Article

The Effects of Climate Change and Tropical Cyclones on Offshore Wind Turbines in Nova Scotia

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The Effects of Climate Change and Tropical Cyclones on Offshore Wind Turbines in Nova Scotia

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Abstract

Nova Scotia, a province on Canada's Atlantic coast, has proposed *Wind West*, a plan to initiate the province's offshore wind industry. A regional offshore wind report identified eight potential development areas (PDAs), of which four were chosen. The areas were selected to avoid ecologically significant and conflict-of-use areas; however, no consideration was given to tropical cyclones (TCs) and hurricanes (intense tropical cyclones). This paper evaluates the effects of climate change and TCs on offshore wind turbines sighted on Nova Scotia's continental shelf by analysing historical TC track data to assess the intensity and frequency of extreme wind and wave events on the continental shelf. Correlations between SSTs and extreme weather events were also examined. The findings show no clear long-term trends in TC intensity or frequency in the selected areas, although there is a clear upward trend in sea-surface temperatures (SSTs) since 1950. No strong correlation between rising SSTs and increased storm intensity or frequency within the available datasets were found, though similar studies suggest that these variables have some correlation on aggregate. While climate change is causing conditions for hurricanes to become favorable along the Scotian Shelf, current TC data shows no clear correlation with increasing intensity and frequency over time. The results are affected by the quality of the data. High uncertainty, spatial resolution, and temporal resolution leave large portions of TC tracks unmeasured. Uncertainty associated with pre- and post-1950 data makes conclusions from the results difficult. We propose a measuring buoy in each of the four selected potential development areas cost C$200,000 to develop and C$35,000 to maintain. Each buoy would have a representative radius of 50km, slightly larger than that of each of the four wind energy zones. The additional data collected would allow developers to pick appropriate design standards based on available environmental data and could additionally be used for climate change research. Currently, Nova Scotia faces many limitations developing its offshore; supplying accurate data to assess the risk from extreme weather events to offshore wind turbines is one of the first steps to ensuring success.

Keywords: offshore wind; tropical cyclones; climate change; sea surface temperatures; Atlantic multidecadal oscillation; Atlantic meridional overturning circulation; scotian shelf; IBTrACS; Nova Scotia; wind turbines

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1. Introduction

Nova Scotia, a province on Canada's Atlantic coast, is the country's second smallest province. The province's location, protruding into the Atlantic Ocean, gives it an excellent wind resource [1]. The province intends to more than double its wind capacity from about 900 megawatts in 2025 to about 2100 megawatts in 2050 [2].To date, all wind turbines have been installed on shore.

In September 2022, the province's Premier, Tim Houston, announced Nova Scotia would have five gigawatts of offshore wind capacity by 2030, making it "… an internation leader in offshore energy" [3]. Three years later, in June 2025, the Premier announced plans for Wind West, a 66-gigawatt offshore wind project "reliably" producing 40 gigawatts (as opposed to gigawatt-hours), which he said was equivalent to about 27% of Canada's electricity needs [4].

The turbines are to be located in the Scotian Shelf, part of the Continental Shelf off Nova Scotia bounded by the Laurentian Channel and the Gulf of Maine and consisting of basins and channels separating shallow banks [5], as shown in Figure 1.

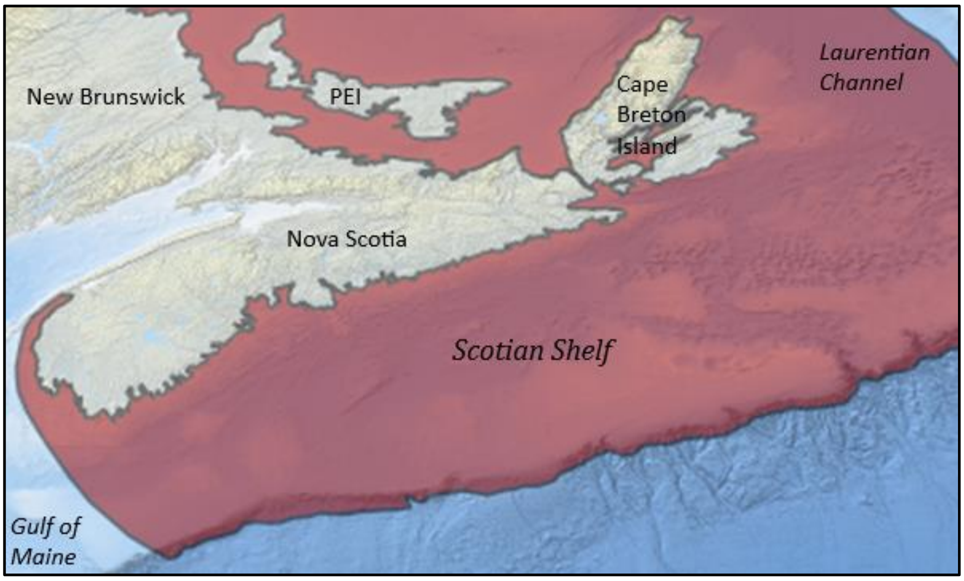

Figure 1. The Scotian Shelf (Chart from [6]).

In early 2025, after almost two years of analysis of the offshore considering physical constraints, conservation areas, and areas of human activity, and consultations with government departments, contractors, First Nations, NGOs, fisheries, and industry experts, the province released the Regional Assessment of Offshore Wind Energy in Nova Scotia [7]. The Regional Assessment identified five "Tier 1" Potential Development Areas (PDAs).

Subsequently, the federal and Nova Scotian governments selected four of the PDAs (referred to as Wind Energy Areas or WEAs) to be open for leases in late 2025 (Sydney Bight, French Bank, Middle Bank, and Sable Island Bank), with the fifth (Emerald Bank) to be opened in 2030 [8].

The four PDAs selected are either over or adjacent to existing natural gas or electricity corridors that have had approval from the federal and provincial governments: Emera's Maritime Link [9] runs past Sydney Bight [7], while the routes of the former natural gas pipelines used by the Sable Offshore Energy Project [10] and Deep Panuke [11] pass through or near French Bank, Middle Bank, and Sable Island Bank [8], as shown in Figure 2 .

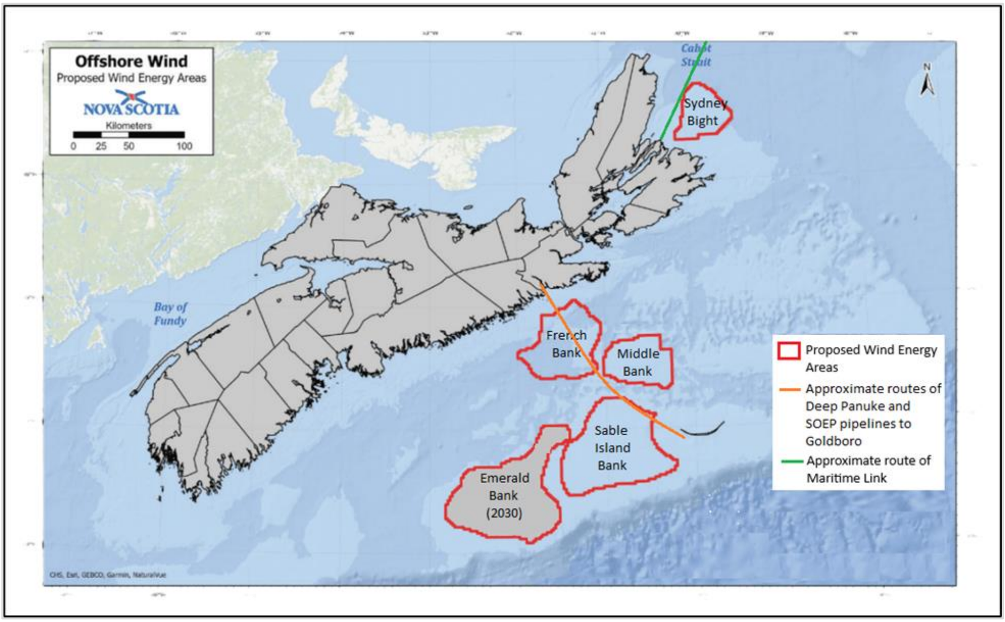

Figure 2. Proposed Wind Energy Areas adapted from (Authors' labels; Chart from [8]).

There are about 11,355 km^2 are available for leasing in the four WEAs. Over half of these (56%) are in relatively shallow water (zero to 60 metres), which is usually the range for turbines built on fixed-bottom foundations driven into or attached to the seafloor, while in deeper waters (greater than 60 metres), turbines are floating, anchored to the seafloor; the comparative depths are shown in Figure 3. Floating turbines are typically more expensive than fixed-bed turbines [12].

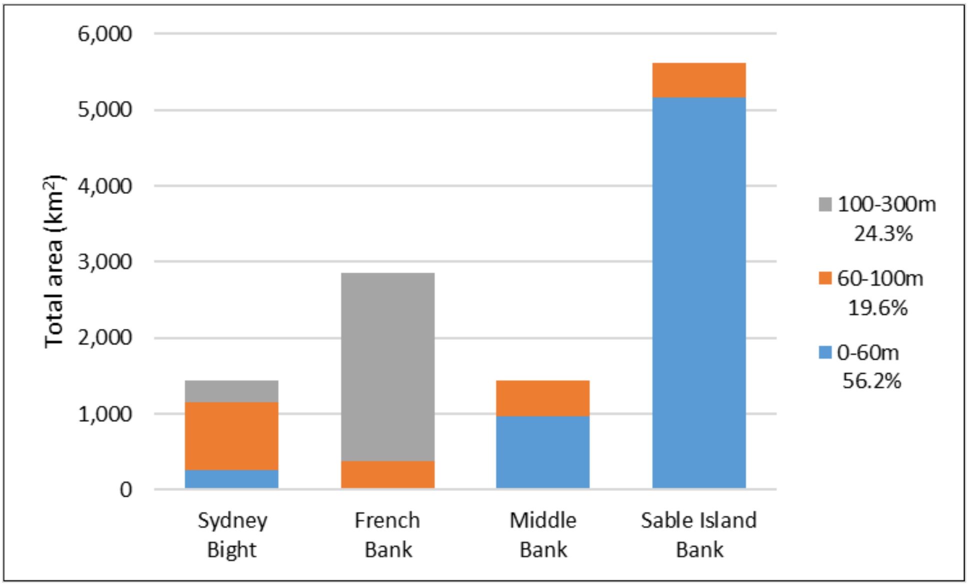

Figure 3. WEA areas depths (Authors' chart; Data from [13]).

In September 2025, Premier Houston released the Wind West Strategic Plan which describes a $60 billion plan for five gigawatts [14]. The Plan assumes the availability of long-term, low-interest funding from the Canada Infrastructure Bank and Investment Tax Credits (ITCs) of 30% for wind and 15% for transmission infrastructure [15].

The Strategic Plan expects five gigawatts of offshore wind capacity to be installed by 2030 and 15 gigawatts by 2040.

However, the federal and provincial Notice of Strategic Direction Respecting Offshore Wind Call for Bids [16], instructed the Canada-Nova Scotia Offshore Energy Regulator (CNSOER) on how to

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proceed with the first call for bids on offshore wind leases. The Notice limits the first call for bids to three gigawatts from three WEAs (Sydney Bight, French Bank, and Middle Bank), not the Strategic Plan's five gigawatts from all four WEAs, see Table 1. Moreover, the Notice intends to "optimize local benefits from projects", specifying where developers can site their windfarms and the maximum capacity allowed (the largest WEA, Sable Island Bank, has been omitted because of distance from the mainland). The province plans to announce its first call for bids for five gigawatts of offshore wind capacity sometime in 2026 [7].

Table 1. Wind Energy Areas and Capacity.

Wind Energy Area	Maximum Total Capacity	Foundation type
Sydney Bight	500 MW	Fixed bottom
Middle Bank	2,000 MW (No single windfarm can be greater than 1,000 MW)	Fixed bottom
French Bank	500 MW	Floating

1.1. Objectives and Contents

As part of our research into the province's offshore wind potential, we found that very little research has been done regarding tropical storms and hurricanes. This is an issue, because Nova Scotia receives the highest number of tropical storms in Canada due to its proximity to the Gulf Coast [17]. With storm tracks moving northward due to rising sea surface temperatures (SSTs), it is expected that more tropical cyclones (TCs) will reach Nova Scotian waters [17,18]. Tropical cyclone is a generic term for a rotating, organized system of clouds and thunderstorms that originates over tropical or subtropical waters.

TCs can cause failures in any of the four main OSW turbine components: the foundation, the tower, the nacelle and the blades. TCs are known to cause blade deformations, tower collapse, foundation overturning, and control system overload all of which can cause serious damage to offshore installations [19]. TC prone areas not only require added adaptive measures from turbines but also carry the risk of escalating in intensity with the changing climate leading to unpredictable TC behavior. It is important to assess the impact of climate change on TCs to mitigate risk to offshore wind infrastructure.

To determine the effect of climate change on TCs, two predominant methods are used: analyzing historical climate data and using climate models to predict future climate changes and their correlation with TC intensity and frequency. Different climate models carry inherent variabilities that cause significant deviations between models; a 2025 study by Sheng et al. suggests an annual upward trend in the occurrence of extreme TCs despite high inter-model variability [20]. The selection of climate model is typically based on the quality of climate data in the specific region of interest [21]. However, many climate models have high spatial resolution, which makes characterizing extreme TCs difficult[20].

This paper aims to estimate the potential impacts of tropical cyclones (TCs) and hurricanes on the Scotian Shelf using historical data. It begins by examining the characteristics of TCs and the factors that limit their development. The paper then describes the data used in the analysis, followed by a discussion of the findings and associated recommendations. A key limitation of this study is the sparse coverage of observations along the Scotian Shelf, which makes definitive conclusions about TC behavior on the Scotian Shelf difficult.

2. Background

This section begins with an overview of the impacts of TCs and summarizes current research on their relationship with climate indices. It then describes the data used to analyze trends specifically for the Scotian Shelf.

2.1. Climate Change and Changing Weather Patterns

Climate change is not only a warming of the planet; it will change weather patterns [22]:

- Increasing average air temperature
- Extreme temperatures
- Annual average precipitation
- Shrinking cryosphere extent and mass
- Rising sea levels
- Rising SSTs

The general trends brought about by climate change are considered to fuel extreme weather events [22].

2.1.1. Tropical Cyclones

TCs are characterized by clouds spiraling around a central eye, resulting in extreme winds and waves. The greatest intensity winds in a TC are found in the cloud wall, with a width of 10-20 km at the edge of the eye [19]. The structure of a typical TC can be seen in Figure 4. Higher SSTs allow greater potential energy for TCs [23], while rising sea levels make storm surges increasingly destructive [21]. Hurricanes are a subset of TCs used to describe storms which have sustained wind speeds of above 119 km/h and are along Atlantic and Northeast Pacific regions.

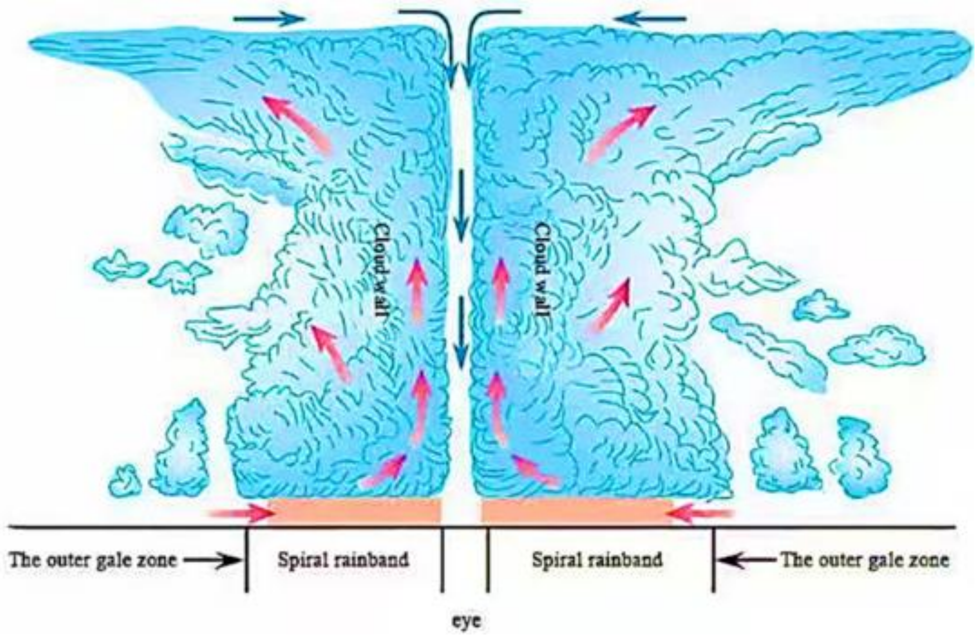

Figure 4. Structure of a Tropical Cyclone [19].

Currently, there is no scientific consensus on whether the effects of climate change directly weaken or strengthen extreme TC winds [24]. A 2024 study by Lipari et al. reported that historical 20-year storms on the North Atlantic Basin now occur every 12.7 years on average showing an increase in wind speed of 9.3 ms^{-1} [22]. A 2022 study by Lakshani & Zhou reports that there is high decadal variance for TCs in the North Atlantic Basin with recent data showing increases in TC frequency but overall lower average intensity [25]. Lack of scientific consensus on how TC intensity and frequency is changing can be attributed to selection of climate model and lack of accurate historical meteorological data [26]. Overall, scientific research into the effect of climate change on TC is evolving slowly. Increased research efforts into regional changes are improving the modeling of TC changes with local changes in the climate.

Research on extreme wave heights caused by TCs is similarly unclear; some studies propose increasing wave heights throughout the North Atlantic basin while others predict small decreases [21]. Despite the lack of consensus on the frequency and intensity of waves and winds in TCs what is clear is that there is a high correlation between TC winds and waves [20,27]. TCs often cause secondary disasters such as huge waves, which in combination with extreme winds, cause significant damage [28]. With conditions favourable for extreme wind and wave conditions increasing throughout the Scotian Shelf, OSW technology must take adaptive measures to combat the presence of TCs.

2.1.2. Tropical Cyclone Formation

Warm air is less dense than cold air and thus rises in a process known as convection [29]. As air rises, atmospheric pressure decreases, resulting in air expanding with the same amount of heat but differing volumes; this is known as adiabatic cooling. The rising warm air beneath a TC lowers barometric pressure at the surface, drawing more air inward toward the storm's center [30].

For the formation of TCs, a key limiting factor is atmospheric moisture. Warmer temperatures induced by greenhouse gas emissions have resulted in higher atmospheric humidity, leading to increased evaporation from water bodies and transpiration rates from vegetation [29]. Because of the increasing humidity the atmosphere can hold approximately 7% more moisture for 1°C of warming [29]. When water vapor condenses into liquid droplets, energy is released, warming the air and subsequently increasing its buoyancy [31].

2.1.3. Waves

TCs are mainly characterized by their extreme wind speeds and precipitation [32]. Extreme winds in combination with increased precipitation result in storm surges and powerful waves, which often cause more damages than the powerful winds [33]. The North Atlantic Ocean is home to the largest significant wave heights (top third percentile of wave data) caused by TCs in the world making it exceedingly hazardous to the offshore industry [34]. As wind blows over water, it creates drag stretching the surface and forming waves. As the height of the wave increases, the surface area of the waves affected by the wind increases, further intensifying the waves [35]. As a result of the lower pressure and increased wind speeds, TCs cause extreme storm surges and waves [32]. The size and strength of the waves are a result of the wind strength, the period in which wind is blowing on the waves, and the fetch [35].

2.1.4. Limiting Factors for TC Formation

There are several limiting factors for the formation and stability of TCs. One is windshear, which is the variation of wind speed and direction with altitude. Strong vertical wind shear displaces warm air parcels, disrupting the convection process needed for the formation and intensification of TCs [36]. Furthermore, wind shear brings colder, drier air within the core of the TC diluting its warm, energy dense core [37]. Another limiting factor for the formation of TCs is SSTs. Increasing SSTs can be attributed to higher potential energy for TCs through surface transfers of heat [23]. Temperatures above 25.5°C accounted for 98.3% of all TC formations [23]. Once a TC moves into an area below the 26°C threshold, it will weaken rapidly [38].

Research has shown that increased SSTs are strongly correlated with increased accumulated cyclone energy (ACE) and intensity during peak TC seasons [39]. Figure 5 displays the increase in TCs with rising SSTs in the North Atlantic.

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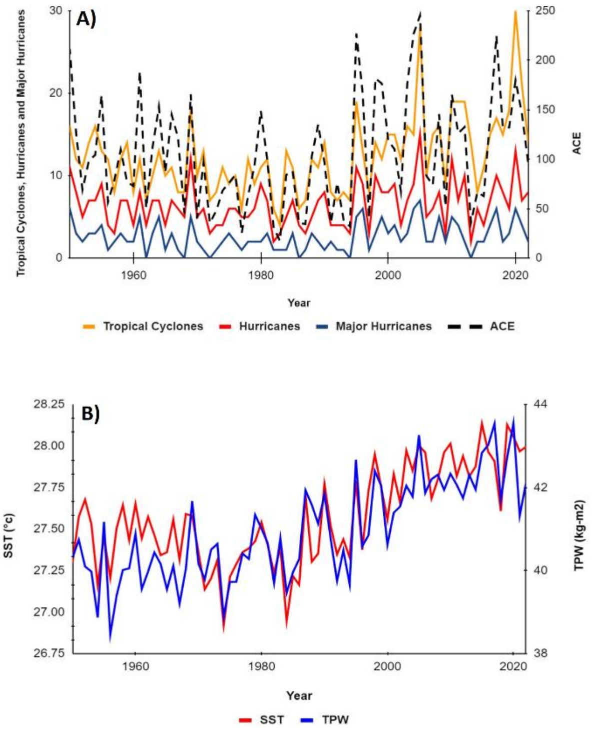

Figure 5. A) Total number of tropical cyclones, hurricanes, major hurricanes and accumulated cyclone energy from 1950 to 2022 in the Atlantic Ocean. B) Area average SST and total precipitable water (TPW) between 1950 to 2022 in the tropical/subtropical Atlantic adapted from [39].

2.1.5. Climate Variability

Climate research has found that ocean oscillations such as El Niño Southern Oscillation (ENSO) and the Atlantic Multidecadal Oscillation (AMO) have added to climatic variability [39].

ENSO comes in three phases [40]:

1. El Niño with above average SSTs and low-level equatorial winds,
2. La Niña with below average SSTs and above average equatorial winds, and
3. Neutral, in which neither of the other phases are present.

Despite ENSO primarily affecting the Pacific Ocean, studies have shown El Niño conditions have been associated with fewer TCs and La Niña with larger amounts of TCs in the North Atlantic [41,42]. Niña conditions are associated with an increase lower-level vorticity and reductions in vertical wind shear, thus, resulting in more TC landfalls on the North Atlantic coast [43].

AMO is another climate cycle with alternating warm and cool phases that last approximately two to four years [42]. The warmer phase results in higher SST temperatures which leads to increased TC intensity. AMO is closely related to Atlantic Meridional Overturning Circulation (AMOC), a process in which warmer top layer salty currents move from equatorial waters into the North Atlantic and colder water moves southward [44]. A 2017 study suggested that AMOC may play an important role in reducing TC frequency in the North Atlantic [36]. Some studies indicate AMOC could induce variations in wind shear through an atmospheric bridge which distributes heat and moisture [36]. In the 2023 Sixth Assessment Report on climate change, the Intergovernmental Panel on Climate Change (IPCC) stated the likelihood for AMOC to weaken under all climate scenarios but it is unlikely to collapse [45]. Despite the IPCC's stance on AMOC, in October of 2024 a panel of climate scientists wrote a letter highlighting new research pointing to a severe risk of AMOC collapsing soon [46]. The collapse of AMOC is an imminent threat caused by climate change that could have major ramifications on TC behavior across the North Atlantic.

2.1. Data

This section describes the different sources of data used throughout the analysis.

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2.1.2. TC Data

Global climate models used in forecasting climate change effects are typically not used for predicting extreme winds. Many climate models offer differing projections of wind speed, making them poorly suited to predicting the effects of extreme weather [24].

This investigation makes use of NOAA's International Best Track Archive for Climate Stewardship (IBTrACS) dataset [47]. The IBTrACS dataset is a collection of TC data from government reporting agencies around the world. The dataset includes TCs from 1851 to 2024, which is interpolated to three-hour averages. Forecasting and tracking fast moving TCs is difficult thus, IBTrACS creates a best track of the TC using available data. TCs in the dataset come with a positional uncertainty of between 10 and 40 km with stronger storms reporting lower uncertainty. Table 2 displays the relative uncertainty values estimated between all reporting agencies of the wind speeds of TCs in North America. The high uncertainty values of the data make definitive conclusions difficult.

Table 2. Qualitative uncertainty level for wind speed (km/h) of TCs in North America (Adapted from [47]).

Period	Uncertainty (km/h)
Pre-1950	±55.56
1950-1965	±55.56
1965-1973	±37.04
1973-1978	±37.04
1978-1984	±27.78
1984-1987	±18.52
1987-1995	±18.52
1995-2000	±18.52
2000 - Present	±12.96

2.2.2. Sea Surface Temperature Data

The SST data used in this analysis is between 1981 and 2024. The data set is derived from NOAA's Sea Surface Temperature–Optimum Interpolation Climate Data Record, which primarily makes use of satellite data from a very high-resolution radiometer [48]. The data set also incorporates data from buoys and ships to adjust for bias from different observation sources [48].

2.2.3. Wave Height Data

Sources of wave height data include satellite data, climate models, and buoys. Of the three, satellites and climate models are not recommended because of long revisit periods for specific locations and poor extreme wave prediction, respectively [49]. Buoy measurements are the most reliable wave height measurement; typically, being used as the reference/truth value to compare other measurements to [50].

An archive of publicly available buoy data measuring wave heights is available for the several locations on the Scotian Shelf. Canada's buoy data is classified into ten categories [51]; however, only two are considered "good" or "acceptable". The classification of buoy data in the set is based on significant wave height, to improve the quality of the data values, those above two standard deviations of the average annual maximum wave height (23.5m) were removed. Of the six buoys located on or in close proximity to the Scotian Shelf, quality data is only available from three, in two locations and shown in Figure 6, offshore buoy 6 (buoy number c44137) located on the Eastern Scotian Slope, and offshore buoy 4 (buoy numbers c44142 and c44150) located in LaHave Basin [51]. These locations were chosen due to their consistent measurements dating back to 1990; historical buoy data from other locations on and near the Scotian Shelf does not possess accurate data over long periods.

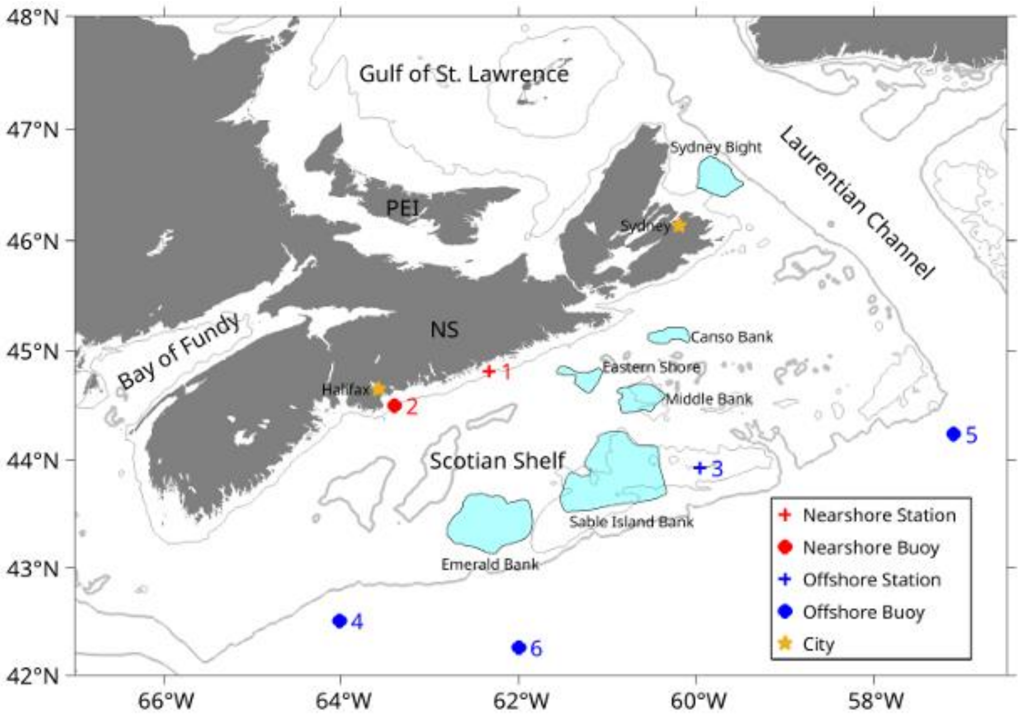

Figure 6. Data Collecting Buoys on and near the Scotian Shelf [52].

3. Environmental Hazards and Climate Impacts

Assessing the risk of climate change to TCs on the Scotian Shelf is vital for the success of Nova Scotia's OSW objectives. With rising SSTs being correlated with higher intensity and more frequent TCs [39], this section examines whether general worldwide connections between climate change and TCs hold true over the Scotian Shelf using the IBTrACS database and from NOAA's Sea Surface Temperature-Optimum Interpolation Climate Data Record to evaluate the trends in historical SSTs and TCs across the Scotian Shelf. Additionally, buoy data from LaHave Basin and the Eastern Scotian Slope [51]. is used to check historical changes in wave heights and correlations between extreme wind and waves on the Scotian Shelf. Historical trends between climate indices and TCs on the Scotian Shelf will aid OSW developers in predicting the future extreme weather conditions along the Scotian Shelf.

3.1. Method

The tracking of all TCs to move through the Scotian Shelf is displayed in Figure 7. The dataset was created using the spatial intersect tool. The spatial intersect was performed between TC Track data from the IBTrACS database [47] and the Scotian Shelf [6].

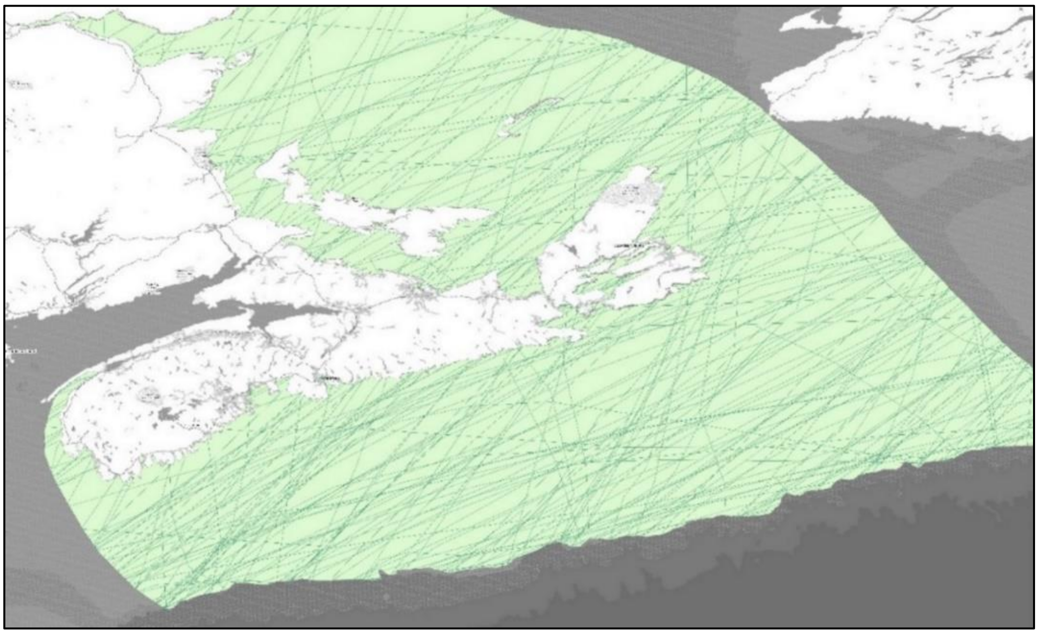

Figure 7. TC Tracks through Scotian Shelf (Figure created by authors using data from IBTrACS dataset [47] and [6]).

Additionally, SST data for the Scotian Shelf was analyzed alongside TC characteristics to explore potential correlations. To estimate extreme wave heights, data from buoys c44137, c44142, and c44150 was also incorporated.

Using the TC tracks, SST data, and buoy data the investigation analyzed the following nine relationships:

Average SST on the Scotian Shelf: This analysis examines the relationship between average annual SSTs on the Scotian Shelf and time. Average SST values (°C) were plotted against time in years.

Average SST on the Scotian Shelf During the Atlantic TC Season: This analysis explores the relationship between average annual TC season SSTs on the Scotian Shelf and time. Average TC season SST values (°C) were plotted against time in years.

Maximum Wind Speed of TCs on the Scotian Shelf: This analysis investigates the relationship between the maximum annual wind speed of TCs on the Scotian Shelf and time. Maximum wind speeds (km/h) were plotted against time in years.

Average Wind Speed of TCs on the Scotian Shelf: This analysis examines the relationship between the average annual wind speed of TCs on the Scotian Shelf and time. Average wind speeds (km/h) were plotted against time in years.

Count of TCs on the Scotian Shelf: This analysis evaluates the relationship between annual TC count on the Scotian Shelf and time. The number of TCs per year was plotted against time in years.

Average Wind Speed of TCs vs. Average SST on the Scotian Shelf: This analysis examines the relationship between average annual TC wind speed and average SST. Average TC wind speed (km/h) was plotted against the corresponding average annual SST (°C).

Maximum TC Wind Speed vs. Average Monthly SST on the Scotian Shelf: This analysis explores the relationship between maximum annual TC wind speed and the corresponding average monthly SST. Maximum TC wind speed (km/h) was plotted against average monthly SST (°C).

Maximum and Significant Wave Height on the Eastern Scotian Slope and LaHave Basin: This analysis investigates the relationship between maximum and significant wave heights and time. Maximum annual overall and significant wave heights (m) were plotted against time in years.

Maximum Wave Height vs. Wind Speed on the Eastern Scotian Slope and LaHave Basin: This analysis examines the relationship between maximum annual wave height and the corresponding wind speed. Maximum wave height (m) was plotted against wind speed (km/h).

3.2. Results

This subsection analyzes the effect of climate change and time on TC frequency and intensity on the Scotian Shelf. The entirety of the Scotian Shelf is considered to determine if the impact of TCs on the Scotian Shelf waters is changing due to climate change.

3.2.1. Sea Surface Temperatures

SSTs are a key limiting factor for TC sustenance and are also a signal of the warming climate. Higher SSTs could provide superior conditions for TCs moving through the Scotian Shelf. Figure 8 shows the average SST temperature by year on the Scotian Shelf since 1982.

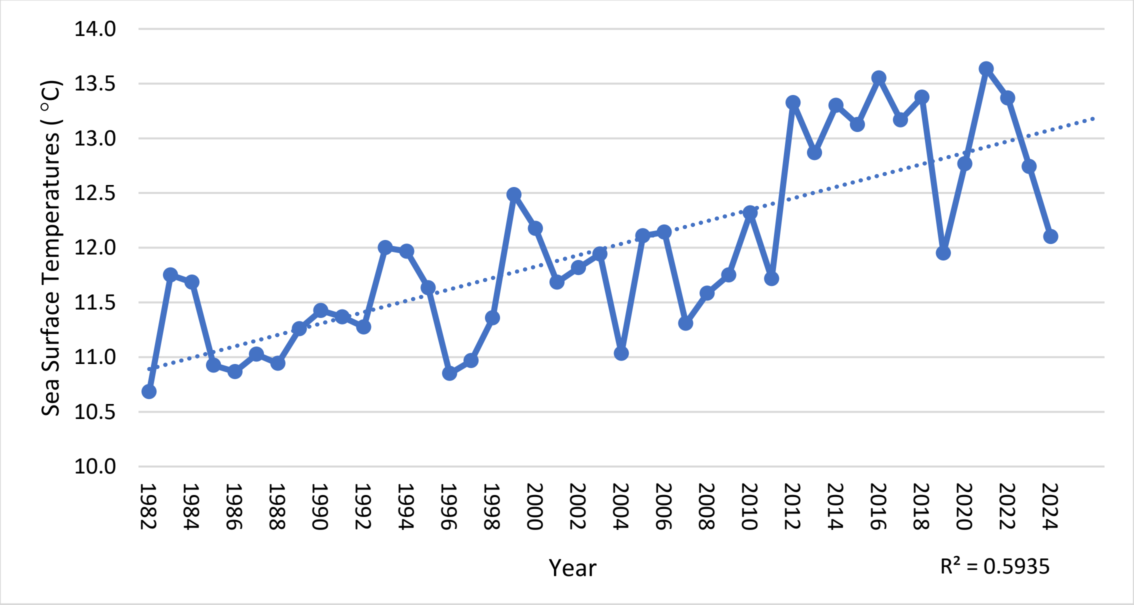

Figure 8. Average SST temperature on Scotian Shelf by Year (Data from [47]).

The above graph has a correlation coefficient of 0.5935 displaying a moderate correlation of SSTs rising with time. Typically, the Atlantic Canada TC season is between 1st June and 30th November [53]; Figure 9 displays the SSTs by year averaged from June to November.

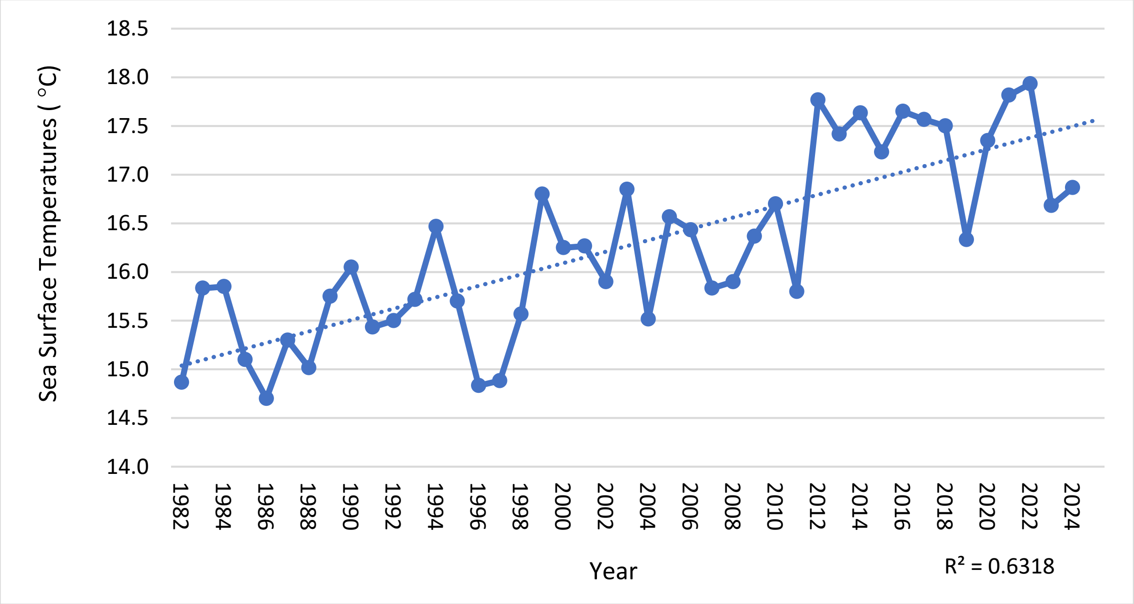

Figure 9. Average SSTs from June to November on Scotian Shelf by Year (Data from [47]).

Temperatures from June to November display a higher correlation between SSTs and time than full year averages. The overall temperature increase over TC season is slightly increased when compared to full year averages. Results indicate that SSTs are rising along the Scotian Shelf with SSTs in the Atlantic TC Season increasing at a higher rate.

3.2.2. TC Frequency and Intensity

This analysis evaluates the changes in frequency and intensity of TCs passing through the entirety of the Scotian Shelf to evaluate changes caused by climate change. The Scotian Shelf has significantly more storms than the PDA areas; therefore, data after 1980 was used to avoid higher uncertainty. Selecting data after the 1980s allows the comparison of data to SSTs across the Scotian Shelf measured during the same period. Figure 10 shows the average wind speed of TCs on the Scotian Shelf since 1980; years with no TCs are not displayed on the graph.

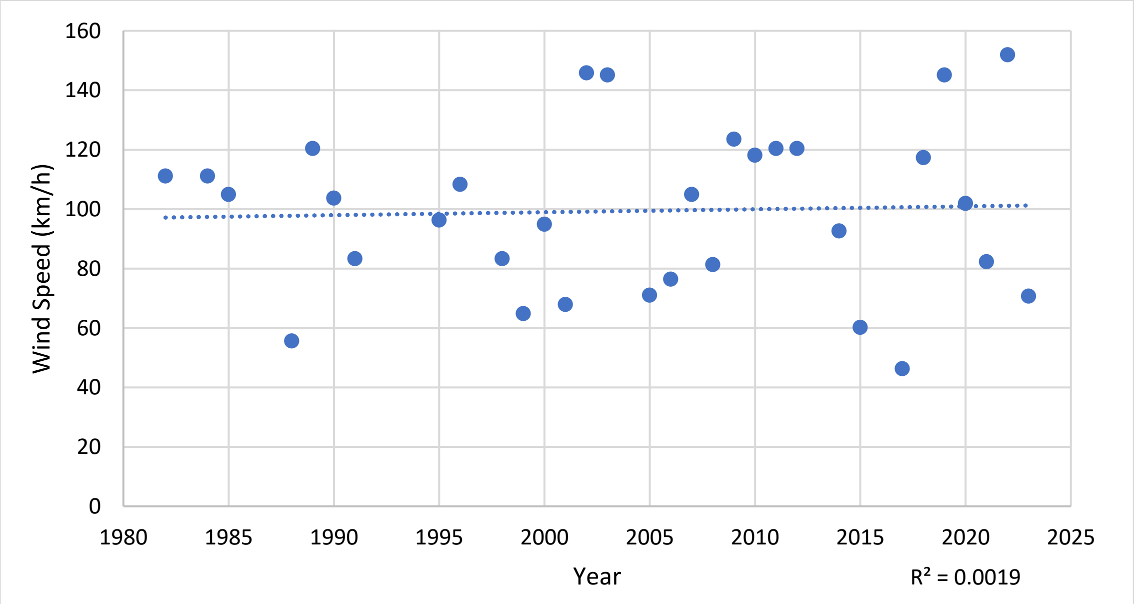

Figure 10. Average Wind Speed of TCs on Scotian Shelf since 1982 (Data from [47]).

The graph displays no trend with low correlation between average wind speed of TCs and time. Figure 11 displays the maximum recorded speed of TCs on the Scotian Shelf.

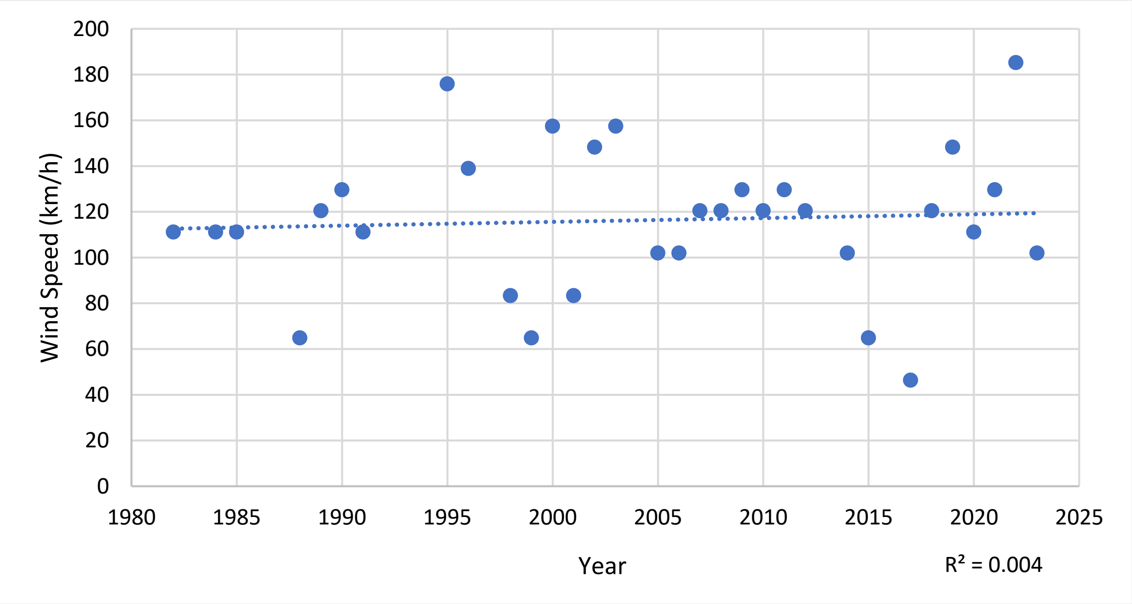

Figure 11. Maximum Wind Speed of TCs on Scotian Shelf since 1980 (Data from [47]).

The graph of maximum wind speeds shows another low correlation value indicating no trend. The graphs indicate that some years such as 2017 resulted in lower average TC wind speeds along with lower extreme wind speeds.

The count of storms on the Scotian Shelf is displayed in Figure 12.

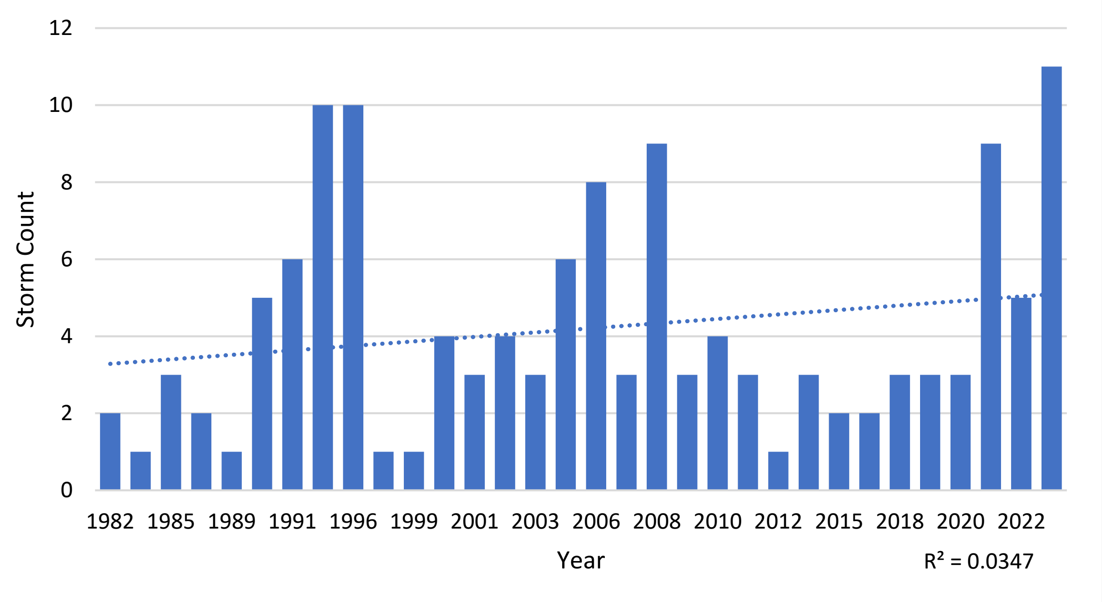

Figure 12. Count of TCs on the Scotian Shelf since 1980 (Data from [47]).

The results show identical correlation values between average TC wind speed, maximum TC wind speed, and TC count. This indicates that some years result in ideal TC conditions which result in more and stronger winds. The analysis shows no clear correlation between time and TC intensity, and frequency on the Scotian Shelf.

3.2.2. Correlations

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This analysis examines the correlation between SSTs and TC intensity on the Scotian Shelf. Research indicates that SSTs are a key limiting factor for TCs [23]; high correlation between the two variables could provide a direct mechanism by which to relate the effects of climate change to TC intensity. Due to the SST data over the Scotian Shelf possessing high spatial resolution, it is difficult to make definitive conclusions about any correlation between SSTs and TC intensity.

Figure 13 displays the average TC wind speeds graphed against average SSTs over the Atlantic TC Season. SSTs during Atlantic TC season are on average 4.3°C higher than average annual SSTs. Except for 9 out of 968 TC data measurements, every TC on the Scotian Shelf took place during the Atlantic TC season.

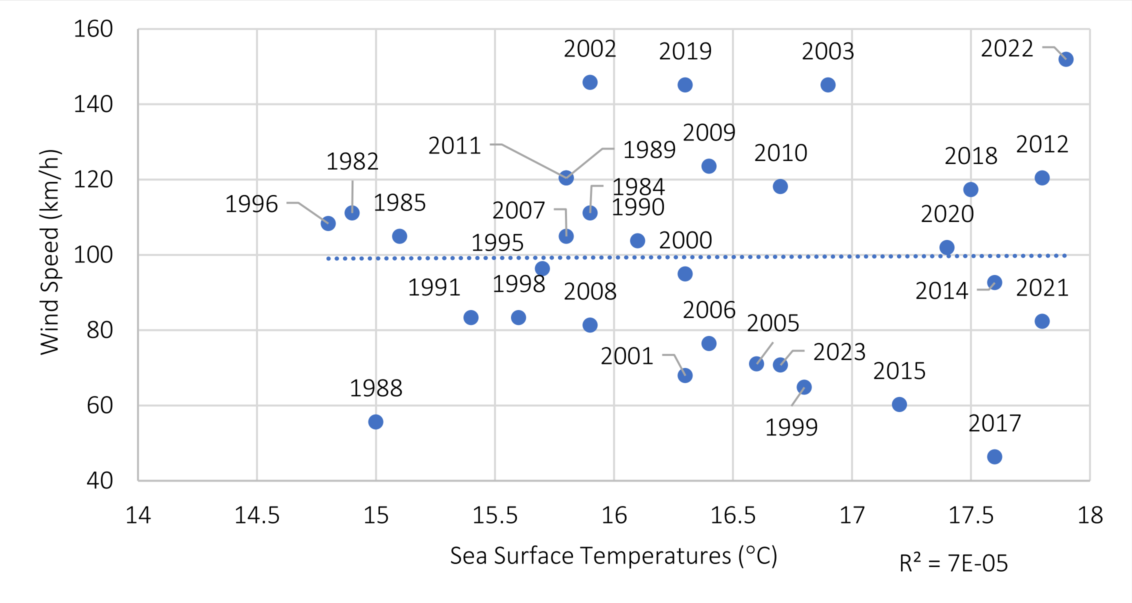

Figure 13. Average Wind Speed of TCs vs Average SSTs during TC Season on Scotian Shelf data from [47] and [48].

The graph shows no trend between SSTs and average TC wind speed. The low correlation coefficient value demonstrates no correlation and indicates that other factors such as wind shear, and atmospheric conditions may affect the variability of TC intensity on the Scotian Shelf. Figure 14 displays the SST during the month of the maximum intensity TC on the Scotian Shelf since 1982.

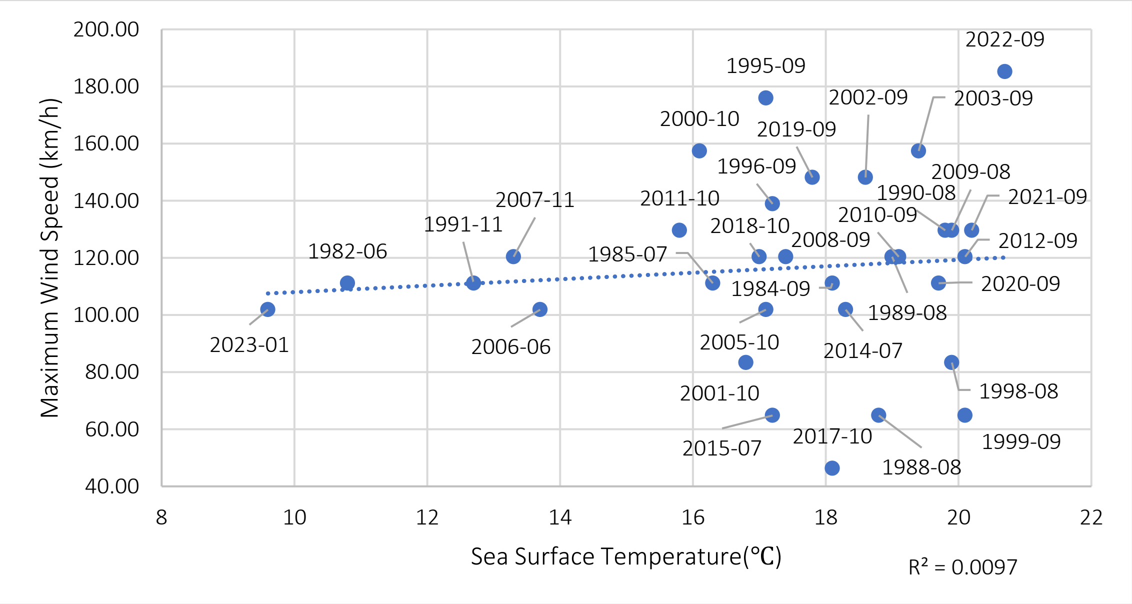

Figure 14. Maximum TC Wind Speed vs. Average Monthly SST on the Scotian Shelf (Data from [47] and [48]).

All maximum TC wind speeds recorded took place during the Atlantic TC season except for 2023 which took place in January contributing to its lower SST. The graph displays no clear trend between maximum TC wind speed and average monthly SST. The result indicates that the most intense TCs to travel through the Scotian Shelf have a variety of atmospheric and climatic factors affecting them. Although access to accurate historical data of TCs on the Scotian Shelf is limited, conclusions drawn from such data may encounter sampling bias. Additionally, SST data taken for the analysis is generalized over the entirety of the Scotian Shelf and may not account for deviations in SST based on location within the Scotian Shelf.

3.2.4. Extreme Wave Events

Buoys c44137, c44142, and c44150 also track wave data over time [51]. Figure 15 displays the maximum significant wave heights and maximum wave heights per year recorded by the buoys. The maximum value between the two locations is taken and represented on the graph.

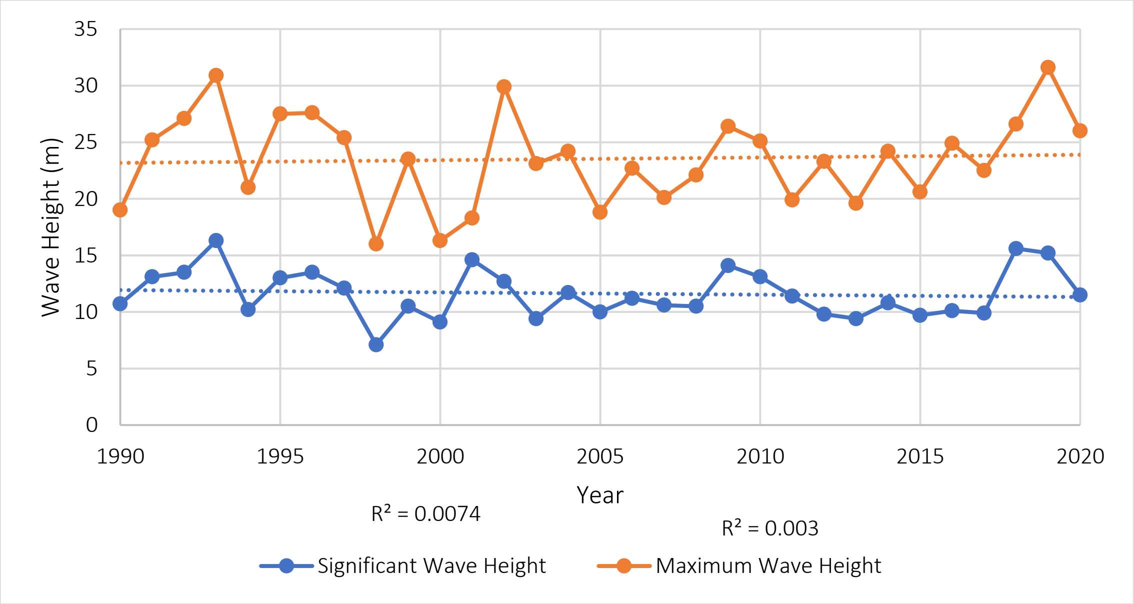

Figure 15. Maximum Zero Crossing Wave Height and Significant Wave Height From 1990 to 2020 of Eastern Scotian Slope and LaHave Basin (Data from [51]).

The data displays no clear trends in changes to extreme and maximum wave heights over time. The average maximum yearly wave height from the data is 23.5 m. Significant waves can be caused by many factors; rogue waves caused by mixing ocean currents are considered unpredictable [35]. The correlation between wind speeds measured by the buoys at the time that maximum wave height was measured is displayed in Figure 16.

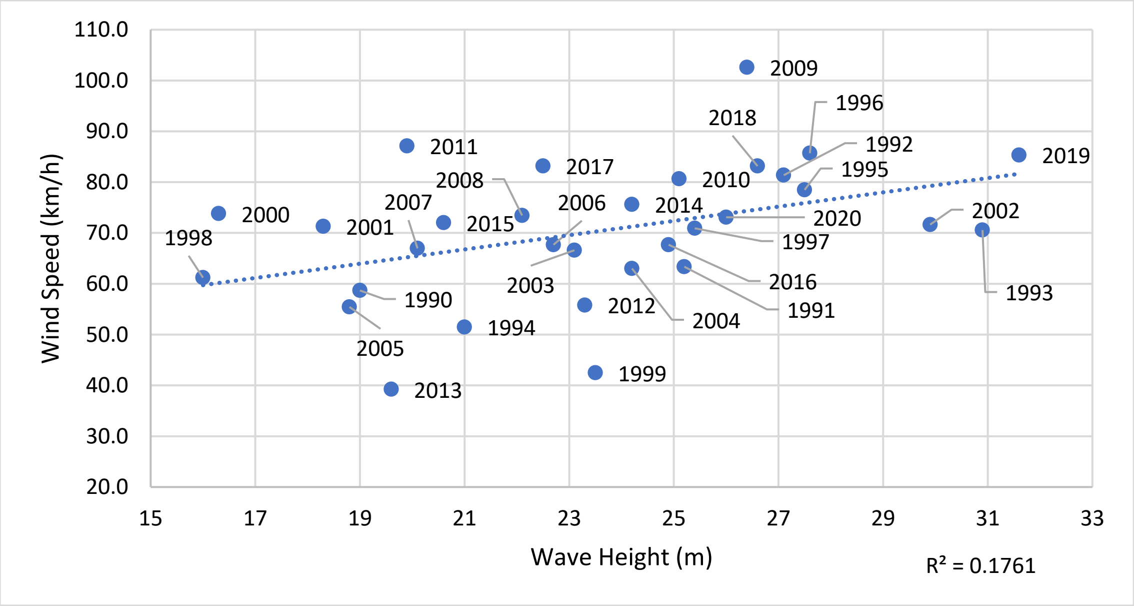

Figure 16. Wind Speed vs Maximum Wave Height per Year of Eastern Scotian Slope and LaHave Basin data from [51]

The graph shows a slight positive linear trend between maximum wave heights and their corresponding wind. The lower correlation coefficient indicates high variability to the trend indicating other factors also contribute to extreme wave heights such as ocean currents.

4. Discussion

Climate change is rapidly warming the planet, creating conditions that make TCs increasingly common on the Scotian Shelf. TCs pose severe risks to OSW installations, with the potential to damage turbine blades, towers, control systems, foundations, and even subsea cable systems. Because climate change introduces uncertainty into future TC projections, the threat of severe weather is a significant concern for the development of OSW energy in Nova Scotia.

Several factors may have influenced the results of the study, including:

- Differences in data availability; areas with more complete records may require less interpolation in the IBTrACS dataset, though this uncertainty is difficult to quantify.
- Uncertainty associated with the SST data; the use of available data may bias the effects of SSTs over the whole Scotian Shelf to just values from available data points.
- Uncertainty associated with wave height data; the two buoy locations used for extreme wave analysis bias the trends towards specific regions rather than generalizing over the entire Scotian Shelf.

Despite the lack of accurate historical data causing selection bias, the analysis continued using the available data. The errors in data availability and resolution suggests that any trends identified in the analysis require further investigation.

Historical analyses of the effects of climate change and extreme wind speeds in Canada have proven weak correlations [24]. Similarly, global climate models carry high spatial resolutions resulting in predictions of extreme winds in specific locations that are highly variable between models [24]. Some studies have found correlation between environmentally favorable conditions such as SSTs, and atmospheric conditions and climate change and TC intensity [29]. Currently, there is no scientific consensus on whether the effects of climate change directly weaken or strengthen extreme TC winds [24].

The investigation showed a high correlation between SSTs and time. The research indicates that average SSTs across the Scotian Shelf are rising with time; SSTs between June and November rising at an increased rate compared to results over the whole year. The correlation between SSTs and time is moderate-to-high despite many factors such as ocean oscillations also affecting SSTs on the Scotian Shelf.

In contrast, the analysis of average TC intensity, maximum TC intensity, and TC frequency on the Scotian Shelf was less conclusive. The analysis finds high variability and no clear trend of annual peak and average TC intensity and annual TC frequency changing. Results display many outliers indicating that some seasons had ideal conditions for TCs while others did not. Some years, despite ideal conditions, received fewer TCs. For example, 2017 recorded fewer and less intense TCs than other years despite 2017 being one of the most active TC seasons on record throughout the North Atlantic [39]. Such a distinct outlier may indicate that the likelihood of TCs on the Scotian Shelf differs from the North Atlantic. The results can be attributed to lower relative sample size and lack of robust data; no significant conclusions can be made. Despite this study’s results, [45] reported that increases in TC intensity and rapid intensification cannot be attributed to variability alone, indicating medium confidence in anthropogenic influence on these trends.

Correlations between SSTs and extreme wind events on the Scotian Shelf show weak positive relationships with high variability. Maximum TC intensity exhibits no clear correlation with SSTs on the Scotian Shelf, indicating that SSTs are just one of many factors influencing TC intensity. A 2024 study [54] reported a 2.1 per cent/°C decrease in TC mechanical efficiency with rising SSTs, that is, how effectively heat energy is converted into kinetic energy. Another study [55], found that despite lower average SSTs in August, it recorded more intense TCs due to other environmental influences. Statistical models show that approximately 50% of the variability in TC events can be explained by a combination of ocean oscillations, SSTs, and atmospheric circulation, with current predictive models nearing the limits of available data [56]. Overall, while SSTs may play a role in shaping TC frequency and intensity, they are part of a complex relationship of environmental factors that also influence TCs.

Extreme wave events recorded by buoys c44137, c44142, and c44150 show no consistent trend over time and exhibit high variability. Although maximum wave heights display a slight positive trend, this too is marked by significant variability. The data suggest that extreme wave events in the region are generally unpredictable, although there is a modest correlation between wind speeds and wave heights. Based on this data, nearby areas such as Sable Island Bank can expect waves approaching 30 m approximately once every 30 years. A 2024 study [57] analyzing historical wave records and climate model projections, concluded that the North Atlantic Basin shows no consistent trends in extreme wave heights. Similarly, A 2021 study [58] reported a possible decrease in significant wave heights across the North Atlantic, though this finding carries high uncertainty. Overall, research on the impact of climate change on extreme wave heights remains inconclusive and consistent with the findings of this study, which identified no clear trends.

4.1. Recommendations

The study finds current data collection needed for extreme weather event prediction to be lacking throughout the Scotian Shelf. Below are the recommendations and suggested future research that could improve understanding of the relationship between TCs, climate change, and turbine siting:

- Expanding the data collection buoy network across the PDAs around the province and near the four selected tier-one PDAs. Expanding this network would improve the estimation of climate-related risks such as extreme waves and high wind events. Additionally, the network could improve site specific energy modeling for offshore wind projects. A larger buoy network would also increase confidence in project planning and investment decisions by providing a comprehensive climate dataset. Buoys are roughly representative of areas within a 50 km radius or an area of 7854 km^2 [59], all tier-one PDAs are smaller than the size of data represented by a buoy. It is recommended to place a buoy in each of the tier-one PDAs.

- Investigating the correlation between several climate factors on TCs such as atmospheric instability, SSTs, ocean oscillations and other climatic indices of TCs. Such an investigation would provide further confidence in the effects of climate change on TCs on the Scotian Shelf.
- Analyzing the effects of tropical cyclones under specific climate emission scenarios; synthetic TC data sets could be created using global climate models and be used to estimate risk accounting for climate change affecting TC behavior.
- Conducting PDA-specific data collection to assess site-specific climate risks and distribute data in an open database. Readily available data would allow developers to make informed decisions about project investments related to adaptation to extreme weather.

Current analyses of climate data for the Scotian Shelf are limited. Expanding research in these areas will be critical for understanding the complex interactions between climate change, TCs, and offshore infrastructure risks.

5. Summary

With the announcement of four offshore wind (OSW) energy zones, Nova Scotia is planning to be the first Canadian province to implement offshore wind. The selection of the four zones is a result of extensive consideration of avoiding conflict with ecologically significant areas, fishing areas, transportation routes and other conflicts of use. Nova Scotia's decision to pursue offshore wind is in part due to its avoidance of land use conflicts and partly due to the increased capacity factor of offshore wind turbines compared to their onshore counterparts.

Current research is still in the process of evaluating the impact of climate change and tropical cyclones (TCs) on the choice of turbine siting. TCs are circular storms with intense winds and tropical origins an example of which is a hurricane which form in areas with high sea surface temperatures (SSTs) and typically sustain themselves through moisture and humidity. Climate change is causing a rise in global SSTs, humidity and moisture leading to favorable conditions for TCs. Other climatic conditions such as Atlantic Meridional Overturning Circulation, Atlantic Multidecadal Oscillation, and as El Niño Southern Oscillation contribute to some years having higher SSTs and moisture, giving more potential energy to TCs.

This study made use primarily of the International Best Track Archive for Climate Stewardship (IBTrACS) dataset, along with NOAA's Sea Surface Temperature-Optimum Interpolation Climate Data Record, and historical buoy data on LaHave Basin and the Eastern Scotian Slope from the Government of Canada. The data was used to analyze the impact of TCs on different potential development areas (PDAs), to assess the impact of climate change on TC characteristics on the Scotian Shelf, and to recommend design standard classes using statistical distributions.

SSTs on the Scotian Shelf are rising; they are considered a key factor in TC formation and intensification. However, the correlation between SST and TC activity on the Scotian Shelf remains highly variable, indicating that multiple atmospheric and climatic factors influence TC behavior. TC frequency and intensity show highly variable trends, making definitive conclusions difficult. Similarly, historical extreme wave data do not reveal clear trends, though waves of up to 30 meters have occurred near the potential development areas.

A key limitation of the study is the lack of publicly accessible accurate TC data; this makes definitive conclusions about TC behavior on the Scotian Shelf difficult to determine. While historical data on TCs is often insufficient (as this paper has shown), climate models can also suffer from biases which cause high inter-model variability. Recommendations include expanding the buoy network, detailed analysis of the effects of all climatic variables on TCs on the Scotian Shelf, and PDA specific data analysis efforts.

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Abbreviations

Term	Definition
ACE	Accumulated Cyclone Energy, a metric to compare the total energy of a TC using maximum sustained wind speeds.
AMO	Atlantic Multidecadal Oscillation, natural variability in sea surface temperatures with warm and cold periods lasting between 60 and 80 years.
AMOC	Atlantic Meridional Overturning Circulation, A ocean current which circulates warm salty water from the tropics to the North Atlantic where it cools and thereby returns southward.
Atmospheric Circulation	Movement of air in the atmosphere; it relates to how thermal energy and storm systems move throughout Earth's surface.
Fetch	The uninterrupted distance over which the wind blows without significant change in direction.
GW	Gigawatt, a unit of electrical power equivalent to 1,000 megawatts (MW).
M	Metre
Mechanical Efficiency	A measure of how effectively a system converts input energy into useful output energy.
PDA	Potential Development Area, an area selected as a candidate for the offshore wind area bidding process.
Significant Wave Height	The average wave height of the top third of wave data at a particular time.
SSP	Shared Socioeconomic Pathways, A set of narratives describing possible future development pathways for human society relating to fossil fuel emissions.
SST	Sea Surface Temperature, temperature of ocean water near sea surface.
Hurricane	An intense tropical cyclone in the Atlantic and Northeast Pacific regions. Hurricanes are classified by a minimum sustained wind speed of 119 km/h.
Tropical Cyclone (TC)	A tropical cyclone is a warm-core low pressure system, that develops over the tropical or subtropical waters and has an organized circulation.
Typhoon	Equivalent term to hurricane referring to storms over the NorthWest Pacific.
Wind Shear	Significant variation in wind velocity and direction with respect to changes in altitude and location.

Appendix

The following tables were used to create the charts.

Table 3. Average SST by Year, TC Season and Yearly Averages for Figure 8 and Figure 9.

Year	Average SST by year (°C)	Average SST by year from June to November (°C)
1982	10.68	14.87
1983	11.75	15.83
1984	11.68	15.85
1985	10.93	15.10
1986	10.87	14.70

1987	11.03	15.30
1988	10.94	15.02
1989	11.26	15.75
1990	11.43	16.05
1991	11.37	15.43
1992	11.28	15.50
1993	12.00	15.72
1994	11.97	16.47
1995	11.63	15.70
1996	10.85	14.83
1997	10.97	14.88
1998	11.36	15.57
1999	12.48	16.80
2000	12.18	16.25
2001	11.68	16.27
2002	11.82	15.90
2003	11.94	16.85
2004	11.03	15.52
2005	12.11	16.57
2006	12.14	16.43
2007	11.31	15.83
2008	11.58	15.90
2009	11.75	16.37
2010	12.32	16.70
2011	11.72	15.80
2012	13.33	17.77
2013	12.87	17.42
2014	13.30	17.63
2015	13.13	17.23
2016	13.55	17.65
2017	13.17	17.57
2018	13.38	17.50
2019	11.95	16.33
2020	12.77	17.35
2021	13.63	17.82
2022	13.37	17.93
2023	12.74	16.68
2024	12.10	16.87

Table 4. Average/Maximum Wind Speed and storm count of TCS on Scotian Shelf since 1980 for data in Figure 10, Figure 11, and Figure 12.

Year	Average of Wind Speed of Storms (km/h)	Maximum Wind Speed of Storms (km/h)	Storm Count
1982	111.1	111.1	2
1984	111.1	111.1	1
1985	104.9	111.1	3

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1988	55.6	64.8	2
1989	120.4	120.4	1
1990	103.7	129.6	5
1991	83.3	111.1	6
1995	96.3	175.9	10
1996	108.3	138.9	10
1998	83.3	83.3	1
1999	64.8	64.8	1
2000	94.9	157.4	4
2001	67.9	83.3	3
2002	145.8	148.2	4
2003	145.1	157.4	3
2005	71.0	101.9	6
2006	76.4	101.9	8
2007	104.9	120.4	3
2008	81.3	120.4	9
2009	123.5	129.6	3
2010	118.1	120.4	4
2011	120.4	129.6	3
2012	120.4	120.4	1
2014	92.6	101.9	3
2015	60.2	64.8	2
2017	46.3	46.3	2
2018	117.3	120.4	3
2019	145.1	148.2	3
2020	101.9	111.1	3
2021	82.3	129.6	9
2022	151.9	185.2	5
2023	70.7	101.9	11

Table 5. Average Wind Speed of TCs vs Average Sea Surface Temperatures during TC Season on Scotian Shelf for Figure 13, Years without TCs are excluded from the data.

Year	Average Wind Speed of Storms (Km/h)	Avg SST of TC Season (°C)
1982	111.1	14.9
1984	111.1	15.9
1985	104.9	15.1
1988	55.6	15.0
1989	120.4	15.8
1990	103.7	16.1
1991	83.3	15.4
1995	96.3	15.7
1996	108.3	14.8
1998	83.3	15.6
1999	64.8	16.8
2000	94.9	16.3
2001	67.9	16.3

2002	145.8	15.9
2003	145.1	16.9
2005	71.0	16.6
2006	76.4	16.4
2007	104.9	15.8
2008	81.3	15.9
2009	123.5	16.4
2010	118.1	16.7
2011	120.4	15.8
2012	120.4	17.8
2014	92.6	17.6
2015	60.2	17.2
2017	46.3	17.6
2018	117.3	17.5
2019	145.1	16.3
2020	101.9	17.4
2021	82.3	17.8
2022	151.9	17.9
2023	70.7	16.7

Table 6. Maximum TC Wind Speed (since 1982) vs. Average Monthly Sea Surface Temperature on the Scotian Shelf for Figure 14.

Year	Month	Max Wind Speed (km/h)	Monthly Average SST (°C)
1982	6	111.1	10.8
1984	9	111.1	18.1
1985	7	111.1	16.3
1988	8	64.8	18.8
1989	8	120.4	19.0
1990	8	129.6	19.8
1991	11	111.1	12.7
1995	9	175.9	17.1
1996	9	138.9	17.2
1998	8	83.3	19.9
1999	9	64.8	20.1
2000	10	157.4	16.1
2001	10	83.3	16.8
2002	9	148.2	18.6
2003	9	157.4	19.4
2005	10	101.9	17.1
2006	6	101.9	13.7
2007	11	120.4	13.3
2008	9	120.4	17.4
2009	8	129.6	19.9
2010	9	120.4	19.1
2011	10	129.6	15.8

2012	9	120.4	20.1
2014	7	101.9	18.3
2015	7	64.8	17.2
2017	10	46.3	18.1
2018	10	120.4	17.0
2019	9	148.2	17.8
2020	9	111.1	19.7
2021	9	129.6	20.2
2022	9	185.2	20.7
2023	1	101.9	9.6

Table 7. Maximum Zero-Crossing Wave Heights and Corresponding Wind Speeds and Significant Wave Heights of Eastern Scotian Slope and LaHave Basin (1989–2020) for Figure 15 and Figure 16.

Year	Wind Speed (km/h)	Maximum Significant Wave Height (m)	Maximum Wave Height (m)
1990	58.7	10.71	19
1991	63.4	13.1	25.2
1992	81.4	13.5	27.1
1993	70.6	16.3	30.9
1994	51.5	10.2	21
1995	78.5	13	27.5
1996	85.7	13.5	27.6
1997	70.9	12.1	25.4
1998	61.2	7.1	16
1999	42.5	10.5	23.5
2000	73.8	9.1	16.3
2001	71.3	14.6	18.3
2002	71.6	12.7	29.9
2003	66.6	9.4	23.1
2004	63.0	11.7	24.2
2005	55.4	10	18.8
2006	67.7	11.2	22.7
2007	67.0	10.6	20.1
2008	73.4	10.5	22.1
2009	102.6	14.1	26.4
2010	80.6	13.1	25.1
2011	87.1	11.4	19.9
2012	55.8	9.8	23.3
2013	39.2	9.4	19.6
2014	75.6	10.8	24.2
2015	72.0	9.7	20.6
2016	67.7	10.1	24.9
2017	83.2	9.9	22.5
2018	83.2	15.6	26.6
2019	85.3	15.2	31.6
2020	73.1	11.5	26

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