) mean annual maximum wind (MAM) from all sites, (3) annual mean of monthly maxima (MMM), (4) number of storm days per month (SD), (5) number of months per year with storms (SM). These metrics account for both stochastic events (i.e., AM) and those associated with seasonal variation and overall climatic trends. Given the limited size of Nova Scotia and the large areas covered by storm paths across the province (e.g., Taylor *et al.* 2020), one would expect these metrics to be highly correlated. After analyzing each metric independently, we then combined them into a single value by standardizing the five metrics, using the Excel function STANDARDIZE, i.e., giving each metric a mean of zero and a standard deviation of 1, and then determining the mean for each year.

To determine if the different sites had similar patterns of changing wind climate, we evaluated the four wind variables (AM, MMM, SD, and SM) together for each site. We first standardized each metric for a given site. Means for each year were determined and a three-year rolling average was calculated in Excel. Three linear regression equations were calculated: (1) over the entire period (1958-2024), (2) from 1958 to the low value in the sequence, and (3) from the low point in the sequence to 2024. If the slopes of these regression equations were significant and in the same direction as the means of the wind metrics, the differences between sites were ignored. This justified the focus on the trends in the wind metrics that incorporated the five sites.

Statistical analyses were carried out using Excel (Microsoft Corporation 2018) for descriptive statistics, with linear regression calculated using GraphPad (2023); and normality tests used an online Shapiro-Wilk test calculator (Statistics Kingdom, 2024). Evaluation of means of monthly wind metrics was done by calculating the average value for the five sites by month and smoothing the values using a three-year rolling average (i.e., 1958-1960, 1959-1961, 1960-1962…). Given that storms are the right-hand tail of wind distribution, much of the data are not normally distributed; significance was based on $P < 0.05$.

RESULTS

Mean annual temperature

There was an overall temperature increase across Nova Scotia of about 1.0°C (Fig 1). Based on the linear regression this change is highly significant (slope = 0.0271°C per year, $R^2 = 0.4150$, $P < 0.0001$). Despite the significance of the overall change, the temperature record resolved into two segments with a step change occurring between 1997 and 1998. This was previously shown by Garbary and Hill (2021, 2025), with each segment showing a different pattern. The early period showed no change (slope = 0.0003°C per year, $R^2 < 0.00001$, $P = 0.9669$), whereas the recent period had a positive trend (slope = 0.0319°C per year, $R^2 = 0.138$, $P = 0.056$). The early and recent periods had annual mean temperatures of 6.3 ± 0.5°C and 7.4 ± 0.7°C,

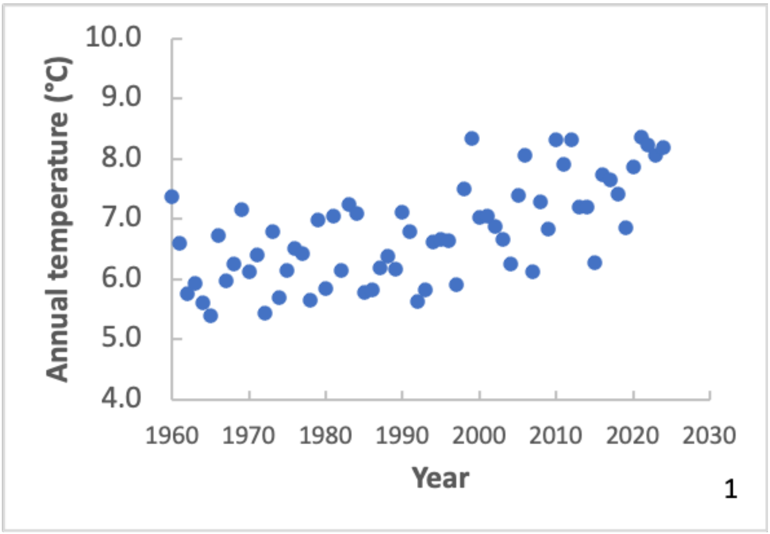


Fig 1 **Changes in mean annual air temperature in Nova Scotia for the five airport sites 1958-2024.**

respectively, and this difference is highly significant (Student's *t*-test, $P < 0.0001$). In only one year (i.e., 2007) was the annual temperature for the recent period below the mean from 1958-1997.

Maximum annual wind gust

Nova Scotia is the windiest province in Canada (ECCC 1990), with the most extreme value in the present study of 188 km h^{-1} occurring in 1976 at Greenwood. Across the province at our five study sites there was an annual maximum (AM) of 121 ± 17 km h^{-1}. While the AM metric would be expected to be the most stochastic of our metrics and show the greatest variation from year to year, a significant overall pattern emerged (Fig 2). The linear regression of the entire period 1958-2024 was negative (slope = -0.3389 km h^{-1} y^{-1}, $R^2 = 0.149$, $P = 0.02$). However, this negative trend masked an early period (1958-2001) that was strongly negative (slope = -0.7971 km h^{-1} y^{-1}, $R^2 = 0.320$, $P < 0.001$), and a later period (2001-2024) that was highly positive (slope = 1.220 km h^{-1} y^{-1}, $R^2 = 0.344$, P = 0.003). The declining period (i.e., wind stilling) showed a change of -1.2 km h^{-1} y^{-1}, whereas the recovery period showed a change of 1.7 km h^{-1} y^{-1}.

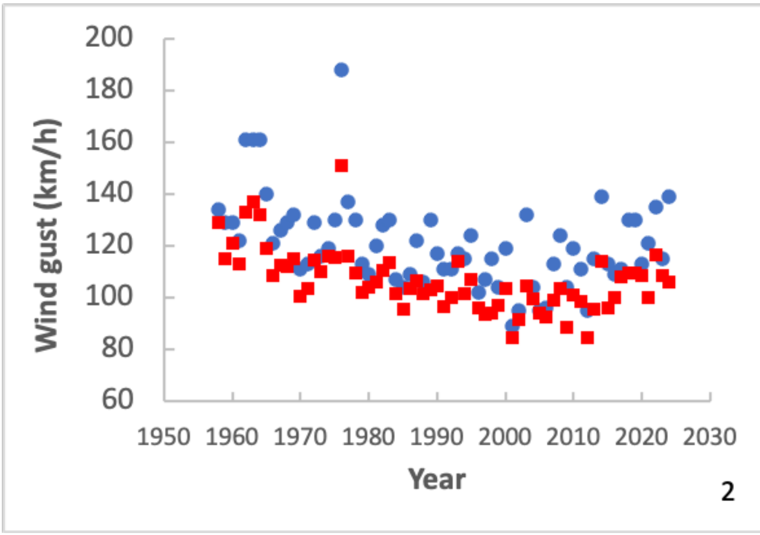


Fig 2 **Changes in annual maximum wind gust speed for Nova Scotia (AM, blue circles) and mean maximum (MAM, red squares) for five airport sites in Nova Scotia) 1958-2024. Note: extreme high values for 1976 are from the Groundhog Day Gale.**

Mean of annual maxima

The mean annual maximum for the five sites (Table 2) ranged from 103 km h^{-1} (at Shearwater) to 110 km h^{-1} (at Greenwood). The trend was higher values in the 1960s (up to 161 km h^{-1}) and a period of lower values between 2001 and 2006 when four of the six years had a maximum wind gust of less than 100 km h^{-1}. Even though values for early and recent periods were significant only for Greenwood and Shearwater ($P < 0.05$), the overall trend was highly significant (Table 2, $P < 0.01$). The linear regression from 1958 to 2022 was negative and significant (as was the early period up to 2000); however, the period from 2001 to 2022 was positive and highly significant (Fig 2). The windiest ten-year period was 1958-1967 (mean annual maximum 135 km h^{-1}), whereas the lowest period was 2001-2010 (mean annual maximum of 107 km h^{-1}). Using a three-year rolling average for maximum annual wind gust up to 2000 resulted in a change of -0.92 km h^{-1} y^{-1} (= -0.26 m sec^{-1} y^{-1}). From 2001 to 2024 the average increase rate was 1.1 km h^{-1} y^{-1} (= 0.30 m sec^{-1} y^{-1}).

Table 2 **Means of annual maximum wind gusts at the five Nova Scotia airport weather stations considered over the entire period (1958-2024), an early period (1958-2000), and a recent period (2001-2024). Values indicate mean ± sd; significance of early versus recent periods based on Student's *t*-tests.**

Site	1958-2024 (km h^{-1})	1958-2000 (km h^{-1})	2001-2024 (km h^{-1})	*P*
Greenwood	110 ± 21	116 ± 21	98 ± 14	< 0.001
Halifax	107 ± 11	108 ± 11	105 ± 13	0.456
Shearwater	103 ± 16	106 ± 15	95 ± 15	0.015
Sydney	109 ± 16	111 ± 16	104 ± 14	0.092
Yarmouth	106 ± 16	108 ±17	101 ± 13	0.074
All sites	107 ± 12	110 ± 12	100 ± 9	0.001

Mean of monthly maximum wind gusts

This metric averages the strongest monthly wind gust for the year from each site. Accordingly, it integrates the monthly storm regime to provide a more generalized description than the metrics in the previous sections. The annual values for means of monthly maxima (MMM) ranged from a high of 93.8 km h^{-1} in 1964 to a low of 64.3 km h^{-1} in 2001 (Fig 3), a decline of 0.57 km h^{-1} y^{-1} (0.16 m sec^{-1} y^{-1}). It subsequently rose to a maximum of 82.3 km h^{-1} y^{-1} in 2022. Linear regressions of the two periods were highly significant ($P < 0.0001$) both in the declining period ($R^2 = 0.662$) and in the recovery period

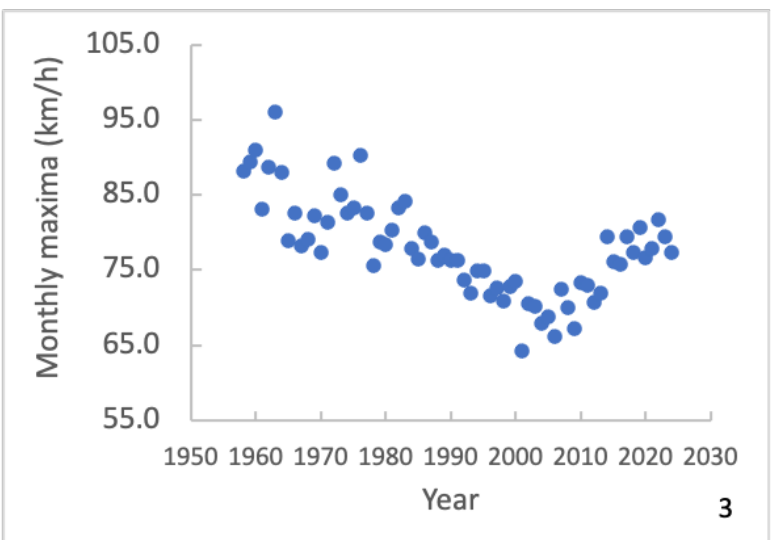


Fig 3 **Changes in annual mean of monthly wind maxima for Nova Scotia 1958-2024.**

($R^2 = 0.7627$). The period 2001-2024 experienced an increase of 0.71 km h^{-1} y^{-1} (0.20 m sec^{-1} y^{-1}), marginally greater than the declining rate.

The difference in wind gusts between the periods of decline and recovery was examined by plotting the monthly maximum wind speeds (MMM) for each month for these distinctive periods (not shown). All months had a similar trend (Table 3). Thus, for every month, the linear regression for the overall period had a negative slope, and except for September this regression was highly significant with $P < 0.0001$. This overall pattern was masked by two opposing trends: a very strong decline in wind strength for all months ending around 2001, and then a strong subsequent recovery. Rates of change during the declining period averaged 0.50 km h^{-1} y^{-1} and ranged from -0.19 km h^{-1} y^{-1} (September) to -0.79 km h^{-1} y^{-1} (October). During the wind recovery period the average yearly increase was 0.63 km h^{-1} y^{-1} and ranged from 0.19 km h^{-1} y^{-1} (August) to 1.27 km h^{-1} y^{-1} (March).

To further demonstrate the magnitude of these changes we considered three ten-year periods: the stormiest, 1960-1969 (84.8 ± 5.9 km h^{-1}), the quietest, 2001-2010 (69.1 ± 2.8 km h^{-1}), and the most recent 2015-2024 (78.2 ± 2.0 km h^{-1}) (Fig 4).

Fig 4 Monthly means of maximum wind gusts shown for three ten-year periods: (1) period of maximum wind velocity, 1960-1969 (blue squares), (2) period of minimal wind velocity, 2001-2010 (brown diamonds), and (3) most recent ten years, 2015-2024 (green circles).

Table 3 **Results of linear regressions of annual means of monthly wind maxima by month based on rolling three-year averages from the five sites. Each month is considered in three time periods: (1) the entire period, (2) from the maximum at the beginning of the time series in 1960 to the minimum, and (3) from the minimum to 2024. NS – not significant.**

Month	Year range	Slope	R^2	Change km h^{-1} y^{-1}	Change m sec^{-1} y^{-1}	*P*
January	1960-2024	-0.3268	0.4663			<0.0001
	1960-2003	-0.4772	0.5260	-0.69	-0.19	<0.0001
	2003-2024	+0.7875	0.7006	0.81	0.23	<0.0001
February	1960-2024	-0.2466	0.2845			<0.0001
	1960-2001	-0.5813	0.5442	-0.63	-0.17	<0.0001
	2001-2024	+0.6700	0.7099	0.68	0.19	< 0.001
March	1960-2024	-0.2583	0.3244			<0.0001
	1960-2006	-0.4549	0.5060	-0.60	-0.17	<0.0001
	2006-2024	+1.1072	0.7196	1.27	0.35	<0.0001
April	1959-2024	-0.2203	0.3390			<0.0001
	1959-2004	-0.4002	0.5351	-0.57	-0.16	<0.0001
	2004-2024	+0.8047	0.7164	0.94	0.26	<0.0001
May	1959-2024	-0.2452	0.4562			<0.0001
	1959-2000	-0.4719	0.6582	-0.33	-0.09	<0.0001
	2000-2024	+0.3518	0.4184	0.32	0.09	<0.0005
June	1959-2024	-0.2411	0.4209			<0.0001
	1959-1999	-0.4232	0.5183	-0.32	-0.09	<0.0001
	1999-2024	+0.4733	0.5613	0.38	0.01	<0.0001
July	1959-2024	-0.1256	0.1541			0.0011
	1959-2005	-0.2549	0.3440	-0.35	-0.10	<0.0001
	2005-2024	+0.5141	0.2138	0.65	0.18	0.0401
August	1959-2024	-0.1261	0.2354			<0.0001
	1959-2002	-0.2155	0.2837	-0.33	-0.0.9	<0.0002
	2002-2024	+0.2268	0.1610	+0.19	+0.20	NS
September	1959-2024	-0.7767	0.0315			NS
	1959-2002	-0.4407	0.5598	-0.61	-0.19	<0.0001
	2002-2024	+1.228	0.6352	2.47	0.69	<0.0001
October	1959-2024	-0.2591	0.3903			<0.0001
	1959-1994	-0.6074	0.4512	-0.79	-0.22	<0.0001
	1994-2024	+0.2264	0.1734	0.36	0.10	0.0198
November	1959-2024	-0.2037	0.3607			<0.0001
	1959-2000	-0.3946	0.5680	-0.50	-0.14	<0.0001
	2000-2024	+0.4024	0.3951	0.48	0.13	0.002
December	1959-2024	-0.2715	0.3431			<0.0001
	1959-2003	-0.5711	0.6168	-0.68	-0.19	<0.0001
	2003-2024	+0.5342	0.2912	0.81	0.23	0.0095

Number of storm days per year

Over the entire period the five sites varied from a minimum of 13.9 ± 14.7 storm days for Greenwood to 21.0 ± 8.3 storm days for Yarmouth, with all sites showing similar trends over time (Fig 5). Thus, from a peak of 45.4 in 1963, mean number of storm days across the province declined to 5.2 storm days in 2001 and increased to 23.8 storm days in 2019 (Fig 5). The mean number of storm days per year mirrors the previously discussed metrics. These changes represent an 88% decline in storm number to the low point in the early 2000s, and then an increase of 500% in the subsequent period to the recent high in 2022. The decreases and increases in the number of storm days represent a reduction of 0.62 storms y^{-1} to the minimum and a subsequent increase of 0.66 storms y^{-1}. The recent higher values are equivalent to the number of storms in Nova Scotia in the 1970s and early 1980s.

Number of months per year with wind ≥ 75 km h^{-1}

The last 65 years have shown dramatic changes in the distribution of storms throughout the year. From a peak of nine to ten months of the year with storms in the 1960s (Fig 6) there was a gradual decline until the early 2000s with fewer than four months with storms. Thus, on average, there was a linear decline of about 50% over the period from maximum to minimum. Once the reversal occurred in the early 2000s this metric increased to almost seven months per year.

Number of storm days per month

The clear difference in number of storm days per year is shown in Fig 6 and this varied both with sites and over the 65 years for which

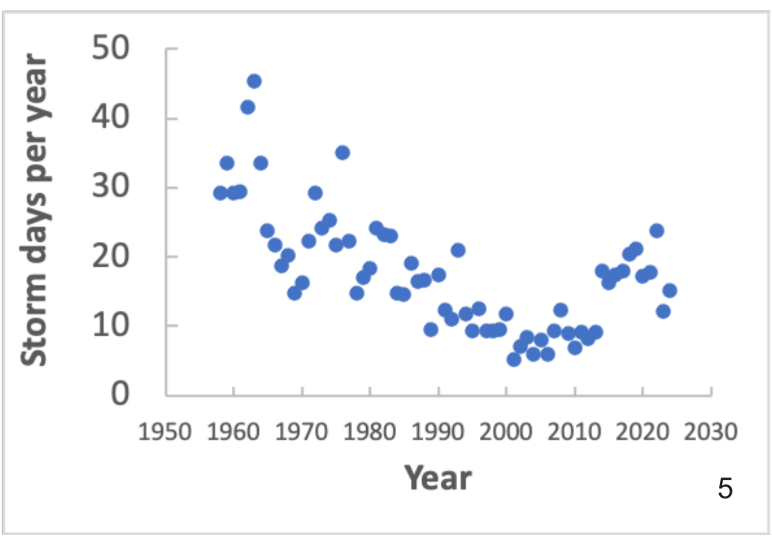


Fig 5 **Changes in number of storm days per year for Nova Scotia 1958-2024.**

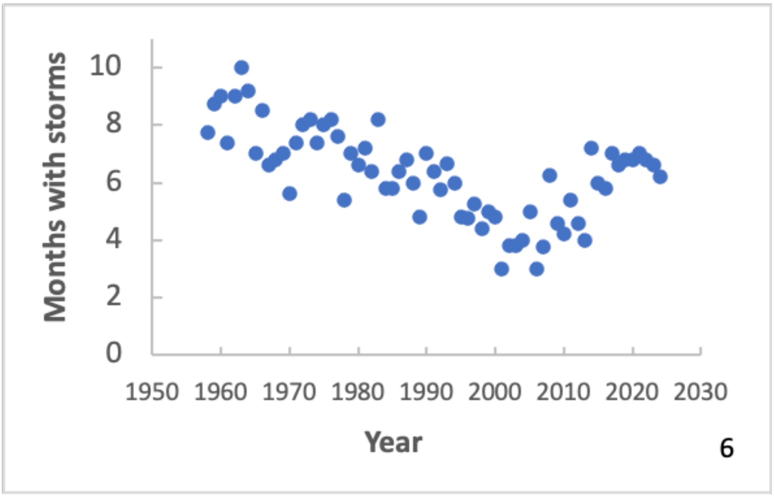


Fig 6 **Annual changes in number of months per year with storms for Nova Scotia 1958-2024.**

we have data that distinguishes a period of stilling and then a period of recovery. These data belie the strong seasonal variation in storm wind for Nova Scotia. Accordingly, storms were more frequent on a monthly basis during stilling than during the more recent wind recovery phase (Fig 7). There was a strong seasonality in the number of storms per month in Nova Scotia; the number was very low from May to September with typically fewer than 0.5 storm days per month. Months from November to March had a storm day frequency almost ten times higher. These differences are accentuated when shown from the perspective of the ten continuous years from the stormiest period in the 1950s and 1960s, the ten least stormy years in the 2000s, and the ten most recent years (Fig 7).

Metrics standardized by site

The combined metrics for each study site (Figs 8-12) were consistent with the combined sites for each storm metric. Of the 15 linear regressions (five sites x 3 time periods), only three had anomalous results, and the remaining 12 had the same slope direction, and high significance of R^2 (i.e., $P < 0.01$; Table 4) as the analyses for each wind metric (Table 5). The largest discrepancy was the 1961-2024 regression for Halifax where the decline during stilling matched the increase in metrics during the recovery period ($P = 0.9306$). The other

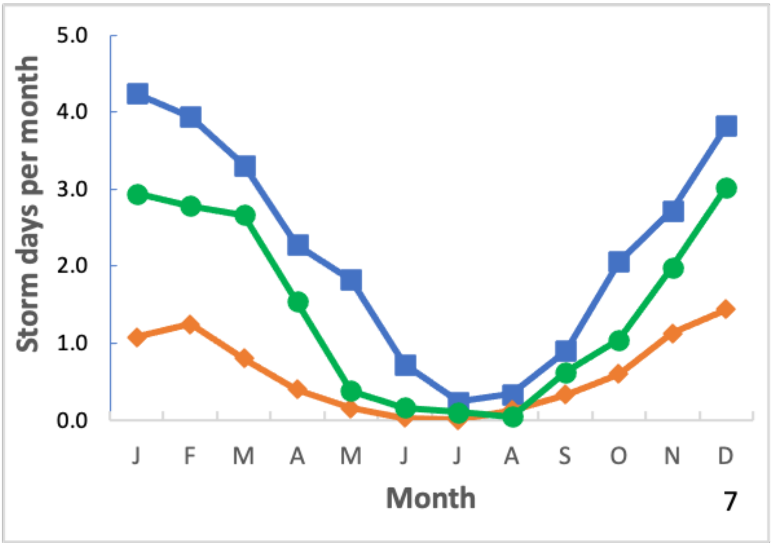


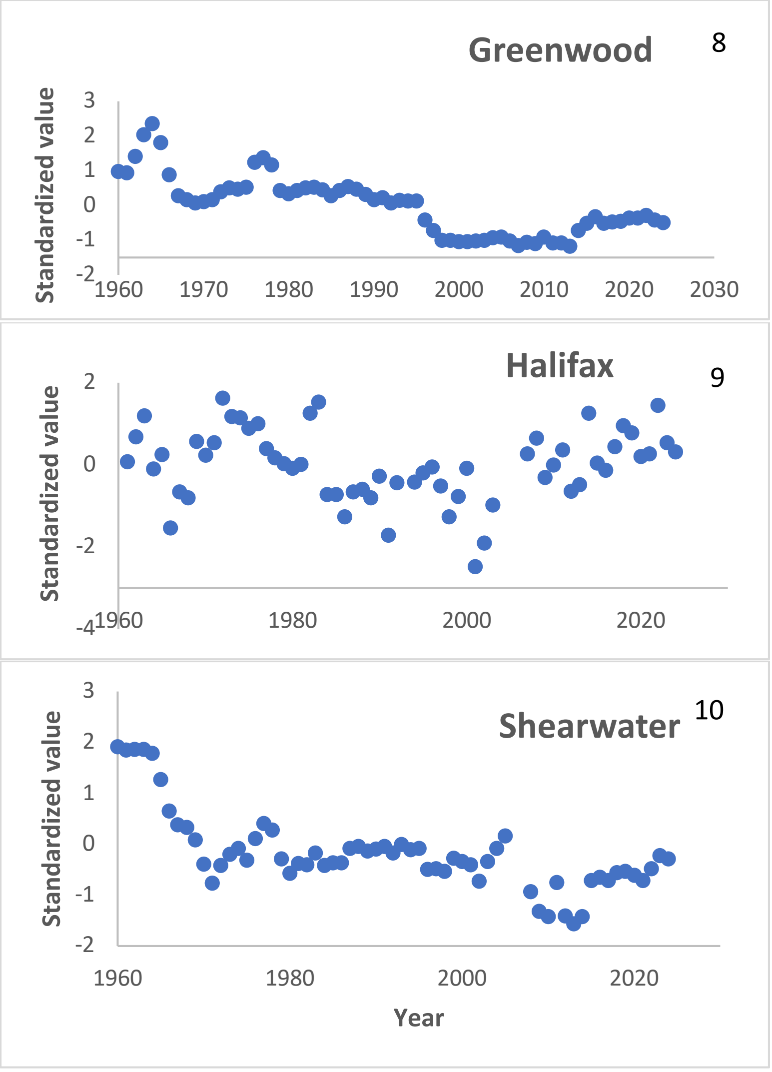
Fig 7 **Monthly means of the number of storm days for three ten-year periods: (1) period of maximum storm days, 1960-1969 (blue squares); (2) period of minimal storm days, 2001-2010 (brown diamonds); and (3) most recent ten years, 2015-2024 (green circles).**

exceptions were the regressions for Yarmouth where $P = 0.0502$ was almost significant and the regression from 2003-2024 for Shearwater where the slope was negative and not significant. The latter trend was possibly compromised by missing data from 2004-2007.

DISCUSSION

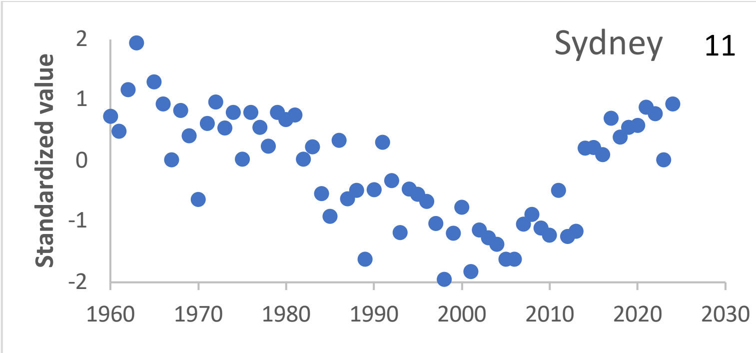
Storm winds of Nova Scotia

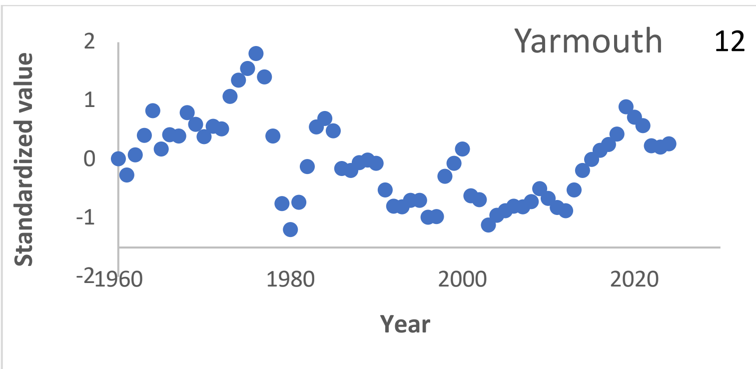
Our data for five Nova Scotia sites over the last 65 years describes changing patterns of air temperature, wind, and storm activity. The overall change in wind velocity based on linear regression is negative, whereas the overall change in temperature is positive (Table 5). Correlations of annual temperature with our five separate wind metrics across all years from 1958-2024 are all negative with Pearson r ranging from -0.246 to -0.359 (all significant at $P < 0.05$). Thus, scatterplots for temperature versus mean maximum wind velocity, number of storm days, and months with storms (Fig 13-15) went counter to the assumption of higher winds associated with higher temperatures. This result is despite a highly significant temperature



Figs 8-10 Means of standardized values for four wind metrics from Greenwood, Halifax, and Shearwater. Note: each point is the rolling mean of values from three years.

increase of 1°C in the last 27 years when storm metrics were increasing. Thus, average wind strength has not been stronger in this recent period (1998-2025) when average temperatures were 1°C greater than during the preceding 40 years (Garbary and Hill 2021). Regardless of storm wind metric, our wind dataset shows a period of reduced





Figs 11-12 Means of standardized values for four wind metrics from Sydney and Yarmouth. Note: each point is the rolling mean of values from three years.

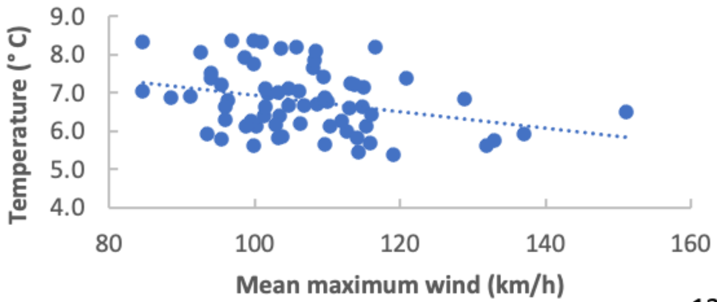
wind activity from the start of our time sequence to the early 2000s. The congruence of the standardized data by site (Table 4) and by wind metric (Table 5) suggests that the resolved trends for Nova Scotia are real, and not an artifact of stochastic processes. These trends are also consistent with a global phenomenon known as wind stilling, and they were consistent for our wind metrics by year and by month. Our results are contrary to those of Hundecha *et al.* (2008) who examined changes in extreme annual wind speed around the Gulf of St. Lawrence and did not resolve significant change over the period 1979-2004. This discrepancy can be attributed to the shorter period examined by Hundecha *et al.* that began only after 20 years of major wind stilling had already occurred. In addition, their account treated a much broader area of eastern Canada, i.e. Quebec, New Brunswick and the island of Newfoundland, with only Sydney overlapping with

Table 4 **Linear regressions of the combined wind metrics for each study site based on the overall period, the wind stilling period, and the wind recovery period.**

Site	Years	Slope	R^2	Significance
Greenwood	1958-2024	-0.0854	0.5246	< 0.0001
	1958-2001	-1.1119	0.4052	< 0.0001
	2001-2024	0.0719	0.3870	0.0012
Halifax	1961-2024	-0.0008	0.0001	0.9306
	1961-2001	-0.0536	0.2357	0.0013
	2001-2024	0.1240	0.4633	0.0007
Shearwater	1958-2024	-0.0567	0.3549	< 0.0001
	1958-2003	-0.0894	-0.3453	< 0.0001
	2003-2024	-0.0139	0.0071	0.7477
Sydney	1958-2024	-0.0256	0.1918	0.0002
	1958-2006	-0.0731	0.7284	< 0.0001
	2006-2024	0.1602	0.7699	< 0.0001
Yarmouth	1958-2024	-0.0139	0.0577	0.0502
	1958-2001	-0.0383	0.1622	0.0067
	2001-2024	0.1054	0.5924	< 0.0001

our study. Using the limited time-period of Hundecha *et al.* in our analysis, two of our metrics (provincial maximum and mean maximum) were consistent with their pattern, i.e., no significant change; however, our remaining three storm metrics were highly significant with $P < 0.0001$. Thus, over the larger region and using only the single metric of annual maximum, the pattern may indeed be consistent with Nova Scotia within the shorter time series.

The absence of a common climate change signal for temperature and wind contradicts patterns showing increasing wind activity in warming tropical oceans (e.g., Young *et al.* 2011) as well as society's expectation that climate change necessarily means more storm activity. We suggest two explanations. First, in eastern Canada the highest wind velocities are typically associated with winter and cold, while the summer wind velocities are typically more moderate. Hence storminess in Nova Scotia is predominantly a winter phenomenon. Thus, on an annual basis, higher temperatures do not positively correlate with the frequency of summer storms (Figs 4, 6). Furthermore, while all months in Nova Scotia have shown significant temperature increases post-1998, these increases are lower in summer and greater in fall and winter (Garbary and Hill 2021, 2025). We have noted that the low point in all storm metrics (between 2001 and 2006), and then their reversal, was preceded by the jump in mean annual temperature beginning in 1998. This change in air temperature was



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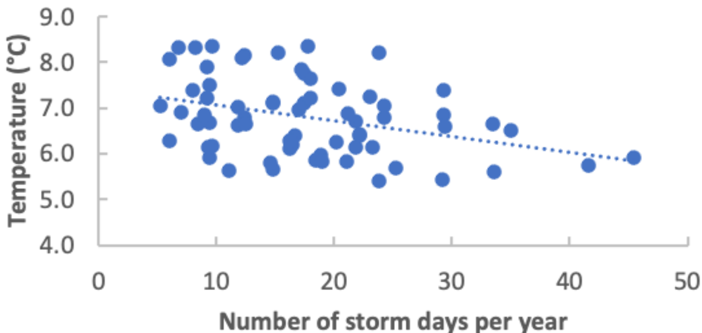

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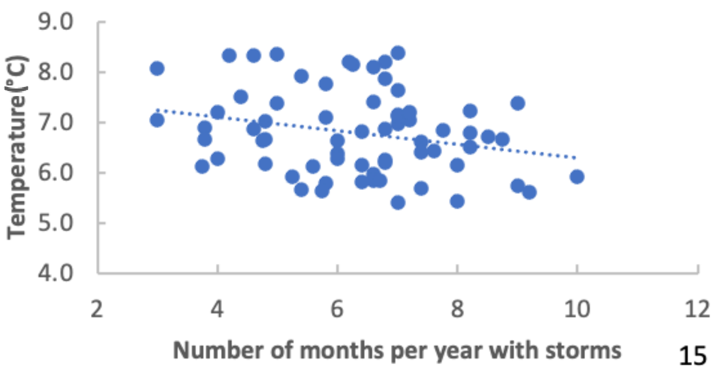

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Figs 13-15 Scatter plot showing negative relationship between temperature and three wind metrics: mean of annual wind maximum, number of storm days per year and number of months per year with storms.

Table 5 Results of linear regressions of mean annual air temperature and annual wind metrics in Nova Scotia from 1958 to 2024.

Temperature and Wind metrics	Years	Slope	R^2	Rate of change	*P*
Mean temperature	1958-2024	0.0264	0.394		< 0.0001
	1958-1997	0.0003	< 0.0001		0.9669
	1998-2024	0.0319	0.138		0.0565
Annual wind maximum	1958-2024	-0.339	0.149		0.0012
	1958-2001	-0.7971	0.320	-1.20 km $h^{-1}y^{-1}$	< 0.0001
	2001-20024	1.220	0.344	1.69 km $h^{-1}y^{-1}$	0.0026
Mean wind maximum	1958-2024	-0.332	0.294		< 0.0001
	1958-2001	-0.679	0.474	-0.92 km $h^{-1}y^{-1}$	< 0.0001
	2001-2024	0.776	0.401	1.07 km $h^{-1}y^{-1}$	0.0009
Mean of monthly wind maximum	1958-2024	-0.210	0.399		< 0.0001
	1958-2001	-0.407	0.662	-0.57 km $h^{-1}y^{-1}$	< 0.0001
	2001-2024	0.614	0.763	0.71 km $h^{-1}y^{-1}$	< 0.0001
Number of storm days per year	1958-2024	-0.277	0.393		< 0.0001
	1958-2001	-0.5491	0.624	-0.62 storms y^{-1}	< 0.0001
	2001-2024	0.641	0.654	0.67 storms y^{-1}	< 0.0001
Number of months with storms	1958-2024	-0.046	0.335		< 0.0001
	1958-2001	-0.092	0.632	-0.13 months y^{-1}	< 0.0001
	2001-2024	0.164	0.686	0.19 months y^{-1}	< 0.0001
Means of standardized values (wind metrics)	1958-2024	-0.029	0.356		< 0.0001
	1958-2001	-0.058	0.614		< 0.0001
	2001-2024	0.083	0.678		< 0.0001

coincident with the development of ocean hotspots in the Gulf of Maine and the outer Bay of Fundy (Saba *et al.* 2015, Seidv *et al.* 2021, Herbert *et al.* 2023).

Our data for Nova Scotia also demonstrates a strong recovery in these wind metrics to levels observed in the 1970s and 1980s but still not reaching the maximum of the 1960s (Figs 4, 7). This is consistent with various reports from around the world (e.g., Azorin-Molina *et al.* 2016, Yang *et al.* 2021, Minola *et al.* 2022). Dunn *et al.* (2022) suggested that the reversal of global stilling in Asia and Europe after 2013 may have resulted from overestimation of average wind speeds that arose from an underestimation of the number of calm periods. This is not applicable to our study as we were working with the number and intensity of storms rather than average wind speeds or calm periods.

What is remarkable about the patterns of stilling and recovery for Nova Scotia are the rates of change. McVicar *et al.* (2008) summarized rates of stilling in average wind speed as between -0.004 m sec^{-1} y^{-1} to -0.017 m sec^{-1} y^{-1}. The rate of change in Nova Scotia for mean of annual maximum (MAM) wind gusts was -0.26 m sec^{-1} y^{-1} and 0.30 m sec^{-1} y^{-1} during stilling and recovery, respectively, an order of magnitude higher than the rates described by McVicar *et al.* (2008). Similarly, our metric for mean of monthly maxima (MMM) showed a decline during stilling of 0.16 m sec^{-1} y^{-1} and an increase of 0.20 m sec^{-1} y^{-1} during recovery; again, an order of magnitude greater than the averages reported by McVicar *et al.* (2008). Whereas the difference between declines of average wind speeds and maximum wind speeds might not be expected to be the same, the order of magnitude difference in Nova Scotia suggests localised forcing in addition to continent-wide forcing, e.g., Klink *et al.* (1999). The rate of change in our wind metrics for Nova Scotia was higher in the wind recovery period than in the wind stilling period. This 8%-48% increase in absolute rates in the opposite direction is a sign of a rapidly changing wind climate.

Mechanisms

Explaining the discrepancy between the patterns of change in temperature and wind in Nova Scotia was beyond the scope of this paper; however, we suggest some phenomena that may be involved. Accordingly, the temperature transition in Nova Scotia between the early period, when mean annual temperatures were mostly 6-7°C, and the latter period when mean annual temperatures were mostly 7-8°C coincided with a strong and long-lasting period of La Niña (NOAA 2025, updated monthly), which is driven by air pressure changes in the tropical Pacific Ocean. It may be circumstantial, but the latest multiyear period of > 8°C mean annual temperature for Nova Scotia (Fig 1) also coincides with a long-lasting La Niña. Changes in the Atlantic Multidecadal Oscillation (AMO) which cycles over a 50-80-year period and involves a change of 0.4°C in ocean temperature (Dijkstra *et al.* 2006, Knight *et al.* 2006, Li *et al.* 2009, Wyatt *et al.* 2012, McCarthy *et al.* 2015) may also be a component of the changes observed in Nova Scotia. At the end of the 1950s the AMO entered a negative temperature regime. This was during a period of high storm intensity regionally and associated with generally higher temperatures in Nova Scotia that subsequently declined (Fig 1). Then, at the end of the 1990s AMO reverted to a positive temperature regime that corresponded with the development of ocean hotspots around Nova Scotia and a general increase in air temperature of 1°C. The development of the ocean hotspot in the Gulf of Maine and outer Bay of Fundy correlates with the increase of mean temperature of almost 2°C on Brier Island (Garbary and Hill 2025). This transition was associated with the return of the AMO to a positive temperature phase. Sutton and Dong (2012) concluded that the AMO was a key factor in climate change (for both temperature and precipitation) that began in Europe in the late 1990s. Sutton and Dong also suggested that a reversal of the AMO into its negative phase would bring about a reversal of this trend. Zhang *et al.* (2024) also used the AMO to explain abrupt warming in northeast Asia in the late 1990s. If this hypothesis is correct, the next transition of the AMO into its negative phase may be associated with a return of the ocean hotspots off Nova Scotia to pre-2000 temperature regimes and a regional increase in storminess to levels last seen in Nova Scotia in the 1960s.

Woolway *et al.* (2019) suggested that wind stilling had a dramatic effect on lakes. They concluded that "atmospheric stilling has influenced lake thermal responses to warming." Accordingly, reduced winds increased lake stratification and a delay in turnover. With very large lakes, a lengthening of the period prior to turnover would influence adjoining land masses by slowing the cooling effects of fall and early winter. The congruence in timing of the development of ocean water hot spots off Nova Scotia coastlines along the Atlantic coasts with raised fall and winter air temperatures (Garbary and Hill 2021) is consistent with a similar mechanism. Accordingly, reduced storm activity since the 1970s may be responsible for warmer sea surface temperatures (SSTs). These have resulted in profound changes in the biology of coastal waters (e.g., reduction or loss of kelp populations, Filbee-Dexter *et al.* 2016; declines in the cod fishery in the Gulf of Maine, Pershing *et al.* 2015), and increased fall and winter air temperatures over Nova Scotia post-1998. The same mechanism could explain the pattern of air temperature increases post-1998 in Prince Edward Island (Garbary 2018).

Forests and coastal plant communities

On a transect across southwest Nova Scotia more than two hundred years ago, Titus Smith (1802) noted areas of windfall on 19 days of his 90-day journey. He wrote of "windfalls from the Great Storm" that were growing up in young fir and of an even-aged hardwood forest, the succession from fire that had followed a hurricane 80 years prior. Wind is a major disturbance that helps shape most of the forests of Nova Scotia, from the vulnerable coastal softwoods subjected to a moderate wind disturbance (30% to 60% trees felled) every 60 years to hardwood forests that regenerate through gap replacement dynamics (Taylor *et al.* 2020, McLean *et al.* 2022). On a regional level, our results inform trends in major wind disturbance and provide empirical data to test the expectation that warmer weather brings stronger winds. Despite the paucity of weather stations with wind records, the data (e.g., Fig 6) support the spatial wind disturbance variation for Nova Scotian forests (Taylor *et al.* 2020).

Nova Scotia is a windy province (Environment and Climate Change Canada 1990), with especially strong winds ‘Les Suetes’, along the west coast of Cape Breton Island (McIldoon and Pilon 2008, The Nature of Things 2021). Wind activity in Nova Scotia is increasing from its 2000s lull. Predicting the impact of increasing wind activity means not simply a return to the past relationship with wind, but rather a contemporary context that differs in several ways from the 1960-1980 period. Increased winds in winter are now occurring in a climate-changed temperature regime where winters have experienced extensive warming, and the duration of soil freezing is greatly reduced (Garbary and Hill 2021). Saad *et al.* (2017) predicted that the decrease in the period of frozen ground in combination with higher winds and wetter soils will lead to an increase in windthrown trees. The increase in windthrow vulnerability increases with greater soil wetness (Xi 2005) and decreased frost penetration (Peltola 1996). Increased wind during warmer wet winters increases the windthrow vulnerability for evergreen conifers (Anyomi *et al.* 2017) and for other shallow-rooted species (Xi and Peet 2011). An increase in wind severity will affect the structure of the forest community and, in turn, can increase the species pool of herbs (Steenberg *et al.* 2011). The spatial patterns of tree uprooting and the differential susceptibility of trees to uprooting were evident after Hurricane Fiona in fall of 2022. We noted (Hill and Garbary, unpublished observations) that while a substantial fraction of other trees (i.e. red maple, white spruce) in a study swamp were uprooted, black ash (*Fraxinus nigra*) alone remained rooted; this tenacity may relate to the greater flood tolerance of black ash than the other sympatric trees which has allowed it to root more deeply and become more deeply anchored in the anaerobic layers of the wetland.

Nova Scotia is part of Braun's hemlock-white pine hardwood region that is "…throughout its extent, a mosaic of hardwood, conifer and mixed forest" (Braun 1950, p 533). A subsequent cluster analysis confirmed Braun's mapping of regional forest types separating this northern forest region into a western (centred around the Great Lakes) and our eastern region which was renamed the northern hardwood-hemlock (Dyer 2006). Gap formation by wind may maintain the species richness of both tree and the understory communities in hardwood forests (Braun 1950, Runkle 1990). A full understanding of how the diversity of herbaceous communities is affected by patch level disturbances in Appalachian hardwood forests, however, remains elusive (Elliott *et al.* 2014). In Nova Scotia, the occurrence of some of the rarest Appalachian deciduous herbs is linked to soil fertility and riparian flood disturbances (Hill and Garbary 2011) but the distribution of the rare upland (S2) *Hepatica americana* is an enigma. Its occurrence, however, in early successional forest communities suggests a dependence on open woodlands that may mimic gap dynamics in pre-contact forests. Analysis of the patch distribution of its congener, *Hepatica nobilis,* in Spain, however, revealed no association between plant size and canopy openness (Pico 2002).

Geographically, the greatest impacts of the most frequent wind type (low severity: annual disturbance rates twice that of each of seven other ecoregions based on analyses of 2800 plots over ten years (2008-2017)) occurred along the Eastern Shore (granite- or quartzite-based spruce forests) and in forests of the Annapolis Valley and the Central zone (Taylor *et al.* 2020). Our weather stations include four of the ecoregions in Taylor *et al.* (2020), yet wind data values are not related to wind disturbance differences (Table 2). The difference between the measurement of wind – our study – and its impact at the tree level has been ascribed to differences in vulnerability to windthrow (Taylor *et al.* 2020). The forests most vulnerable to wind are the coastal softwood and hardwood forests (MacLean 2022) that are exposed to onshore winds and salt spray. These coastlines along the Atlantic coast of Nova Scotia, and those in the Gulf of Maine, have experienced the greatest increases in temperature associated with ocean-warming hotspots (Hobday and Pecl 2014, Pershing *et al.* 2015, Du *et al.* 2022, Lotze *et al.* 2022, Garbary and Hill 2024). Many of the Atlantic coast plant communities are dominated by evergreen, needle-bearing plants, forests by *Picea* spp., and coastal heathland by *Empetrum nigrum* (Porter *et al.* 2020). Evergreen leaves allow needle-bearing plants to photosynthesize in winter though they are vulnerable to freezing embolisms and frost-drought (Niinemets 2016, Maruta *et al.* 2020). Wind exacerbates the loss of water from evergreen leaves in winter when the soil is frozen, and the xylem cannot replace the water stripped from leaves by wind. Winterkill of *E. nigrum* was observed in summer following extreme warming events in the Arctic (Bokhorst *et al.* 2009). We have documented that loss of the crowberry mat is restricted to its open heathland and did not occur in the shelter of the spruce forest (Hill *et al.* 2012). Saville (1972) discussed how arctic environmental factors impact extracellular and intracellular freezing, and snow abrasion and desiccation restrict the mat-forming, evergreen-needled heath, *Cassiope tetragona,* to leeward hollows out of the wind and covered with snow. Although the changes in plant distribution occur in response to multiple factors, changing wind can alter climate change predictions based solely on temperature. An open-top chamber study that increased ambient temperature partly by shielding the chamber from wind, showed positive shoot growth and biomass in *E. nigrum*; however, the authors noted that at continental level, the plant was retreating northward at its southern edge of range (Burt *et al.* 2012). The interaction of increased wind and warmer winter temperatures may generate large changes in these coastal ecosystems by increasing seasonal windfalls. Furthermore, the reduction and fragmentation of forests in Nova Scotia over the last century may result in greater windfalls because of edge effects.

At the shore level, winds of the post-tropical storm Fiona in September 2022 caused massive erosion of beaches and shorelines to both Nova Scotia and Prince Edward Island (e.g., Halam 2022, Parks Canada 2022, Davidson-Arnott *et al.* 2024, Garbary *et al.* 2025). During the stilling reversal period the rates of monthly maximal wind gusts were high from November to April (increases of 0.17 m sec^{-1} y^{-1} to 0.44 m sec^{-1} y^{-1}, Table 3). These wind velocities, though not as high as during storms in the early to mid-period of stilling, are impacting coastal ecosystems facing another temperature-related change: a large reduction in coastal ice in the southern Gulf of St. Lawrence (Greenan *et al.* 2018). If shorelines are not protected by ice, increasing wind velocities will exacerbate shore erosion, already a major problem associated with sea level rise. The combined effects of storms and sea-level rise have already had a major impact on coastal forest margins (Robichaud & Bégin 1997) before the increase in storm intensity and number that we document. These effects will only be exacerbated if current trends continue.

CONCLUSIONS

We can now answer the questions posed in the introduction. First, there has been no overall positive relationship between increasing temperate and increasing storm activity in Nova Scotia over the last 65 years; indeed, the overall relationship is negative for our storm metrics. Secondly, through much of this period, storm number and intensity have declined. Thirdly, reductions in storm activity occurred throughout the year with the least change occurring during summer. Our data are a clear demonstration of wind stilling, a brief period of relative stability followed by a reversal of the stilling process, similar to global patterns. Finally, further moderation of winter temperatures and increasing storm frequency and intensity will likely negatively impact coastal forests and maritime habitats.

Acknowledgements We thank David Richardson and two anonymous referees for constructive comments. This work was supported by grants from the Natural Sciences and Engineering Research Council of Canada to DJG, and the Department of Fisheries and Oceans to DJG and the Gulf Aquarium and Marine Centre Cooperative, Grand Étang.

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