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Original Article

The relationship of the sea surface temperature and climate variability modes with the North Atlantic tropical cyclones activity

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Relación de la temperatura superficial del mar y los modos de variabilidad climática con la actividad ciclónica del Atlántico Norte.

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ABSTRACT: In this study, a climatology analysis of the cyclonic activity in the North Atlantic (NATL) basin was performed to improve our understanding of how sea surface temperature (SST) and climate variability modes modulate tropical cyclones (TCs) activity. The information on the TCs was extracted from the International Best Track Archive for Climate Stewardship database, while the SST was obtained from the Centennial Time Scale dataset. The SST analysis reveals a warming trend of approximately 0.23 °C/decade for the NATL basin during the TC season between 1980 and 2019, while the TC activity shows an increase of ~1.4 TC/decade in the number of TCs that reach the tropical storm category. Nevertheless, the observed increase in the frequency of hurricanes is not significant. The increasing frequency of TCs after 2000 concerning the 1980-1999 period was probably caused by increasing favourable conditions for cyclonic development, such as positive SST anomalies. Moreover, the eastern regions of the NATL basin exhibit an increase in storm track density, which explains the observed decrease in track density near the Lesser Antilles Arc. In addition, the Atlantic meridional mode, the Atlantic multidecadal oscillation, and El Niño-Southern Oscillation have a significant influence on the TCs activity; however, they cannot fully explain the tendency to increase the TCs frequency in the last decades.

Keywords: tropical cyclones activity, climate variability modes, sea surface temperature.

RESUMEN: En este estudio se realizó un análisis climatológico de la actividad ciclónica en la cuenca del Atlántico Norte (NATL) con el objetivo de mejorar nuestra comprensión de cómo la actividad de los CTs es modulada por la temperatura superficial del mar (TSM) y la variabilidad climática,. La información sobre los CTs se extrajo de la base de datos IBTrACS, mientras que la TSM se obtuvo la base de datos Centennial Time Scale. El análisis de la TSM revela una tendencia al calentamiento (~0.23 °C/década) del NATL tropical durante la temporada ciclónica entre 1980 y 2019, mientras que la actividad ciclónica muestra un aumento de 1.4 CTs/década en la frecuencia de tormentas tropicales; sin embargo, el incremento observado en la frecuencia de los huracanes no es significativo. La creciente frecuencia de CTs después de 2000 con respecto al período 1980-1999 puede ser el resultado del aumento de las condiciones favorables para el desarrollo ciclónico, como las anomalías positivas de la TSM. Además, las regiones orientales de la cuenca NATL exhiben un aumento en la densidad de la trayectoria de las tormentas, lo que explica la disminución en la densidad de la trayectoria cerca del Arco de las Antillas Menores. Finalmente, el modo meridional del Atlántico, la oscilación multidecadal del Atlántico y El Niño-Oscilación Sur tienen una influencia significativa en la actividad de los CTs; sin embargo, no pueden explicar completamente la tendencia al aumento de la frecuencia de CTs observada en las últimas décadas.

Palabras claves: actividad de los ciclones tropicales, modos de variabilidad climática, temperatura superficial del mar.

1. INTRODUCTION

Tropical cyclones (TCs) are one of the most destructive atmospheric phenomena in the tropical regions. Recent studies have reviewed how the compound effects of changes in climate, population growth in coastal areas, and socioeconomic development increase vulnerability to the devastating effects of TCs (Noy, 2016; Ye et al. 2020).

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It is also well known that SST plays an important role in TCs genesis and intensification (Shen et al., 2000). The theoretical upper limit for TC intensity is given by the Potential Intensity theory, which depends on the sea surface temperature (SST), the Sea-Level Pressure and the vertical profiles of humidity and temperature (Bister and Emanuel, 2002; Emanuel, 2007; Vecchi and Soden, 2007). Therefore, more intenses TC are expected in a warmer cliamte (Fraza and Elsner, 2015), however, SST in its own may not always be sufficient to fully determine TC intensification (Arora and Dash, 2016). Lim et al. (2018) pointed out that the SST anomaly contributed by the long-term linear trend is positive throughout the Atlantic basin. From the Clausius-Clapeyron relationship, warmer air has a greater capacity to retain water vapour. Held and Soden (2006) suggest that for the mean temperature of the lower levels of the atmosphere, the saturated specific humidity increases approximately 7% for each degree Celsius increase in SST. However, some climatic studies (e.g. Liu et al., 2019; Jiang et al., 2008) have found a significant increase in TCs rainfall rates that exceed the increase in environmental water vapour estimated with the Clausius-Clapeyron relationship. Furthermore, intense TCs tend to produce more rainfall than weak TCs. Thus, the increase in the intensity of the TC can explain the increase in TCs rainfall rates in a warmer climate, in agreement with Liu et al. (2019). In addition, the results of Bhatia et al. (2019) suggest an increase in the intensification rates of TCs in the NATL basin, with positive anthropogenic forcing.

The prediction of the future activity of TCs is a challenge due to the complex interactions between the climatological factors that influence their evolution. TC activity is influenced by natural modes of climate variability. For example, the positive phase of the El Niño-Southern Oscillation (ENSO) is associated with a significant enhancement of vertical wind shear over large parts of the main development region (MDR), especially over and around the Caribbean Sea (Aiyyer and Thorncroft, 2006), which contribute to unfavourable conditions for TC genesis, while an opposite pattern is observed during the negative phase (Deser et al., 2010). The impact of ENSO on TC activity is mostly through the modulation of changes in vertical wind shear (Gray, 1984), humidity, vorticity in the lower levels of the atmosphere, the strength and position of subtropical highs and upper-ocean heat content and structure (Lin et al., 2020). As well as the ENSO, other factors influence the NATL TC activity, such as the Atlantic meridional mode (AMM) (Kossin et al., 2010; Vimont and Kossin, 2007); the Madden-Julian oscillation (MJO) (Klotzbach, 2010); and the Atlantic multidecadal oscillation (AMO) (Goldenberg et al., 2001; Klotzbach and Gray, 2008).

The Atlantic Warm Pool (AWP) and the tropical NATL SST (TNA) modify the hurricane activity (Keith and Xie, 2009). Higher SST values in the tropical NATL lead to a lower MSLP, which reduces vertical wind shear and moistens the air in the middle troposphere (Knaff, 1998). These atmospheric conditions, together with other factors (Gray, 1968; Montgomery, 2016), are necessary for the TCs genesis. The North Atlantic Oscillation (NAO) and the intensity of the North Atlantic subtropical high pressure system (NASH) can also influence the activity in NATL (Keith and Xie, 2009; Knaff, 1998). The negative NAO phase leads to an increased in landfalling frequency on the east and southeast coasts of the United States, while the positive phase leads to a more east-west dipole in the TC track (Elsner, 2003; Xie et al., 2005).

In this study, it is analyze the NATL TC activity using historical records with the goal of improving the understanding of how the TC activity is modulate by de SST and the climate variability modes in the context of global warming.

2. MATERIALS AND METHODS

2.1 Dataset

The tropical cyclone records were extracted from the International Best Track Archive for Climate Stewardship (IBTrACS; Knapp et al., 2010), which is freely available at https://www.ncdc.noaa.gov/ibtracs/index.php?name=climatology. The IBTrACS is officially recognized by the WMO Tropical Cyclone Programme as an official TC data resource and is under the auspices of the World Data Center for Meteorology located at NOAA's National Centers for Environmental Information. It widely discuss by several authors (e.g. Bathia et al., 2019; Kossin et al., 2013; Vecchi and Knutson, 2008; Chang and Guo, 2007) that before the era of air reconnaissance flights and meteorological satellites, the detection of TCs depended on fortuitous encounters with ships or their impact on populated areas. This means that the reliability of the long-term hurricane record is dependent on who was measuring them, and how, at any given time. Therefore, the quality of the satellite images made possible to determine the location and classification of the TCs more reliable after the 1970s. In agreement with Bathia et al., 2019, in this study were used the tropical cyclone records from 1980 to 2019. Also, two different statistical tests - The Power of Pruned Exact Linear Time (PELT) (Killick et al., 2012) and Binary Segmentation (BINSEG) (Scott and Knott, 1974)- were applied to determine the change points in this time series and corroborate our selection.

From the Centennial Time Scale (COBE SST2) dataset (Hirahara et al., 2014) of the National Oceanic and Atmospheric Administration (NOAA), freely available at https://psl.noaa.gov/data/gridded/data.cobe2.html, was obtained the monthly mean SST data.

The COBE SST is a monthly mean of global fields created during June, 2011 at NOAA's Physical Sciences Division (PSD) of the Earth System Research Laboratory (ESRL) using the gridded data from the Japanese Reanalysis Project (JRA). Moreover, all the climate variability modes used here were extracted from the NOAA Physical Sciences Laboratory at https://psl.noaa.gov/data/climateindices/list/. The NAO consists of a north-south dipole of anomalies, with a centre located over Greenland and the other centre of opposite sign that covers the central latitudes of the NATL between 35°N and 40°N. The NAO index is defined as the normalized pressure difference between the Azores and Iceland (Hurrell, 1995; Jones et al., 1997). The AMO is a climate variability mode that also occurs in the NATL; its index is calculated as the area weighted average SST over the North Atlantic, basically between 0° to 70°N (Enfield et al., 2001). On the other hand, the AMM mode describes the meridional variability in the tropical Atlantic Ocean applying Maximum Covariance Analysis (MCA) to the SST and the zonal and meridional components of the 10m wind field (Chiang and Vimont, 2004). The Caribbean index (CAR) is the SST anomalies averaged over the Caribbean Sea, and the NTA index is the SST anomalies averaged over 60°-20°W and 6°-18°N, and 20°-10°W, 6°-10°N. Both indices were calculated relative to the 1981-2010 climatology and smoothed by three months running mean procedure (Penland and Matrosova, 1998). The quasi-biennial oscillation (QBO) is a quasi-periodic equatorial zonal wind oscillation between the east and west winds in the tropical stratosphere with a mean period of 28 to 29 months. It is calculated from the zonal average of the 30mb zonal wind at the equator (Andrews et al., 1987; Naujokat, 1986). The Tropical Northern Atlantic (TNA) and Tropical Southern Atlantic (TSA) indices are the anomalies of the average of the monthly SST respect to climatology 1971-2000 from 5.5°-23.5°N and 15°-57.5°W, and from 0°-20°S and 10°E-30°W, receptively (Enfield, 1999). The Bivariate ENSO index (Smith et al., 2000) is used to represent the ENSO conditions combining the traditional Niño 3.4 SST and the Southern Oscillation Index (SOI).

2.2 Methodology

First, from the historical record was separated the frequency of TC activity by each TC intensity (from tropical depression to category 5 hurricane). To estimate where TCs were frequently generated, where intensity changes occur including hurricane intensity changes according to the Saffir-Simpson scale (Saffir,1973; Simpson, 1974), where maximum intensity was reached by each TC, and their track paths, the nonparametric kernel density estimation (KDE) was applied (Loader, 1999). An important limitation of the KDE application is that it allows the genesis or TCs intensification over land. In this article, for the statistical analyses, the points over land were eliminated according to the grid point of SST. Additionally, the statistical t-test was applied to determine the significance of the Pearson correlations at the 95% significance level.

3. RESULTS AND DISCUSSION

3.1 NATL tropical cyclones climatology

The application of the PELT (Killick et al., 2012) and BINSEG (Scott and Knott, 1974) methods identified significant change points in the frequency of TC genesis in the historical records in the NATL basin in 1930, 1965, 1980, and 2000 (Figure 1). The change points observed before 1980 are not relevant for this study. The 1980 change point is a consequence of changes in data collection techniques, specifically the improvements in observation methods based on satellite products and the change point detected in 2000 (Figure 2) divides the study period in two 20-year subperiods, 1980-1999 (TCsP1) and 2000-2019 (TCsP2). The whole period from 1980 to 2019 shows a slightly increasing trend in the frequency of TCs; however, both TCsP1 and TCsP2 show a decreasing trend. All trends are not statistically significant, however. The TCsP1 and TCsP2 periods exhibit an average of 14 and 17 TCs genesis events, respectively. The 1981 season was the most active of the TCsP1 period with 22 TCs, followed by less TC activity in 1982 (eight TCs) and 1983 (six TCs). Similarly, in the TCsP2 period, the 2005 season was the most active with 31 TCs followed by a less-active season in 2006 with 10 TCs.

The monthly variation in the number of genesis events and TCs that reached each category shows a maximum in September, for all cases, followed by a secondary maximum in August (Figure 2). Between both months, the 57.6% of TCs genesis is observed. This can be directly linked to SST, as both August and September are the warmest months of the hurricane season (Wang et al., 2017). Outside the NATL TC season, one tropical storm was formed in January, three in April, 12 in May, and six in December. Furthermore, the most active season was 2005 (not include here the 2020 TC season), with 31 TCs (including tropical depressions). During this season, the highest historical number of tropical storms (27), category 1 hurricanes (15), category 3 hurricanes (7), and category 5 hurricanes (4) were formed; the highest historical number of category 2 hurricanes (9) was recorded during the 2010 season. Additionally, the highest number of category 4 hurricanes with 5 storms occurred during both the 2005 and 2010 seasons. The mean lifetime of TCs in the NATL basin was 6.7 days and the mean maximum intensity was 89.3 km/h.

Figure 3 shows an increasing trend in the number of TCs in the NATL basin of approximately 0.8 TCs/

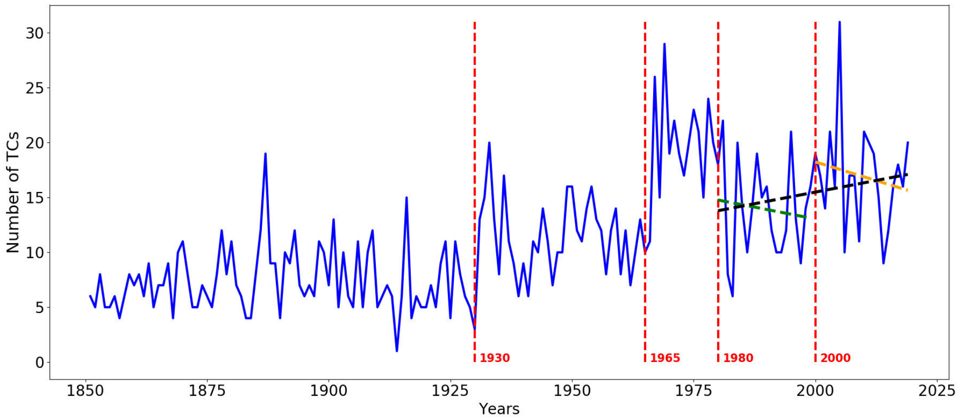

Figure 1. Number of TCs formed in the NATL basin from 1851 to 2019 using the HURDAT2 database (solid blue line). The red vertical lines represent the change points detected in the series applying the PELT and BINSEG methods. The dashed green, orange, and black lines represent the linear trend for the subperiods of 1980-1999, 2000-2019, and 1980-2019, respectively. No statistically significant trends were observed.

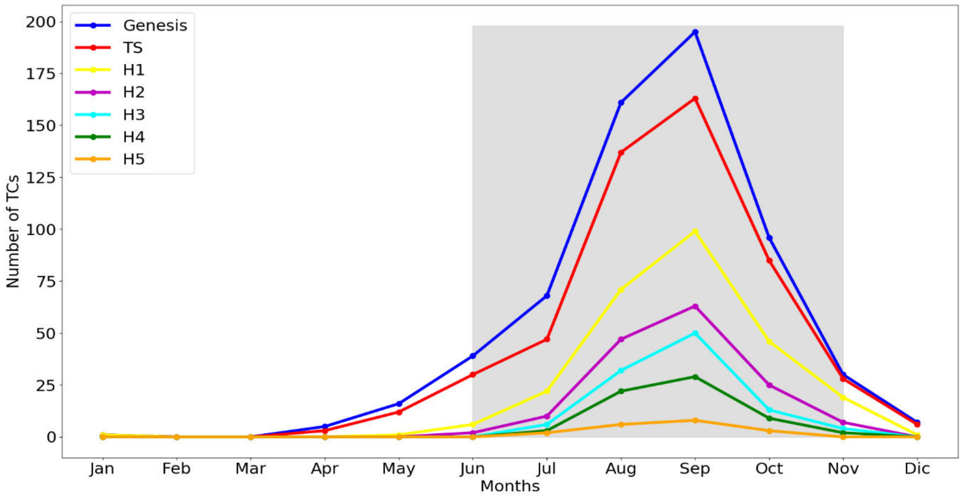

Figure 2. Monthly variation in the number of tropical cyclones (TCs) formed in the NATL basin from 1980 to 2019. The shaded grey area represents the NATL TC season from June to November. Note that the TCs that reached the hurricane category are included in the TS counts, likewise, in each hurricane category counts are included TCs that reached the next intensity category.

decade. However, this trend was only statistically significant for those TCs that developed into tropical storms (TS) on the Saffir-Simpson wind scale ($p < 0.05$) with an increase of approximately 1.4 TS/decade from 1980 to 2019 (note that each TC category is referred as the maximum category reached by a TC in its lifetime). This is further evidence of the continued increase in cyclonic activity in the NATL basin during this period. A negligible trend was observed for hurricane category. These results support the findings of Murakami et al. (2014), who state that TC activity in the NATL basin has shown a marked positive anomaly in the number of TC genesis events, their mean lifespan, and their mean maximum intensity.

Figure 4a shows the seasonal distribution of TC genesis using the classical kernel density estimation. The highest density is observed in the tropical NATL between the Lesser Antilles Arc and the West Africa coast, in agreement with DeMaria et al. (2001) and Neumann (1993). In this region, the necessary conditions for barotropic-baroclinic instability are fulfilled, which acts as a source of energy for tropical waves (Molinari et al., 1997). Another region with higher density values is the area between the Western Caribbean Sea, the Yucatan Peninsula, and the Bay of Campeche, associated with the reversal potential vorticity gradient (Molinari et al., 1997).

The trajectory density (Figure 4b) shows the highest values in the Gulf of Mexico and northeast of the Florida Peninsula, which are associated with the tracks of the systems formed within the region. In comparison, systems formed near the West African coast show more dispersed trajectories. In this area, TCs that move towards the Caribbean Sea are as frequent as those that move directly towards the central NATL. Similar to the behaviour observed for the genesis density, similar areas of the tropical North Atlantic and the Gulf of Mexico show the highest density values where TCs reach tropical storm status (Figure 4c). Furthermore, the regions where TCs reach hurricane status have the

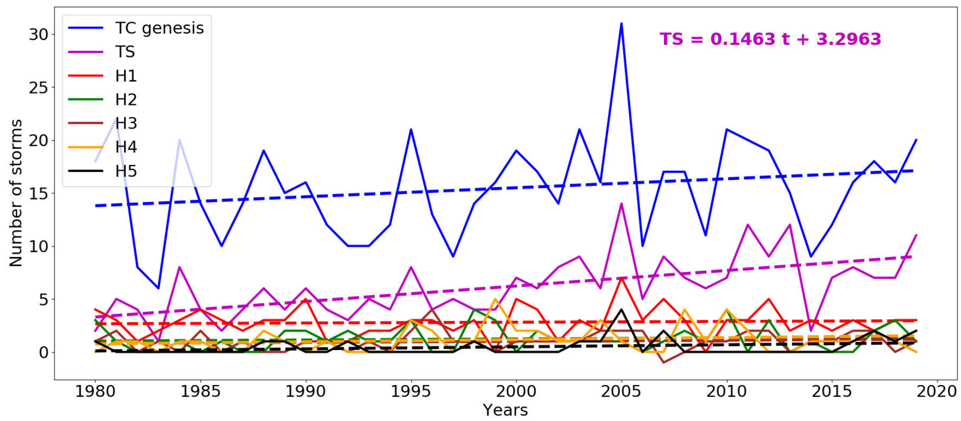

Figure 3. Temporal evolution and linear trends (dashed lines) in the number of TCs genesis events, tropical storms (TS), and hurricanes (H_N, N = 1, 2, 3, 4, 5) on the Saffir-Simpson wind scale from 1980 to 2019 in the NATL basin. Statistically significant trends (95% significance level) were observed for TS. In the linear equation, *t* represents the number of years since 1980.

highest density values in the Caribbean Sea, the Gulf of Mexico, the tropical NATL region at the east of the Lesser Antilles Arc, and the northeast of the Bahamas archipelago (Figures 4 d-f). The tropical NATL (below 20° latitude) and the Gulf of Mexico show the highest density values, where TCs achieve maximum intensity (Figure 4g).

Furthermore, Figure 5 shows a slight poleward migration of the mean latitude where TCs reached maximum intensity, with a not statistically significant trend of 0.17° latitude per decade This confirms the findings of Kossin et al. (2014), who found that the HURDAT2 and ADT-HURSAT (Kossin et al., 2013) datasets both show no clear trend in the NATL basin for the period 1982-2009. In addition, an increase in storm track density is observed in the eastern regions of the NATL basin, which explains the decrease in track density near the Lesser Antilles Arc as shown in Figure 6. This behaviour can be attributed to changes in the steering flow of the tracks, associated with the variability of the NASH ridge.

3.2 Sea surface temperature and TC activity

The annual average SST (from June to November) in the NATL basin from 1980 to 2019 are shown in Figure 7. This confirms a significant warming trend of approximately 0.23 °C/decade ($p < 0.05$), which is similar to the trend reported by Taboada and Anadón [66] for the period 1982-2010 (0.25 °C/decade). The abrupt increase in ocean temperature since the 1970s has also been attributed to the effects of anthropogenic and natural forcing. It is notable that after (before) 2000 predominate positive (negative) SST anomalies during the hurricane season.

Figure 8 shows mean SST (computed between 5°-50°N y 10°-100°W) for the TC season in the NATL basin. No visual differences in the SST pattern can be seen; however, the 27 °C isotherm is shifted to the east in the last decade (not shown) relative to 1980-1999. The mean SST values from 1980 to 2019 show that the Gulf of Mexico was the warmest region with values higher than 29 °C from July to September; the warmest region in October and November was south of this, in the Caribbean Sea. In general, SST is higher than 27 °C in the Main Development Region of TCs in the NATL basin (MDR; 10°-25°N, 80°-20°W, Caron et al., 2015), which favours their genesis and development. Generally, high SST values favour evaporation over the sea surface, which leads to an intense upward moisture transport due to persistent convection, phase changes, and the consequent release of latent heat, all of which are necessary for the genesis and intensification of TCs. Positive and negative SST anomalies are observed after and before 2000, respectively, for all months of the TC season. This supports the findings of Dare and McBride (2011) who pointed out that SST during TC genesis were warmer after 1995.

The spatial analysis of monthly SST also indicates warming in the NATL over the last 40 years (Figure 9). This is reflected in alterations in oceanic circulation, as evidenced by modifications in energy and mass fluxes (Hakkinen et al., 2004; Hakkinen et al., 2004; Toggweiler, 2008) that create more favourable conditions for the formation and intensification of TCs. Cione and Uhlhorn (2003) showed that changes in SST are directly related to changes in TC intensity as the ocean provides the necessary energy to establish and maintain deep convection. Therefore, more favourable conditions are expected for the intensification of TCs in areas with higher SSTs. Moreover, Xu et al. (2016) observed a nonlinear increasing trend in the maximum potential intensification rate of TCs with increasing SSTs. They also found that the TC intensification occurs most frequently in regions where SSTs are higher than 27 °C.

Another important result shown in Figure 9 is the significant increasing SST trend above 0.3 °C/decade north of 50°N (not shown), which can lead to ice melt in the Arctic and the consequent changes in

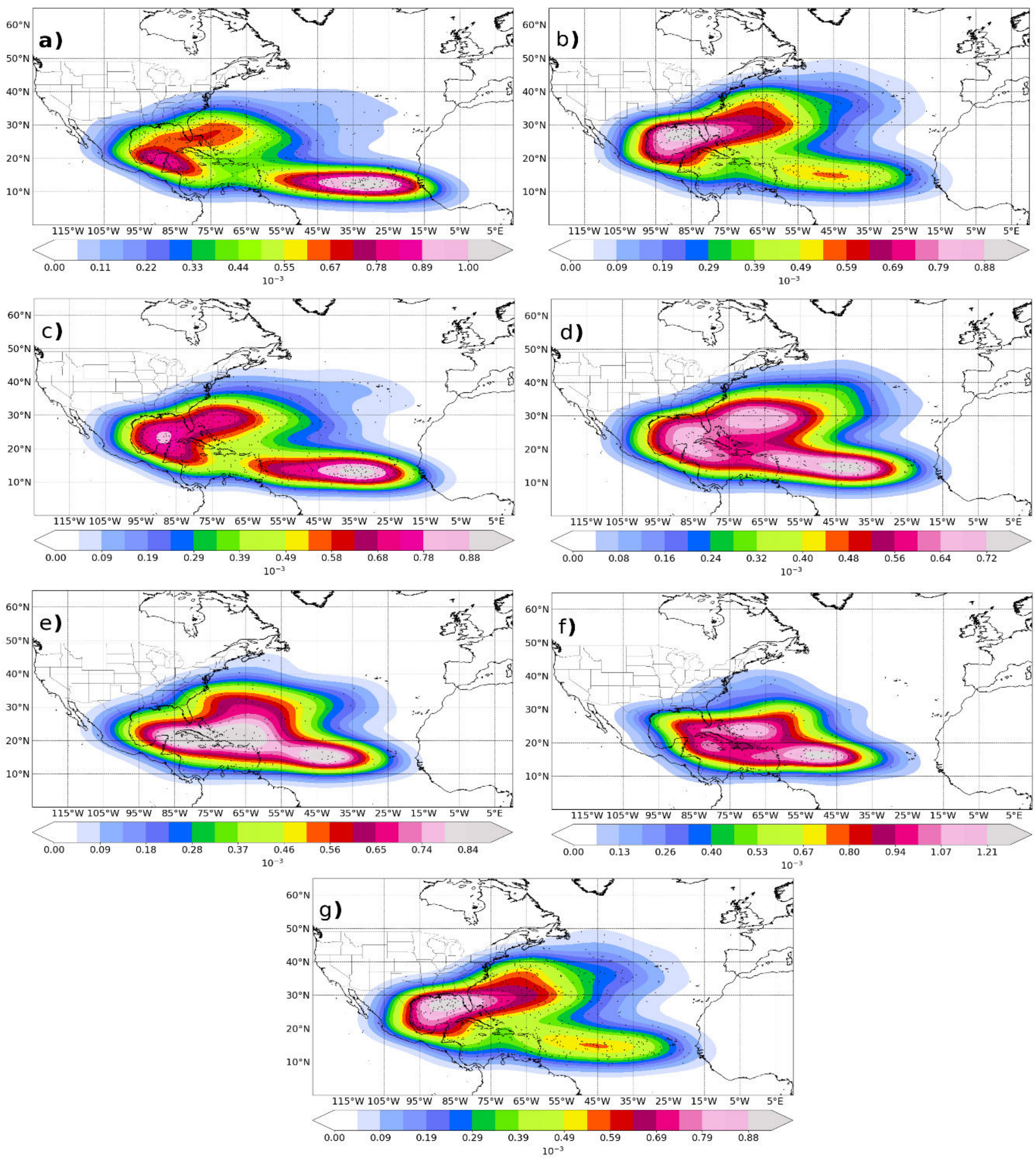

Figure 4. Kernel density estimation for TCs (a) genesis, (b) trajectory, (c) locations of tropical storm status, (d) category 1 hurricanes, (e) category 2 hurricanes, (f) major hurricanes (category 3+), and (g) TC maximum intensity.

the oceanic thermohaline circulation. This has direct implications for SST anomalies (Mendelsohn et al., 2012) and implies a consequent impact on TC activity over the NATL basin, although more in-depth studies are needed to explore this further.

Figure 10 shows monthly mean SST anomalies, the number of TCs, and the TC count for different hurricane categories. A clear transition from negative to positive anomalies is observed; negative values occur before 1995 and positive anomalies occur after 2000. Similar patterns can be seen in the number and category of TCs, with positive anomalies in 1996, 2005, 2010, and 2017.

The increase in TC activity in recent years may be directly linked to the predominant positive SST anomalies after 2000. These results seem to be related to the impact of a warming climate; however, simulations with high-resolution global models tend to indicate a decrease in the frequency of TCs under a warmer climate (Knutson et al., 2015; Park and Latif, 2005), associated with a saturation deficit due to higher SSTs and broadly constant relative humidity (Wehner et al., 2015). However, these arguments have not been adequately developed and tested (Held and Soden, 2006), and projections of a decrease in the

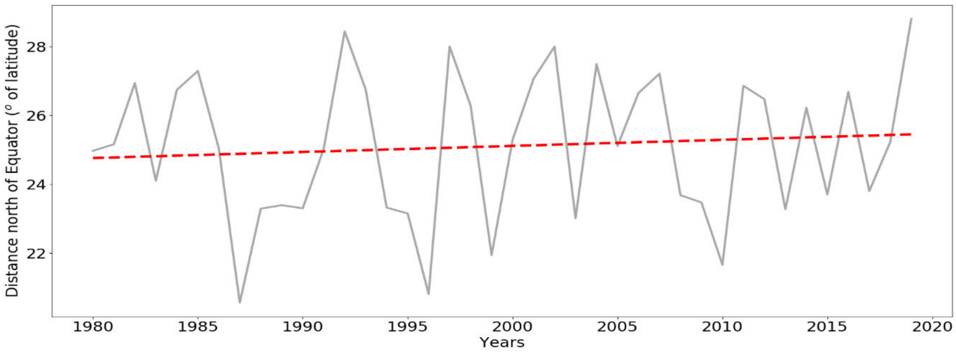

Figure 5. Temporal evolution in the latitude of lifetime-maximum-intensity TCs from 1980 to 2019. The dashed red line shows the trend of the series, which is not statistically significant.

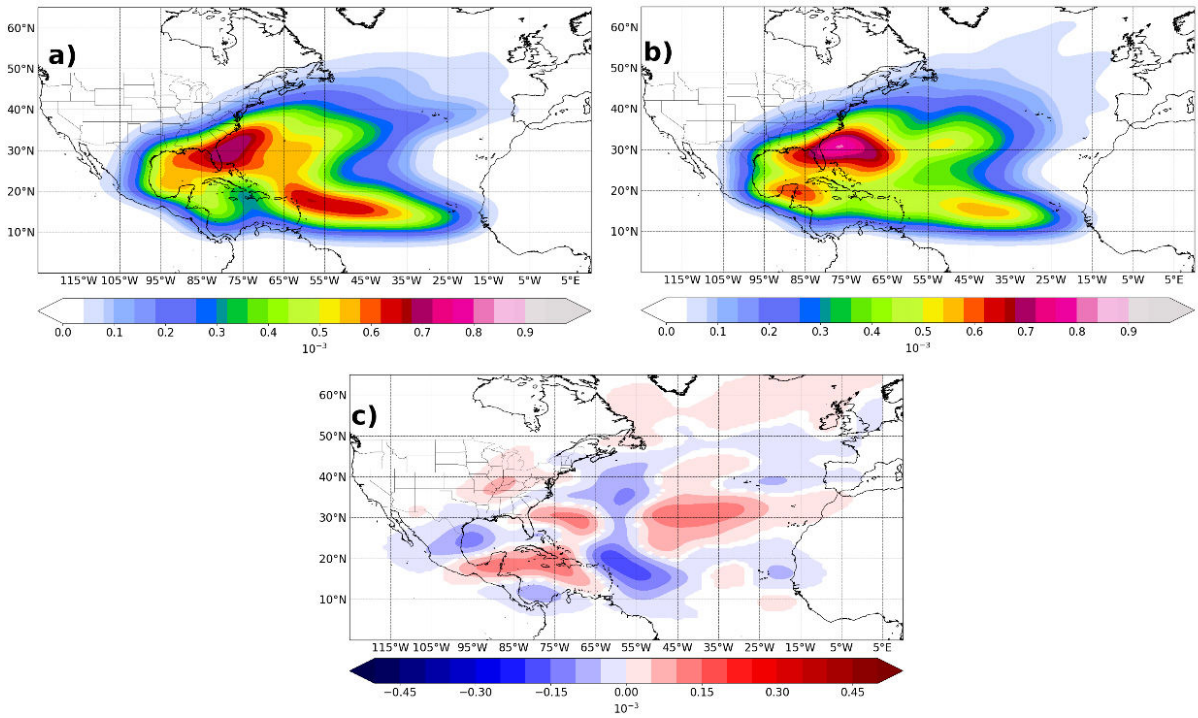

Figure 6. Kernel density estimation (KDE) for the trajectory during (a) 1980-1999 and (b) 2000-2019, and (c) differences in KDE for trajectories between 2000-2019 and 1980-1999.

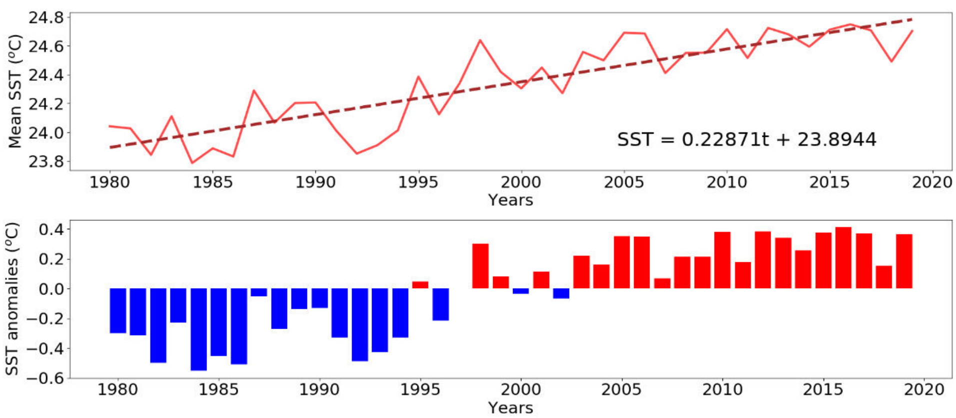

Figure 7. Mean SST time-series (solid red line) and linear statistically significant trend in annual mean SST ($p < 0.05$). In the linear equation, t represents the number of years since 1980 (top) and annually SST anomalies (bottom).

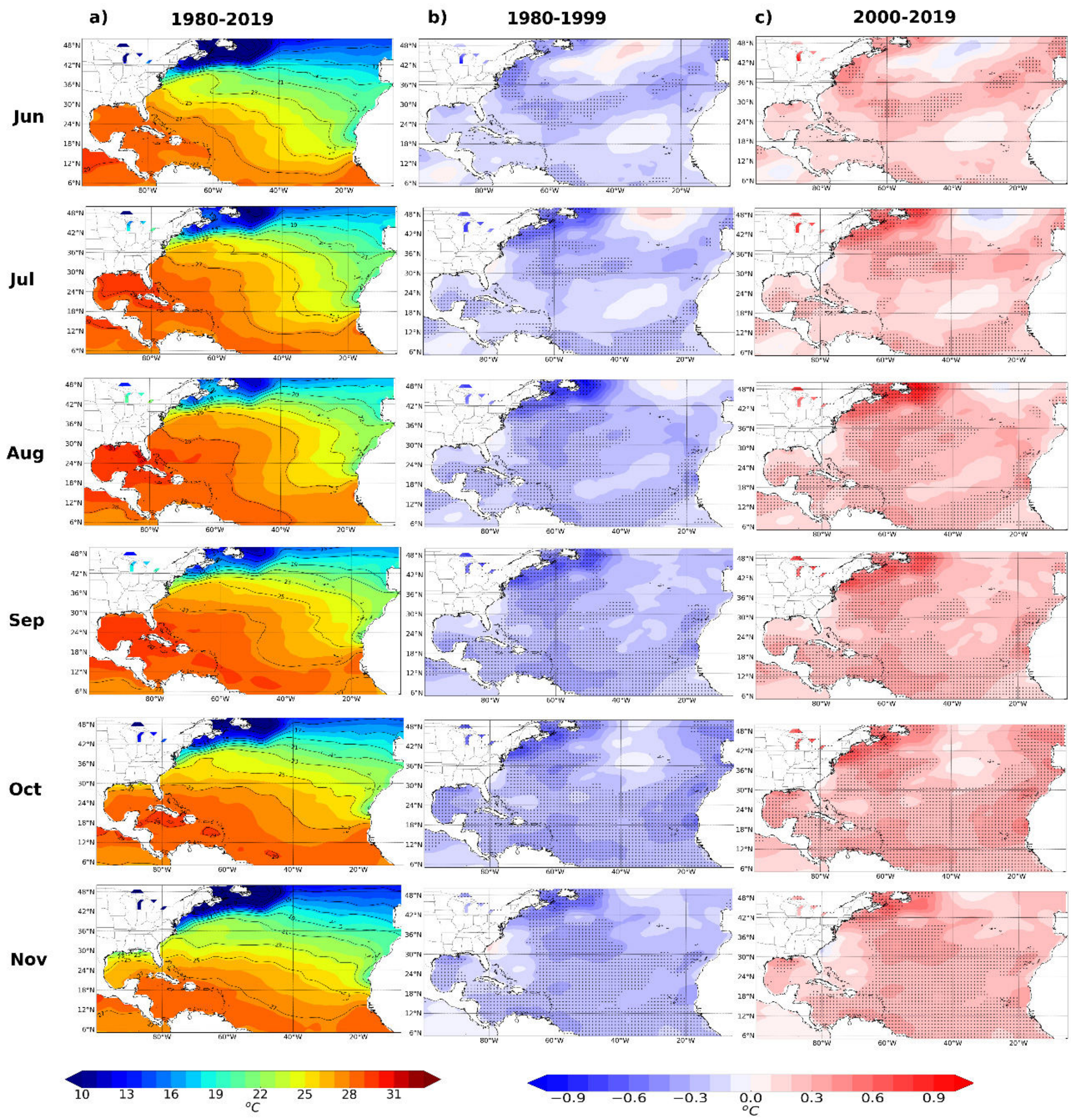

Figure 8. (a) Monthly mean SSTs from June to November (top to bottom) during the period 1980-2019 and SST anomalies for (b) 1980-1999 and (c) 2000-2019 periods relative to 1980-2019. Dots represent statistically significant anomalies ($p < 0.05$).

frequency of TCs with warming are considerably more uncertain than projected increases (Emanuel, 2013).

3.3. Relationship between the TC activity and the climate variability modes

TC activity is influenced by several large-scale modes of climatic variability that strongly modulate seasonal patterns over different timescales (Neumann, 1993). During the period with strong positive TC genesis anomalies (i.e., the 2005 season), many of the climate modes were in a positive phase (i.e., AMO, TNA, AMM, TSA, CAR, and NTA) combined with the negative phase of NAO and a neutral ENSO phase (Figure 11). The possible impact of mode variability on TC activity in the NATL occurs during the 2010 season, when the NAO and ENSO were in their negative phase and all other indices were in their positive phase; this was associated with the formation of 21 TCs. Notably, 2005 and 2010 were also dominated by positive SST anomalies (Figure 11).

In comparison, in 1983, when only six TCs occurred, most climate modes were in their negative phase, and the ENSO, NAO, and AMM were in the following modes: the ENSO was in a weak positive in July-August and a negative phase in September-November; the AMM was in a positive phase in June-July and November, and a negative phase in August-October; and the NAO was in a positive phase in June-August and October, and a negative phase in September and

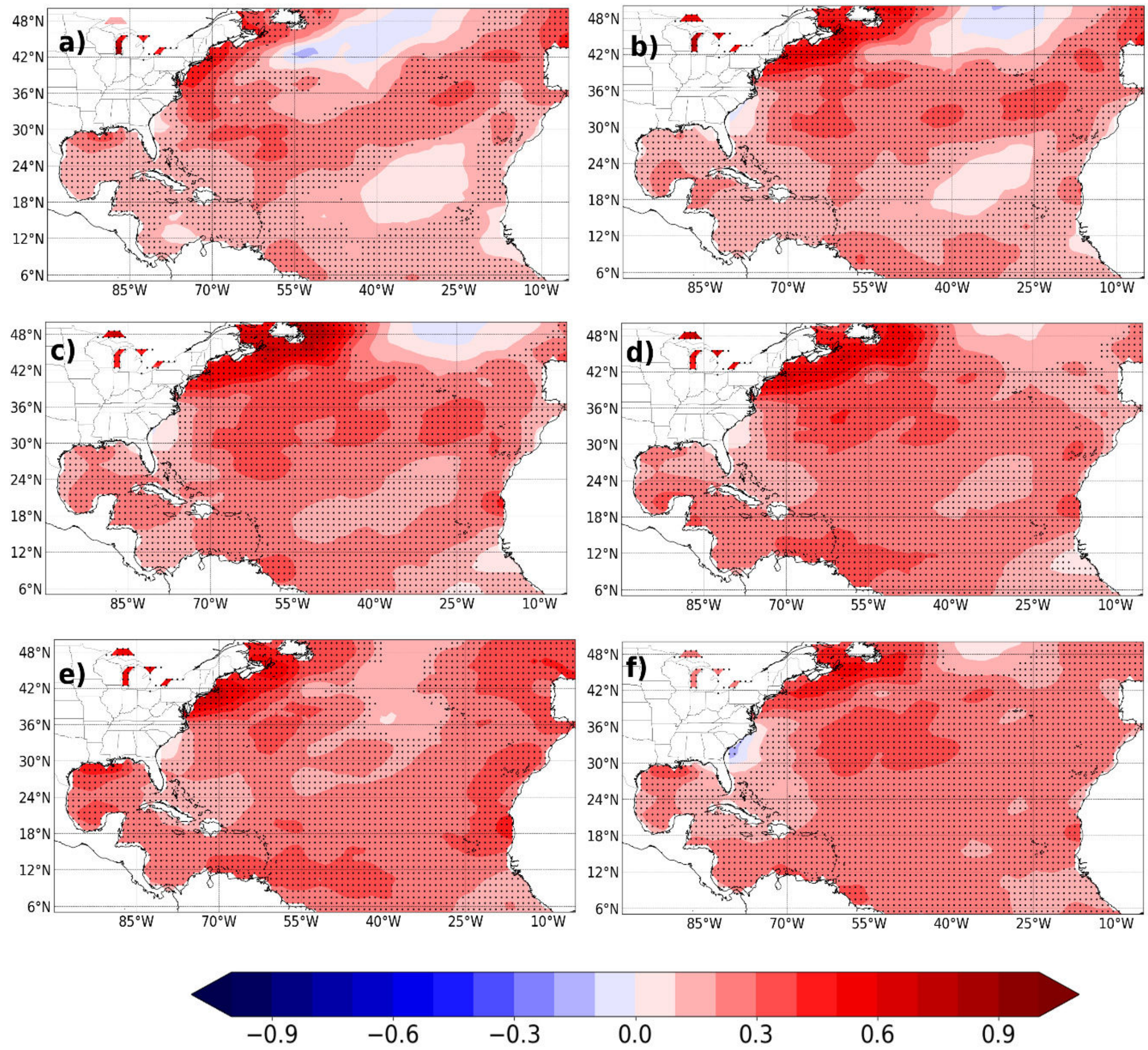

Figure 9. Spatial linear trend of SST (°C/decade) in the North Atlantic basin in (a) June, (b) July, (c) August, (d) September, (e) October, and (f) November from 1980 to 2019. Dots represent statistically significant trends ($p < 0.05$).

November. In 2013, all indices were positive with the exception of a weakly negative ENSO. A positive NAO induces positive anomalies in the MSLP leading to moderate vertical wind shear over the tropical NATL. These results suggest that the NAO and the AMM might modify and even oppose known ENSO impacts, which is in agreement with Lim et al. (2016).

Pearson's correlations between the different TC activity measures and the NAO were not significant (Table I). The strongest positive correlation coefficients were obtained for TC genesis and the AMO, AMM, TNA, and a negative correlation was obtained for the ENSO (r = 0.19); the negative phases of the QBO, NAO, and TSA are weakly correlated with TC genesis (r ranging from 0.13 to 0.3; Table I); and the ENSO is also inversely correlated with category 5 (r = -0.11) and category 1 (r = -0.23) hurricanes.

It is known that TCs exhibit a quasi-linear response to the ENSO in the NATL basin (Krishnamurthy et al, 2016). The inhibition of TC activity during positive ENSO phases is attributed to increases in vertical wind shear and reductions in atmospheric humidity (Gray, 1984; Lin et al., 2020; Camargo et al., 2007) Furthermore, a positive ENSO induces tropospheric warming and disequilibrium with SST, creating unfavourable conditions for TC genesis (Tang and Neelin, 2004). An opposite pattern is observed during negative ENSO phases (Deser et al., 2010).

The weak correlation between TC activity in the entire NATL basin and the CAR index likely reflects the definition of this index, which is calculated solely using SST anomalies in the Caribbean Sea. Furthermore, the TSA index shows no direct relationship with cyclonic activity in the NATL, yet Pazos and Gimeno (2017) and Pérez-Alarcón et al. (2020) demonstrated that the South Atlantic is an important source of moisture for TC genesis near the coast of West Africa. This behaviour supports an indirect influence of South Atlantic SST on cyclonic activity in NATL due to its effect on evaporation over the sea surface, which injecting moisture into the atmosphere.

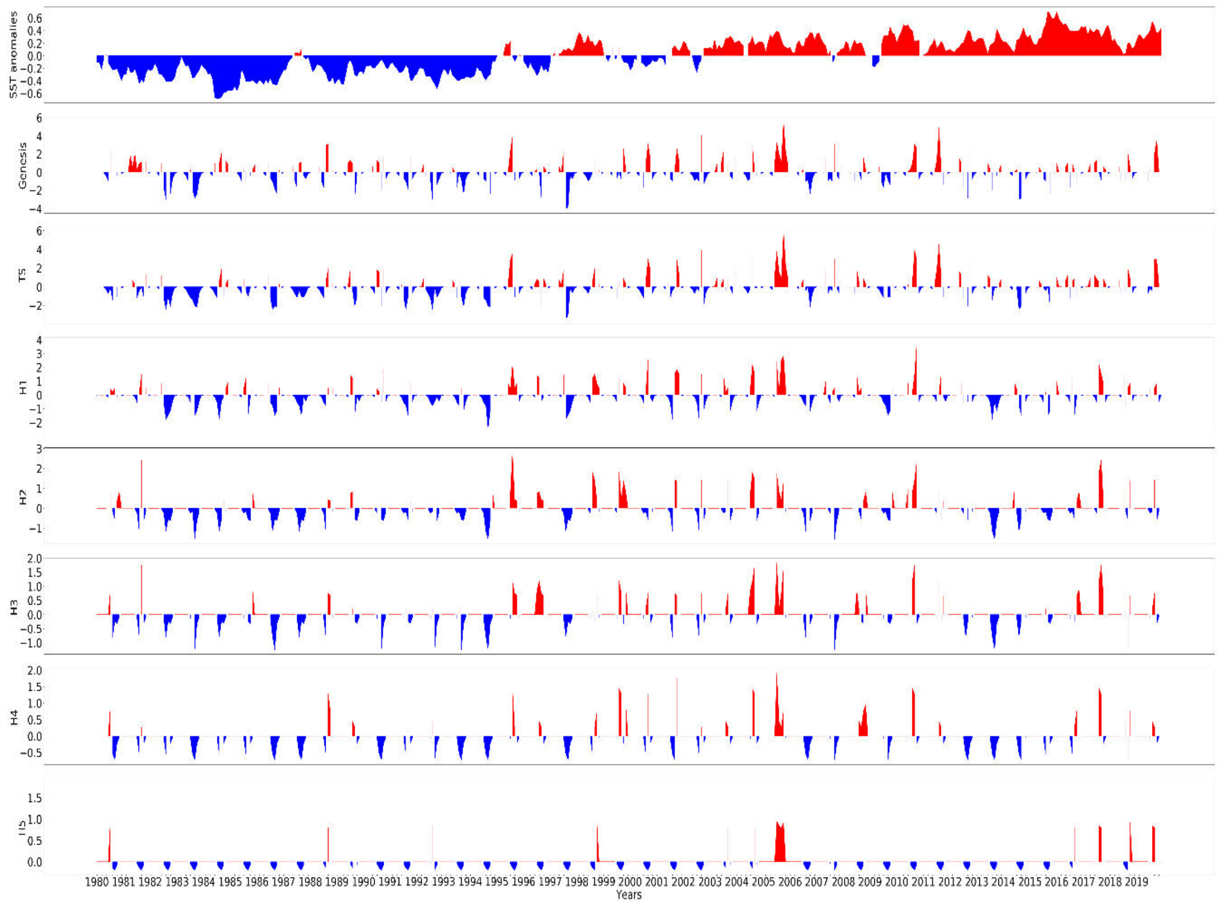

Figure 10. Monthly time-series of SST and TC count (genesis and TC intensity categories) anomalies from 1980 to 2019.

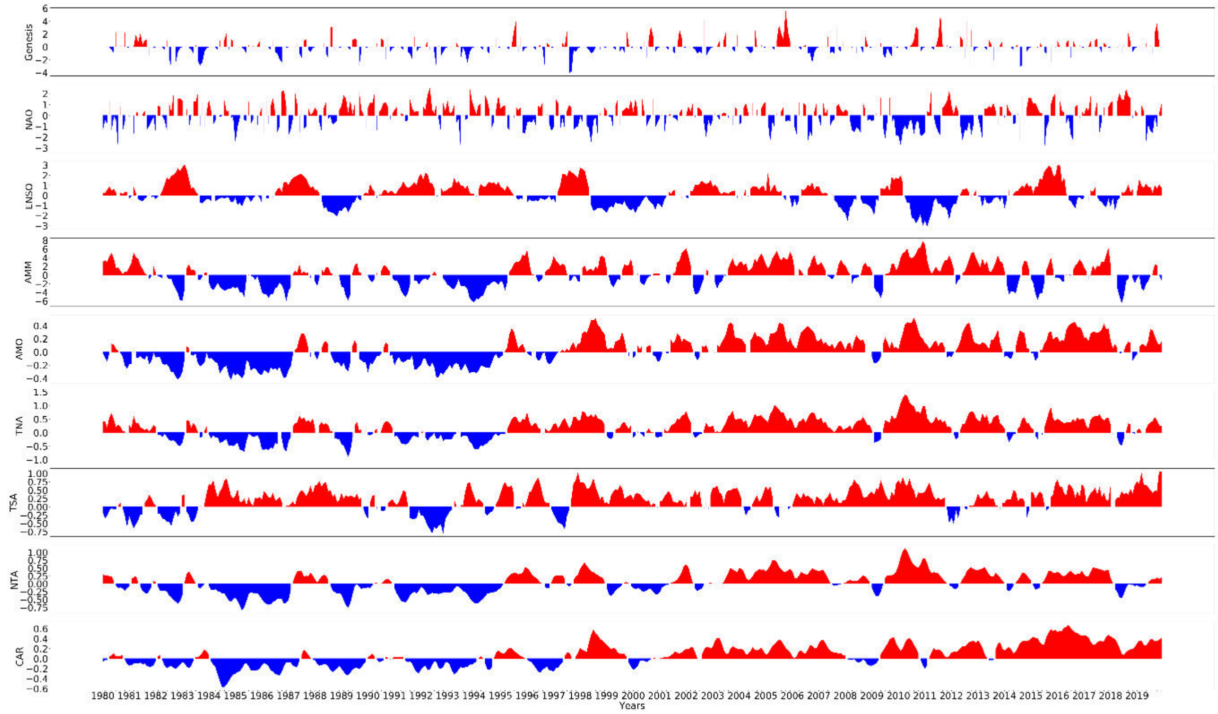

Figure 11. Monthly time-series of TC genesis anomalies and the NAO, ENSO, AMM, AMO, TNA, TSA, NTA, and CAR climatic indices from 1980 to 2019.

Table I. Pearson's correlation coefficients between tropical cyclone activity parameters and climatic variability modes. GEN: TC genesis, TS: tropical storm, HN (N = 1, 2, 3, 4, and 5): hurricanes with different categories on the Saffir-Simpson scale, LMI: mean TC maximum intensity, and MLT: mean TC lifetime. For the genesis, tropical storm, and hurricane categories, correlation was established between the number of TCs and the climatic variability modes. Statistically significant correlations are shown in bold text ($p < 0.05$)

	AMO	ENSO	AMM	QBO	NAO	TNA	CAR	NTA	TSA
GEN	**0.22**	**-0.19**	**0.2**	-0.05	-0.04	**0.2**	0.05	0.15	-0.008
TS	**0.3**	**-0.2**	**0.26**	-0.04	-0.03	**0.28**	**0.14**	**0.24**	0.025
H1	**0.26**	**-0.23**	**0.28**	-0.06	-0.04	**0.25**	0.11	**0.19**	0.007
H2	**0.27**	**-0.22**	**0.28**	-0.03	-0.06	**0.27**	0.14	**0.21**	0.04
H3	**0.26**	**-0.2**	**0.27**	-0.02	-0.02	**0.25**	0.13	**0.21**	0.02
H4	**0.22**	**-0.24**	**0.24**	-0.02	-0.01	**0.21**	0.1	**0.17**	0.03
H5	**0.16**	-0.11	**0.16**	-0.13	0.03	**0.13**	**0.16**	0.13	-0.02
LMI	**0.17**	**-0.23**	**0.22**	-0.04	**0.1**	**0.16**	0.1	0.13	0.03
MLT	**0.23**	**-0.18**	**0.2**	-0.07	0.08	**0.18**	0.12	**0.16**	0.07

4. CONCLUSIONS

This research briefly analyzed the relationship between tropical cyclones activity and SST in the North Atlantic basin from 1980 to 2019. This results confirm previous research findings on the increasing of TC activity in the last two decades. The spatial analysis of the monthly SST indicated a statistically significant warming (~ 0.23 °C/decade) during the last 40 years, which may be one of the most powerful reason for the significant increasing in the tropical storms frequency. Nevertheless, the increasing trend observed in hurricanes frequency is not statistically signifcant.

Moreover, it was found a slight poleward migration of the mean latitude where TCs reached maximum intensity, but not statistically significant. Furthermore, the eastern regions of the NATL basin exhibit an increase in storm track density, which explains the decrease in track density near the Lesser Antilles Arc. This behaviour can be attributed to the variability of the NASH, but further studies are required to improve the understanding about the influence of NASH on the spatial distribution of TC trajectories.

According to results obtained in this study, the NAO and the AMM can significantly modify-and may even oppose-the known impacts of the ENSO. This suggests that climatic variability modes cannot fully explain the increase in TC activity that has occurred between 1980 and 2019. This is not conclusive, however, as higher-quality TC records are only available after the beginning of the meteorological satellite era. Moreover, more in-depth studies are required to understand the complex relationship between the climate variability modes and tropical cyclones activity in the North Atlantic basin, as well as its evolution on a warmer climate.

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