UNIVERSIDADE DE LISBOA
FACULDADE DE CIÊNCIAS
DEPARTAMENTO DE ENGENHARIA GEOGRÁFICA, GEOFÍSICA E ENERGIA

Are Cyclones with Tropical Origin A Risk for Portugal?

Tiago Saraiva Marques Ferreira

Mestrado em Ciências Geofísicas
Especialização em Meteorologia e Oceanografia

Dissertação orientada por:
Doutor Alexandre Miguel Ramos
Doutor João Paulo Afonso Martins

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ABSTRACT

Tropical Cyclones are weather systems well-known for causing considerable damage to both human life and property. As global climate change continues to be an area of concern and significant scientific inquiry, there are many questions on how tropical cyclones frequencies and intensities may be affected by a warming climate. In the North Atlantic, most systems originate and remain near the Caribbean Sea, the Gulf of Mexico and even along the east coast of North America. Only a few actually reach the western and northwestern Europe. Recent research suggests that climate warming causes a poleward and eastward extension of the tropical cyclone genesis area, but it is still uncertain whether these changes, along with the increase of sea surface temperature, are large enough to allow tropical cyclones to reach Europe. Over the last two decades, some significant cases of cyclones with tropical characteristics have occurred in the northeast Atlantic which some impacted western Europe. The interest of the scientific community in these events is due to the idea that tropical cyclones could not in principle develop over these regions. However, an apparent recent increase in their occurrence, as well as in the number of subtropical systems and tropical transitions has brought this topic to discussion. These tropical cyclones that undergo a tropical transition form in environmental conditions distinct from the classical tropical cyclone environment.

This work analyzes the spatial and temporal variability of tropical cyclones in the Northern Atlantic basin, with particular emphasis on systems affecting its northeastern sector, from 1979 to 2019. Besides providing a climatology of these systems, relying on reanalysis and observational data, specific parameters that influence the genesis and development of tropical cyclones were analyzed in particular detail, namely: i) the Sea Surface Temperature (SST); ii) Vertical Wind Shear (VWS); iii) and the low- to mid- tropospheric Lapse Rate (Γ). The analysis is made comparing two time periods: i) June 1 to November 30 (the North Atlantic Hurricane Season); and ii) September 1 to November 30 (period in which the northeast Atlantic is more propitious to tropical cyclone activity).

At the decadal scale, our results show an evident increase in SSTs and a northward expansion of warm oceanic conditions, while seasonal averages of VWS and Γ alone do not point towards a clear increase of favorable conditions for TC development and maintenance at higher latitudes. However, and after analyzing the specific surface and environmental conditions around the center of five storms affecting the area of interest, a set of empirical thresholds for each variable is proposed in order to identify the combined regimes that favors the occurrence of these storms. The analysis of joint distributions of these variables revealed that there is a non-negligible increase in the frequency of these joint events, where the analyzed variables range within the proposed thresholds simultaneously, at daily scales. This analysis supports an increase in the frequency of episodes favoring the formation and maintenance of tropical systems, as well as the occurrence of hybrid/subtropical systems, particularly during the September-November timeframe, which we have shown to be the more favorable season for TC occurrence within the study area. It is important to note that this is a first approach towards the definition of potential thresholds for tropical cyclone formation and maintenance in the northeastern Atlantic. Despite being a preliminary attempt based on five case studies, the obtained results demonstrate its potential for operational use.

Keywords:

Tropical Cyclones; Sea Surface Temperature; Vertical Wind Shear; Lapse Rate;

RESUMO ALARGADO

As alterações climáticas e as suas implicações na superfície, na atmosfera e no oceano têm sido alvo de um número crescente de estudos que têm contribuído para a sua melhor compreensão, em particular nas alterações já mensuráveis no clima atual. Neste contexto, a comunidade científica tem vindo a concentrar-se cada vez mais no seu impacto sobre os ciclones que apresentam características tropicais, por serem classificados como sistemas meteorológicos com impactos devastadores e graves consequências a nível social e económico.

A atividade ciclónica de origem tropical na região do Atlântico Norte apresenta uma grande variabilidade climática, caracterizada por grandes flutuações interanuais (por exemplo em termos do número de ciclones, apenas 9 ciclones ocorreram em 2014 enquanto em 2020 foram registados mais de 30). A formação destas tempestades está geralmente concentrada numa área, definida entre os 10 ºN e 20 ºN desde a costa oeste de Africa até à América do Norte, que é denominada de '*Main Development Region*', a este da América do Norte e do Golfo do México.

Desde o final do século XX, o nordeste do Atlântico Norte tem vindo a apresentar um aparente aumento de ciclones com características tropicais. O interesse da comunidade científica nestas tempestades deve-se à ideia de que a ocorrência de ciclones tropicais é altamente improvável nas latitudes médias, devido ao ambiente hostil caracterizado por valores relativamente baixos da temperatura da superfície do mar e elevado efeito de corte do vento (*wind shear*). No entanto, a formação de ciclones subtropicais (com características híbridas entre sistemas tropicais e extratropicais) torna a ocorrência dos ciclones tropicais, nestas latitudes, mais plausível, pois através de um processo denominado por transição tropical, um ciclone subtropical pode transformar-se num sistema com características tropicais. Estes sistemas híbridos formam-se através da ocorrência de instabilidade baroclínica, que compensa a falta de energia de águas quentes necessária para manter sistemas tropicais. Estudos revelam que no nordeste do Atlântico, os ciclones tropicais resultantes da transição tropical ocorrem sobre temperaturas do mar abaixo do tradicional 26.5 ºC, mas em ambientes caraterizados por estabilidade reduzida ou caraterizados pela presença de uma perturbação na alta troposfera. Esta última característica poderia então reduzir a altura da tropopausa e aumentar a taxa de variação da temperatura com a altitude (*lapse rate),* o que facilita o desenvolvimento de convecção profunda e a ocorrência da transição tropical.

Importa então perceber as razões que poderão estar na base desta modificação fundamental do clima da região nordeste do Atlântico Norte, que tem permitido a ocorrência de sistemas híbridos de origem tropical e subtropical. Com base na literatura disponível sobre o assunto, foram identificados três fatores essenciais para a manutenção deste tipo de tempestades: 1) temperatura da superfície do mar, 2) o efeito de corte do vento, medido entre os níveis baixos e os níveis altos da troposfera (*wind shear*), e 3) a taxa de variação da temperatura (o gradiente adiabático ou '*lapse rate'*) entre a baixa e a média troposfera (1000-500 hPa). Neste trabalho, e numa primeira abordagem, foram analisadas as distribuições espaciais e as alterações a longo prazo destas variáveis, para a estação de tempestades tropicais do Atlântico Norte (que vai desde 1 de junho até 30 de novembro) e também para um período de tempo mais curto, definido entre 1 de setembro e 30 de novembro (período este onde se tem verificado maior incidência deste tipo de tempestades no nordeste do Atlântico). Nesta análise, a temperatura da superfície do mar, as componentes zonal e meridional do vento horizontal aos 850 e aos 200 hPa, e a temperatura do ar aos 1000 e aos 500 hPa foram obtidos da reanálise '*European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis ERA5*' para o período 1979 - 2019. Esta análise é complementada com informações observacionais da base de dados HURDAT (*HURicane DATabase*), que consiste numa

análise a posteriori de cada ciclone tropical, em cada ponto da sua trajetória, com indicação de variáveis fundamentais para a caracterização destas tempestades, como a localização, a pressão mínima, a rajada máxima, o raio de ação dos ventos ciclónicos, entre outras.

Os resultados apontam para uma consistente expansão das áreas de elevadas temperaturas do mar para norte/nordeste. A área de interesse (definida entre os 10º-35 ºW e 30º-50 ºN e denominada no contexto deste trabalho por nordeste do Atlântico) é caracterizada por temperaturas entre os 15-23 ºC, claramente abaixo do limiar típico considerado para génese de ciclones tropicais (26.5 ºC). Quanto ao efeito de corte do vento (gradiente adiabático), as alterações a longo prazo apontam para um aumento (decréscimo) nesta região durante o período de estudo, sendo estas variações mais evidentes no período entre setembro e novembro.

Sendo extensamente documentada na literatura a necessidade de valores elevados da temperatura do mar e valores baixos de efeito de corte do vento para a manutenção de sistemas tropicais, a abordagem anterior aponta para efeitos contraditórios destas variáveis ao longo do período de estudo. Para uma análise mais detalhada e aprofundada, foram então estudadas estas três variáveis para cinco casos de estudo, que incluem a Tempestade Vince em 2005, a Tempestade Ophelia em 2017, a Tempestade Leslie em 2018 e as Tempestades Lorenzo e Pablo em 2019. Esta análise mostra que as tempestades que não tiveram uma génese típica das latitudes baixas (tais como Vince e Pablo), formam-se num ambiente de temperaturas do mar relativamente baixas (valores entre os 20º e os 26 ºC), e com *wind shear* não demasiado intenso (com valores entre os 15 e 25 m/s). Os valores teoricamente insuficientes da temperatura do mar são então compensados por um gradiente adiabático favorável (i.e., com valores próximos dos 6 ºC/km), implicando elevada instabilidade e, por conseguinte, a ocorrência de convecção profunda e libertação de calor latente, necessários para o desenvolvimento e formação de tempestades com características tropicais. Alguns estudos recentes já demonstraram que metade das tempestades tropicais que se desenvolvem no Norte do Atlântico estão localizadas em regiões de forte instabilidade baroclínica, suplementando fluxos de energia entre a superfície e a atmosfera.

Com a análise detalhada destes casos de estudo foi então possível definir alguns limiares empíricos para as três variáveis consideradas, permitindo identificar regiões com: i) condições mínimas de SST e máximas de efeito de corte do vento onde é possível a manutenção de ciclones tropicais, fora dos quais o sistema se dissipa ou transita para um sistema extratropical e ii) um intervalo de valores para cada variável no qual um sistema com origem não puramente tropical se pode formar e desenvolver (e eventualmente sofrer uma transição tropical). Estes limiares empíricos são definidos pela primeira vez para a região do Atlântico nordeste próxima da Península Ibérica, e apesar do seu caráter exploratório, apresentam elevado potencial operacional. Desta forma, foram observadas as alterações a longo prazo das distribuições individuais de cada variável (a partir dos seus dados diários), assim como da ocorrência conjunta para cada par de variáveis na região nordeste do Atlântico Norte. Esta abordagem permitiu identificar que no nordeste do Atlântico Norte existe um aumento de casos com coincidência de temperaturas do mar relativamente altas (embora abaixo do limiar tradicional dos 26.5 ºC) e um baixo efeito de corte do vento e/ou gradiente adiabático entre 5 e 6 ºC/km. Quando observamos a sobreposição dos limites definidos/propostos às distribuições combinadas observamos que nos regimes contidos nestes limites, o nordeste do Atlântico Norte é caraterizado por um aumento da frequência em todas as combinações favoráveis, tanto no período junho-novembro como em setembro-novembro (mas com uma maior incidência neste último).

Assim, no geral, a génese de ciclones tropicais ‘puros’ continua a ser improvável no Atlântico Nordeste, visto esta região apresentar valores climatológicos ainda afastados dos requisitos mínimos. Todavia, os resultados obtidos mostram que a manutenção destes sistemas até latitudes mais elevadas

antes de sofrerem um processo de extra-tropicalização (ou dissipação), assim como a formação e manutenção de sistemas híbridos (que podem vir a transitar para ciclones tropicais), parece cada vez mais plausível, como consequência das tendências de alteração climática. Assim, importa estender o estudo da evolução destas variáveis num contexto de clima futuro, em particular tendo em conta o tipo de análise proposto neste trabalho. No entanto, a relação entre os ciclones tropicais e as alterações climáticas não está totalmente entendida, devido ao facto da formação destes sistemas não ser uma teoria geral, não sendo possível calcular com significância o número de ciclones tropicais que irão ser gerados. Embora tenha havido um grande progresso no problema da formação e intensificação, a sua ligação com alterações no clima não é bem conhecida ainda. Compreender estas ligações no clima presente é então fundamental para melhorar a confiança das projeções futuras.

Palavras-chave:

Ciclones Tropicais; Temperatura da superfície do mar; Efeito de corte do vento; Gradiente Adiabático;

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LIST OF ABBREVIATIONS

TC	Tropical Cyclone
TS	Tropical Storm
TD	Tropical Depression
SS	Subtropical Storm
SD	Subtropical Depression
HU	Hurricane
EX	Extratropical Cyclone
SST	Sea Surface Temperature
VWS	Vertical Wind Shear
Γ	Low- to Mid-Tropospheric Lapse Rate
JJASON	Period from June to November
SON	Period from September to November
MDR	Main Development Region
AEWs	African Easterly Waves
SAL	Saharan Air Layer
NA	North Atlantic Basin
ERA5	ECMWF Reanalysis 5th Generation
HURDAT2	North Atlantic Hurricane Database
ET	Extratropical Transition
TT	Tropical Transition

1. INTRODUCTION

A low-pressure system in which the air pressure has dropped below the standard atmospheric pressure (1013 millibar) and winds converge in a counterclockwise in the northern hemisphere and clockwise in the southern hemisphere is defined as a cyclone (Paul et al. 2017). But any low-pressure system may be characterized as a cyclone so a distinction must be made. First, there are the mid-latitude extratropical frontal cyclones, that develop approximately between 35º and 55 ºN and S, and second there are the tropical cyclones. A tropical cyclone (TC) is an intense atmospheric vortex characterized by a warm, low-pressure center, a closed low-level atmospheric circulation, strong winds, and a spiral arrangement of cumulonimbus that produce heavy rain. It may be represented as a rotating cylinder with a horizontal dimension of ~500-1000 km and a vertical dimension of ~10-16 km (Chan 2005; Wang et al. 2016; Kepert 2010; Guishard et al. 2009).

Almost all intense TCs are characterized by a boundary layer inflow (in a cyclonic pattern), an eye and an eyewall, rainbands, and an upper tropospheric outflow (with an anticyclonic pattern). The eye is a clear region in the center of the storm with calm winds and the lowest surface pressure that is surrounded by the eyewall - an organized band of thunderstorms with the strongest winds that produce heavy rain. The rainbands are curved segments of clouds and thunderstorms capable of producing heavy bursts of rain and wind, as well as tornadoes (Kepert 2010).

Tropical Cyclogenesis is a topic of extensive ongoing research and is not fully understood. Although a few conditions appear to regulate the formation, tropical cyclones may occasionally form without meeting all criteria. First, the ocean temperature needs to be at least 26.5 ºC, down to a minimum of 50-meter depth, in order to maintain warm the air above the ocean so the system can draw the energy it requires from the moist air through convection (Chan 2005; Evans et al. 2017; Xu et al. 2016; Kepert 2010; Emanuel 2003). Second, there needs to be a pre-existing atmospheric disturbance (e.g. disturbance within the Intertropical Convergence Zone, a tropical wave, the remaining of a frontal system, or any other low-level feature with sufficient vorticity to initiate tropical cyclogenesis) (Patricola et al. 2018). Third, the vertical wind shear must be weak (lower than 10 m/s between the surface and the tropopause) (Paterson et al. 2005)(Paterson et al. 2005)(Paterson et al. 2005)(Paterson et al. 2005). Fourth, the TC airmass must be instable in moist atmospheres in order to occur development of thunderstorms, which over warm waters may lead to tropical cyclogenesis (Tory et al. 2015; Wu et al. 2005). And finally, there needs to be a displacement away from the equator in order to induce significant planetary vorticity.

A pre-existing atmospheric disturbance in the North Atlantic Basin (NA) can be attributed to the African Easterly Waves (AEWs) and the Saharan Air Layer (SAL) (Wang 2012). They modulate the TC development/genesis, owe their origin to moist convection triggered by topography upstream of the central and eastern Africa region during the monsoon season (typically between May and October and peak in August and September), form close to the level of the African Easterly Jet (AEJ) and move westward at speeds of 7-8 m/s (Zhang et al. 2020; Patricola et al. 2018). The SAL is most prevalent off the west African coast, forms from deep mixing over the Saharan Desert that results in a dry, well-mixed boundary layer that can extend up to 500 hPa (Daloz et al. 2012; Wang et al. 2017; Patricola et al. 2018; Russell et al. 2017).

After their formation, TCs are pushed poleward by the beta-effect which results from vortex interactions with the Earth’s background vorticity gradient and is typically smaller than the steering, but its impact on the storm direction can sometimes have substantial impacts on the storm interacting with different phenomena (e.g. SST anomalies). Combined with the ambient prevailing westward trade winds, this causes the initial path of Atlantic TCs to be in a north-westerly direction, possibly: i) making landfall on the east coast of North America, experiencing increased surface drag, lower over the ocean when compared to land (e.g., Jones et al. (2003), that when combined with the reduction of latent and sensible surface heat fluxes will cause changes in the storm structure; ii) or they might get caught by the predominant westerly winds at the mid-latitudes, turning in a north-easterly direction, with the possibility of reaching western Europe (Haarsma et al. 2013; Dacre et al. 2009; Chan et al. 2016; Emanuel 2003). Those landfalling storms represent only a portion of the total number of storms (Msadek et al. 2016), with about 37% of the total number of storms within the study period making landfall in the east coast of North America, the Azores islands and in western Europe.

Atlantic TC activity is controlled by multiple factors that vary geographically and by season: local and remote, dynamic, and thermodynamic, from the basin scale to the synoptic scale. Several studies have established that the environmental conditions include the magnitude of the shear of the horizontal wind through the depth of the troposphere, sufficient ocean thermal energy, low-level vorticity, the humidity of the lower and middle troposphere, and atmospheric stability (Zhang et al. 2013; Zhang et al. 2016; Emanuel 2008; Bin et al. 1998; Goldenberg et al. 2001; Defforge et al. 2017; Kossin et al. 2007; Paterson et al. 2005; Zhao et al. 2012; Scoccimarro et al. 2018; Xu et al. 2016; Yan et al. 2018; Wang et al. 2017; Caron et al. 2012; Patricola et al. 2018; DeMaria et al. 2001; Takemi et al. 2020). In this work focus will be on the SST as an energy source, on the vertical wind shear as a mean of storm maintenance if it is weak, and on the low- to mid-level lapse rate (Γ) as a source of baroclinic energy that counteracts the lack of high SSTs at mid and high latitudes. These variables should be the most limiting for TCs development and maintenance in hostile extratropical environments such as those found in the northeastern Atlantic. Other variables, such as relative vorticity and humidity, are also relevant for TC activity, however, and since they are mostly relevant for genesis processes within the subtropics, these are not addressed in this work.

Typically, tropical storms form over relatively warm waters. About 70 years ago a sea surface temperature (SST) threshold for TC formation of 26.8 – 27.8 ºC was proposed. This threshold was widely accepted, until a study suggested a threshold of 26.5ºC (Gray 1968). When SSTs are colder than some threshold, it is assumed that the ocean-atmosphere energy transfer is not sufficient to maintain deep convection on the spatial and temporal scales necessary to influence TC formation. However, a storm might be able to form in SSTs cooler than the threshold if it is supplemented by energy from the release of baroclinic instability. Therefore, this threshold can only be applied to developing storms with minimal baroclinic influence (Tory et al. 2015; Evans 1993). The SST sustains the life cycle of a TC because it provides the energy (through the release of latent heat) necessary for convection. That release of heat is gained when warm and moist air rises, expands and cools, leading to condensation and cloud formation (Paul et al. 2017; Hansen et al. 2020; Zhao et al. 2018).

Wind shear affects the entrainment rate, the strength, movement, precipitation, and lifetime of convective clouds and storms (Cotton et al. 2010). When vertical wind shear is weak (typically early in the local summer, increasing as the tropical and subtropical oceans warm), the storms forming the cyclone grow vertically, and latent heat from condensation is released directly above the storm, aiding in its development (Hansen et al. 2020). When there is stronger wind shear (>10-15 m/s), the axisymmetric organization of deep convection is disrupted and hence inhibit the formation and intensification of hurricanes (Goldenberg et al. 2001; Yan et al. 2017; Paterson et al. 2005; Saunders et al. 2008; Yan et al. 2018; Msadek et al. 2016; Caron et al. 2012; DeMaria et al. 2001; Zeng et al. 2010).

The effect of atmospheric static stability on hurricane intensity is not well documented. This necessary factor for TC formation is defined as the stability of the atmosphere in hydrostatic equilibrium with respect to vertical displacements (Mbengue et al. 2019; Wickström et al. 2020; Gates 1961; Salby 2012). There are several ways of calculating the static stability. In this study it will be calculate the low- to mid-tropospheric lapse rate, Γ. The air temperature generally decreases with altitude in the lowest 10 km of the atmosphere. The rate of this temperature change with altitude, the 'lapse rate', is, by definition, the negative of the change in temperature with altitude, i.e., $\Gamma = -\frac{dT}{dz}$ and depends on the vertical air masses (Finlayson-Pitts et al. 2000; Dutra et al. 2020). When averaged over time and over a large geographic region, the Γ is usually positive and is typically ~6-7 ºC/km as a consequence of the significant amounts of water vapor that cools as the air parcel rises. It has been known from the 70s that the atmosphere sensitivity to static stability is most acute below 500 hPa (Staley et al. 1977). The low-level Γ is used to identify regions of deep mixing (high values of Γ), because it would result in a weakening convective inhibition that precedes the development of thunderstorms. This low-level Γ determines the mount of CAPE (Convective Available Potential Energy) and so controls the updraft intensity, thereby affecting the degree of the organization of Mesoscale Convective systems (MCSs) (Takemi et al. 2020).

A TC can cease to have tropical characteristics in several different ways. The main five are:

1st. If it makes landfall, therefore being deprived of the large surface latent heat flux it needs to power itself, which make the storm lose strength and dissipate or merge into a frontal trough. As the storm advances inland, it can produce a huge amount of rain and might evolve into a frontal cyclone that continues causing damage, until it is fully dissipated.

2nd. If it moves over waters significantly below 26.5 ºC, it begins to weaken and might dissipate or if it gets caught by the mid-latitude westerlies and starts to recurve to the northeast it can transition into an extratropical storm.

3rd. When the warm season ends, the strength and frequency of cold fronts increase. When a TC approaches a land mass these fronts might deflect the storm, or the storm may entrain cool, dry air stopping the convection that drives the storm.

4th. The trough of high pressure that keeps the storms heading westward might break down, resulting in strong upper-level westerlies diving down and imposing the upper-level support structure.

5th. If it encounters a region with high VWS, the eye of the storm will be 'ventilated' which results in the loss of the warm core at the upper levels, rising of the central pressure and the weakening of the storm. The 'ventilation' causes the upper level flow to transport heat and moisture away from the center of the storm which inhibits the development of the storm (Gray 1968).

Tropical cyclones that move poleward often interact with the mid-latitude flow, undergo profound structural changes, and transition into Extratropical cyclones (the process is generally referred to as ET). During this transition, the cyclone experiences changes in its environment. These changes include a rapid structural change, as they transform from a deep, warm-core cyclone to a cold-core cyclone, with increased baroclinity and vertical shear, meridional humidity gradients, decreased SST or strong SST gradients (e.g. those associated with the Gulf Stream), increased Coriolis parameter, dry air intrusion, or landfall (Jones et al. 2003; Keller et al. 2019; Veren et al. 2009; Evans et al. 2017).

Typical extratropical cyclones form along the polar front, largely as a consequence of the temperature gradients and wind shear intrinsic to those latitudes, and then decay as the instability is removed with occlusion (Guishard et al. 2009; Hart 2003; Pinto et al. 2009). The polar front is a baroclinic zone, located between the warm subtropical air masses and the cold polar air masses widening over the mid-latitudes of both hemispheres (Pinto et al., 2009). This type of cyclones can still produce high wind speeds near the surface that cause damage to its physical structures, fatalities, and enormous financial losses. It is rather common that strong midlatitude cyclones without tropical genesis reach Europe; they form when baroclinic disturbances over the NA undergo rapid intensification, leading to a fall in surface pressure and steep pressure gradients (Befort et al. 2019; Trigo 2006).

Based on idealized model simulations (**Figure 1.1**), Evans et al. (2017) defined a 3-step transformation stage. First, the TC's outer circulation encounters a midlatitude baroclinic zone and travels poleward over decreasing SSTs (Step 1). During this process, TCs weaken as they encounter decreasing SSTs and increasing vertical wind shear. As the cyclone weakens, deep, moist convection and associated precipitation becomes more asymmetric, the wind field expands, and the TC warm core weakens. Second, the cyclone becomes nearly intrinsic with the midlatitude baroclinic zone, starts to acquire significant vertical tilt, and develops structures such as conveyor belts (Step 2). These are characteristics of extratropical cyclones. During these second step, deep and moist convection becomes constrained to the northwest, with strong vertical flux in the eyewall and a thin cirrus shield to the north and northeast. Third, the structural evolution that started in step 2 finishes as the TC becomes embedded within the midlatitude baroclinic zone and loses its tropical structure.

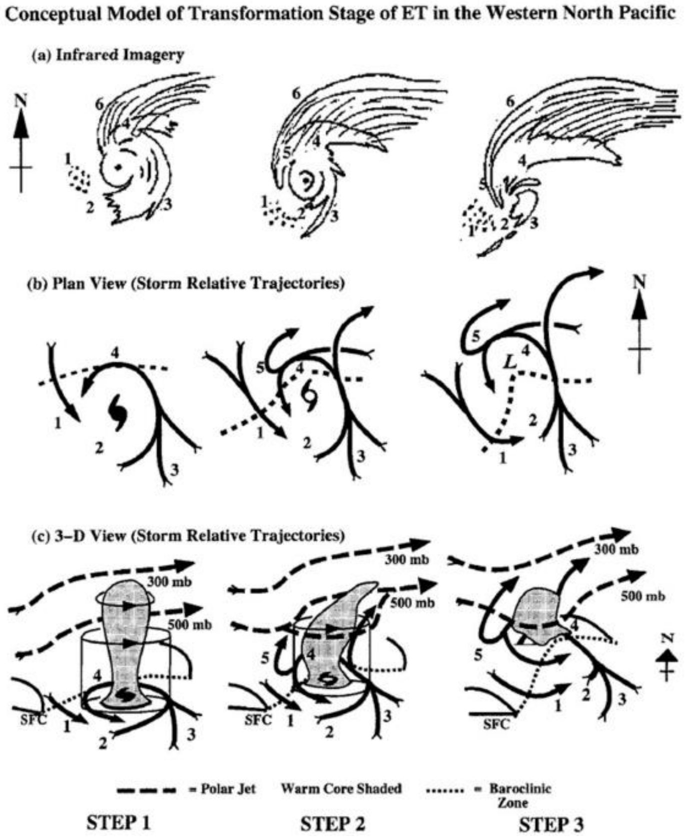


Figure 1.1 - Conceptual model of the transformation stage of ET in the western North Pacific. Figure taken from Evans et al. (2017, their Fig. 3) and reproduced from Klein et al. (2000, their Fig. 5).

A TC can also develop from an incipient cyclone that is initially forced baroclinically. According to Davis et al. (2003) a surface low that is induced baroclinically might be initiated via quasi-geostrophic dynamics and be amplified though convective diabatic heating, building a warm core from the surface upward. These hybrid cyclones have a cold-core at the upper-levels and a warm core in the lower-levels, characteristic of named subtropical storms (Tory et al. 2010). The formation of these systems makes the occurrence of TCs, in the northeast Atlantic, more plausible, due to the Tropical Transition (TT) process. The TT can either change an extratropical system into a tropical system or induce a hybrid cyclone (Guishard et al. 2009; Bentley et al. 2016). The hybrid structure will continue until the convection erodes the upper vorticity maximum to the point when the storm becomes more tropical as a consequence of the imposing low tropospheric warm core (Evans et al. 2009). An example with this characteristics is Hurricane Pablo in 2019 (later described) that started as a baroclinic low over the NA, transformed into a subtropical cyclone and then suffer TT to a tropical storm with a 'central dense overcast and developing anticyclonic outflow' (Beven 2019). These hybrid systems are formed through the occurrence of baroclinic instability, which compensates for the lack of energy from the warm waters necessary to maintain tropical systems.

When looking to the present climate, the meridional atmospheric temperature gradient drives the majority of west-European storms (essentially extratropical in nature), but with global warming, due to increased concentrations of greenhouse gases, this temperature gradient will decrease, as a consequence of a faster Artic warming when compared to the equatorial regions. This implies that baroclinic instability will reduce as a consequence of changes in the large scale atmospheric and oceanic circulation (Haarsma et al. 2013; Hand et al. 2019; IPCC 2013). Based on recent studies, the strong SST gradients in the mid-latitude regions, as the ones observed in the Gulf Stream and its extension, define the key-regions for ocean-atmosphere interaction. As a result of SSTs warming, a poleward and eastward extension of the hurricane genesis area is expected (Hand et al. 2019; Haarsma et al. 2013).

Although rare, occasionally TCs can bring strong winds and heavy rain to western Europe. Hurricane Leslie (2018) and Subtropical Storm Alpha (2020) are two examples of recent tropical-like cyclones that impacted the Iberian Peninsula. Leslie made landfall in the central region of Portugal, made numerous material damage in Figueira da Foz, and placed thirteen districts under red warning due to strong wind and wind waves (**Figure *1.2*** left). It was considered the biggest storm to hit Portugal since 1842. Alpha was classified as a subtropical storm in a very unusual northeastern sector of the Atlantic, very close to Iberia, and made landfall also in coastal areas of central Portugal. Severe weather and wind waves related to this storm also caused extensive damage, especially in the south of Portugal, where at least two tornadoes were observed (**Figure *1.2*** right). A fatality was registered in Spain, associated to the impacts of Alpha.

Figure 1.2 – Left: Leslie's destruction at Vieira Beach, Marinha Grande (Paulo Cunha, Sic Noticias). Right: Alpha's destruction in the south of Portugal (Catarina Coutinho, Sic Noticias).

Most storms that affect Europe occur between September and November. According to Hickey (2011), the TCs that reach these regions form west of Africa and recurve to the northeast, or form over the east coast of North America and travel eastward. The occurrence of this systems in the northeast Atlantic have been increasing. One explanation is the rise of SST due to global warming that can help maintain TCs that travel from the tropics to high latitudes. With high winds, high precipitation and flooding, these systems can cause extensive fatalities and damage. Haarsma et al. (2013) found that the eastward expansion of the tropical cyclone genesis is making the storms to form further east and recurve towards Europe with the possibility of undergoing extratropical transition and eventually re-intensifying as an extratropical cyclone. If the northeastern Atlantic basin is not known as a hospitable region for TC formation, how then do TCs form in this environment? Do the general necessary conditions for tropical cyclogenesis, presented by Gray (1968), apply to all TCs, even those from non-tropical origins or the TCs with non-tropical origins have different characteristics?

Motivated by that poleward and eastward extension of tropical cyclone activity, especially the increase of tropical systems in western Europe and its impacts (Hickey 2011; Haarsma et al. 2013; Baatsen et al. 2015), this work assesses whether the environmental factors that allow the maintenance and formation of cyclones with these characteristics show poleward trends that may cause an increase in their frequency over eastern Europe in the near future. Data and methods applied to this work are described in section 2. In section 3 the results are presented and examined. We discuss our results and state our conclusions in sections 4 and 5, respectively.

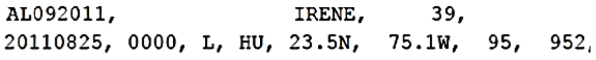
2. DATA AND METHODOLOGY

2.1. Cyclone Best-track Observation

The historical record of hurricane activity in the Atlantic dates back to the late 19th century and has been more widespread than any other basin owing to the aircrafts reconnaissance that started in the late 1940s (Msadek et al. 2016).

The North Atlantic Hurricane database (HURDAT2; (Landsea et al. 2013)), also known as the best-track data set, maintained by the U.S. National Oceanic and Atmospheric Administration (NOAA) National Hurricane Center (NHC), was used to examine the TC activity, including genesis, storm tracks, from 1979 to 2019. This database consists of 6-hourly TC center position (latitude and longitude), maximum 1-min mean sustained surface wind speed v_{max}, central SLP, and so on.

An example of the database for the Atlantic Basin is:



```
AL092011,            IRENE,     39,
20110825, 0000, L, HU, 23.5N,  75.1W,  95,  952,
```

Where at the first line: AL is the general location of the cyclone, that is, if it is located in the Atlantic (AL) or Pacific Basin (EP); 09 is the cyclone number for that year; 2011 is the year in which the cyclone occurred; IRENE is the cyclone's name, if available (otherwise it is defined as 'UNNAMED'); 39 is the number of best track entries (or rows) to follow. And in the second line: 2011 is the year in which the cyclone occurred, 08 is the month and 25 is the day; 0000 is the hour of occurrence in UTC (Universal Time Coordinate); L is the record identifier (L-landfall; otherwise it's blank); HU is the status of the system (options are described at **Table 2.1**); 23.5N is the latitude; 75.1W is the longitude; 95 is the maximum sustained wind (in knots); 952 is the minimum pressure (in millibars).

Table 2.1 – Different nomenclature for cyclone status within the HURDAT2 database. The storm is defined by its wind intensity.

TD	Tropical cyclone of tropical depression intensity (<34 knots)
TS	Tropical cyclone of tropical storm intensity (34 – 63 knots)
HU	Tropical cyclone of hurricane intensity (≥64 knots)
EX	Extratropical cyclone (of any intensity)
SD	Subtropical cyclone of subtropical depression intensity (<34 knots)
SS	Subtropical cyclone of subtropical storm intensity (≥34 knots)
LO	A low that is neither a tropical cyclone, a subtropical cyclone, nor an extratropical cyclone (of any intensity)
WV	Tropical Wave (of any intensity) (not shown)
DB	Disturbance (of any intensity) (not shown)

For this study, the data used was from 1979 to 2019 for the region defined as 10º - 60 ºN and 100 ºW – 5 ºE (**Figure 3.1**).

2.2. Reanalysis

Daily Sea Surface Temperature, zonal (U) and meridional (V) wind components (at 850 and 200 hPa) and the 500 and 1000 hPa temperature data every 3 hours from the European Centre for Medium-

Range Weather Forecasts (ECMWF) fifth reanalysis, named ERA5 (Hersbach et al. 2020), in the period 1979-2019, were considered here.

ERA5 is the latest climate reanalysis produced by ECMWF, that provides hourly data on many atmospheric, land-surface and sea-state parameters. Data is available in the climate data store with a 0.25ºx0.25º resolution grid, with atmospheric parameters on 37 pressure levels. Reanalysis combines model data with observations from across the world into a globally complete and consistent dataset using the laws of physics.

For the purpose of this study the data used was extracted for the period June 1979 – November 2019 for the region defined as 10º - 60 ºN and 100 ºW – 5 ºE.

2.3. Methodology

The spatial and temporal distribution of NA tropical cyclones activity are represented using the HURDAT2 data. The SST, VWS, and Γ are presented in several different ways: 1) a basin wide averaged from June to November and from September to November, 2) a difference between the mean values in the last ten years (2010-2019) and the first ten (1979-1988) as a long-term change representation, 3) a storm-centered average to capture the ambient environment for each storm, and 4) an individual and combined distributions for the northeast Atlantic, defined between 10º-35 ºW and 30º-50 ºN. For the storm-centered averages, a box of 2000 km x 2000 km around the storm center was used (as defined by Downs et al. (2020)).

The vertical wind shear (VWS) was calculated first, as the magnitude of the vector difference between 200- and 850- hPa monthly mean wind fields (Zhang et al. 2016; Kossin et al. 2014)

$$VWS = \sqrt{(\bar{u}_{200} - \bar{u}_{850})^2 + (\bar{v}_{200} - \bar{v}_{850})^2} \tag{2.1}$$

And last, the atmospheric lapse rate (Γ) was calculated (based on Holton et al. (2012)) as:

$$\Gamma = \frac{P_{med}\, g}{R\, T_{med}} \frac{dT}{dP} \tag{2.2}$$

between the 500 and 1000 hPa levels. Here g is the gravitational acceleration, P_{med} is the mean pressure value of the column, R is the ideal gas constant (287 $JKg^{-1}K^{-1}$), T_{med} is the mean temperature of the layer, and $\frac{dT}{dP}$ is the vertical gradient of absolute temperature.

These three variables are then studied for the 1979-2019 period, considering two distinct seasonal timeframes: 1) June 1 to November 30, defined here as JJASON, and 2) September 1 to November 30, defined here as SON. These intra-annual periods were selected because June-November is considered the North Atlantic hurricane season, and since September-November, defined as ‘early autumn’, are the months were there is a peak in cyclone activity in the northeast Atlantic (Emanuel 2003; Wickström et al. 2020; Schultz 2001; DeMaria et al. 2001).

3. RESULTS

3.1. North Atlantic Tropical Cyclone Activity

As mentioned in section 2.1, data from the Hurricane Database (HURDAT2) was used to characterize the spatial and temporal distributions of the North Atlantic Tropical Cyclones. The spatial distribution can be observed in **Figure 3.1** top panel. Cyclones that underwent an extratropicalization process are the most frequent in the northern and north-eastern areas of the North Atlantic basin (NA), while the remaining phases are mostly confined in the 10º-40 ºN latitudinal band. As we can see, there is a typical cyclone track pattern that begins in the lower latitudes in the eastern Atlantic, where storms form from tropical easterly waves and are subsequently directed towards the west and west-northwest by the easterly trade winds and the beta effect. As the storms approach the east coast of the American continent, they can make landfall and/or recurve and move towards the northeast creating, as we can see, a clear 'belt' that begins on the east coast of North America and extends northeast, up to the Scandinavian Peninsula. Usually they reach the United Kingdom and northern Europe essentially in their extratropical phase. According to Shapiro et al. (1998), the systems that form in the 'Main Development Region' (MDR), defined between 10º and 20 ºN, form from easterly waves, while many of the systems that develop north of 25 ºN have baroclinic origin. Even though we have significantly less cyclonic activity in the west coast of Portugal (**Figure 3.1** bottom panel), compared to other coastal regions, this region is characterized by EX, TD, TS, and HU activity, with EX and TD cyclones having made landfall in continental Portugal. In the Azores archipelago, cyclones in an extratropical phase are more frequent in winter and in September/October tropical cyclones prevail (Ramalho 2018). An example is Hurricane Ophelia in October 2017 (see section 3.3.1).

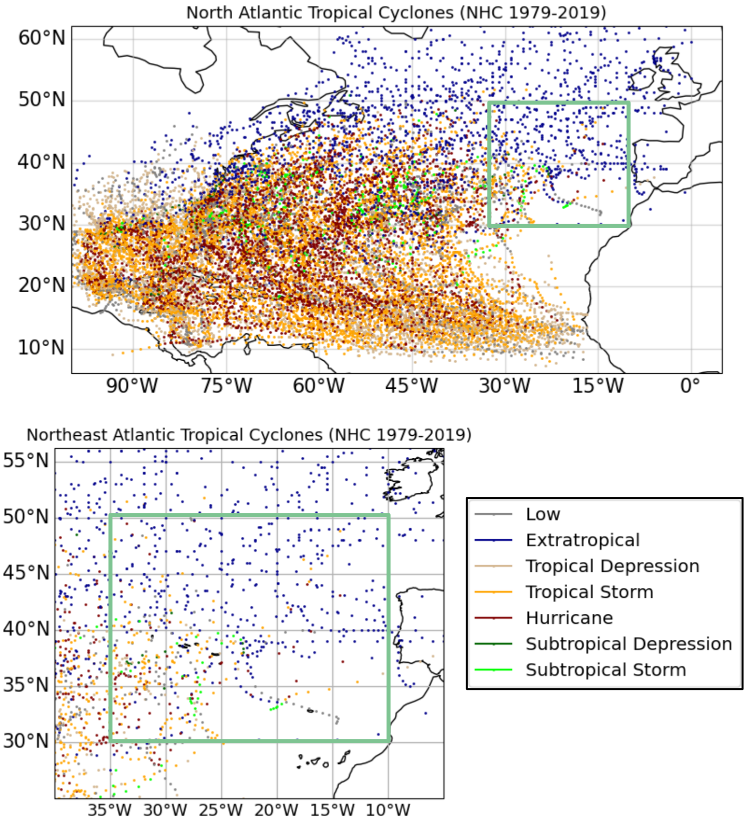


Figure 3.1 - Geographic distribution of North Atlantic (top panel) storms and the storms in the area of interest (bottom panel; defined by the green box) in the HURDAT2 best track data over the 1979-2019 time period, color coded by systems' phase. The system's phase is based on the wind intensity as defined in **Table 2.1**.

Figure 3.2 shows the location of occurrence of a transition to an extratropical cyclone (extratropical transition (ET), purple dots) or to a tropical cyclone (tropical transition (TT), pink dots), based on the phase of the previous location. The coastal Atlantic areas most likely to be impacted by a transitioning tropical cyclone (transition to extratropical) are the northeast United States, the Canadian Maritimes, and Western Europe. These extratropical cyclones are mostly observed between 30º and 50 ºN, with the highest frequency between 40º and 50 ºN.

The TT refers to the change from extratropical or subtropical to tropical characteristics, meaning that the system suffers a transition from a cold core vortex to a warm core vortex. This type of transitions is somewhat less frequent, with only 64 transitions to tropical, compared to 237 transitions to extratropical.

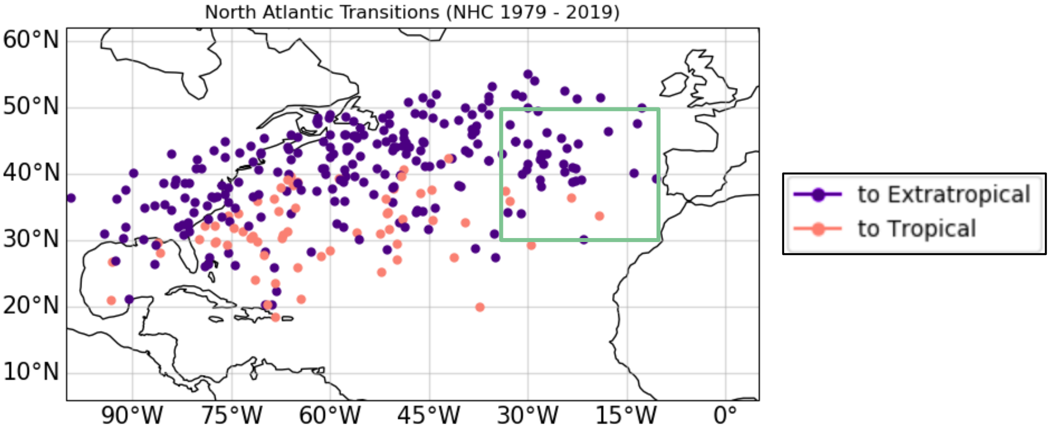


Figure 3.2 - Representation of the locations of occurrence of a transition to an extratropical cyclone (in purple) and to a tropical cyclone (in pink). These transitions are defined considering the cyclone phase in its previous location, i.e., for the transition to extratropical if the previous point is TC, TS, HU, SS or SD, that point is considered the moment of transition. For the transition to tropical if the point preceding a TD, TS or HU phase is SD, SS or EX, that point is considered the moment of the transition. The green box represents the defined northeast Atlantic area of interest.

The temporal distribution of these transitions can be seen in **Figure 3.3**. No significant tendency close to western Europe can be inferred from this visual analysis, since only a few sample points exist. However, an increase in the number of systems transitioning (both to tropical and to extratropical) is observed in the second half of the study period. According to the data plotted, there are 100 transitions to extratropical from 1979 to 1999 and 135 from 2000 to 2019, and there are 25 transitions to tropical in the first period and 38 in the second. In the area of interest (green box, defined between 10º - 35 ºW and 30º - 50 ºN) we see that the ET (left panel) have been occurring close to land since the 2000s, and the TT (right panel) have been occurring more to the east, in the NA, but in the area of interest there is only four data points, so we cannot say that there has been any consistent change.

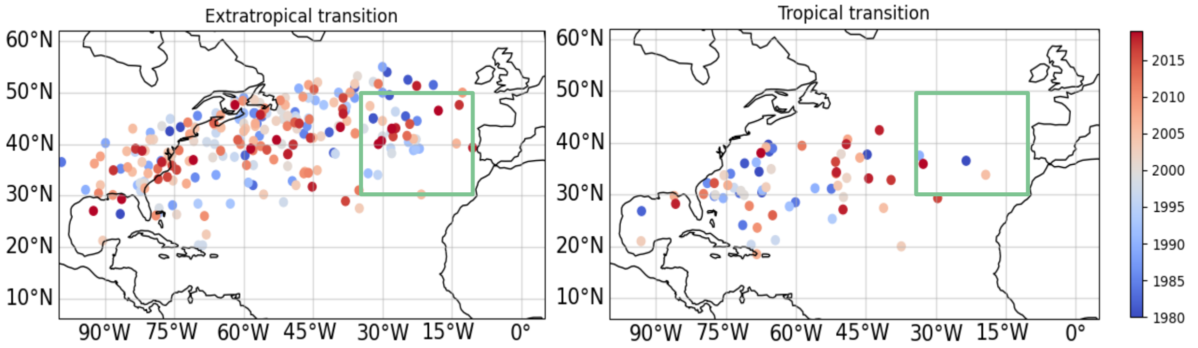


Figure 3.3 - Temporal Distribution of the extratropical (left panel) and tropical (right panel) transitions, color coded by year of occurrence. The green box represents the defined northeast Atlantic area of interest.

From definitions in the Global Guide to Tropical Cyclone Forecasting (WMO 2017), tropical cyclone genesis may be described as the development from a tropical disturbance – i.e. “a discrete tropical (or subtropical) weather system of apparently organized convection” – to a tropical depression or tropical storm – i.e. “a warm-core, non-frontal, synoptic-scale cyclone with organized deep convection and a closed surface wind circulation about a well-defined center” (Tang et al. 2020). **Figure 3.4** shows the genesis (left panel) and lysis (right panel) locations for all systems in the database, color coded by year of occurrence. As we can see in the left panel, the genesis of cyclones is mostly confined to the MDR (10º-20 ºN) and to the Southeast of North America. The principal explanation for high genesis points close to Africa is the presence of the AEWs and the SAL, pre-existing disturbances necessary for TC formation. Considering the area north of 30 ºN and East of 45 ºW, we see that there was a great number of cyclones forming in the second half of the study period. On the contrary, the dissipation of a system has no pattern nor so specifically depends on its geographic location, but rather on the interaction between the various atmospheric factors and the sea-land interaction.

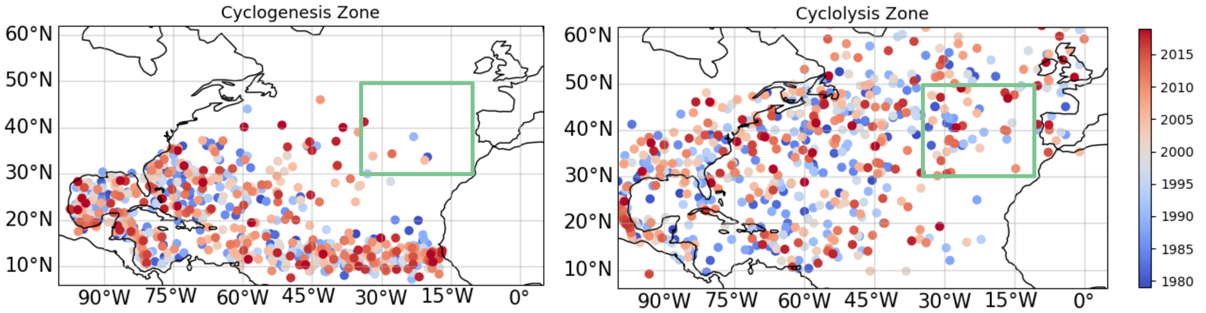


Figure 3.4 - Cyclogenesis and Cyclolysis locations for all North Atlantic Tropical Cyclones for the period 1979-2019, color coded by year of occurrence. The green box represents the defined northeast Atlantic area of interest.

There are 638 systems spread throughout the entire study period. Five case studies that affected our area of interest (identified by a green box), and which underwent distinct genesis processes and life-cycles, were selected and are presented in **Figure 3.5**. Vince was the first known tropical cyclone to reach the Iberian Peninsula and formed from a deep-layer frontal low (Franklin 2006). Ophelia’s origin was non-tropical and it spent its entire lifetime in the northeastern part of the NA (Stewart 2018). Leslie started as an extratropical cyclone and wandered across the subtropical Atlantic for about three weeks shifting from a subtropical depression to a tropical storm and then to a hurricane before hitting Portugal as an extratropical cyclone (Pasch et al. 2019). Lorenzo formed from a tropical wave that moved off the west coast of Africa. Initially it moved westward and then was steered by a subtropical ridge to its north, intensified and became an extratropical cyclone hitting the northwest Ireland (Zelinsky 2019). Pablo formed from a non-tropical low at high latitudes, starting as an extratropical cyclone that moved to the east and northeast Atlantic, mainly as a tropical storm, and then dissipating as an extratropical cyclone north-northeast of the eastern Azores (Beven 2019).

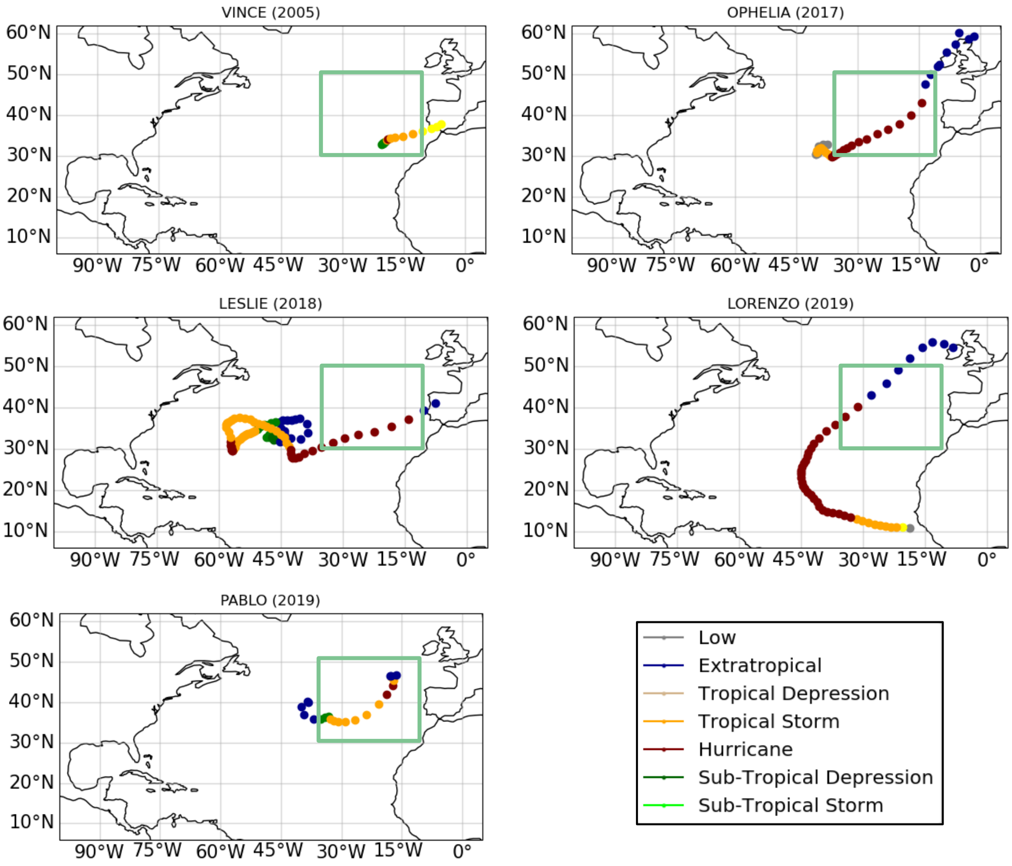


Figure 3.5 - Case Studies selected as systems that formed in the North Atlantic Basin and traveled northeast towards the vicinities of Portugal. The green box represents the defined northeast Atlantic area of interest.

3.2. Spatial Distributions of Tropical Cyclone's Governing Factors on the North Atlantic Basin

In this section, spatial distributions and tendencies are presented for the entire NA. For each variable, five panels are shown. First and second, the mean values from 1979 to 2019 are presented for the entire NA hurricane season (June – November (JJASON)) and for September – November (SON), respectively. Third, the differences between the late season (SON) and the entire (JJASON) mean values are analyzed. Fourth and fifth, a difference between the mean values in the last ten years (2010-2019) of the study period minus the mean values in the first ten years (1979-1988) of the series, for JJASON and SON, respectively.

3.2.1. Sea Surface Temperature

Observations and numerical simulations of TCs show that evaporation from relatively warmer ocean waters is essential to the development of reasonably intense storms. These warm waters play a direct role in fueling incipient TC with sensible and latent heat. As the SST increases, the atmospheric stability decreases, favoring convection and deepening of individual storms, making them more resistant to environmental vertical wind shear. With the evaporation from warm waters comes a surface cooling along the TC trajectory that decrease the sea-air energy fluxes under the storm (Vincent et al. 2014).

Local SST greater than 26.5 ºC is usually considered to be a necessary condition for TC development, and higher SSTs generally increase the overall tropical cyclone activity (Goldenberg et al. 2001; Defforge et al. 2017; Kossin et al. 2007; Wu et al. 2005; Zhao et al. 2012).

The spatial and temporal distributions of SST can be seen in **Figure 3.6**. At the top panels the mean SST for JJASON (top left panel) and for SON (top right panel) are presented. Comparing them we see a slight northward expansion of the areas with relatively higher SSTs. As shown by Strazzo et al. (2013), the maximum values occur in the south sector of the NA, including the Caribbean Sea and the Gulf of Mexico. The west coast of Portugal is characterized by mean SSTs of 18.5º-20.5 ºC. This relatively low SSTs can be attributed to the upwelling of subsurface cool water that occurs during the summer, as a consequence of alongshore northerly winds. The middle panel marks the difference between the mean SST in SON and the mean SST in JJASON. There is a clear northwest-southeast contrast, highlighting more favorable conditions in the target area later in the season. In fact, in the Northeast Atlantic, SSTs are in average 0.5 to 1 ºC higher in SON when compared to JJASON, which could help explain why some cyclones are able to maintain most of their tropical characteristics for longer periods and moving further to the northeast during these months. In the MDR, SSTs are also higher in SON, with a peak offshore the west coast of Africa. The last two panels represent the change between the first (1979-1988) and last (2010-2019) 10-year periods, for JJSASON and SON, respectively. The SST presents an increase, higher than one standard deviation, throughout almost the entire NA, with the highest changes being observed above 40 ºN off the east coast of North America. A few exceptions occur in the North Atlantic Subtropical Gyre and in the northwest coast of Africa, this clearer in JJASON. In the northeast Atlantic, there is also an overall increase in SSTs, both in JJASON and in SON, with a slightly larger area with differences larger than one standard deviation during JJASON.

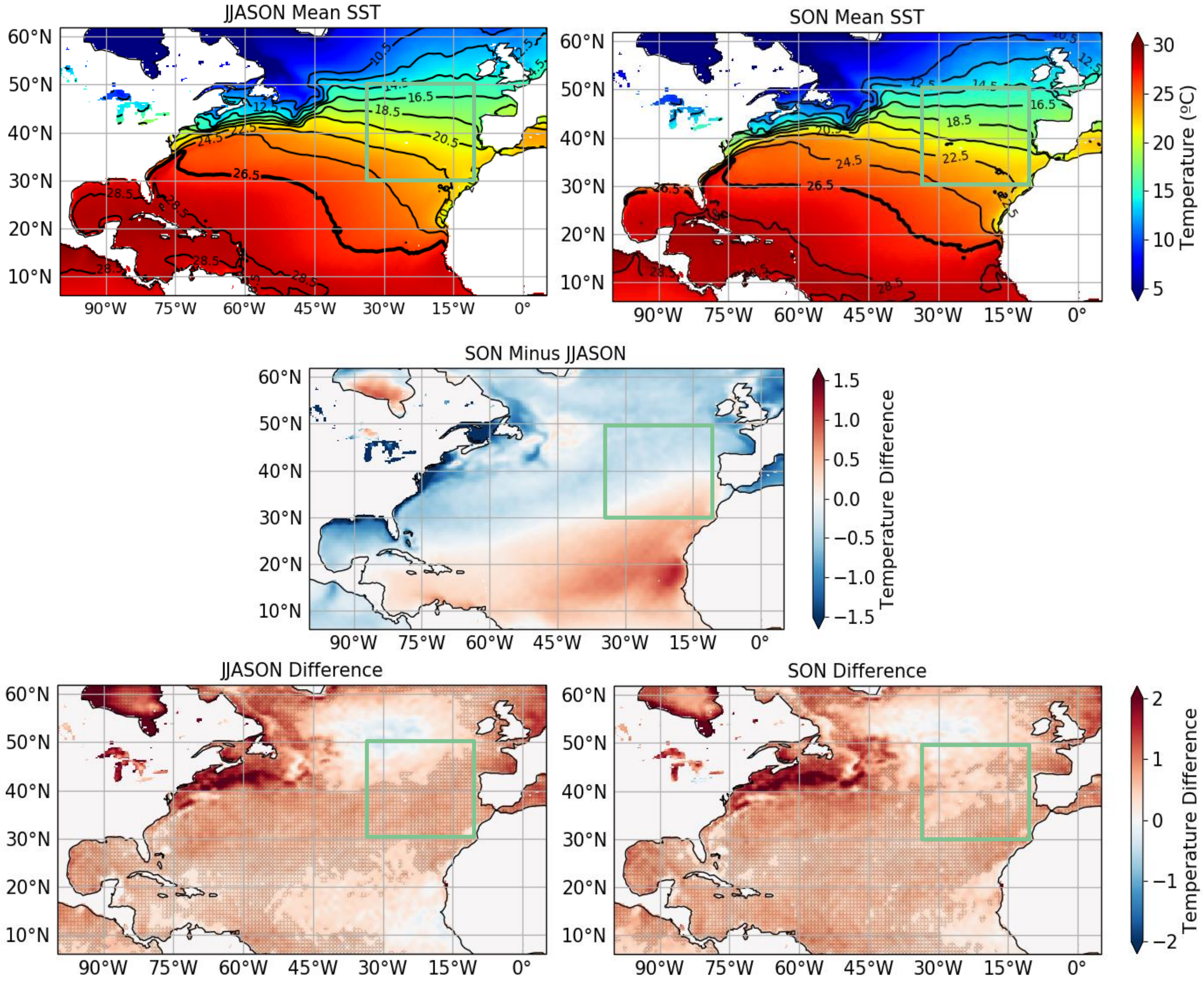


Figure 3.6 – Mean SST in JJASON (top panel left) and in SON (top panel right) from 1979 to 2019. The middle panel shows the difference between the top right panel and the top left panel. The bottom panels represent the difference between the mean SST during 2010-2019 and 1979-1988 averaged for JJASON (left panel) and for SON (right panel). Hatched areas in the bottom panels correspond to the regions where this temperature difference is larger than 1 standard deviation. The green box represents the defined northeast Atlantic area of interest.

The mean location of the 26.5 ºC SST isotherm is shown in **Figure 3.7**, for each 10-year period average and for each month in the hurricane season from 1980 to 2019. The mean location of this threshold extends from the African West coast, generally between 10º and 20 ºN, to the North America East Coast, ranging from about 25 ºN to 40 ºN, with strong seasonal variability. The shape of the isoline is modulated by the Gulf Stream. Some decadal tendencies are observed, namely an eastward displacement of the isoline in the mid-Atlantic in the later years, as well as a northeast displacement in the Gulf Current region. These changes are especially noticeable from August to October. It should be noted that in August and September, the isoline has been extended northeastward, almost entering our area of interest.

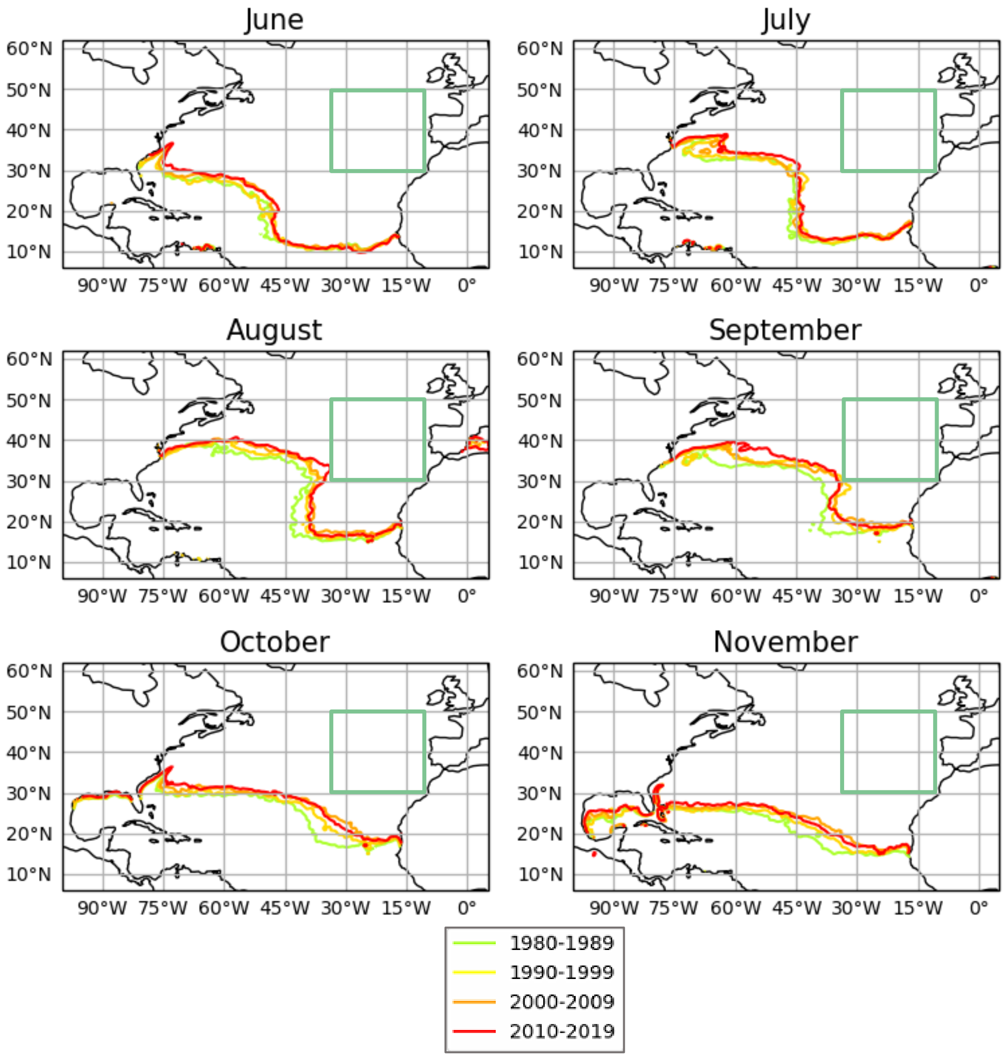


Figure 3.7 – Changes in the mean location of the 26.5 ºC isotherm (June to November), considering 10 years' time intervals, spanning from 1980 to 2019. The green box represents the defined northeast Atlantic area of interest.

Although warm SSTs are known to be a necessary condition for TC genesis, it is well recognized that warm SST is not sufficient for that purpose. According to Goldenberg et al. (2001), vertical wind shear of the horizontal wind is a more important aspect that affects the TC frequency over the NA, as discussed in the following sub-section.

3.2.2. Vertical Wind Shear

As described in the Introduction, the environmental Vertical Wind Shear (VWS) is a crucial factor for TC development and maintenance. According to Finocchio et al. (2016) and Gray (1968), VWS prevents tropical storm intensification by releasing latent heat in convection away from a developing storm. Thus, weak wind shear preserves the structure of the system, and maintains the low-level inflow, while strong wind shear disrupts the vertical structure of the system, and inflow weakens (Jones et al. 2020; Zeng et al. 2010).

Figure 3.8 represents the same as for **Figure 3.6** but for the vertical wind shear. As we can see from the top panels there is a broad area of relatively higher VWS in SON, along the entire eastern coast of North America, and between 15º and 25 ºN off the west coast of Africa. Oceanic areas closer to Portugal are characterized by average VWS values of 15-20 m/s in both periods. The VWS middle panel shows a clear path between the subtropical area up to the Iberian Peninsula, of lower shear conditions during the later stages of the TC season (SON). Therefore, average lower VWS combined with higher SST during SON, should be a factor explaining why more TC affect our target region in SON.

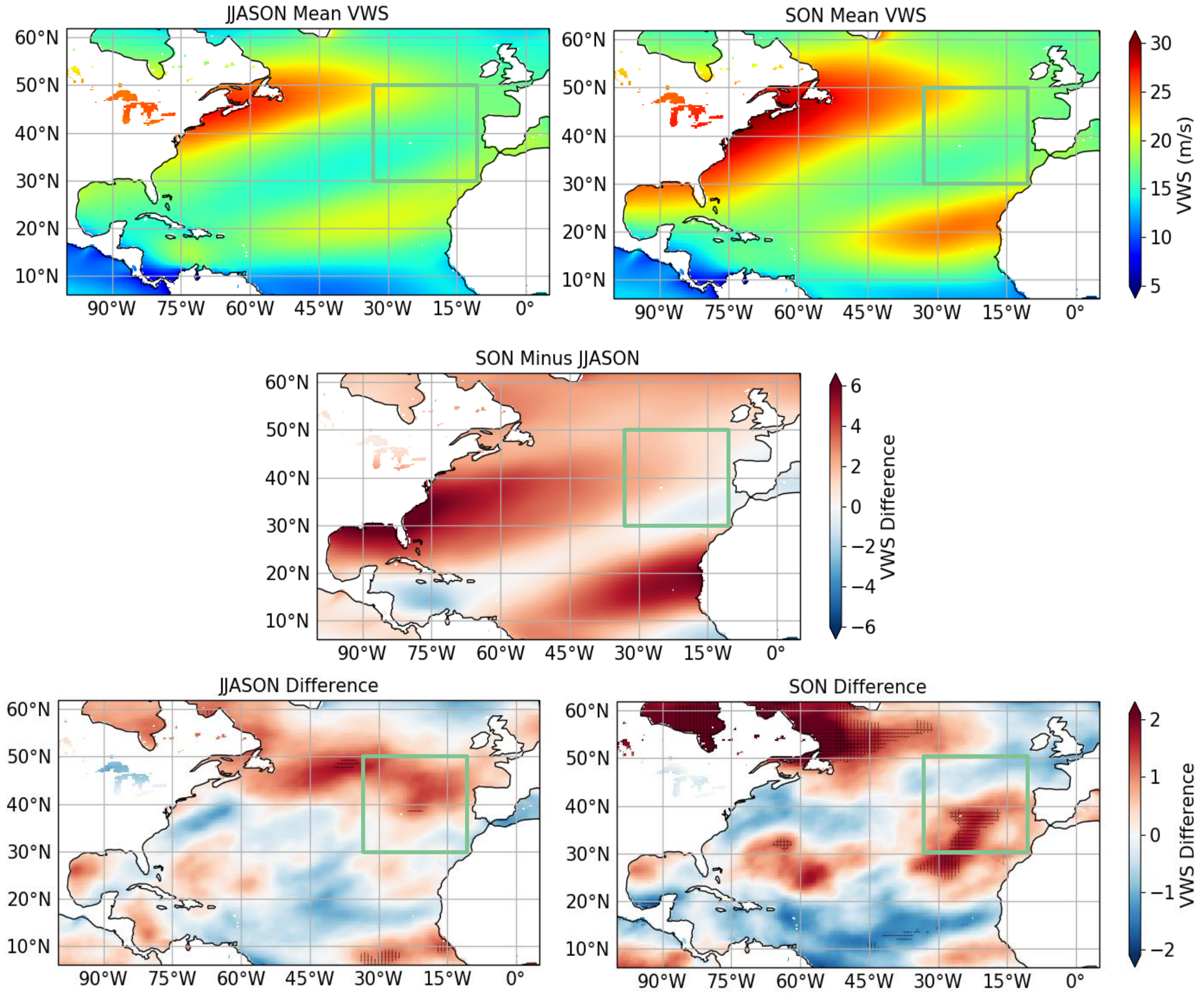


Figure 3.8 – Same as for Figure 3.**6** but for the Vertical Wind Shear. The green box represents the defined northeast Atlantic area of interest.

Regarding long-term changes, the bottom panels from **Figure 3.8** reveal an increase, larger than one standard deviation, in VWS during SON, along the west coast of Portugal, Azores, Madeira, north-western coast of Africa, east coast of Canada, and in the Sargasso Sea. This does not suggest a modification towards more favorable VWS conditions for TC development and maintenance in our interest area, at least from a seasonal scale perspective alone. On the contrary, the North Equatorial Current and later the Gulf Stream, and then the North Atlantic Current are characterized by a long-term decrease of VWS.

3.2.3. Lapse Rate

The Γ refers to the variation of temperature with height in the atmosphere. The steeper the environmental Γ (i.e. when temperature decreases rapidly with height), the more unstable is the atmosphere, which translates into favorable conditions for convection and tropical storm formation and maintenance. Usually, the de-stabilization of the lower atmosphere is achieved by increased SSTs which favor latent and sensible heat transfer from the ocean to the lower atmosphere. However, the presence of a cold air mass aloft may also increase the atmospheric instability, as in the case of cutoff lows (Muñoz et al. 2020). Therefore, since some of the storms with tropical genesis affecting the area of interest were not necessarily associated to SSTs above the usual threshold of 26.5 ºC, it is relevant to investigate if the typical Γ are changing and if it could help maintain these weather systems in the NE Atlantic.

Figure 3.9 has the same meaning as **Figure 3.6** but for the low- to mid- Level Lapse Rate (Γ). From the top panels we can see that the area where the Gulf Stream intersects the Labrador Current is characterized by a north-south gradient, with $\Gamma < 5\ {}^{\circ}C/km$ at the Labrador Current and $\Gamma > 5.6\ {}^{\circ}\mathrm{C/km}$ at the Gulf Stream. The west coast of Portugal has higher values of Γ in SON ($\Gamma > 5.6\ {}^{\circ}\mathrm{C/km}$) when comparing to values of 5.2 – 5.4 ºC/km in JJASON. According to the middle panel, there is an increase of Γ at the eastern/northeastern side of the NA as the hurricane season progresses, contrarily to its left basin. This is in agreement with the similar analysis performed for SSTs and VWS, thus indicating that SON is clearly the most favorable period for deep convection in the NE North Atlantic, climatologically speaking. At the bottom panels of **Figure 3.9**, regarding long-term changes in Γ, we only see an increase larger than one standard deviation in the Gulf of Mexico and Caribbean Sea. Increases lower than one standard deviation can be appreciated in regions close to the European continent and decreases lower than one standard deviation are present throughout the NA. Once again, like the VWS, the Γ shows less favorable conditions in the usual ‘track region’ for cyclones affecting the northeastern Atlantic (only SSTs show a clear favorable tendency, in terms of long-term changes at seasonal scales).

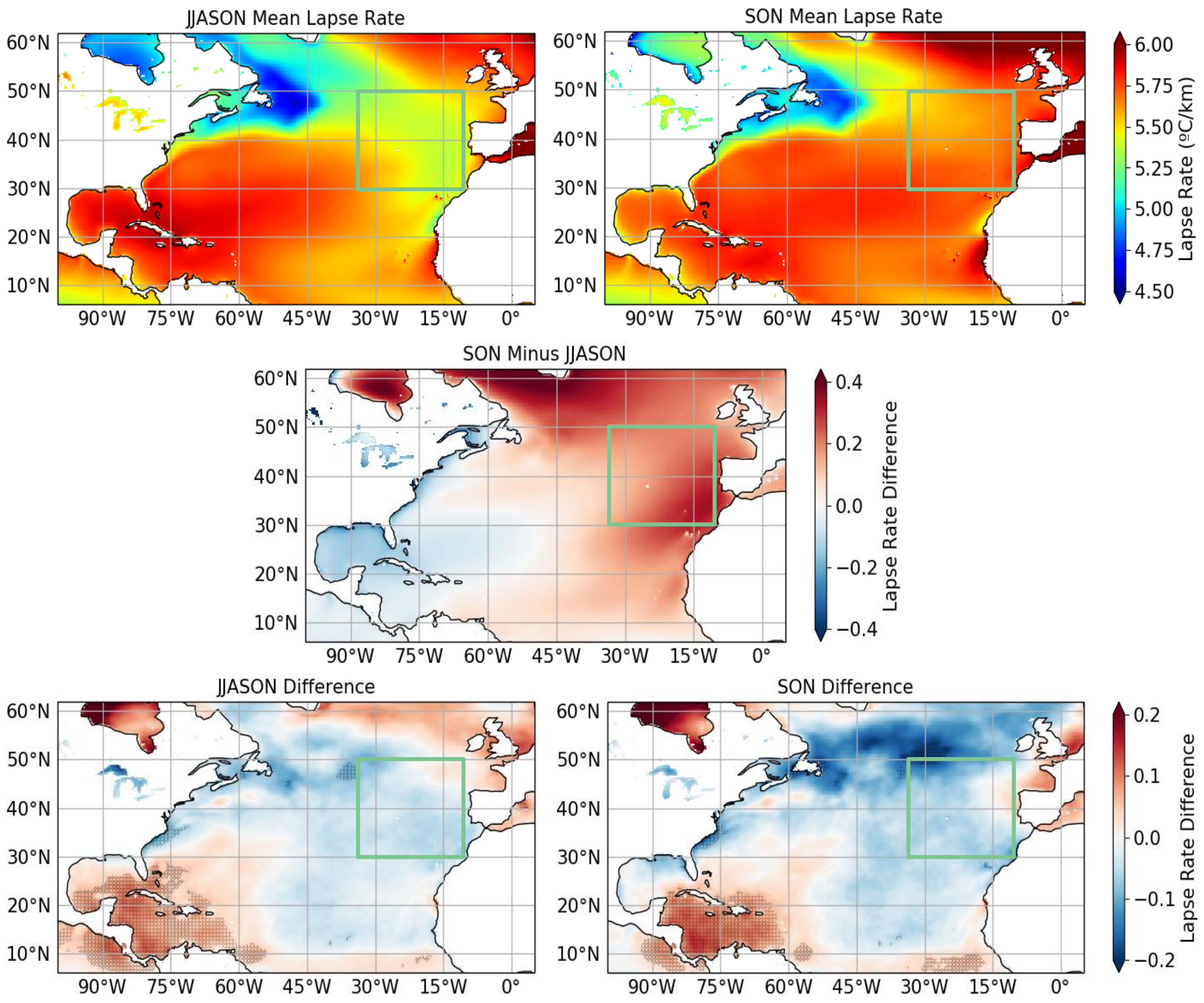


Figure 3.9 -Same as for **Figure 3.6** but for the *Γ*. The green box represents the defined northeast Atlantic area of interest.

3.3. Case Studies

The best track data for five case studies was presented in **Figure 3.5**. Here, the same case studies are analyzed in terms of its surface and atmospheric conditions in a 2000x2000 km storm centered box, as mentioned in section 2.3. This will allow more insight on the particular conditions that led to the occurrence of these storms in such unusual locations.

3.3.1. Cyclone Ophelia: 9-15 October 2017

According to Stewart (2018), Ophelia originated from a mid- to upper-level through. This trough transformed into a low with weak convection and, as we can see in **Figure 3.10**, SSTs of 25 ºC combined with VWS of 15-20 m/s. The system was classified as a tropical storm with an SST of 25 ºC and VWS of ~15 m/s. The Γ was around 5.9 ºC/km, which supported vigorous deep convection. Ophelia became a hurricane with approximately the same environmental characteristics of the TS phase. Soon after, the hurricane started moving northeastward, with decreasing SSTs and a very significant increase of VWS (close to 30 m/s), eventually causing the system to suffer transition to an extratropical cyclone. On the moment of this transition, Γ was around 6.3 ºC/km meaning that the system was initially embedded into a colder atmosphere, and latter suffered a new Γ decrease to values of about 5.7 ºC/km. Ophelia made landfall in Ireland as an extratropical cyclone within cold SSTs (12 ºC), VWS of ~20 m/s and again a cold atmosphere with a Γ of 6.2 ºC/km.

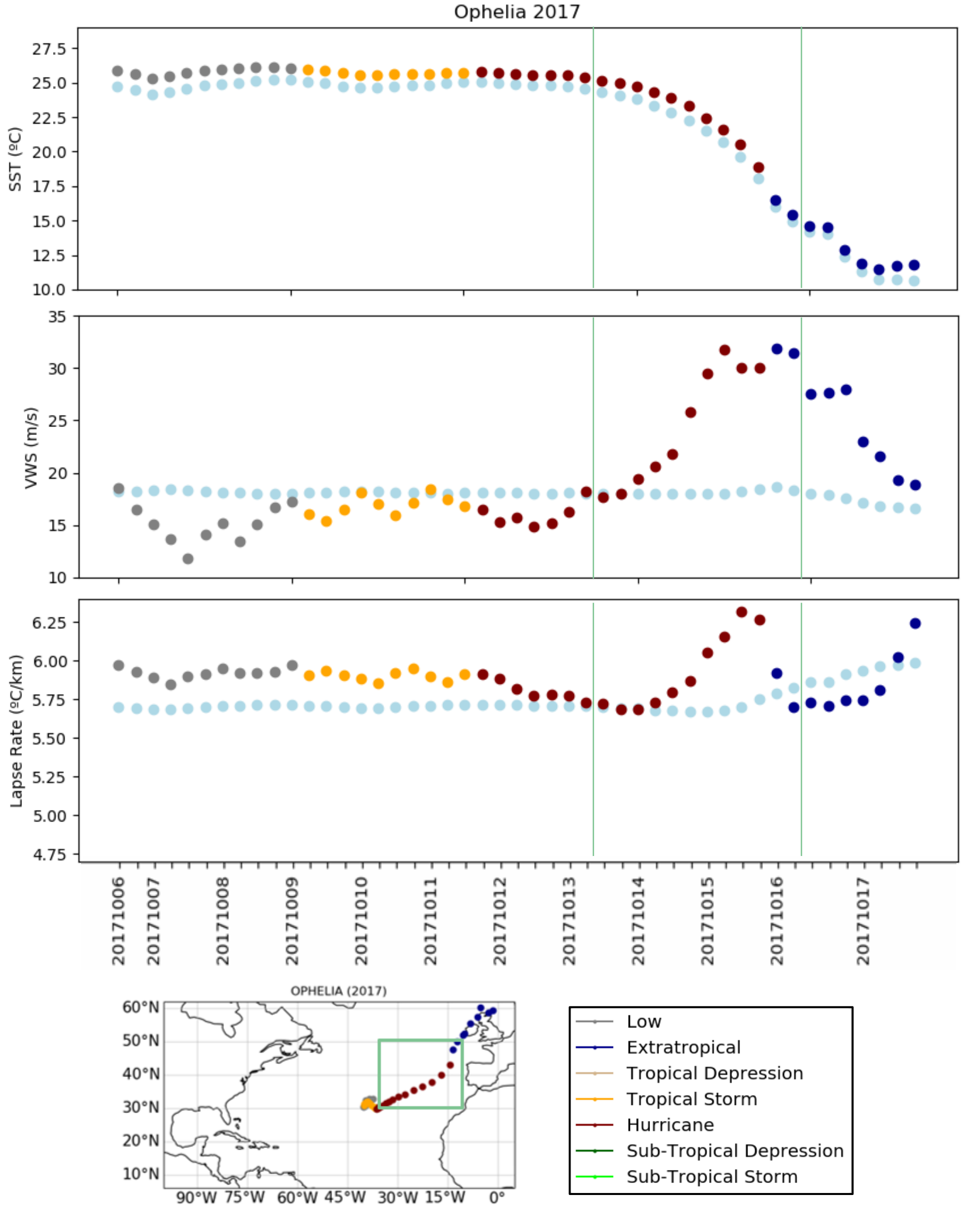


Figure 3.10 - Ophelia's atmospheric characteristics at each location. The x axis corresponds to the date of each best track entries given by HURDAT2. The light blue dots represent the mean value of the variable, as a mean of 40 years (excluding the year in which the storm occurred) and within the 2000x2000 km box around each instantaneous location. Within the green vertical lines there are the positions in which the system travel inside our area of interest.

3.3.2. Cyclone Vince: 8-11 October 2005

According to Franklin (2006), Vince was the first known TC to reach the Iberian Peninsula. From the dissipation of the frontal structure and the increase of convection near the circulation center, Vince, initiated by a deep-layer frontal low, and was designated as a subtropical storm on October 8th. It started, as we can see in **Figure 3.11**, with relatively modest SST for TC development (~23 ºC), relatively high

VWS (~18 m/s), and a Γ of ~5.9 ºC/km. Vince lost its cold-core in the upper-troposphere and formed a mid- to upper-level warm core, becoming a tropical storm. An eye developed and Vince developed into a hurricane with a Γ of ~6 ºC/km and a VWS of ~14 m/s. After becoming a hurricane, Vince weakened back to a tropical storm with a small decrease of the SST, and a small increase of the VWS to values of 17-18 m/s. As it approached southern Portugal, Vince weakened to a tropical depression. The SST kept decreasing and the VWS was still relatively high, until the system eventually dissipated.

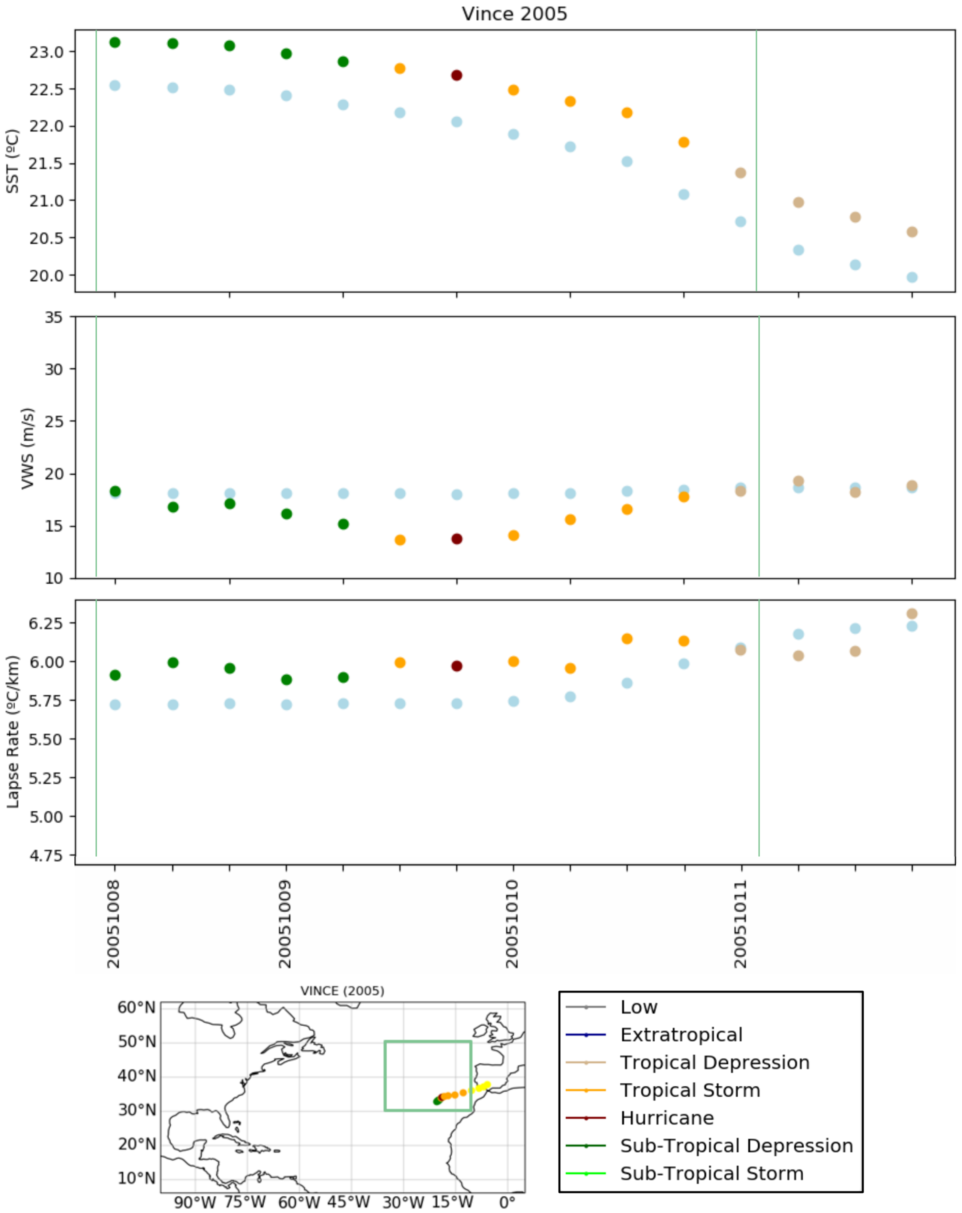


Figure 3.11 – Same as **Figure 3.10** but for Hurricane Vince.

3.3.3. Cyclone Leslie: 23 September – 13 October 2018

According to the report by Pasch et al. (2019), Leslie lived for about three weeks across the subtropical Atlantic before hitting Portugal as an extratropical cyclone. Leslie, **Figure 3.12**, was developed from an extratropical low that formed on a frontal boundary, with relatively high values of SST (>25 ºC), high VWS (~20 m/s), and a Γ of about 6 ºC/km. The VWS decrease (to about 12.5 m/s) favored the system to be designated as a subtropical depression. According to the report, Leslie combined with a frontal zone and returned to an extratropical status, with increasing VWS and a small decrease of SST. The system continued moving along the northeastern Atlantic with relatively high SSTs, a mean VWS of 20 m/s, and a decreasing Γ. After regaining hurricane status for the second time, the storm approximated the west coast of Portugal, moving over decreasing SSTs, while the VWS and Γ reached a relative maxima and minima, respectively, that made the system transition to an extratropical cyclone, making landfall near Figueira da Foz, still producing significant damages (Oliveira et al. 2020).

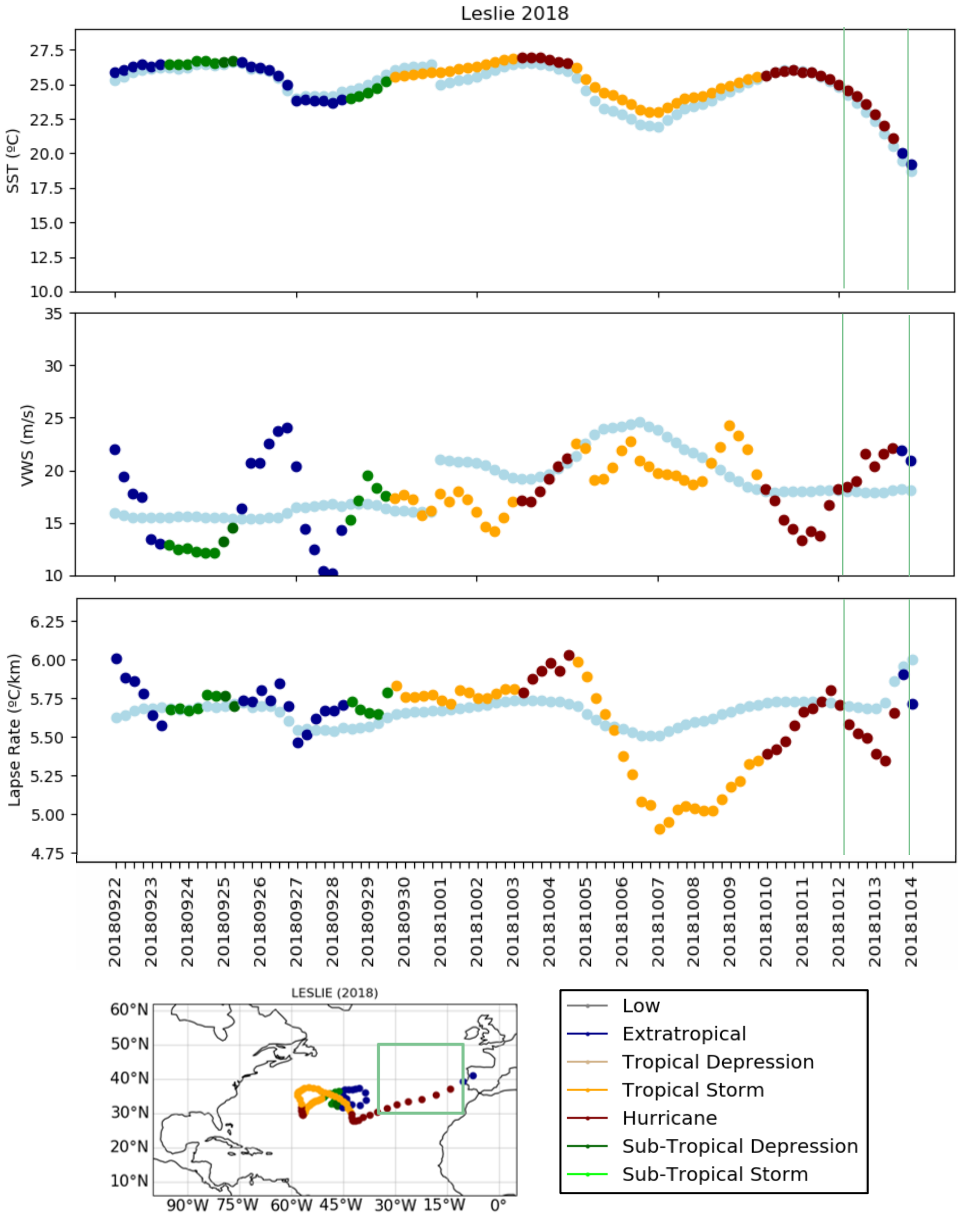


Figure 3.12 – Same as **Figure 3.10** but for Hurricane Leslie.

Two other case studies, hurricanes Lorenzo and Pablo, are presented in Appendix 7.1. Lorenzo, **Error! Reference source not found.**, was a very typical system because it gained tropical depression status with SSTs of 27.5 ºC, VWS of 15 m/s and Γ of 5.7 ºC/km, which were well within the required conditions for TC formation discussed in section 1. Lorenzo traveled over regions with high SST and low VWS in the low latitudes but then started to move northeastward (Zelinsky 2019), with decreasing SST and increasing VWS. According to Beven (2019) and may be seen in **Figure 7.2**, Pablo originated from an extratropical low with high values of VWS. The system suffered a tropical transition despite the relatively low SST (<26.5 ºC) conditions. One explanation that could respond to the TT is that the Γ was steep, meaning that Pablo was embedded in a cold atmosphere that allowed the generation of deep convection. The tropical storm intensified and became a Hurricane, despite the SST decrease from ~20 ºC to ~17 ºC, and the relatively high VWS (from ~24 m/s to ~22 m/s), with a Γ lapse rate around 5.8 ºC/km to 5.7 ºC/km. It weakened again to a tropical storm, and soon after it became an extratropical cyclone over low SSTs and Γ, and detrimental high values of VWS.

To summarize what was found in these few case studies and as a way of providing potential future values for an operational forecast tool, **Table 3.1** shows the proposed thresholds (or the range of values) that characterize the moments of transition between different phases. It is important to stress that this approach is merely exploratory, as the calibration of thresholds was merely empirical, relying on a sample of five case studies. These experiments were performed in order to make a first assessment of the potential added value provided by this kind of approach. In the future, the systematization of this methodology to all systems moving in the northeast of North Atlantic should be done. The table presents i) a minimum SST and a maximum VWS below and above which, respectively, TCs (with tropical origin) tend to lose their tropical characteristics and suffer transition to an extratropical cyclone or dissipate, and ii) a set of thresholds describing environmental conditions that favor the formation and development of a non-tropical origin TC.

Table 3.1 – Proposed Empirical Thresholds for two conditions: First, a minimum SST and a maximum VWS for tropical origin tropical cyclone maintenance (meaning that outside of these limits, TCs might suffer extratropical transition or dissipate) and second, thresholds for SST, VWS, and *Γ* in which cyclones with non-tropical genesis can form and eventually develop/transition into tropical systems.

	SST (ºC)	**VWS (m/s)**	**Γ (ºC/km)**
i)	>20	<30	5 - 6
ii)	20 - 25	<25	5 - 6

3.4. Joint Probability of occurrence of synoptic conditions favorable to tropical systems maintenance along the Northeast Atlantic

In the previous sections, the spatial variability, as well as the long-term trends, of three determinant variables for TC life cycles were analyzed for the NA. In this section we perform a more detailed analysis for the area of interest located in the northeastern NA, taking into account the information gathered in the analysis of the case studies shown in the previous section. In particular, we will look for increases/decreases in the frequency of concurrent favorable conditions for TC activity of SSTs, VWS and Γ, regardless of the changes in their seasonal means. To do that, the green box presented throughout the previous figures, defined between 30º - 50 ºN and 10º - 35 ºW, is used. Firstly, the individual distributions of each variable are analyzed, using each grid point data, every 3 hours, in the defined area, for two periods: JJASON and SON (**Figure 3.13**).

The JJASON period (**Figure 3.13** left panels) show that:

1) the SST (top left panel) suffered a decrease of probability of occurrence between ~13-16 ºC and ~21-22 ºC and an increase between ~17.5-20 ºC and ~22-28 ºC, with the latter interval already including 'the minimum energy required' for TC formation;
2) the VWS (middle left panel) experienced an increase in the probability of occurrences of values between ~5 m/s and ~20 m/s. These relatively low values are conductive to the maintenance of TCs;
3) the Γ (bottom left panel) suffered a decrease in values >~6 ºC/km. As discussed above, the Γ needs to be between 5 and 6 ºC/km to warrant TC formation and development. In this panel, there is an increase of occurrences between ~5 – 5.5 ºC/km.

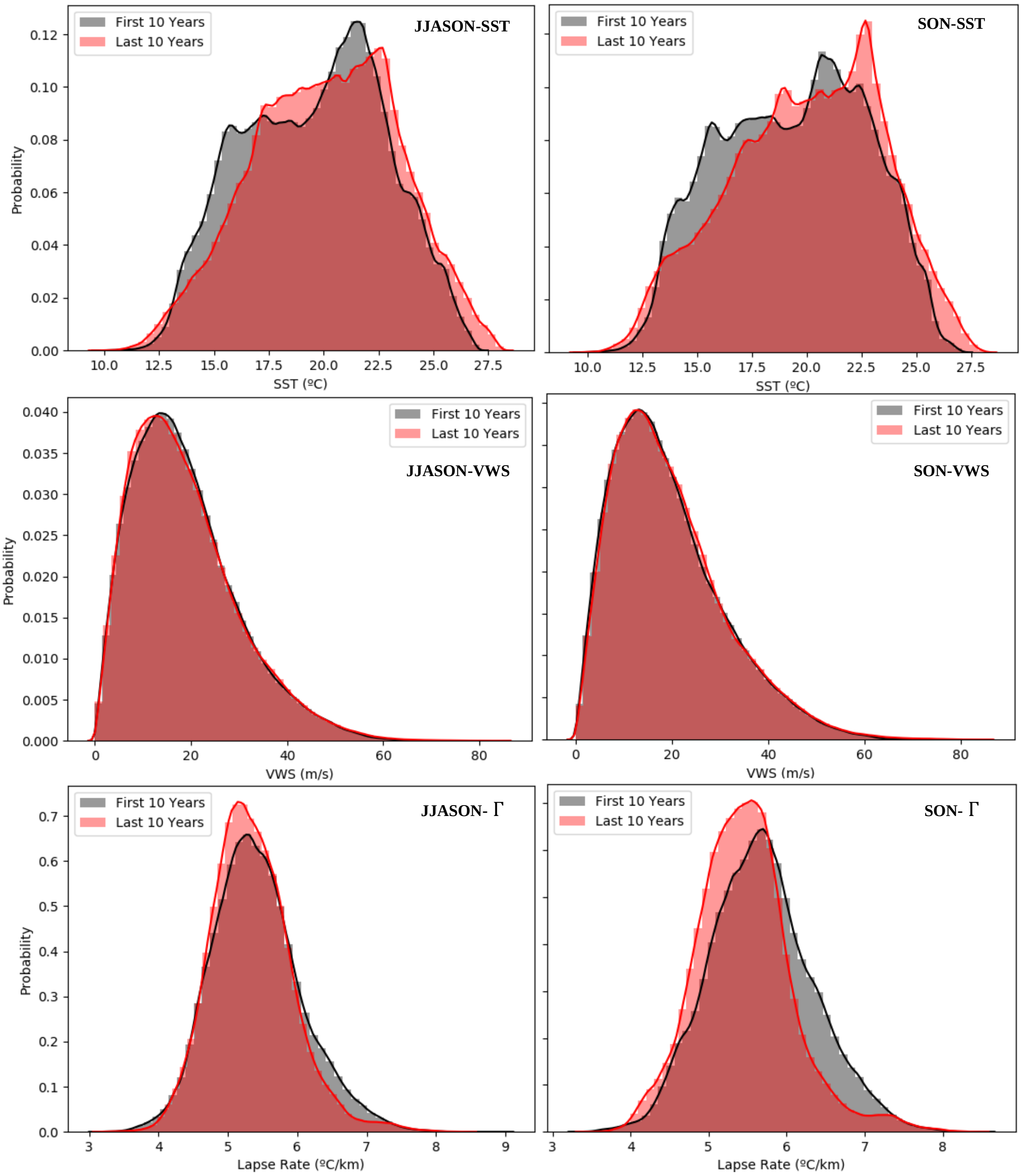


Figure 3.13 – Individual Distributions of the SST, VWS, and *Γ* conditions for JJASON (left panels) and for SON (right panels) for the northeast Atlantic (30º-50 ºN; 10º-35 ºW). The y axis represents the probability of occurrence for each variable's value range.

In the SON period (**Figure 3.13** right panels) it is shown that:

1) the SST (top right panel) suffers an increase of frequency in values between ~18º-20 ºC and in values >22 ºC, as well as decrease between ~20º-22 ºC;
2) the VWS has a very similar distribution to the JJASON period;
3) again, the higher frequency of occurrences of Γ is within the proposed threshold of 5 to 6 ºC/km.

In order to see how each variable's distribution (***Figure 3.13***) is changing within the proposed thresholds for condition ii) referring to the hybrid systems (presented in **Table *3.1***), each probability is calculated and presented in ***Table 3.2***. As we can see the probability of the tropical cyclogenesis minimum SST of 26.5ºC has increased from the first 10 years to the last 10 years, both in JJASON and in SON. As for the proposed thresholds, the SST and Lapse Rate limits have a higher probability in the last 10 years than the VWS, this both in JJASON and in SON.

		JJASON		**SON**	
		First 10 years	Last 10 years	First 10 years	Last 10 years
SST (ºC)	>26.5	0.003	0.019	0.002	0.016
	20 - 25	0.429	0.463	0.418	0.467
VWS (m/s)	<25	0.767	0.765	0.747	0.740
LR (ºC/km)	5 - 6	0.520	0.564	0.483	0.535

Table 3.2 – Probabilities of occurrences of condition ii), from **Table 3.1**, corresponding to the hybrid systems, and the probability of occurrence of the tropical cyclogenesis minimum SST of 26.5ºC.

Secondly, the difference in joint occurrences between the last 10 years (2010-2019) and the first 10 years (1979-1988) of the data series is calculated by combining these variables in pairs, also for JJASON (**Figure 3.14** left panels) and SON (**Figure 3.14** right panels). The combination in pairs, means that we will have 3 plots (SST vs VWS; SST vs Γ; VWS vs Γ). In JJASON (left panels), for SSTs between 20-25 ºC, there is an increase of cases with relatively low VWS, which seems associated to a decrease of cases with high VWS, associated to the same range of SST. The Γ decrease from values >6 ºC/km towards values of ~4.5-6 ºC/km. In SON (right panels), the SST and the VWS changes are similar to JJASON. There seems to be an increase of relatively low SSTs associated to lower Γ , at the cost of cases higher of SSTs associated to lower Γ, and of cases with relatively low SSTs with higher Γ . These changes are clearer when we consider the SON period alone. Regarding the joint distributions of VWS and Γ, the two periods seem to tell two different stories: although there is an overall increase of cases with low VWS and relatively low Γ, in JJASON that increase seems to come at the cost of a reduction in cases with high VWS and low Γ, while for SON the increase is compensated by a decrease of cases with high Γ .

The red boxes in **Figure 3.14** represent the empirical thresholds proposed in **Table 3.1** for the condition ii), that refers to the formation/maintenance of non-tropical origin TCs. We can see that for this condition, this region is characterized mostly by increasing frequencies within the proposed thresholds. For the SST vs VWS top panels, the negative frequencies are present for VWS >~20 m/s with SSTs between 20 – 25 ºC, both for JJASON and SON, with more pronounced positive changes in frequencies during SON. For the SST vs Γ middle panels, the negative changes in frequencies are now for SSTs>~23.5 ºC with Γ between 5-6 ºC/km, again for JJASON and SON with more pronounced increasing frequencies during SON. For the VWS vs Γ bottom panels, in JJASON there are positive changes in frequencies within the proposed thresholds, with higher frequencies for values closer to 6 ºC/km and 10 m/s. In SON, there is a small region with negative frequencies for VWS~20 m/s and Γ~6 ºC/km.

In summary, this analysis of joint probabilities clearly points to an increase in the frequency of simultaneous favorable conditions (of SST, VWS and Γ) for the occurrence of tropical systems in the vicinities of the Iberian Peninsula during the study period (1979-2019), which is particularly notable during the late TC season (SON), as clearly depicted in the areas contained within the red boxes in **Figure 3.14**.

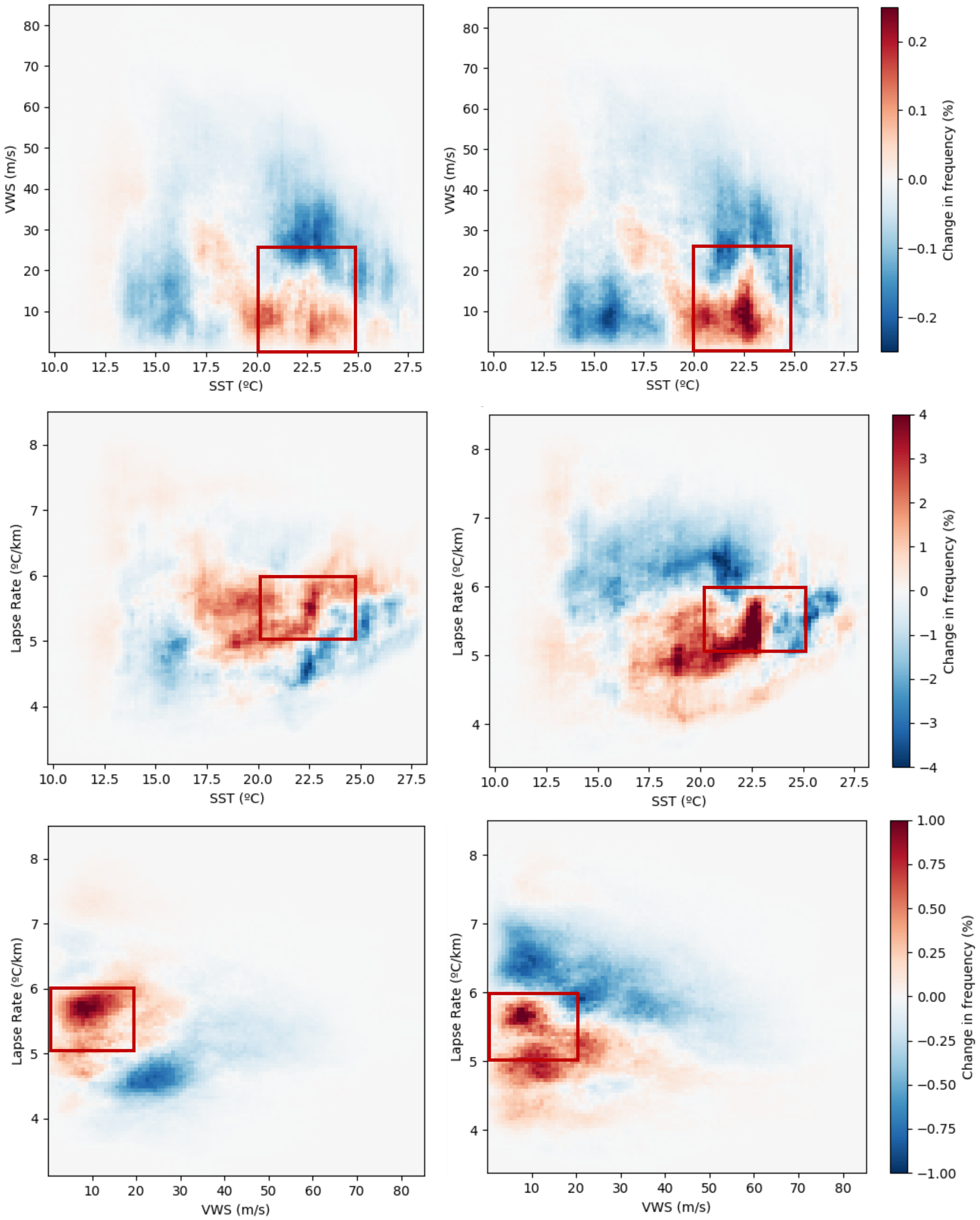


Figure 3.14 – Two dimensional distribution for each possible pair of conditions for the northeast Atlantic (30º-50 ºN; 10º-35 ºW) for JJASON (left panels) and for SON (right panels). The colorbar represents the decrease or increase of the number of occurrences between the last 10 years and the first 10 years. Please note the different axes of the color bars. The red boxes represent the proposed empirical thresholds for the formation/maintenance of non-tropical origin TCs in **Table 3.1**.

4. DISCUSSION

Tropical cyclones in the North Atlantic (NA) present a characteristic track pattern from lower latitudes (i.e., from the Main Development Region (MDR)) towards the western NA, although sometimes turning northwards or northeastwards, towards the northeastern part of the basin, as confirmed in our analysis based on the HURDAT2 dataset, spanning from 1979 to 2019. A similar result, but for the period between 1988 and 2002 was found by Kimball et al. (2004).

As described in Section 1, an extratropical transition (ET) usually occurs when the TC encounters a low SST and high VWS environment, while a tropical transition (TT) tends to occur under opposite changes in the environment where the cyclone is located. According to the HURDAT2 database, the ET occur above 30 ºN and the TT occur predominantly between 20º and 40 ºN (**Figure 3.3**). According to our results, the ET area is characterized by mean SSTs lower than the traditional 26.5ºC threshold, a mean VWS that ranges from 15 to 30 m/s off the east coast of North America to the western coast of Europe (with higher VWS in SON) and a contrast between low Γ values north of 40 ºN and high Γ between 30 and 40 ºN. The TT area is characterized by SSTs between 28.5 ºC in the Gulf of Mexico and 20.5 ºC southwest of Portugal, VWS usually lower than 15 to 20 m/s, and Γ between 5.2 ºC/km southwest of Portugal and 5.8 ºC/km in the central and western part of NA. These contrasting observations (particularly for SSTs) suggest the possibility of different mechanisms involved in the transition process in distinct sectors of the Atlantic basin. One factor that might help the systems to undergo a transition to a TC without the typical minimum 26.5 ºC SST might be additional convective processes due to favorable Γ conditions, and the presence of marginal values of VWS (below a detrimental intensity). These values show that the mid-troposphere is cold, which when associated with also marginal SST values could still provide enough vertical instability to enhance convection. In this sense, the occurrence of cut-off lows could be one determining factor for these type of episodes, in particular in the northeastern Atlantic, which is one of the preferential areas for their occurrence (Nieto et al. 2005). According to Tang et al. (2020), TT events above 25 ºN can occur over colder SSTs (SSTs<26.5 ºC) due to the presence of an upper-tropospheric disturbance that could cause a steeper Γ and help the development of deep convection. These large values of Γ favor tropical cyclogenesis by increasing the release of latent heat in active convection.

The overall warming trend in NA SSTs throughout the study period (1979-2019) exhibits details such as a pattern consisting in a slight cooling in the subpolar gyre, a minimum warming throughout the NA, and a pronounced warming in the vicinity of the Gulf Stream and its extension. This is in agreement with the IPCC (2013), that showed a prominent positive temperature trend from 1971 to 2010 in the Northern Hemisphere, particularly in the NA. Haarsma et al. (2013) projected an increase in SST, between 40º and 50 ºN in the western Atlantic, when comparing the end of the XXI century (2096-2098) with the present (2002-2006). Here, an increase can already be noted in the recent past with **Figure 3.6** bottom panels, with a warming of at least 1.5 ºC in the SST within that region since 1979. They also showed that in the current climate, the main tropical cyclogenesis zone is located at the western tropical Atlantic, which is the area of higher SSTs. **Figure 3.4** corroborates that finding and adds the MDR as an area of formation. These two areas are characterized by SSTs>26.5 ºC.

According to Woollings et al. (2012), the AMOC (Atlantic Meridional Overturning Circulation) is projected to weaken due to global warming. This weakening will induce a warming of the SST, and as a consequence, an increase of the meridional gradient in the mid-latitude NA, and an increase of the baroclinic instability. As discussed in the IPCC (2013) report, this SST warming in the NA will cause 'an increase in storm activity and a downstream extension of the storm track into Europe', with increases in storm activity over western Europe close to 50%. The typical low SST found along the west coast of

Portugal, mentioned in section 3.2.1, might be attributed to the upwelling mechanism that transports colder waters to the surface, which implies a more stable lower troposphere. Therefore, the knowledge of how the winds, which generate the upwelling, will be affected by climate change is necessary since this mechanism will affect the SST along the west coast of Portugal and as a consequence, will affect atmospheric instability.

VWS is one of the limiting factors for TC activity and maintenance. Our results show that the VWS tends to be weaker early in the summer in most of the Atlantic basin. However, here we show a relevant area of opposite changes throughout the season. A relatively narrow corridor pointing directly from the tropics towards Iberia is characterized by decreasing VWS in the late season, thus probably explaining why SON is particularly favorable for unusual occurrences of TC in the northeast Atlantic. According to Grist et al. (2002) and Patricola et al. (2018), the African Easterly Jet (AEJ) peaks from July to September probably as a consequence of high VWS. Here, we found a region of high VWS between 10º and 25 ºN along the west coast of Africa. Garner et al. (2009) showed that in the MDR, from 1980 to 2006, the VWS trend points to a 30% decrease of magnitude. Here, our results show a negative difference in magnitude throughout the entire MDR, both in JJASON and in SON, but with a higher negative difference in SON. These regions of negative 'anomalies', according to DeMaria et al. (2001), enhance TC formation.

While it is certain that greenhouse gas forcing will increase the SST, it is not clear how the VWS might be affected. When we look to the change in average VWS during the study period, we see a small increase in a broad area of the northeast Atlantic. However, results from Haarsma et al. (2013) show a small regional decrease of VWS by the end of the 21st century along the Portuguese west coast according to the EC-EARTH global climate model. Such an eventual reduction in the intensity of the western Iberian coastal jet might be enough to maintain intact those TCs capable of reaching this unusual area. However, projections to the end of the 21st century are still unclear. According to Vecchi et al. (2007) these changes result from variations in the upper tropospheric zonal winds and the reduction of the Pacific Walker circulation.

Our results for the NA Γ show that it varies between 5.5 – 5.9 ºC/km from the tropical Atlantic to latitudes of 40 ºN, for both JJASON and SON. In SON, however, Γ is higher in the northeast Atlantic between Azores and Portugal, thus also somehow favoring deep convective processes in the area later in the season, as previously discussed. Regarding long-term changes, Γ decreases throughout almost the entire NA but there is a small increase along continental margins, including the west coast of Portugal, probably reflecting enhanced surface warming over land areas in recent decades.

The Gray (1968) SST threshold of 26.5 ºC is usually thought to be the minimum SST for supporting deep convection in the tropics. The development of TCs over these high SSTs increases the sensitivity to VWS. According to Mauk et al. (2012), the SST and VWS for the formation of late-season tropical cyclones with a non-tropical origin are not consistent predictors. According to their work, and for the northeast Atlantic, the convective environment might be a better predictor. Taking into account the climatological analyses presented here, we further explored this hypothesis, by analyzing specific cases studies, and considering the role played by vertical instability (via the Γ).

The chosen case studies show that for 'typical' tropical origin cyclones, like Lorenzo (2019) or Ophelia (2017), the environmental characteristics for their maintenance include high SST, associated with relatively low VWS. SST decreases to values <20 ºC as a result of the displacement to high latitudes, together with detrimental VWS>30 m/s and decaying vertical instability (Γ <5.5 ºC/km) are critical parameters for the process of ET and/or TC dissipation. Regarding cyclones which had a non-tropical genesis, like Vince (2005) or Pablo (2019), their onset occurred with SSTs between 20º – 26 ºC, moderate VWS (ranging from 15 to 20 m/s), and Γ between 5-6 ºC/km, thus pointing to a certain balance between these variables as a premise for this type of subtropical genesis.

To further explore long-term changes in favorable environmental conditions, the previous results from the case study approach provided an empirically determined and experimental set of thresholds delimiting ideal regimes for TC maintenance, and for conditions ideal for subtropical/hybrid systems development. The two dimensional distributions for the variables used in this approach (presented in **Figure 3.14**) reveal an increase in the frequency of occurrence of 'favorable conditions for TC activity' in the northeast Atlantic (region that is relevant for the western Europe tropical storm track), meaning that we have increasing occurrence of simultaneous low VWS associated to relatively high SSTs (between 20-25 ºC), low VWS and the Γ between the proposed threshold of 5-6 ºC/km, and/or the same Γ range with relatively high SSTs. These favorable trends in joint distributions are observed for the two intra-annual periods, JJASON and SON, but with a higher impact in SON, which is relevant, since this season is the most favorable for TC occurrence in the northeast Atlantic, as already shown in the climatology section (section 3.2).

Therefore, our results show, at a first approach, that it seems possible to actually identify, with the use of reanalysis, an increase in favorable conditions to the maintenance of tropical systems in the northeast Atlantic and, especially, an increase in favorable conditions the occurrence of tropical systems with a non-tropical genesis. Furthermore, and already in 2020, six storms have affected the northeast Atlantic, reinforcing this apparent increasing trend. One example is Subtropical Storm Alpha (18-19 September). This system did not become a 'pure' TC, but it formed northwest of Portugal, around 45 ºN as a non-tropical low, became better defined early on September 18 and was designated as a Subtropical storm. It made landfall just north of Lisbon and weakened to a remnant low. A second example is Tropical Storm Theta (10-15 November) that started as a non-tropical low in the northeast Atlantic. Theta developed into a Subtropical Storm and became later fully tropical. It traveled eastward and weakened to a tropical depression before it dissipated and changed course northward, passing west of Madeira Island.

5. CONCLUSIONS

This study investigates the changes in tropical cyclonic activity, and its relationship with changes in sea surface temperature, vertical wind shear and low- to mid-tropospheric lapse rate in the NA, with particular emphasis in the northeastern NA, using observation and reanalysis data from 1979 to 2019. Several approaches are pursued in this work. First, a climatology and analysis of long-term changes of these variables are carried out, for two periods, JJASON and SON. As discussed briefly in the results, besides an evident increase in SSTs and a northward expansion of warm oceanic conditions, in average, there seems to be no clear improvement of the favorable conditions for TC development at higher latitudes for the remaining variables (e.g. the VWS seems to increase to the west of Portugal, while for TC development and formation low values of VWS are more favorable).

The previous result is in contrast with the actual apparent increase in the frequency of observed TCs affecting our target region. Therefore, a different approach was performed, consisting firstly in analyzing the surface and environmental conditions around the center of five specific recent storms which reached the study area in the northeast Atlantic, thus affecting Portuguese territory or adjacent oceanic areas. The analysis of these case studies enabled a preliminary empirical estimation of a set of thresholds for the variables related with TC maintenance and transition processes (SST, VWS and Γ . Then, changes in the joint distributions of these variables were assessed, by taking the difference between distributions at the final of the study period against the joint distributions in the earlier period. There are clear and consistent changes in the northeast Atlantic, meaning that the increase in tropical cyclone activity in this region is consistent with an increase in the frequency of episodes with simultaneous relatively high SSTs and low VWS and ideal Γ between 5 and 6 ºC/km. Therefore, in the northeast Atlantic, three intervals must be considered when analyzing TC formation and development, in particular regarding those systems that were developed through a tropical transition process. As a ‘rule of thumb”, our approach points that such systems occur under very specific conditions. First, the SST must be between 20 and 25 ºC. Second, the relatively low SSTs must be complemented by a steep Γ between 5 and 6 ºC/km. And last, the VWS should not exceed 25 m/s. In fact, our analysis also shows that VWS values above 30 m/s, together with SSTs lower than 20ºC, are a typical threshold for ET or dissipation. While high VWS contributes to the lack of organization of the system, strong convective instability (via high SSTs or ideal Γ) is also a crucial condition for TC maintenance, which requires intense convection.

The idea that VWS is a key environmental condition for TC development does not seem to hold within the region of interest. In the chosen case studies, the VWS is less relevant and varies from system to system. The Lapse Rate seems to have a more relevant impact on the evolution of each storm. A WVS less than 10 m/s has been acknowledged as the threshold below which there are conditions for the occurrence of TCs (Paterson et al. 2005). However, we find that for the storms evaluated in this work, values were considerably higher and therefore we propose a threshold between 20 and 25 m/s for TC (with non-tropical origin) occurrence in the northeast Atlantic.

In summary, our results show that despite continuing to be a region well outside the minimum requirements for the genesis of ‘pure’ tropical cyclones in the present climate, the northeast Atlantic is having more and more ‘windows of opportunity’ of favorable conditions able to: i) form and maintain hybrid systems, some of them generated from initially non-tropical disturbances, but which may eventually become tropical systems; ii) maintain systems that conserve tropical status for a longer time before they suffer the transition to an extratropical cyclone due to detrimental environmental conditions.

Future climate scenarios associated with the three variables used in this work (SST, VWS and Γ) would help identify expected changes in the long term, especially those associated with the increase/decrease of northeast Atlantic SSTs and VWS. Also, a more detailed and systematic analysis incorporating further case studies, and eventually all systems in the target area, could help identify, in a more rigorous way, the thresholds for TC formation/maintenance/development for the tropics and subtropics which are proposed here, in this preliminary approach. These thresholds could be incorporated in a pseudo-cyclogenesis parameter applicable to cyclone tracking algorithms. This threshold based approach could be combined with an analysis of cyclone phase space, developed by Hart (2003). This method helps to objectively characterize the stage of any cyclone throughout its lifetime by the estimation of simple parameters characterizing its symmetric and the associated thermal wind. We believe that this complementary approach could have relevant operational use, and thus aim to calibrate and automate the methodologies presented in this work.

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7. APPENDIX

7.1. Case Studies Lorenzo and Pablo

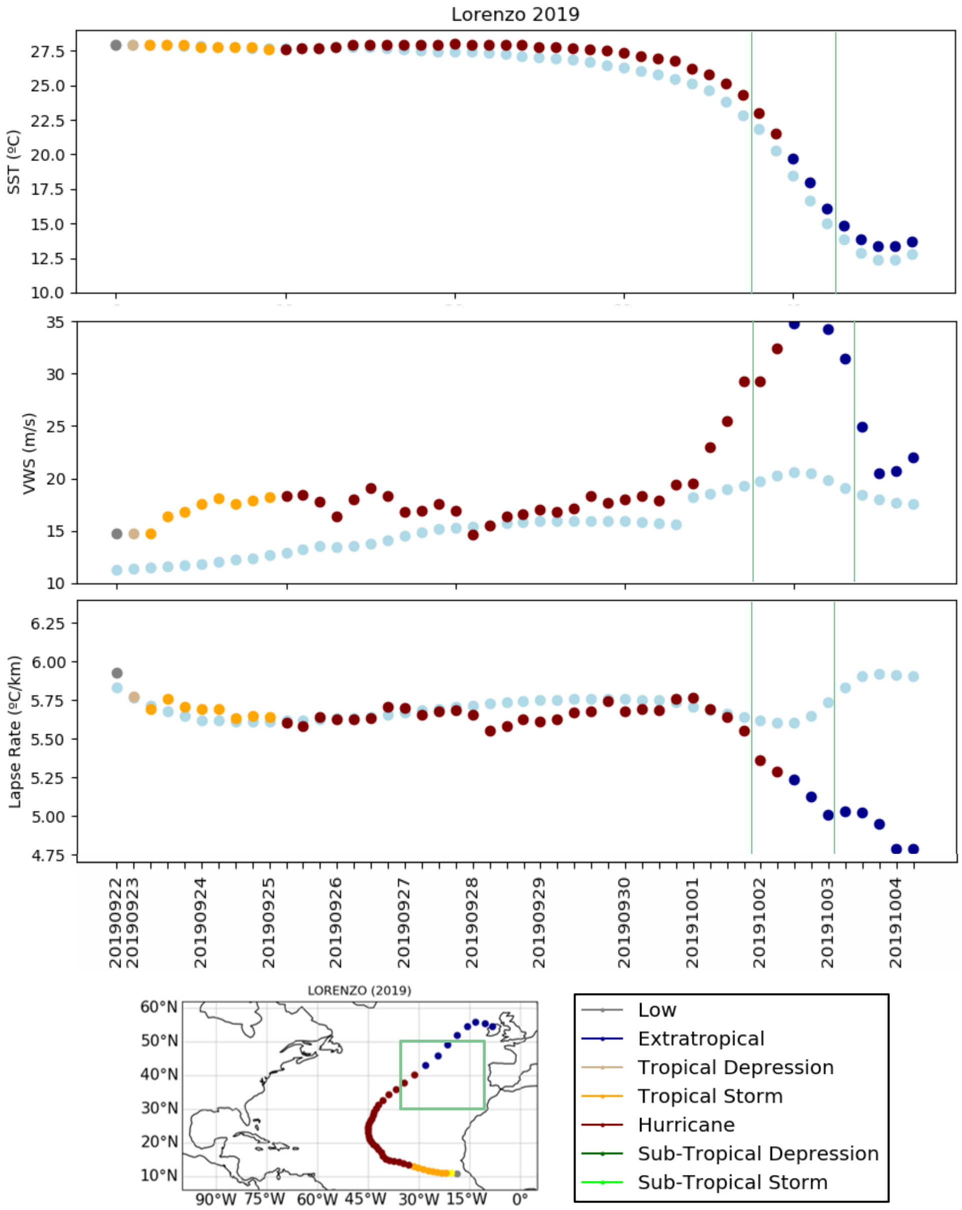

Figure 7.1 - Lorenzo’s atmospheric characteristics at each location. The x axis corresponds to the date of each best track entries given by HURDAT2. Lorenzo was the 13th hurricane in 2019 and lived from 23 September to 2 October. The light blue dots represent the mean value of the variable, as a mean of 40 years (excluding the year in which the storm occurred) and within the 2000x2000 km box around each instantaneous location. Within the green vertical lines there are the positions in which the system travel inside our area of interest.

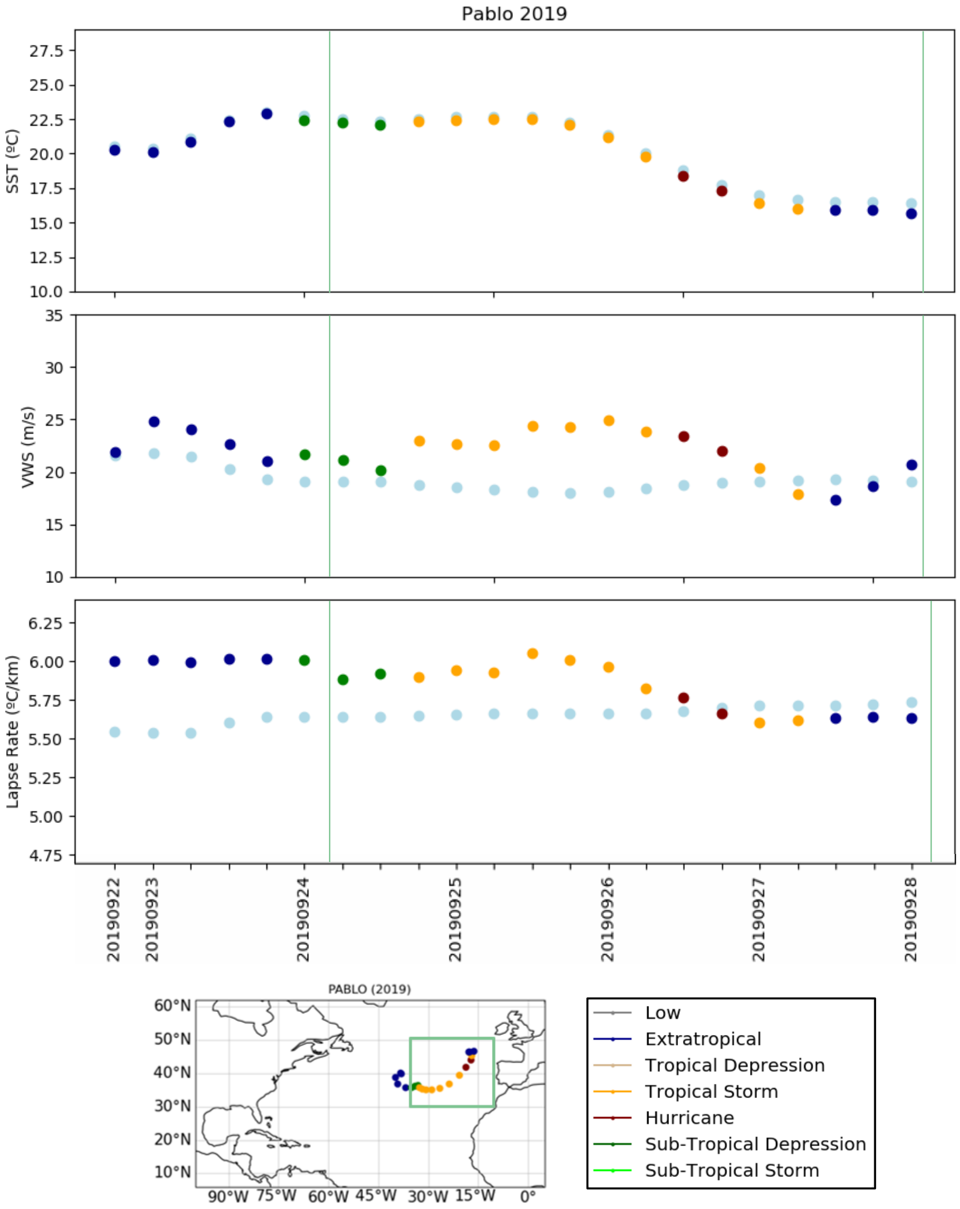

Figure 7.2 - Pablo's atmospheric characteristics at each location. The x axis corresponds to the date of each best track entries given by HURDAT2. Pablo was the 18th hurricane in 2019 and lived from 25 to 28 October. The light blue dots represent the mean value of the variable, as a mean of 40 years (excluding the year in which the storm occurred) and within the 2000x2000 km box around each instantaneous location. Within the green vertical lines there are the positions in which the system travel inside our area of interest.