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Sea Surface Temperatures and Vertical Wind Shear as Precursors to Tropical Cyclone Activity in the Caribbean and an Expanding Main Developing Region

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Abstract

Catastrophic tropical cyclone (TC) events have impacted the Caribbean and the U.S. with more frequency and intensity over recent decades. In 2017, Hurricane Harvey devastated the Houston area, followed by Hurricane Irma and Maria, affecting Florida, Puerto Rico, and much of the Caribbean. Assessing all attributable risks of severe weather events is imperative because of their socioeconomic and catastrophic impacts on the U.S., Caribbean, and surrounding regions. This study investigates the effects of rising Sea Surface Temperatures (SSTs) and a changing Vertical Wind Shear (VWS) on tropical storm activity in the Main Developing Region (MDR) to identify the possible correlation with these tropical storms' frequencies and intensities. Understanding the role SSTs and wind shear play in the occurrence of TCs is vital for coastal communities' efforts for environmental hazard mitigation. SSTs and VWS are essential to TC formation; TCs need warm SSTs and low shear for genesis. Increasing SSTs and VWS changes influence storm development. This work analyzes SST and VWS trends for the Caribbean, the surrounding region, and the Atlantic MDR from 1982 to 2020. Tropical storm intensity increases significantly during this period. Annual and seasonal trends show regional SSTs in the MDR are warming annually (0.0219°C yr^{-1}) and per season (0.0280°C yr^{-1}) with comparable trends to global SSTs. Simultaneously, VWS decreases during the late rainfall season (LRS) at 0.0556m/s yr^{-1} in the MDR and 0.0167m/s yr^{-1} in the Caribbean and the surrounding area, while the Atlantic Warm Pool (AWP) is expanding at 0.51km^2 per decade. Increased upper atmospheric winds are driving VWS changes. Correlations of large-area averages do not show significant relationships between TC intensity and frequency and SSTs or VWS during the LRS. The observed changes appear to be associated with regional warming SSTs impacting TC changes.

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Introduction

Sea surface temperatures (SSTs) in the mid-Atlantic and the Caribbean have steadily increased for several decades (Antuna et al., 2015; Glenn et al., 2015 & 2020). Mid Atlantic SSTs are warming faster during the late rainfall season (LRS – August to November) than any other season (dry – December to March) and early – April to July) with temperatures reaching 26.5°C and higher, the threshold considered for deep convection (Gadgil et al. 1984; Graham and Barnett 1987). Upward trends in the Atlantic SSTs may lead to tropical cyclonic (TC) activity intensification, posing more significant risks to coastal communities. Research shows that storms in the North Atlantic have increased in frequency and intensity since the 1980s (Melillo et al., 2014). Additionally, the Caribbean and the U.S. have experienced increasingly intense hurricanes, potentially linked to increasing SSTs (IPCC, 2014). More than 80% of Atlantic TC systems that turn into major hurricanes are formed within the main developing region (MDR, 10°N-20°N, 20°W-80°W), where TCs primarily form from easterly waves originating in Western Africa (Goldenberg and Shapiro, 1996). Thus, understanding the connection between a changing climate and TCs frequency and intensification trends in this region is particularly important.

Previous studies have analyzed the role of various environmental factors in major hurricane activity in the MDR. Mann and Emanuel (2006) showed growing SST trends strongly correlated to TC counts in the MDR, unrelated to the Atlantic Multidecadal Oscillation (AMO). At the same time, Vecchi and Soden's 2007 work spoke about how wind shear may increase due to climate change, making it more difficult for hurricanes to form. Although previous studies of the correlations between SSTs and TC frequency and SST and deep convection have been conducted elsewhere, we have not found research on these topics within the MDR. Thus, the objective of this study is to investigate the connections between recent SSTs (1982-2020), vertical wind shear (VWS) trends, and the possible linkages to recent observations in TC activity in the Caribbean and the surrounding region and the MDR. The area of interest is shown in Figure 1.

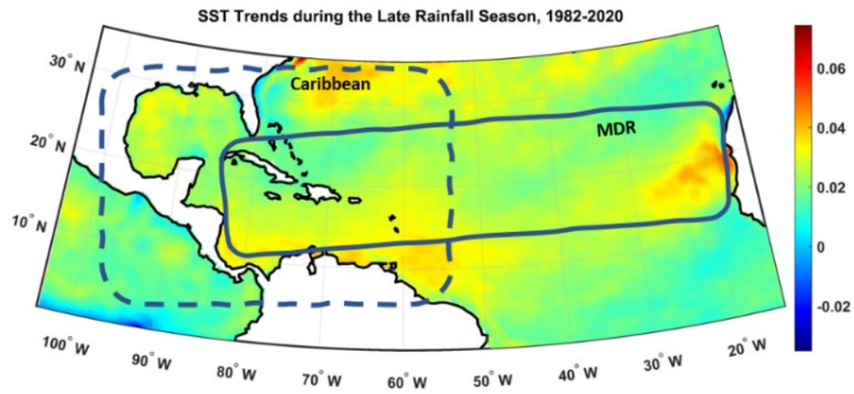


Figure 1: Spatial Map depicting trends from 1982 to 2020 during the Late Rainfall Season (LRS), indicating warming trends up to and exceeding 0.4°C per decade in the Main Developing Region (MDR) (10°N-20°N, 20°W-80°W), and the Caribbean and the Surrounding Region (5°N -31°N, 100°W -55°W). Areas marking these regions are not drawn to scale and are an approximation.

1.1 Background

Historical climate analyses have shown a consistently increasing SST trend in the Tropical North Atlantic (TNA) and the Caribbean in the past and over recent years. Antuna et al.'s (2015) examination of the TNA between 1906 and 2005 showed that the TNA, including the Caribbean Sea, has warmed significantly over the past century. Deser et al. (2010) reported that the tropics and the subtropics had increasing trends ranging between 0.4-1.6°C/century between 1900 and 2008. Similarly, Glenn et al.'s (2015) most recent findings on the wider Caribbean and its surrounding region show statistically significant annual regional increases at 1.5°C/century between 1982 and 2012. The authors also find that the magnitude of their warming trends is consistent with other studies based on reanalysis and point-based observations, and future projections by Jury (2011) and McLean et al. (2015). Glenn et al. (2015) also noted that regional warming is increasing faster than the global rate of 1.1°C/century, suggesting that the global trend is present in the climate-sensitive region but is more intense. Though regional warming rises over time, warming intensification trends, as reported by Antuna et al. (2015), occur in the southern Lesser Antilles with temperatures rising to 1.5°C/century and off the Caribbean coast of Columbia and Venezuela.

The Atlantic Warm Pool (AWP), which comprises the Gulf of Mexico, the Caribbean Sea, and the Western TNA, a large body of water warmer than 28.5°C (Wang et al., 2006), shows temperatures ideal for intense tropical cyclone formations. Previous research documented that warmer ocean waters cause more intense storms; however, other variables like VWS contribute to tropical cyclone genesis and may be associated with increased intensity. "SSTs are of secondary importance to vertical shear in modulating hurricane formation, explaining only ~10% of the interannual variability in hurricane frequency over the ~50% explained by vertical shear, proving that warmer SSTs are the main driver for enhanced hurricane development (Shapiro and Goldenberg, 1998)".

Furthermore, studies show that when the AWP is at its maximum extent, moisture contribution to the Caribbean, the region of the Inter-tropical Convergence Zone (ITCZ), and the North Atlantic are increased (Sori et al., 2015). Where 26.5°C is considered the convection threshold for tropical cyclone genesis, seasonal SST variations have been linked to the AWP's evolution. Moisture transported to the Caribbean sea via the Caribbean Low-Level Jet (CLLJ) is influenced by the easterly winds produced by the North Atlantic Subtropical High (NASH) and controlled by AWPs intensity. Significant to hurricane formation/activity, the interrelationship between VWS, SSTs, and the CLLJ have been highlighted in prior work (Wang et al., 2006 and 2007).

Additionally, the Atlantic Multidecadal Oscillation (AMO) is a naturally occurring series of changes in sea surface temperatures in the North Atlantic Ocean (NAO) that occur at long durations, with cool and warm phases lasting 20-40 years (NOAA; Enfield et al., 2001). Considering other time scale variabilities like this could help further understand SST trends, as previous studies have linked the AMO to SSTs. Glenn et al. (2015) and Antuna et al. (2015) found strong correlations between North Atlantic SSTs and the AMO during their respective observation periods. Historical records show that the AMO went into a warm phase during the late 1990s, accounting for some of the SST warming trends in the Intra-Americas Region (IAR) and the apparent shift in SST anomalies.

2 Data and Methods

2.1 Analytical Techniques

Climatological analyses of the study region were analyzed over 71 years. The first SST dataset used in this study is the NOAA's Optimum Interpolated Sea-Surface Temperature (OISST). This is a 0.25° High-Resolution Optimum Interpolation (OI) Sea Surface Temperature v2.1 dataset with a daily temporal resolution combined with the infrared satellite SST estimates in-situ observation data from buoys and ships (Huang et al., 2021. For the earlier period (1982-2020), the Pathfinder and infrared and operational satellite captured SST estimates are used for daily updates. The second SST dataset used (1950-2020) in this study is the ERSST v5, derived from the International Comprehensive Ocean-Atmosphere Dataset (ICOADS). It is a monthly 2°x2° horizontally gridded dataset that uses the NOAA Global Surface Temperature product to integrate ERSST data with land surface temperature from the Global Historical Climatology Network Monthly dataset combined surface temperature analyses (Huang et al., 2020). The NCEP/NCAR Reanalysis 1 dataset provided vertical wind shear data with monthly temporal and 2.5°x2.5° spatial resolution. Atlantic hurricane data used for this project are taken from the NOAA HURDAT2 Reanalysis project, last updated in November 2019.

2.2 Regional Analysis

SST trends for the study region were evaluated using the NOAA OISST and ERSST products. Regional values were averaged monthly and yearly to determine the temperature changes over 71 years. Linear regression and two-tailed tests were performed to assess the significance of these changes. SST trends and values were later calculated seasonally for the LRS from 1950 to 2020 for ERSST and the DS, ERS, and the LRS using the OISST dataset from 1982 to 2020. Similarly, annual and seasonal trend analysis and climatology for VWS over the Caribbean, the surrounding region, and the MDR were performed.

By taking the averages of our 39-year study period from both the ERSST and OISST datasets, then subtracting the difference between those averages from the ERSST dataset, we removed the systematic bias in the ERSST dataset.

This study primarily uses the NOAA OISST dataset because of its accuracy, relatively higher resolution, and consistency since 1982. Our focus is on recent (1982-2020) trends and their effect on changes to the Atlantic Warm Pool (AWP) and TC activity in the Atlantic main developing region (MDR) and how these changes, if any, are affecting the Caribbean and the surrounding area.

2.3 Trend and Grid Analysis

A non-parametric test for trends was performed for this study because of its large and variable datasets. The Mann-Kendall (M-K) trend test was applied to regional, seasonal averages, and gridded analyses for annual, DS, ERS, and LRS from the OISST dataset. To observe SST and VWS trends annually and seasonally, trends (slope) and associated significance (p-values) for SSTs and VWS from 1982 to 2020 throughout the study region were calculated. If calculated p-values were less than 0.05 (95% confidence level), trends were considered statistically significant.

2.4 Correlations

The correlation coefficient is used to evaluate the strength of a relationship between variables. Using the OISST dataset, the Pearson Correlation Coefficient (PCC) test was used for this study; values between 0.7 and 0.9 are usually highly correlated for these time series. In contrast, values between 0.5 and 0.7 are moderate, and less than 0.4 is weak. Correlation analyses were performed between SST and VWS and the hurricane counts and intensity during the LRS for the Caribbean, surrounding region, and MDR. Each correlation was tested for statistical significance at the 95% test level.

2.5 Hurricane Count and Intensity

The Saffir-Simpson hurricane wind scale was used to analyze hurricane strength for hurricane analysis. The scale is used to classify tropical cyclones in the Western Hemisphere that exceeds the intensity of a tropical depression. Storms are assigned one of five categories (1-5) distinguished by the intensities of their sustained winds. Changes to hurricane intensity and frequency during the LRS were investigated over 150 years (1851-2020) for the Caribbean, the surrounding region, and the MDR.

2.6 Atlantic Warm Pool

Multidecadal variability of TC activity in the North Atlantic has often been linked to the Atlantic Multidecadal Oscillation (AMO). The AMO produces variations in SST in higher latitudes in the North Atlantic and the Atlantic Warm Pool (AWP) in lower latitudes (Wang et al., 2008). The AWP has SST above 28.5°C and extends through the Gulf of Mexico, the Caribbean Sea, and the western tropical North Atlantic (Wang et al., 2006), reaching its maximum size during the LRS. Its size and intensity are correlated with the amount of rainfall that the Caribbean and surrounding regions experiences during the LRS (Glenn et al., 2015). Given that the AWP is in the path of TC activity, it is plausible that changes in TC activity could be related to AWP variability. Low-latitude SSTs play a vital role in hurricane activity, suggesting that the AWP links the AMO and Atlantic hurricane activity (Wang et al., 2008). Previous studies have indicated that the AMO can contribute to TC variations; however, other factors like seasonality and global warming should be considered and maybe more critical. This study aims to identify whether the AWP changes in magnitude and extent over time during the LRS.

3 Results and Figures

3.1 Trend Analysis Results

SST analysis shows statistically significant increasing trends during the LRS. The MDR temperatures increase at 0.28°C/decade and 0.24°C/decade in the Caribbean and the surrounding area. Both are significant at the 95% confidence level. Warming is most consistent during the LRS and most notably during the latter half of the study period. SSTs have been anomalously warm since 1995 in the MDR and since around 1998 in the Caribbean region, Figure 3. For the study areas, daily averages (not shown) were calculated along with daily anomalies. Observation of daily anomalies shows an increase in SSTs during the LRS over the past 25 to 27 years.

Further observation of daily SST variabilities (Figure 4) indicates more days above the convection threshold (26.5°C), notably after 1995 in the MDR and 1998 in the Caribbean region. Further examination of the individual months during the LRS (Figure 2) shows that SSTs are cooler at the beginning of the season and are much warmer later. October has notably warmer SSTs, indicating that October stays warmer and temperatures increase over time, Figures 2(a, b).

Further analysis shows that SSTs have not only increased but are spreading regionally. An analysis of the area of SSTs greater than 28°C increased over time, expanding the Atlantic Warm Pool. Furthermore, VWS for individual months shows that shears in June/July are stable with no notable changes, while August/September shows more favorable shear values for TC development. October shears are higher than August/September but are steadily decreasing. Emmanuel and Mann (2006) found that the AMO does not appear to play a role in changes in tropical cyclone activities dating as far back as the 19th-century. Instead, anthropogenically forced large-scale warming and the 20th-century anthropogenic tropospheric aerosol forcing may be the underlying factors. Consistent with Emmanuel and Mann (2006), shear changes do not seem large enough to explain TC changes. After observing the AMO and global and regional SST trends in the Intra-Americas Region (IAR) region, Glenn et al. (2015) found that even after the AMO shift from a cold to warm phase during their 31-year study period, IAR SSTs continued to follow global trends. Consistent with our findings, SSTs appear to be the primary driver of Atlantic TC activities; these warming trends during the LRS are similar to global trends (figure 3), suggesting these changes are attributed to global warming.

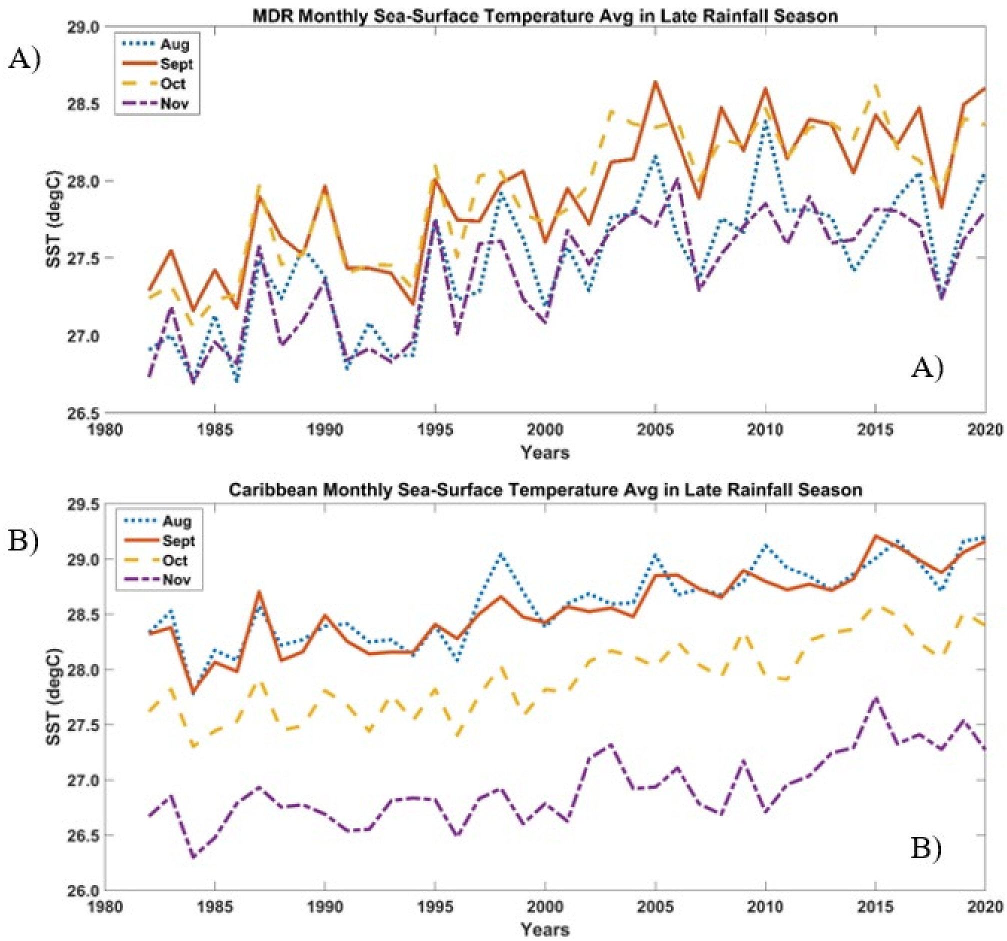


Figure 2: Monthly regional SST trends from 1982 to 2020 using NOAA OISST product: (a) SST temperatures during the LRS in the MDR, (b) SST in the LRS during the Caribbean and the surrounding region.

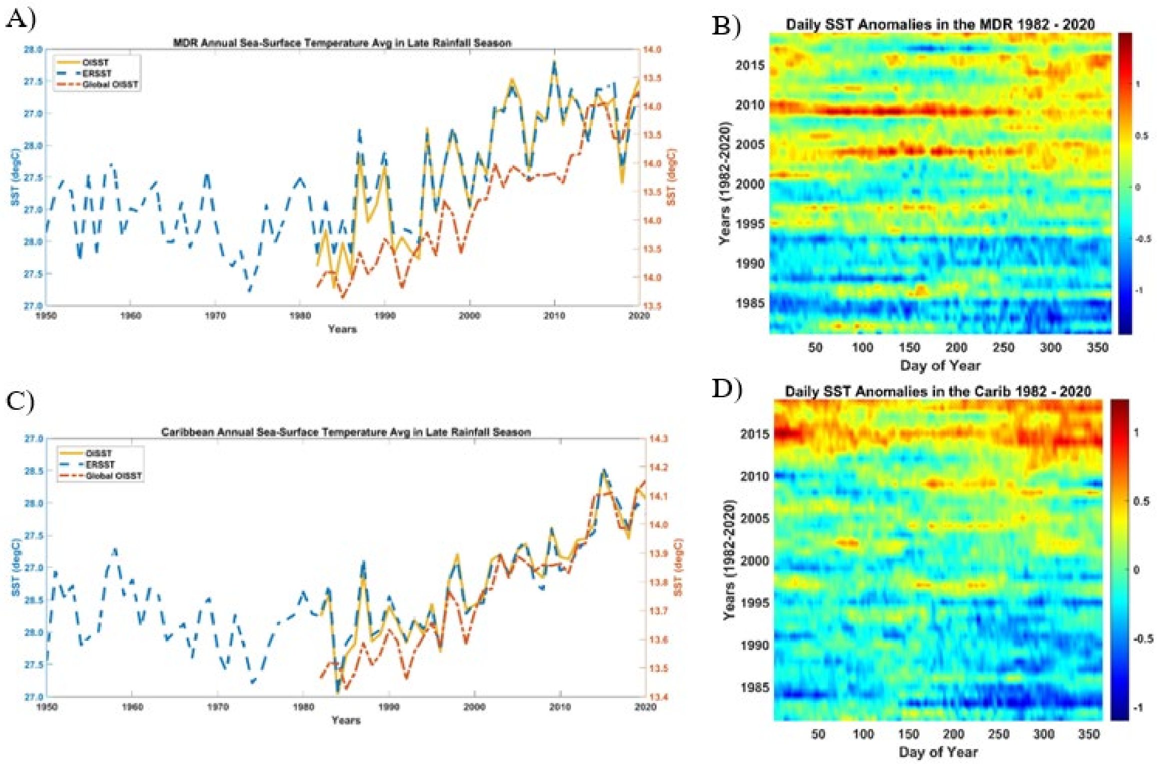


Figure 3: Annual SST trends and daily anomalies. (a, c) annual average SSTs during the LRS for the MDR and the Caribbean and the surrounding region, depicting current and global SST trends from 1982-2020 using the NOAA OISST and 1950-2020 ERSST dataset (b, d) regional daily SST anomalies during the LRS for the MDR and the Caribbean and the surrounding region. The color bar is SST in degrees Celsius.

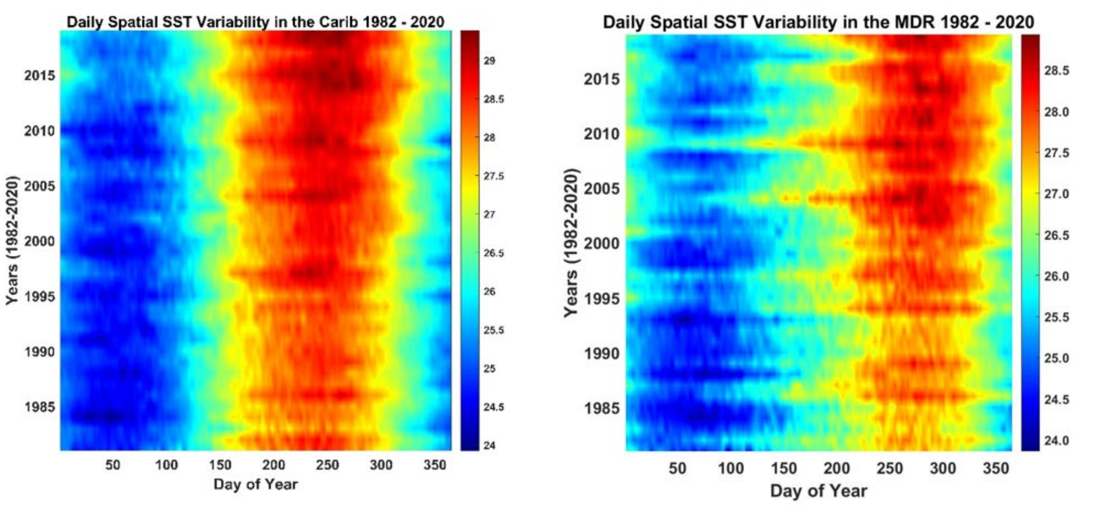


Figure 4: Daily Spatial Variability trends in the Caribbean and the Main Developing Region from 1982 to 2020. Plots indicate more days over the convection threshold of 26.5°C. The color bar is SST in degrees Celsius.

3.2 Correlation Analysis Results

Table 1 summarizes the LRS correlation of TC intensity against SST and VWS in the study region. The relationship between SSTs and wind speed has been explored for decades (Bjerknes 1964; Shakula and Misra 1977, and Hurrell 1995). The negative relationship between SST and wind speed is due to increased wind speeds cooling surface ocean temperatures through vertical mixing and enhanced evaporation. Wang et al. (1999) found that increasing surface wind speed produces more evaporation, leading to cooler SSTs, causing the surface wind speed to rise further and vice versa. However, a study by Xie (2004) indicated that the relationship between SST and wind speed could be positively correlated in small-scale regions, showing that surface winds may be higher locally over warmer waters (Qu et al., 2012).

SST and VWS correlations with storm intensities in the Caribbean and the surrounding region.					
	Category 1	Category 2	Category 3	Category 4	Category 5
SST LRS	$<10^{-3}$	0.002	**0.198**	0.007	0.037
VWS LRS	0.013	0.007	0.008	0.038	0.001
SST and VWS correlations with storm intensities in the MDR.					
	Category 1	Category 2	Category 3	Category 4	Category 5
SST LRS	0.002	0.003	**0.273**	0.038	0.033
VWS LRS	$<10^{-3}$	0.008	0.058	0.001	0.040

Table 1: Summary of regional SST and VWS correlations with storm intensities in the Caribbean, surrounding regions, and MDR. The bold type indicates statistical significance at the 95% test level.

3.3 Vertical Wind Shear and Atlantic Warm Pool Results

An analysis during the LRS from 1982 to 2020 showed significant SST warming trends and an expansion of the warming area. In a grid-based study of the AWP, the area with SSTs at or above 28.5°C, which reaches its maximum during the LRS (Wang et al., 2007), is increasing in extent and magnitude at a rate of 0.51km^2 per decade. Simultaneously, VWS trends are decreasing in the MDR at a rate of 0.056ms^{-1} per year and 0.0167ms^{-1} per year in the Caribbean and the surrounding area (Figure 5), consistent with the AWP-induced atmospheric changes related to tropospheric vertical wind shear and the thermodynamical parameter of convective instability. Further analysis of VWS winds and components shows winds in the upper atmosphere are driving VWS changes; these changes could be associated with the expansion of the Hadley Cell (Xian et al., 2021). The increased warming and growth of the AWP and low VWS in the region favor increased TC development.

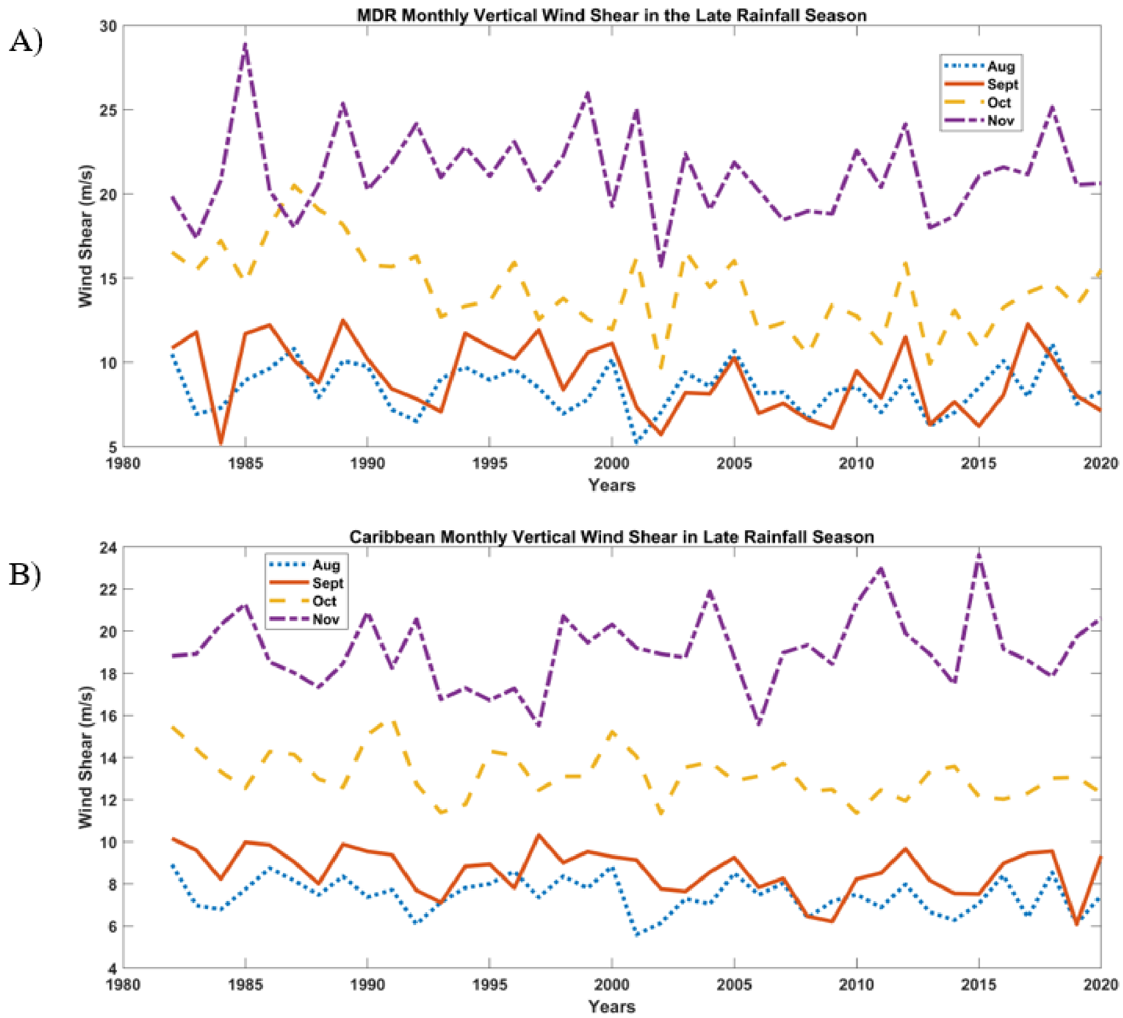


Figure 5: Monthly regional VWS trends from 1982 to 2020 using NCEP/NCAR Reanalysis1 product: (a) VWS during the LRS in the MDR, (b) VWS in the LRS during the Caribbean and the surrounding region.

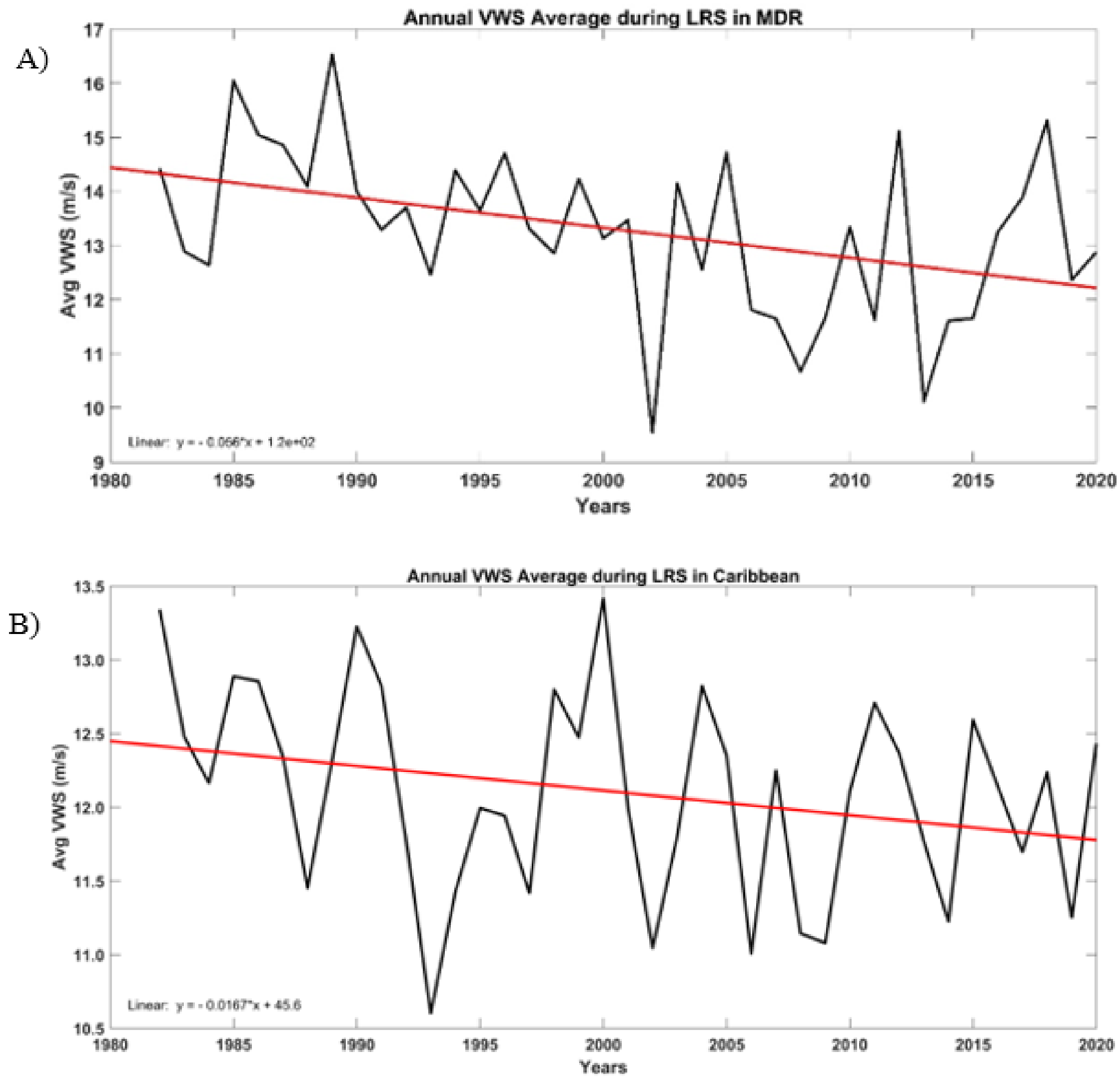


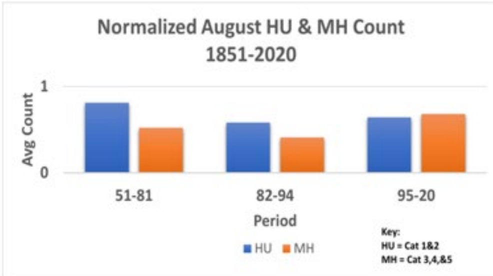
Figure 6: (a) Annual Average of VWS during the LRS from 1982 to 2020 in the MDR, showing a decreasing trend at $0.56ms^{-1}$ per decade, (b) Annual Average of VWS during the LRS from 1982 to 2020 in the Caribbean and the surrounding region, showing a decreasing trend at $0.16ms^{-1}$ per decade.

3.4 Hurricane Count and Intensity Results

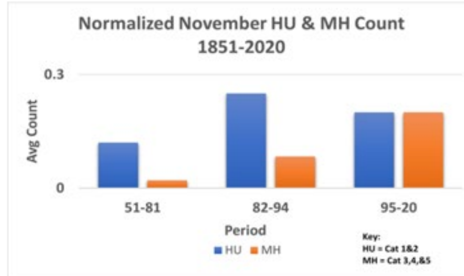
Until the mid-1960s, satellite data usage was not available for storm tracking; therefore, early storm counts were less reliable. Television Infrared Observation Satellites (TIROS) were the first weather monitoring satellites. These systems were still unable to provide daily storm images. Over time, weather and storm tracking satellites have improved with advancing technology, with good satellite coverage since the late 1970s. Recently 2020 has surpassed 2005 as the most active season on record, though the 2005 season still holds the record for most hurricanes.

Using our most current storm tracking systems, this study examined hurricane counts over the 39 years of our study period. In addition, storm counts from the past 130-years were included to place the more recent period into historical context. The 39-year study period counts were separated and normalized into two parts, before and after 1995, due to the warm shift in SSTs. Observation of the individual months helps us quickly identify when the most notable changes occur. August and September, with warmer SSTs, show substantial differences in hurricane counts and intensity. There were no August category four storms before 1995 and ten after. In September, there were eight categories, one and two storms before 1995. Storm count increased by eleven, and category three storm count increased by thirteen after 1995. October presents a striking increase in storm counts, where there are more category five storms after 1995 than any other month during the LRS, Figure 6. Observations of storm count from 1851 to 1981 show more HU storms than MH. Consistent with Vecchi et al., 2021 storm frequency and intensity do not show a longer-term trend, and there are fewer storms in the mid to late 20th century. Storm frequency and intensity have increased during the more recent period (1982-2020), with no increase in lower-intensity storms and an increasing number of high-intensity storms.

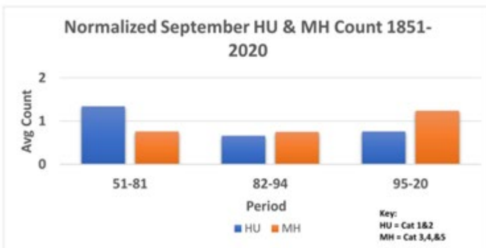
Hurricanes are becoming more intense during the latter half of the season, specifically during September. October storms have increased in frequency and intensity, notably after 1995.



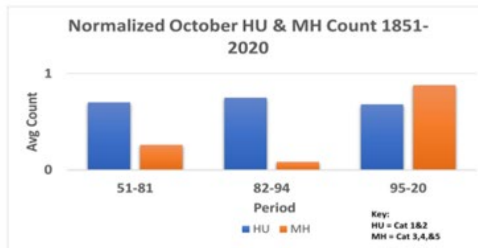
Period	Number	Num Per Year
1851-1981	174	1.33
1982-1994	12	1
1995-2020	33	1.32



Period	Number	Num Per Year
1851-1981	19	0.146
1982-1994	4	0.33
1995-2020	10	0.4



Period	Number	Num Per Year
1851-1981	275	2.11
1982-1994	17	1.41
1995-2020	50	2



Period	Number	Num Per Year
1851-1981	127	0.97
1982-1994	10	0.83
1995-2020	39	1.56

Figure 7: Categories 1&2 Atlantic Hurricane (HU) and Categories 3 to 5 Atlantic major hurricane (MH) counts over the LRS months, 1851-2020. The blue bars (HU) indicate low-intensity storm counts, and the orange bars (MH) indicate high-intensity storm counts. Tables show the overall storm counts vs. average storm occurrence per year for that study period.

4 Conclusions

There have been warming SSTs in the Caribbean, the surrounding region, and the MDR over the past 39 years (1982-2020), with the most significant changes occurring over the past 25-27 years. These changes have implications for increased hurricane activity and intensity. SSTs are warmer at the end of the season, and October SSTs are warming over time (Figures 2&3). The AWP increases in magnitude and intensity during the LRS, most prominently in the latter half of the study period at 0.51km^2 per decade. This is important because of the oceanic-atmospheric interactions caused by changes to the AWP, where Atlantic TCs typically form and grow.

VWS results show that annual averages are stable. There are slight decreasing trends, but the subtle change does not seem to be a significant cause for changes in Atlantic TC activity. Analysis of long-term yearly and seasonal trends for SSTs and VWS suggests that warming SSTs is the primary cause of increased hurricane frequency and intensity. Hurricane intensity is highly correlated with sea-surface temperature, implying that future warming will lead to more frequent or intense storms, increasing the chances of TCs making landfall with increased destructive potential.

While August and September are peak hurricane season months, increasing frequency and intensity in October suggest we may need to consider October as a part of the peak hurricane season. Despite recently reported higher shears, the warmer SSTs could be a factor in the increasing number of October. Additionally, with the expansion of the AWP, SST warming trends in the Caribbean, the surrounding region, and the MDR and increasingly frequent and intense storms in the area, we may need to consider expanding the definition of the MDR.

Future research is needed and will continue to analyze the impact of additional potential variables that influence TC activity, specifically ocean heat content, sea-level height, mixed-layer depth, and connections to AMO.

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