

Article

The Extremely Active 2020 Hurricane Season in the North Atlantic and Its Relation to Climate Variability and Change

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Abstract: The 2020 hurricane season in the North Atlantic basin was the most active on record, with 30 named tropical cyclones. In this study, climate trends in oceanic and atmospheric parameters (including the sea surface temperatures, ocean heat content, cloud cover, mid-level humidity, vertical wind shear, and sea level pressure) were used to model the tropical cyclone, hurricane, and major hurricane frequency in the post-satellite era (1966–2020). The relationships between storm frequency and climate variability factors (including the El Niño Southern Oscillation, the North Atlantic Oscillation, the Atlantic Multidecadal Oscillation, and the Atlantic Meridional Mode) were also examined. This was performed to determine the factors that exerted the greatest influence on the most active hurricane seasons on record. Mann–Kendall trend tests, Pearson’s correlations tests, stepwise Poisson linear regression models and spatial analysis techniques were used to identify the climate change and variability factors that best explained the tropical cyclone frequency in the North Atlantic. Our results show that hyperactive hurricane seasons, such as that of 2020, tend to be associated with higher cloud cover development, lower sea level pressure patterns, higher sea surface temperatures, positive phases of the Atlantic Multidecadal Oscillation and the Atlantic Meridional Mode, and weaker wind shear environments. Seasons with more major hurricanes had higher ocean heat contents and weaker wind shear environments. The 2020 and 2005 seasons had similar cloud cover and sea level pressure patterns, yet the wind shear was lower in 2020 than in 2005, which was associated with La Niña dominant conditions that could explain why 2020 surpassed 2005 in the total number of storms.

Keywords: tropical cyclones; hurricanes; climate variability; climate change; statistical modeling



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1. Introduction

The main development region (MDR) of the North Atlantic (NA) Ocean (10–20 N, 20–80 W) is one of the tropical regions where the conditions for tropical cyclone (TC) formation are ideal, mostly between the months of June and November, which are considered to form the official hurricane season of the NA (Goldenberg and Shapiro, 1996). While each hurricane season varies in the TC frequency, recent research has shown that, on average, North Atlantic tropical cyclone activity and destruction have increased in recent times, particularly over the last three decades [1–4]. Studies that have focused on the frequency and intensity of TCs in the NA have detected an increase in the number of major hurricanes (Cat 3 or higher) and also a rise in the total number of storms that formed outside of the official hurricane season months [5–9].

More recently, the 2020 hurricane season in the NA produced the highest number of TCs (30) on record, yielding a higher amount of TCs than the previous most active season in 2005. Most of the TCs (20) developed between August and November, with five powerful hurricanes occurring in the months of October and November and various short-lived TCs. Hurricanes Delta, Zeta, Eta, and Iota caused considerable devastation in the

Central American countries of Honduras, Nicaragua, and El Salvador, where the combined economic losses were USD 17 billion. The 2011–2020 decade in the North Atlantic has also been found to be the period with the most recorded tropical cyclones, with 165 different storms, but also the period with the highest number of storms forming before the official start date of the hurricane season [9].

Before the extremely active hurricane season of 2020, 2005 was the most active season on record. Prior to 2005, only two years (1960 and 1961) produced two hurricanes reaching category 5 in the same season [10]. In the 2005 season, four major (≥ 3) hurricanes (Dennis, Katrina, Rita, and Wilma) made landfall in the United States [2]. In this same year, Hurricane Wilma became the most intense hurricane ever measured, at 882 mb. Previously, Hurricane Gilbert (888 mb), which struck Jamaica and the Yucatan Peninsula in 1988, had been the most intense hurricane [11]. Two other hurricanes in 2005, Rita (897 mb) and Katrina (902 mb), became the fourth and sixth most intense Atlantic hurricanes on record thus far.

The tropical cyclone activity in the NA basin during the 2020 hurricane season was hyperactive, starting on May 19 with the subtropical storm Arthur, and after all of the names from the predefined list were used, it ended with Hurricane Iota, derived from the Greek alphabet, on November 13. The total number of tropical storms in 2020 broke the all-time record set in 2005. However, we also observed more examples of rapid intensification and very slow-moving hurricanes, which have recently been linked to climate change [12–14]. In 2020, there were ten notable hurricanes that intensified rapidly (Hanna, Laura, Sally, Teddy, Gamma, Delta, Epsilon, Zeta, Eta, and Iota), some of which underwent explosive intensification in a relatively short time, and there were two hurricanes that practically stopped moving when they made landfall in Central America (Sally on the Gulf Coast and Eta in Central America). Both Hurricanes Eta and Iota made landfall in Nicaragua, causing extensive damage.

In general, the 2020 Atlantic hurricane season (Figure 1) was extremely active, with an activity well above the normal level for the season. A record thirty named storms formed, of which thirteen became hurricanes and six became major hurricanes (category 3 or higher) according to the Hurricane Saffir–Simpson wind scale. An important factor to note regarding the 2020 season is that the La Niña conditions involved weakening higher-level winds, which enhance tropical cyclone development and intensification by enabling tropical convection with little disruption [15]. In addition, the great influence of the warm pool in the western hemisphere [16,17] was observed in both the 2020 and 2005 seasons. In general, when the warm pool is observed in this region, the TCs may increase in intensity over a short time, as observed in the case of the 2020 Hurricanes Dennis, Katrina, Rita, etc., while in 2005, Hurricanes Hanna, Laura, and Sally, among others, reached a record intensity in a short period of time due to the high SSTs of the Gulf region.

Studies examining the conditions that lead to higher TC formation suggest that warmer conditions and lower windshear environments increase the hurricane season activity and destruction [1–5,15]. More recently, increased TC frequency has been linked to a rise in the sea surface temperatures that directly impacts the ocean-atmospheric conditions that lead to more active hurricane seasons [3,18]. Prior to 2020, the most active hurricane season on record was in 2005, which generated USD 100 billion in property damage and caused approximately 1700 deaths [2]. Later, in 2017, one of the seventeen named storms, Hurricane Harvey, generated USD 125 billion in damage alone, ending in total economic damage worth USD 260 billion [3].

There have been various studies conducted in recent years with notable hurricane seasons. Although not exceedingly elevated, the recent historic active years of 1995, 2001, 2005, 2010, and 2017 all had relatively high SST anomalies [18]. Other atmospheric circumstances that provide favorable conditions for tropical cyclone activity in the Atlantic are the sea level pressure (SLP), vertical wind shear (VWS), potential intensity (PI), and upper-level outflow temperature [18]. The highly active 1995 Atlantic hurricane season was influenced by factors such as the El Niño Southern Oscillation (ENSO), but the primary factor for the

increased tropical cyclone activity was attributed to a pattern of favorable and extremely weak wind shear across the main development region (MDR) in the North Atlantic [19]. The highly active hurricane season of 2005 was categorized as having SSTs reaching the warmest temperatures ever observed in the Atlantic Ocean [2]. Another factor that likely influenced the activity that year was the anomalous ridging that occurred in the middle troposphere, persisting over the eastern United States for some time [2].

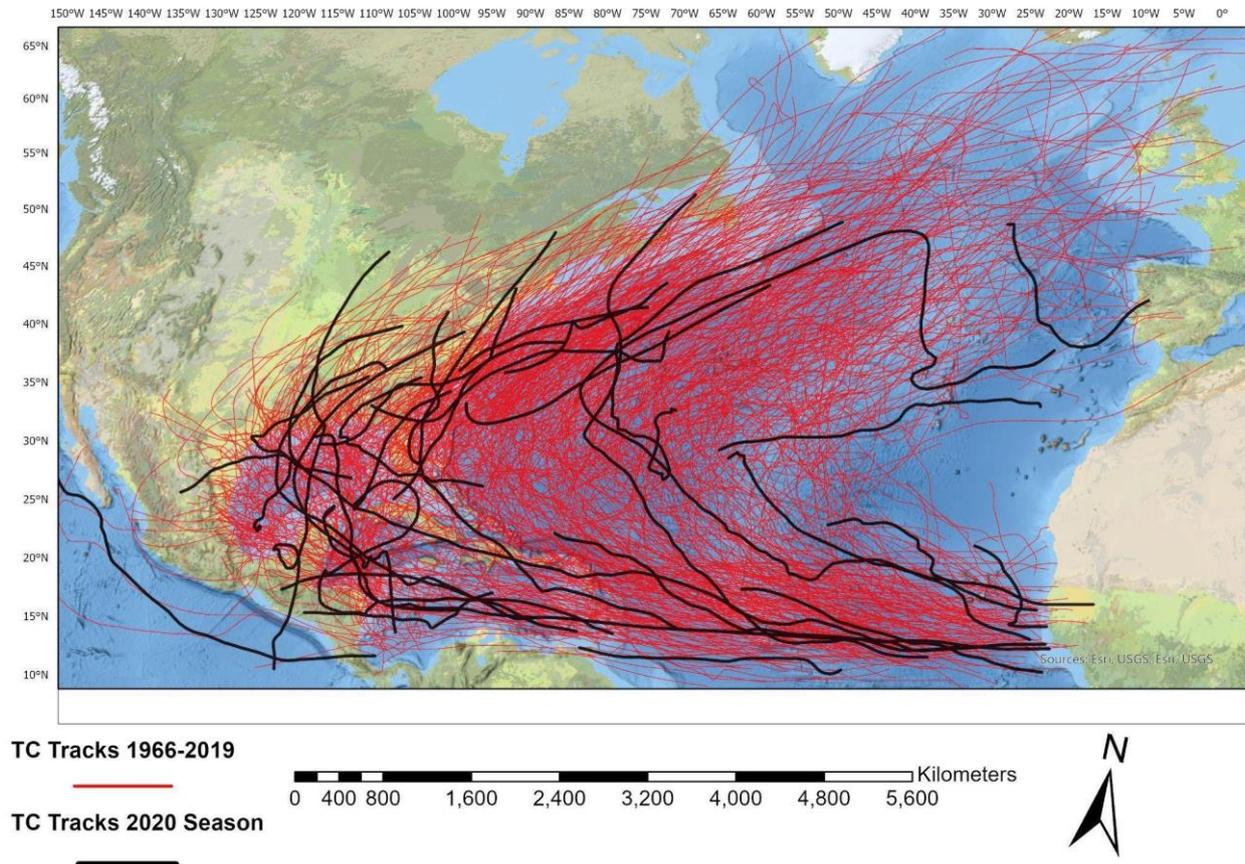


Figure 1. All tropical cyclones that formed in the North Atlantic basin from 1966 to 2020. The 2020 hurricane season tracks are highlighted in black.

For the 2017 hurricane season, another fairly active year in terms of the named storms and accumulated cyclone energy, it has been noted that the surface heat flux anomalies that developed from April to July were the dominant factor driving the SST anomalies that year [4]. This same study revealed, for the first time, that positive SST anomalies can be generated by different factors. Surface fluxes were the driving factor in 2017, but the active 2005 and 2010 seasons were primarily driven by Atlantic meridional overturning circulation. Recent research has found that there are two main driving forces of hurricane activity involving the ocean: changes in the ocean circulation in late winter, and late spring or early summer shifts in the air–sea heat flux [4]. Another study showed that abnormally warm SSTs coupled with a high ocean heat content (OHC) were two key factors influencing the significant tropical cyclone development in 2017 [18]. Additionally, the same study found that the Atlantic Meridional Mode (AMM), North Atlantic Oscillation (NAO), and ENSO, together, created favorable wind shear conditions that year, and the AMM also enhanced the atmospheric instability and generated the very warm ocean. In the case of 2020, a recent study [15] found that the combination of above-average SSTs and weaker wind shear environments associated with La Niña conditions were probably the main factors that drove the TC activity and intensification in the late hurricane season months of October and November.

The aim of this study is to examine the climatic factors behind the North Atlantic 2020 hurricane season, the most active season on record since 1966. Trend analyses were employed to determine whether trends in the TCs, hurricanes, or major hurricanes were detected in the NA basin. Individual correlation tests and stepwise Poisson linear regression models were used to determine whether the total number of TCs, hurricanes, and major hurricanes per season in the North Atlantic could be best explained by specific natural variability or climate change factors. In the final step, we compared the spatial characteristics of the significant ocean-atmospheric environments of the two most active hurricane seasons on record, the 2020 and 2005 seasons. Based on previous research [15,18], we argue that climate change drove the record-breaking SST patterns in the North Atlantic that led to higher moisture environments, in combination with weak wind shear conditions that promoted higher tropical cyclone development in the MDR.

2. Data and Methods

Six-hourly TC track data for all the seasons in the post-satellite era from the NOAA's International Best Track Archive for Climate Stewardship (IBTrACS) dataset [20] were used to extract all of the storms that formed in the hurricane seasons of the North Atlantic (Figure 1). TC track data for the pre-satellite era were not included, since there is an undercount bias in TC occurrences [21–23]. The extracted TC track data was then used to construct a time series that shows the total number of TCs, hurricanes, and major hurricanes during the hurricane season for the 1966–2020 period (Figure 2). Mann–Kendall tests were performed for trends in order to determine whether the number of TCs, hurricanes, or major hurricanes has increased over time and whether any of the climate variability or change factors exhibited any trends.

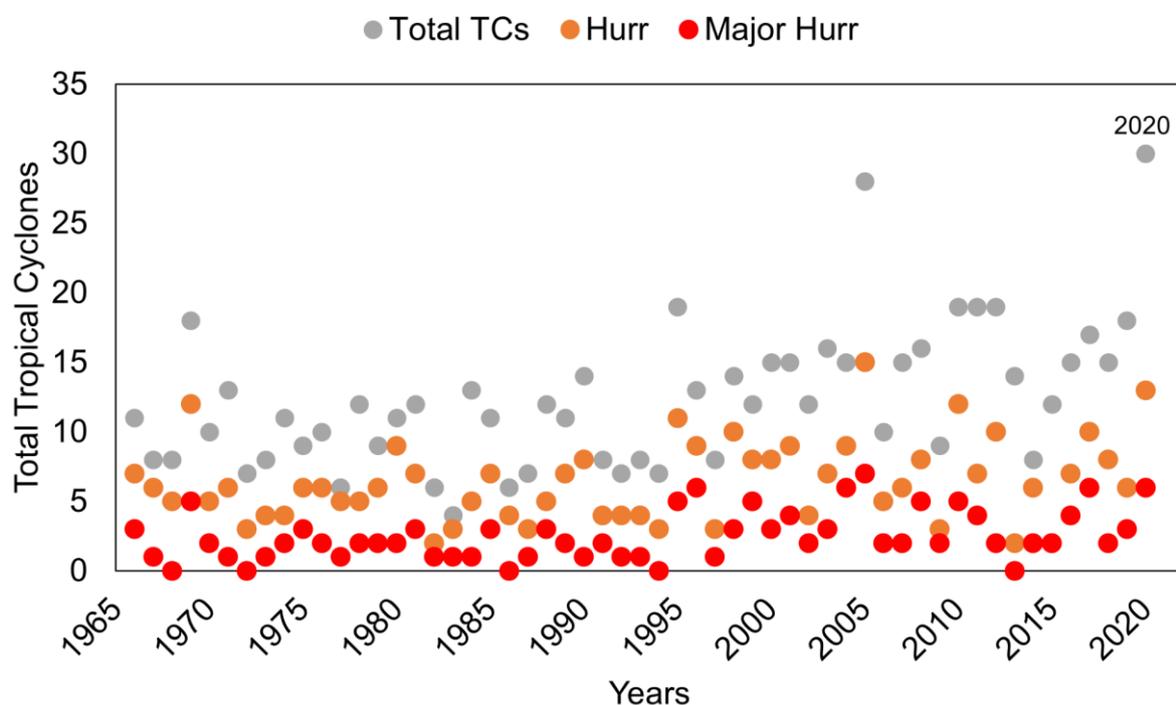


Figure 2. All the tropical cyclones, hurricanes, and major hurricanes that formed in the North Atlantic basin per season for the 1966–2020 period.

SST data for the main development region (MDR) in the North Atlantic, where TCs develop (10–20 N, 20–80 W) during the months of the hurricane season (June–November), were obtained from the Extended Reconstructed Sea Surface Temperature (ERSST) v3b dataset. The sea level pressure (SLP) and vertical wind shear (VWS) data (850–200 mb) for the MDR were obtained from the NCEP/NCAR Reanalysis Project [24]. Cloud cover (CC)

data were obtained from the ICOADs dataset for the MDR during the hurricane season months in the North Atlantic [25–27]. Cloud cover data have been used as an indicator of the average regional condensation and moisture in previous studies on hurricanes in the North Atlantic basin, in which it has also been found to be one of the most important factors behind the TC frequency and extreme precipitation [9,28]. Mid-level specific humidity (MLH) data were obtained from the NCEP/NCAR Reanalysis Project [24]. OHC data for the hurricane season months in the MDR were obtained from the National Oceanographic Data Center for the 1966–2020 period [29].

El Niño Southern Oscillation (ENSO) Niño 3.4 data (5° N– 5° S and 170° – 120° W in the equatorial Pacific) were obtained from the NCAR for the hurricane season months in the MDR of the North Atlantic [30]. AMO, NAO, and AMM data were retrieved from the NOAA Physical Sciences Laboratory Climate Time Series dataset using the same temporal parameters as those for the Niño 3.4 data [31,32]. Several studies [9,33–35] have shown that the SST has been used as a significant predictor to investigate the relationship between the thermal state of the North Atlantic basin and its TC activity. Other studies have also examined the relationship between the SLP, associated with the weakening–strengthening of the NA high-pressure system, and the TC frequency and intensity, as well as the connection between weaker VWS, associated with La Niña conditions, and higher late-season TC activity in the NA basin [15,36–38].

The hurricane season averages for all of the climate variability and change variables in the MDR were calculated for the 1966–2020 period in order to examine the relationships between the different climate variability and change factors and the total number of TCs, hurricanes, and major hurricanes that occurred in the North Atlantic basin. Mann–Kendall non-parametric tests [38] were used to identify trends for the dependent variables, as well the climate variability and change factors. The Kendall Tau coefficient obtained from the Mann–Kendall test [39] was used to determine whether any of the variables analyzed exhibited statistically significant trends. Pearson’s tests for correlations between each of the factors and the number of TCs, hurricanes, and major hurricanes were performed before employing stepwise multivariate Poisson regression models. Since the dependent variable is a count of the TCs, hurricanes, and major hurricanes, Poisson regression models (PRM) were used to model the relationships between the TC and hurricane frequency and the different climate variability and change factors. The Poisson regression model is a standard model for count data, in which the dependent variable is in the form of an event count, such as the number of tropical cyclones that occurred within a given hurricane season [40]. The Poisson regression models have been used to model storm frequency count data and how they relate to other climatic factors [41–46].

Stepwise selection PRM models were used to identify the climate variability or change factors with the most statistically significant contributions to the total annual TC frequency [9]. Here, a stepwise forward-backward selection method was implemented. In this technique, one begins with no predictors in the model, and then it sequentially adds the factors that explain most of the variance in the dependent variable. After adding each new predictor, this stepwise method eliminates the factors that no longer provide an improvement in the model fit [47]. The stepwise PRM models for the total number of TCs, hurricanes, and major hurricanes were run in the R Project for Statistical Computing using the MASS package [48].

Finally, spatial analyses of the factors that were found to best explain the high TC frequency of the 2020 hurricane season were performed using a geographic information system (GIS). Spatial anomalies in the important climate factors were calculated in order to examine the similarities and differences between the two most active hurricane seasons in the North Atlantic, the 2020 and 2005 seasons.

3. Results and Discussion

When examining the total number of tropical cyclones (Figure 2), hurricanes, and major hurricanes that formed in the North Atlantic for all the seasons since 1966, we found

that 2020 and 2005 were the years with the most TCs, with 30 and 28, respectively (Figure 2). The 2005 season had the most hurricanes and major hurricanes. Other prominent hurricane seasons with a high TC and hurricane frequency were 1995 and 2010. With regard to the total TC, the total number of hurricanes and major hurricanes per season during the 1966–2020 period, we can observe a higher overall frequency since the mid-1990s compared to the present.

The Mann–Kendall trend test results suggest that the total number of TCs per season has been increasing since 1966, with the most active hurricane seasons occurring during the last three decades (Table 1). The total number of hurricanes per season also exhibit an increasing trend in the 1966–2020 period, yet this increase is not as statistically significant as the rise in the number of major hurricanes (Table 1). Previous studies have identified increasing trends in the total number of major hurricanes [18,44], yet no clear trends were found in the frequency of all the TCs [49–51]. These results confirm what different modeling studies have found [1,44,49,52], i.e., that the North Atlantic basin will more than likely experience a higher number of major hurricanes and a higher amount of tropical cyclone activity attributed to climate change in the following decades.

Table 1. Mann–Kendall trend test results for all the variables. Higher Tau coefficients (>0.2) are associated with statistically significant probability values (*p*-values) of 0.05 or less.

Variables	Acronym	Tau Coeff.	<i>p</i> -Value
Dependent Variables			
Tropical Cyclones	TCs	0.408	0.000
Hurricanes	Hurr	0.166	0.086
Major Hurricanes	Maj. Hurr	0.297	0.004
Climate Variability & Change Factors			
El Niño Southern Oscillation	ENSO	0.104	0.267
Atlantic Multi-Decadal Oscillation	AMO	0.569	0.000
Atlantic Meridional Mode	AMM	0.343	0.000
North Atlantic Oscillation	NAO	−0.222	0.017
Sea Surface Temperature	SST	0.567	0.000
Ocean Heat Content	OHC	0.775	0.000
Cloud Cover	CC	0.636	0.000
Mid–Level Specific Humidity	MLH	0.078	0.399
Sea Level Pressure	SLP	−0.244	0.009
Vertical Wind Shear	VWS	−0.354	0.000

The Mann–Kendall trend tests showed that many of the climate factors analyzed in this study exhibited statistically significant trends. The factors of the SST, OHC, AMO, and AMM exhibited statistically significant increasing trends in the 1966–2020 period in the MDR of the NA basin, confirming, once again, that the ocean heat and surface temperatures have been rising steadily in the area over the last 54 years (Table 1). It is important to note that a positive AMO phase was ending in the late 1960s, and a cold AMO phase was beginning. Another climate factor that showed a significant increasing trend in the MDR was the CC, which suggests that rising ocean energy and temperatures might also be driving higher condensation and cloud development. On the other hand, some climate factors, such as the VWS, SLP, and NAO, showed a statistically significant decreasing trend in the MDR during the period of study, suggesting that wind shear environments and atmospheric pressure patterns are becoming more ideal for higher TC activity in the NA basin. The two climate factors that did not exhibit any significant trends in the 1966–2020 period were the ENSO and MLH.

4. Statistical Characteristics and Model Results

Pearson’s tests for correlation between all of the factors that were analyzed in this study exhibited a variety of individual statistical relationships between the numbers of TCs,

hurricanes, and major hurricanes (Figure 3). As expected, we found that the total number of TCs per season in the NA basin was strongly positively correlated with the AMO, AMM, SST, and CC, and strongly negatively correlated with the SLP and ZWS. The correlations between the different factors and hurricanes exhibited similar statistical relationships, yet those correlations were not as strong as the ones shown for all the TCs. The individual factors that exhibited the strongest correlations with major hurricanes were also the AMO, AMM, and SLP. The TCs, hurricanes, and major hurricanes showed weak correlations with the ENSO (Nino 3.4). The factor that exhibited the strongest individual correlation with all the TCs, hurricanes, and major hurricanes was the SLP, which demonstrates that seasons with a lower-than-normal atmospheric pressure in the MDR of the NA basin tend to experience a higher number of storms of all intensities [52]. These results also show that seasons with higher SSTs and weaker VWS environments tend to be associated with higher TC frequency [15,18,52].

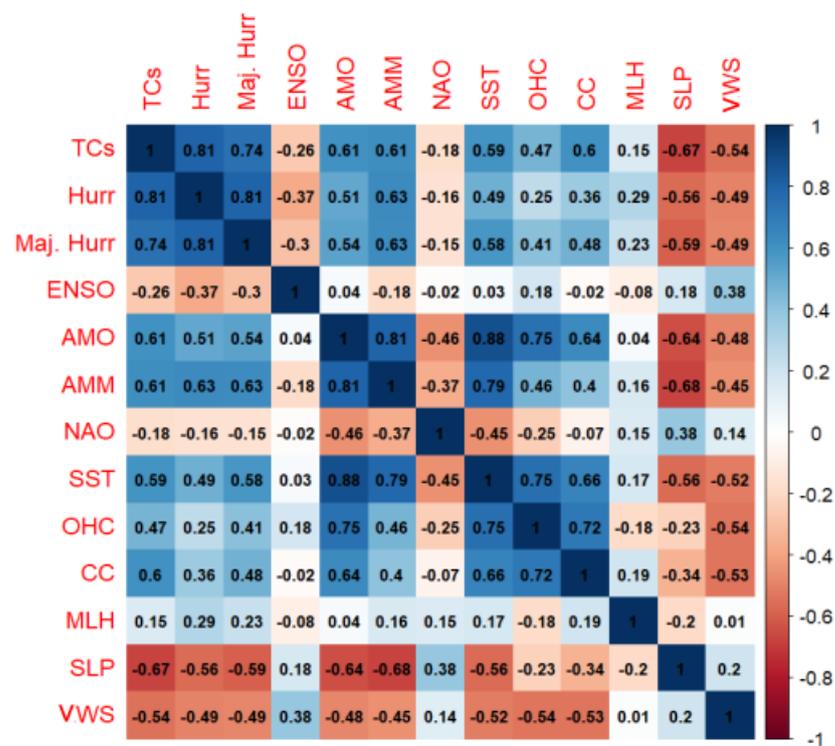


Figure 3. Results of Pearson’s correlation tests between all dependent and independent variables.

When the relationships between the 10 factors and TCs were examined (Figure 4) using Poisson regression models (PRM), we found that the 2020 hurricane season in the North Atlantic exhibited unusual atmospheric-oceanic conditions that made it the most active season on record. Out of 55 hurricane seasons analyzed in this study, we found that 2020 ranked #6 in the average SST, #1 in the average CC, which suggests its high moisture environments, and #3 in the mean OHC (Figure 4a–c). These three factors, the SST, CC, and OHC, respectively, accounted for 31%, 36%, and 21% of the variability in the total TC frequency per season. The results show that VWS alone can explain around 29% of the storm season TC activity in the NA basin (Figure 4d). The 2020 hurricane season also had the third-lowest average VWS in the MDR, which shows that the combination of high oceanic energy and temperatures, high evaporation rates, which lead to cloud condensation, and weak wind shear in the upper troposphere were some of the important factors causing it to be the most active season on record [15].

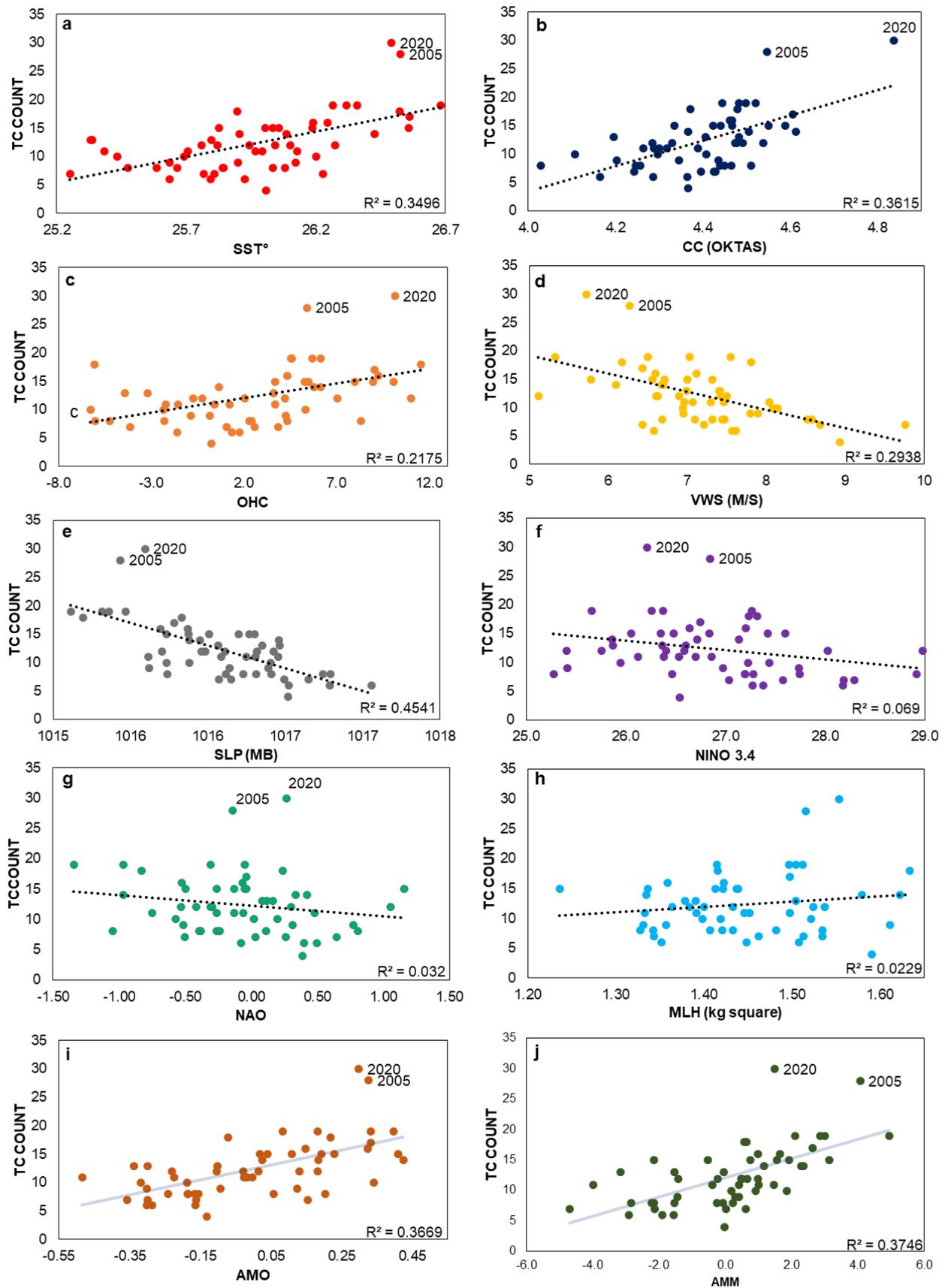


Figure 4. Correlation plots between the total TC count and SST (a), CC (b), OHC (c), VWS (d), SLP (e), ENSO (f), NAO (g), MLH (h), AMO (i), and AMM (j).

With regard to the SLP and TCs, we observed the highest negative correlation between these variables, accounting for around 45% of the variance, suggesting that seasons with lower-than-normal atmospheric pressures were associated with a higher total number of storms (Figure 4a). In the case of 2020, this year was found to have the seventh-lowest mean SLP in the MDR of the NA basin. Overall, the relationship between the ENSO and TCs seems to be the weakest when compared to the other factors analyzed (Figure 4f), yet it is important to note that the 2020 season was enhanced by weaker wind shear environments associated with La Niña conditions. The other two climate factors that exhibited weak relationships with the total TCs were the NAO and MLH. The individual Poisson regression model of the correlation between the TCs and AMO shows that a higher number of storms occurred during the seasons with a positive phase [18,53]. With regard to the 2020 season, we found that it was within the top 10 seasons with higher AMO indexes (Figure 4i). Similar to AMO, we found that hurricane seasons with a higher total number of storms occurred during the positive phases of the AMM, with 2020 among the top 12 seasons with higher AMM indexes (Figure 4j). Individually, the AMO and AMM factors can explain around 36–37% of the variance in the total TC counts during the hurricane season.

The stepwise multivariate Poisson regression models (SMPRM) were used to predict TC, hurricane, and major hurricane counts (Table 2) based on the climate variability and change factors. When modeling the total TCs with all the factors included in the model, we found that the variables selected by the model that explained most of the variance in the TC frequency were the CC, SLP, and ZWS. Those three factors accounted for around 65% of the variability in the total TC counts, and the model was statistically significant at the 0.001 level. It is important to note that these three factors also exhibited statistically significant trends in the MDR, which suggests that climate change might be driving lower pressures and a higher cloud cover, while also producing weaker wind shear environments that promote a higher TC frequency in the area. A recent study focusing on the October and November months of 2020 also found that these late months of the hurricane season exhibited warmer SSTs, higher moisture environments, and weaker VWS in the MDR [15].

Table 2. Stepwise multivariate Poisson regression model results.

Stepwise Poisson Regression Models	Factors	Coefficients	R–Squared	p–Value	AIC
Tropical Cyclones	CC	0.807	0.652	0.000	276.4
	SLP	−0.476			
	VWS	−0.12			
Hurricanes	ENSO	−0.186	0.445	0.000	241.7
	AMM	0.158			
	SLP	−0.743			
Major Hurricanes	ENSO	−0.241	0.465	0.000	185.4
	OHC	0.054			

The stepwise SMPRM results for the hurricanes identified ENSO and AMM as the most important factors behind the total hurricane counts per season. These results show that seasons with La Niña conditions, also associated with weaker wind shear conditions, and higher SSTs associated with the positive phase of the AMM tend to be the most important factors explaining the higher hurricane frequency in the NA basin [54]. In the case of the major hurricanes, the SMPRM-selected factors that explained most of the variance were the SLP, ENSO, and OHC. Two of those factors, the SLP and OHC, were also found to have increasing seasonal averages in the MDR for the 1966–2020 period, which suggests that climate change trends in the ocean heat and a decreasing trend in the atmospheric pressure in the region tend to explain the occurrence of seasons with a higher number of major hurricanes. Similar to the stepwise SMPRM results for the hurricanes, we found that seasons with a higher number of major storms tend to occur in weaker wind shear environments during La Niña periods.

5. Spatial Comparisons between 2020 and 2005

Since the 2005 and 2020 hurricane seasons in the NA basin produced the highest numbers of named storms on record, this section of the study focuses on examining the spatial characteristics of the three main factors (CC, SLP, and ZWS) that were identified as the most important factors behind the higher TC frequency using the stepwise PRM model. When the CC anomalies in the MDR for the 2005 hurricane season in the NA basin were examined, we found that most of the area experienced an above-average CC (Figure 5a) with an anomaly MDR mean of 0.097 oktas. The area with the highest CC anomalies (>0.4 oktas) for 2005 was found in the northeastern sector of the MDR, especially the Caribbean. The 2020 hurricane season exhibited higher CC anomalies when compared to 2005 (Figure 5b), with a higher anomaly MDR mean of 0.326 oktas and higher (>0.4 oktas) CC anomalies across the region. These results suggest that 2020 had a higher number of total TCs than the 2005 season, since higher CCs, very likely driven by higher average SSTs and OHCs (Figure 4a,c), were present in most of the MDR in the NA basin. It is important to note that the CC was also found to be strongly correlated with the SST and OHC in the MDR (Figure 3), which could be associated with the higher evaporation and condensation rates that lead to higher cloud development in those warmer hurricane seasons.

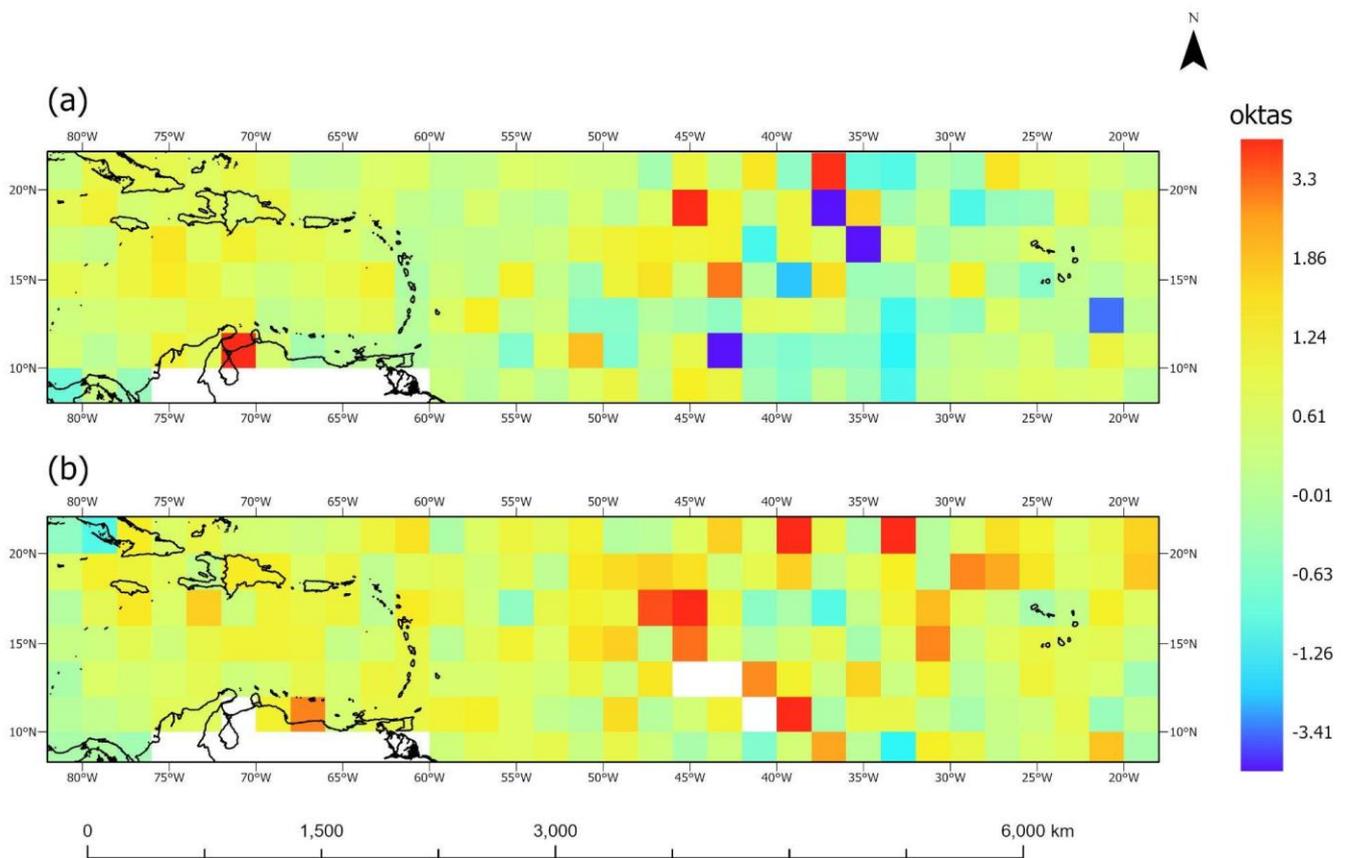


Figure 5. Cloud cover (CC) composite anomalies in the MDR of the NA basin for the 2005 (a) and 2020 (b) hurricane seasons (June–November).

Our comparisons between the sea level pressure anomalies (Figure 6) show that 2005 had a slightly lower anomaly average sea level pressure (-0.7) than 2020 (-0.4). The 2005 hurricane season exhibited lower anomalies in the northern area of the MDR, especially in the Caribbean (Figure 6a). The SLP anomaly plot for the 2020 hurricane season (Figure 6b) shows a wider area of below-normal SLP in the MDR of the NA basin that corresponds to the region where most of the TCs formed in that season. Overall, we found that 2005 exhibited higher SLP patterns in the far-eastern area of the MDR than 2020, yet 2005

showed lower SLP patterns in the western part of the MDR (Figure 6a). These SLP patterns correspond with the higher number of TCs that formed in the western area of the MDR in 2005 and the higher number of TCs that formed in the eastern North Atlantic and southern Caribbean regions in 2020. These results suggest that lower pressure patterns in the western or eastern sectors of the MDR can lead to very active hurricane seasons.

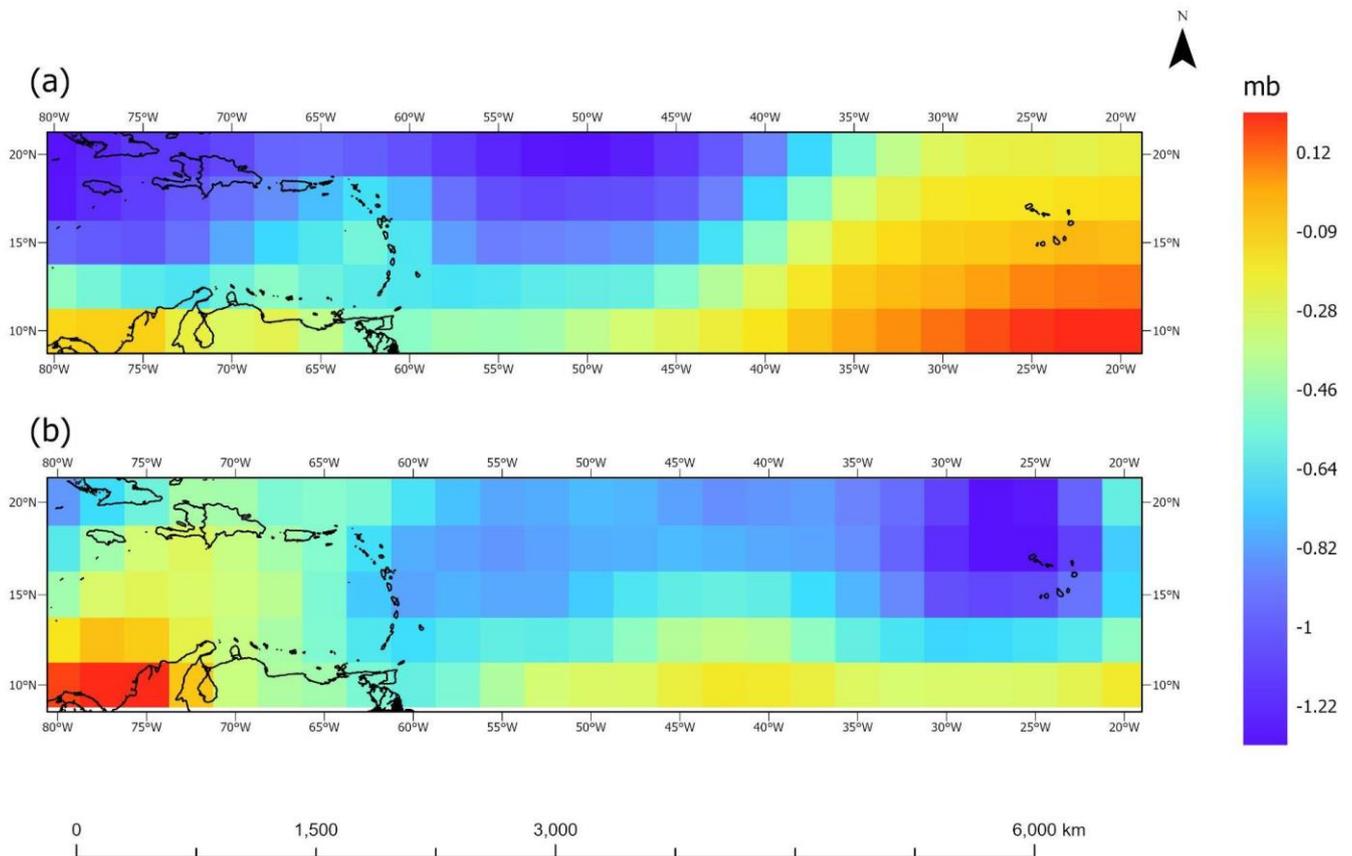


Figure 6. Sea level pressure (SLP) composite anomalies in the NA basin for the 2005 (a) and 2020 (b) hurricane seasons (June–November).

Our comparisons between the anomalous VWS environments show that the 2005 (-1.1 m/s) season had an overall stronger wind shear than the 2020 (-1.3) season (Figure 7a,b). The 2005 hurricane season exhibited weaker VWS environments in the southern Caribbean and the western MDR. On the other hand, the 2020 season shows weaker VWS environments (Figure 7b) in the southeastern section of the MDR and along the Caribbean, while stronger VWS patterns were observed in the northern area of the MDR. These lower VWS patterns were also associated with La Niña conditions, which have been found to produce weaker shear environments that can promote a higher TC frequency [54]. Overall, both the 2005 and 2020 seasons had lower-than-normal VWS environments, yet the 2020 season exhibited a larger area with a below-average VWS that may be associated with La Niña conditions, which tend to promote a higher TC frequency by weakening high atmospheric winds [15].

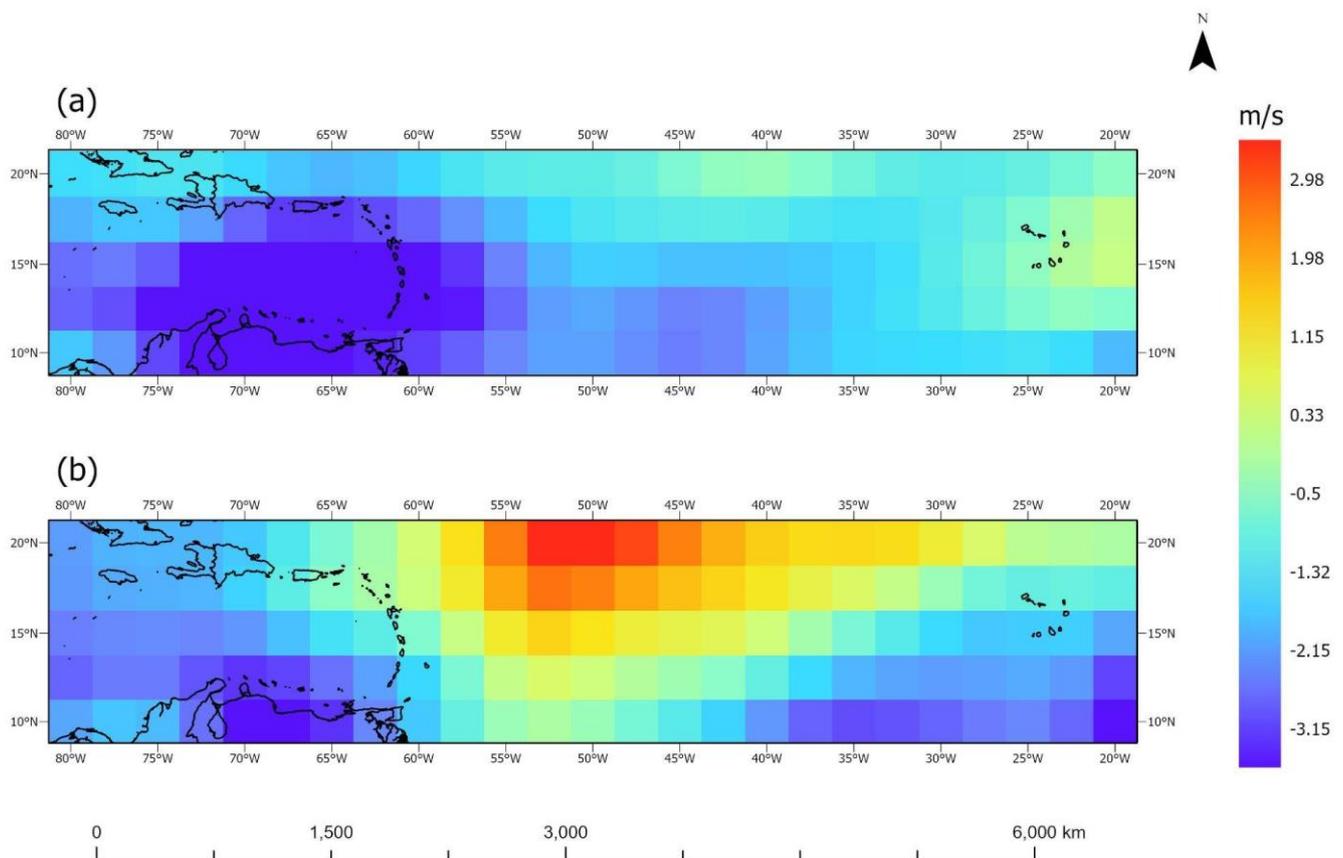


Figure 7. VWS composite anomalies in the NA basin for the 2005 (a) and 2020 (b) hurricane seasons (June–November).

6. Conclusions

The aim of this study was to identify which atmospheric/oceanic or climate variables were the leading factors that made the 2020 North Atlantic hurricane season the most active on record, with 30 named storms. Here, we hypothesized that factors enhanced by climate variability and change caused record-breaking SST patterns that resulted in higher cloud cover and moisture environments, in addition to weak wind shear conditions, which favored higher tropical cyclone development in the MDR. Ten different climate variability and change factors were analyzed in order to determine their relationships with active hurricane seasons, such as that of 2020. All of the variables were examined using trend analyses, correlation techniques, and stepwise multivariate Poisson regression models to determine which factors are most significant in predicting the high TC, hurricane, and major hurricane frequency in seasons such as 2020. A spatial analysis of the most important factors was performed to compare 2020 to 2005, the second most active hurricane season on record.

The Mann–Kendall trend analyses show that the total tropical cyclones and major hurricanes per season have exhibited an increasing trend since 1966. The trend analyses also suggest that the MDR averages of the SST, CC, OHC, AMO, and AMM exhibit statistically significant trends, while the MDR means of the VWS and SLP show significant decreasing trends. The only two factors that did not exhibit a significant trend were the ENSO and MLH. Individual Pearson’s correlation tests identified the CC, SST, VWS, SLP, OHC, AMO, and AMM as the factors that, individually, can account for 40% or more of the variance in the total TCs per season.

Individual correlations between the total TCs and climate factors identified the ZWS, AMO, and AMM as the most significant factors (>0.6). In regard to the total number of hurricanes and major hurricanes per season, the individual correlation analyses suggest that

the SLP and AMM were the most important factors. The independent Poisson regression model plots show that the SST, CC, SLP, AMO, and AMM were the most important factors behind the more active hurricane seasons in the North Atlantic. From these results, we conclude that seasons with higher SST and moisture environments in positive phases of the AMO/AMM, as well as a lower SLP and weaker VWS conditions, tend to be associated with a higher TC frequency in the NA basin.

The stepwise multivariate Poisson regression model results for the total tropical cyclones identified the CC, SLP, and VWS as the factors that best predicted the TC frequency during the hurricane season. The model accounted for 65% of the variance in the TC frequency. The stepwise Poisson regression model for the hurricanes identified the ENSO and AMM as the climate variability factors that best predicted the total hurricane frequency, accounting for around 44.5% of the variance. The model showed that the factors that best predicted the total number of major hurricanes were the SLP, ENSO, and OHC, which, combined, accounted for around 46.5% of the variance in the number of major hurricanes. The results of all of the stepwise Poisson regression models suggest that a combination of climate variability and change factors best explained the TC, hurricane, and major hurricane frequency, with the most active seasons generally exhibiting higher SSTs, higher cloud cover development, lower sea level pressure patterns, and weaker wind shear environments.

The spatial analysis comparisons of the cloud cover anomalies for both seasons showed that 2005 had a slightly lower CC than 2020, with 2005 having a higher CC in the southwestern and northeastern sectors of the MDR, and 2020 showing higher anomalies in the eastern section of the MDR and the Gulf of Mexico. The sea level pressure anomalies showed that 2005 had a slightly lower average pressure than 2020, with 2005 exhibiting lower anomalies in the northern area and 2020 showing anomalous pressure patterns in the eastern part of the main development region. We also found that 2020 had a lower average wind shear than 2005, which could be the main factor that explaining why 2020 had a higher number of tropical cyclones. Overall, our results suggest that both the 2005 and 2020 seasons had similar ocean-atmospheric conditions in the North Atlantic basin that enhanced the TC occurrence. Both seasons had ideal CC, SLP, and VWS conditions that allowed for a high number of storms to develop, with many of these becoming hurricanes. However, the average VWS was lower in 2020 than in 2005, which was associated with La Niña dominant conditions in the MDR that could explain why 2020 surpassed 2005 in the total number of named storms.

Our future work will examine the interactions between the tropical Pacific and Atlantic and their connections to the SST and VWS within the context of the TC frequency. Previous studies [55,56] have suggested that the change in cross-Central American winds is important for the VWS in the main TC development region of the North Atlantic Ocean. Both the tropical Pacific and North Atlantic SSTs can induce zonal wind change across Central America [55,56]. Since this study found that VWS was one of the most important factors behind the occurrence of more/less active hurricane seasons in the North Atlantic, our future work will examine the atmospheric-oceanic forces behind the stronger and weaker wind shear environments in the MDR of the basin.

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References

1. Klotzbach, P.J.; Gray, W.M. Multidecadal variability in North Atlantic tropical cyclone activity. *J. Clim.* **2008**, *21*, 3929–3935. [[CrossRef](#)]
2. Beven, J.L.; Avila, L.A.; Blake, E.S.; Brown, D.P.; Franklin, J.L.; Knabb, R.D.; Pasch, R.J.; Rhone, J.R.; Stewart, S.R. Atlantic hurricane season of 2005. *Mon. Weather. Rev.* **2008**, *136*, 1109–1173. [[CrossRef](#)]
3. Klotzbach, P.J.; Schreck, C.J., III; Collins, J.M.; Bell, M.M.; Blake, E.S.; Roache, D. The Extremely Active 2017 North Atlantic Hurricane Season. *Mon. Weather Rev.* **2018**, *146*, 3425–3443. [[CrossRef](#)]
4. Hallam, S.; Marsh, R.; Josey, S.A.; Hyder, P.; Moat, B.; Hirschi, J.J.M. Ocean precursors to the extreme Atlantic 2017 hurricane season. *Nat. Commun.* **2019**, *10*, 1–10. [[CrossRef](#)]
5. Klotzbach, P.J. Trends in global tropical cyclone activity over the past twenty years (1986–2005). *Geophys. Res. Lett.* **2006**, *33*, L10805. [[CrossRef](#)]
6. Wang, C.; Lee, S.K.; Enfield, D.B. Atlantic warm pool acting as a link between Atlantic multidecadal oscillation and Atlantic tropical cyclone activity. *Geochem. Geophys. Geosystems* **2008**, *9*. [[CrossRef](#)]
7. Knutson, T.R.; McBride, J.L.; Chan, J.; Emanuel, K.; Holland, G.; Landsea, C.; Held, I.; Kossin, J.P.; Srivastava, A.K.; Sugi, M. Tropical cyclones and climate change. *Nat. Geosci.* **2010**, *3*, 157–163. [[CrossRef](#)]
8. Strazzo, S.; Elsner, J.B.; Trepanier, J.C.; Emanuel, K.A. Frequency, intensity, and sensitivity to sea surface temperature of North Atlantic tropical cyclones in best-track and simulated data. *J. Adv. Model. Earth Syst.* **2013**, *5*, 500–509. [[CrossRef](#)]
9. Hernández Ayala, J.J.; Méndez-Tejeda, R. Increasing frequency in off-season tropical cyclones and its relation to climate variability and change. *Weather. Clim. Dyn.* **2020**, *1*, 745–757. [[CrossRef](#)]
10. Pasch, R.J. Tropical Cyclone Report—National Hurricane Center. 2006. Available online: https://www.nhc.noaa.gov/data/tcr/AL252005_Wilma.pdf (accessed on 10 June 2021).
11. Shein, K.A. State of the climate in 2005. *Bull. Am. Meteorol. Soc.* **2006**, *87*, S1–S102. [[CrossRef](#)]
12. Bhatia, K.T.; Vecchi, G.A.; Knutson, T.R.; Murakami, H.; Kossin, J.; Dixon, K.W.; Whitlock, C.E. Recent increases in tropical cyclone intensification rates. *Nat. Commun.* **2019**, *10*, 635. [[CrossRef](#)] [[PubMed](#)]
13. Wang, C.; Wang, X.; Weisberg, R.H.; Black, M.L. Variability of tropical cyclone rapid intensification in the North Atlantic and its relationship with climate variations. *Clim. Dyn.* **2017**, *49*, 3627–3645. [[CrossRef](#)]
14. Chan, K.T. Are global tropical cyclones moving slower in a warming climate? *Environ. Res. Lett.* **2019**, *14*, 104015. [[CrossRef](#)]
15. Klotzbach, P.J.; Wood, K.M.; Bell, M.M.; Blake, E.S.; Bowen, S.G.; Caron, L.P.; Collins, J.M.; Gibney, E.J.; Schreck, C.J., III; Truchelut, R.E. A Hyperactive End to the Atlantic Hurricane Season: October–November 2020. *Bull. Am. Meteorol. Soc.* **2021**, *103*, 1–57. [[CrossRef](#)]

16. Foltz, G.R.; McPhaden, M.J. Unusually warm sea surface temperatures in the tropical North Atlantic during 2005. *Geophys. Res. Lett.* **2006**, *33*. [[CrossRef](#)]
17. Wang, C.; Enfield, D.B.; Lee, S.K.; Landsea, C.W. Influences of the Atlantic warm pool on Western Hemisphere summer rainfall and Atlantic hurricanes. *J. Clim.* **2006**, *19*, 3011–3028. [[CrossRef](#)]
18. Lim, Y.K.; Schubert, S.D.; Kovach, R.; Molod, A.M.; Pawson, S. The roles of climate change and climate variability in the 2017 Atlantic hurricane season. *Sci. Rep.* **2018**, *8*, 16172. [[CrossRef](#)]
19. Landsea, C.W.; Bell, G.D.; Gray, W.M.; Goldenberg, S.B. The extremely active 1995 Atlantic hurricane season: Environmental conditions and verification of seasonal forecasts. *Mon. Weather. Rev.* **1998**, *126*, 1174–1193. [[CrossRef](#)]
20. Knapp, K.R.; Kruk, M.C.; Levinson, D.H.; Diamond, H.J.; Neumann, C.J. The International Best Track Archive for Climate Stewardship (IBTrACS): Unifying tropical cyclone best track data. *Bull. Am. Meteorol. Soc.* **2010**, *91*, 363–376. [[CrossRef](#)]
21. Mann, M.E.; Sabbatelli, T.A.; Neu, U. Evidence for a modest undercount bias in early historical Atlantic tropical cyclone counts. *Geophys. Res. Lett.* **2007**, *34*, L22707. [[CrossRef](#)]
22. Landsea, C.W. Counting Atlantic tropical cyclones back to 1900. *EOS T. Am. Geophys. Un.* **2007**, *88*, 197–202. [[CrossRef](#)]
23. Sobel, A.H.; Wing, A.A.; Camargo, S.J.; Patricola, C.M.; Vecchi, G.A.; Lee, C.Y.; Tippett, M.K. Tropical cyclone frequency. *Earth's Future* **2021**, *9*, e2021EF002275. [[CrossRef](#)]
24. Kalnay, E.; Kanamitsu, M.; Kistler, R.; Collins, W.; Deaven, D.; Gandin, L.; Iredell, M.; Saha, S.; White, G.; Woollen, J. The NCEP/NCAR Reanalysis 40-year Project. *Bull. Amer. Meteor. Soc.* **1996**, *77*, 437–471. [[CrossRef](#)]
25. Eastman, R.; Warren, S.G.; Hahn, C.J. Variations in cloud cover and cloud types over the ocean from surface observations, 1954–2008. *J. Clim.* **2011**, *24*, 5914–5934. [[CrossRef](#)]
26. Freeman, E.; Woodruff, S.D.; Worley, S.J.; Lubker, S.J.; Kent, E.C.; Angel, W.E.; Berry, D.I.; Brohan, P.; Eastman, R.; Gates, L.; et al. ICOADS Release 3.0: A major update to the historical marine climate record. *Int. J. Climatol.* **2017**, *37*, 2211–2232. [[CrossRef](#)]
27. Aleksandrova, M.; Belyaev, K. Climatology and interannual variability in statistical characteristics of cloud cover over the North Atlantic during 1950–2017. In *Proceedings of the IOP Conference Series: Earth and Environmental Science*; Moscow, Russia, 16–18 May 2018, IOP Publishing: Bristol, UK, 2019; Volume 231, p. 012005.
28. Keellings, D.; Hernández Ayala, J.J. Extreme rainfall associated with Hurricane Maria over Puerto Rico and its connections to climate variability and change. *Geophys. Res. Lett.* **2019**, *46*, 2964–2973. [[CrossRef](#)]
29. Levitus, S.; Antonov, J.I.; Boyer, T.P.; Baranova, O.K.; García, H.E.; Locarnini, R.A.; Mishonov, A.V.; Reagan, J.R.; Seidov, D.; Yarosh, E.; et al. NCEI ocean heat content, temperature anomalies, salinity anomalies, thermocline sea level anomalies, halosteric sea level anomalies, and total steric sea level anomalies from 1955 to present calculated from in situ oceanographic subsurface profile data (NCEI Accession 0164586). *NOAA Natl. Cent. Environ. Information. Dataset.* **2017**, *10*, v53f4mvp. [[CrossRef](#)]
30. Rayner, N.A.; Parker, D.E.; Horton, E.B.; Folland, C.K.; Alexander, L.V.; Rowell, D.P.; Kent, E.C.; Kaplan, A. Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res.* **2003**, *108*, 4407. [[CrossRef](#)]
31. Mestas-Núñez, A.M.; Enfield, D.B. Eastern equatorial Pacific SST variability: ENSO and non-ENSO components and their climatic associations. *J. Clim.* **2001**, *14*, 391–402. [[CrossRef](#)]
32. Vimont, D.J.; Kossin, J.P. The Atlantic Meridional Mode and hurricane activity. *Geophys. Res. Lett.* **2007**, *34*, L07709. [[CrossRef](#)]
33. Villarini, G.; Vecchi, G.A. Projected increases in North Atlantic tropical cyclone intensity from CMIP5 models. *J. Clim.* **2013**, *26*, 3231–3240. [[CrossRef](#)]
34. Lin, I.I.; Black, P.; Price, J.F.; Yang, C.Y.; Chen, S.S.; Lien, C.C.; Harr, P.; Chi, N.-H.; Wu, C.-C.; D'Asaro, E.A. An ocean coupling potential intensity index for tropical cyclones. *Geophys. Res. Lett.* **2013**, *40*, 1878–1882. [[CrossRef](#)]
35. Scoccimarro, E.; Bellucci, A.; Storto, A.; Gualdi, S.; Masina, S.; Navarra, A. Remote subsurface ocean temperature as a predictor of Atlantic hurricane activity. *Proc. Natl. Acad. Sci. USA* **2018**, *115*, 11460–11464. [[CrossRef](#)] [[PubMed](#)]
36. Latif, M.; Keenlyside, N.; Bader, J. Tropical sea surface temperature, vertical wind shear, and hurricane development. *Geophys. Res. Lett.* **2007**, *34*. [[CrossRef](#)]
37. Ryglicki, D.R.; Cossuth, J.H.; Hodyss, D.; Doyle, J.D. The unexpected rapid intensification of tropical cyclones in moderate vertical wind shear. Part I: Overview and observations. *Mon. Weather. Rev.* **2018**, *146*, 3773–3800. [[CrossRef](#)]
38. Tutz, G. Poisson Regression. In *International Encyclopedia of Statistical Science*; Lovric, M., Ed.; Springer: Berlin/Heidelberg, Germany, 2011. [[CrossRef](#)]
39. Mann, H.B. Nonparametric tests against trend. *Econom. J. Econom. Soc.* **1945**, *13*, 245–259. [[CrossRef](#)]
40. Kendall, M.G. *Rank Correlation Methods*; Griffin: New York, NY, USA, 1948.
41. Solow, A.; Nicholls, N. The relationship between the Southern Oscillation and tropical cyclone frequency in the Australian region. *J. Clim.* **1990**, *3*, 1097–1101. [[CrossRef](#)]
42. Elsner, J.B.; Schmertmann, C.P. Improving extended-range seasonal forecasts of intense Atlantic hurricane activity. *Wea. Forecast.* **1993**, *8*, 345–351. [[CrossRef](#)]
43. McDonnell, K.A.; Holbrook, N.J. A Poisson regression model of tropical cyclogenesis for the Australian–southwest Pacific Ocean region. *Wea. Forecast.* **2004**, *19*, 440–455. [[CrossRef](#)]
44. Mestre, O.; Stéphane, H. Predictors of Tropical Cyclone Numbers and Extreme Hurricane Intensities over the North Atlantic Using Generalized Additive and Linear Models. *J. Clim.* **2009**, *22*, 633–648. [[CrossRef](#)]

45. Villarini, G.; Vecchi, G.A.; Smith, J.A. Modeling the dependence of tropical storm counts in the North Atlantic basin on climate indices. *Mon. Wea. Rev.* **2010**, *138*, 2681–2705. [[CrossRef](#)]
46. Tippett, M.K.; Camargo, S.J.; Sobel, A.H. A Poisson regression index for tropical cyclone genesis and the role of large-scale vorticity in genesis. *J. Clim.* **2011**, *24*, 2335–2357. [[CrossRef](#)]
47. Bruce, P.; Andrew, B. *Practical Statistics for Data Scientists*; O'Reilly Media: Sebastopol, CA, USA, 2017.
48. Venables, W.N.; Ripley, B.D. *Modern Applied Statistics with S*, 4th ed.; Springer: Berlin/Heidelberg, Germany, 2002.
49. Herring, S.C.; Christidis, N.; Hoell, A.; Hoerling, M.P.; Stott, P.A. Explaining Extreme Events of 2019 from a Climate Perspective. *Bull. Amer. Meteor. Soc.* **2021**, *102*, S1–S112. [[CrossRef](#)]
50. Klotzbach, P.; Gray, W.; Fogarty, C. Active Atlantic hurricane era at its end? *Nat. Geosci.* **2015**, *8*, 737–738. [[CrossRef](#)]
51. Camargo, S.J.; Wing, A.A. Increased tropical cyclone risk to coasts. *Science* **2021**, *371*, 458–459. [[CrossRef](#)]
52. Hallam, S.; Guishard, M.; Josey, S.A.; Hyder, P.; Hirschi, J. Increasing tropical cyclone intensity and potential intensity in the subtropical Atlantic around Bermuda from an ocean heat content perspective 1955–2019. *Environ. Res. Lett.* **2021**, *16*, 034052. [[CrossRef](#)]
53. Goldenberg, S.B.; Landsea, C.W.; Maestas-Nunez, A.M.; Gray, W.M. The recent increase in Atlantic hurricane activity: Causes and implications. *Science* **2021**, *293*, 474–479. [[CrossRef](#)] [[PubMed](#)]
54. Pielke, R.A., Jr.; Landsea, C.N. La Niña, El Niño, and Atlantic hurricane damage in the United States. *Bull. Am. Meteorol. Soc.* **1999**, *80*, 2027–2034. [[CrossRef](#)]
55. Wang, C.; Lee, S.K. Co-variability of tropical cyclones in the North Atlantic and the eastern North Pacific. *Geophys. Res. Lett.* **2009**, *36*. [[CrossRef](#)]
56. Wang, C.; Wang, L.; Wang, X.; Wang, D.; Wu, L. North-south variations of tropical storm genesis locations in the Western Hemisphere. *Geophys. Res. Lett.* **2016**, *43*, 11–367. [[CrossRef](#)]