Tropical / Subtropical cyclonic activity in the Canary Islands region

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1. Introduction

Tropical cyclone (TC) activity is a term that encompasses number, duration, location and intensity of cyclones formed over tropical latitudes (Vincent et al., 2014). This activity varies according to the atmospheric conditions and influences the characteristics of each cyclone, including its intensity. It is considered that the stronger the winds the cyclone produces, the stronger the intensity of the TC, allowing experts to classify these according to a series of conditions. These classifications go from Tropical Depression to Hurricane of category 5.

Most research focuses on the TC intensity and number (Murakami et al., 2020). However, in this study, spatial distribution is probably the most important. Cyclonic genesis in the North Atlantic Ocean starts in the Caribbean Sea or under Cape Verde, where the Sea Surface Temperature (SST), wind shear, Coriolis effect as well as vorticity, influence TC genesis (Emanuel, 2018). Here they gain energy from the surface layer of the ocean, via thermodynamic exchange, varying their intensity, and setting a track influenced also by atmospheric conditions.

These tracks are registered by NOAA (National Oceanic and Atmospheric Administration). However, due to lack of technology at the beginning of the 20th century, information on TC was lacking and mapping of TC tracks was only done via station observations (like ships or local meteorological stations). In 1970, with the introduction of satellite information, tropical cyclone activity phenomena were further investigated, and track analysis improved and became more precise. We could argue that global TC activity had increased due to the improvement in detection methods and not because of meteorological reasons, shown by downscaled climate reanalysis (Emanuel 2021).

Modern technology has proved that the most common TC tracks move either towards the equator where, Coriolis ceases its effect, inducing a quick dissipation into the African west coast or, towards high latitudes, where the water temperatures are cooler, producing a debilitating effect on the core of the cyclone (Emanuel, 2018); usually dissipating into the coast of Europe around the height of France and United Kingdom, just below the Northern Sea.

This spatial distribution leaves an area of almost no tropical or extratropical cyclone track activity near the African coast, between latitudes 24º N and 40º N. It is due to the meteorological characteristics of this area that during the last century only a few TC have been registered; 1980, 2005, 2010, 2012, 2018 and 2020. The lack of investigation is what has encouraged this study.

Our main objective is the analysis of these exceptional cases which have occurred close to the Canary Islands. The importance of the analysis is based on the study of the general climate conditions. We will analyze synoptically each of these cases and the climate conditions during the activity of the cyclones in the area.

The next objective is the analysis of the conditions of the occidental basin, focusing on the impact of El Niño Southern Oscillation (ENSO), observing how El Niño and La Niña affected TC activity near the Canary Archipelago, as well as the effect of Quasi-Biennial Oscillation (QBO) during the life of the TCs.

The final objective of our research is a projection of the future. Considering the effects of Climate Change (specially the increase of CO_2) on the climatology of our planet, and the impact on TC activity over the North Atlantic, and specially our area of study.

2. Methods

Most of the results shown below were obtained using the ERA5 dataset produced by the Copernicus Climate Change Service (C3S) at ECMWF (available online at https://cds.climate.copernicus.eu). ERA5 is the fifth generation ECMWF atmospheric reanalysis of the global climate covering values from January 1950 to present, where quality assured monthly updates of the data from 1979 to present are published within 3 months of real time, providing hourly estimates of a large number of atmospheric, land and oceanic climate variables at reduced spatial and temporal resolutions. The data is available at single levels, different pressure levels, as well as others, covering the Earth on a 30 km grid and resolve the atmosphere using 137 levels from the surface to a height of 80 km. In this work we have used the 850 hPa and 250 hPa pressure levels to obtain most of our u-wind data, as well as single levels for SST values.

We also used the National Oceanic and Atmospheric Administration/Climate prediction Center (NOAA/CPC) to gather data on the ENSO index, where we used Nino3.4 sea surface temperature index (available at https://www.cpc.ncep.noaa.gov/data/indices/), as well as the QBO dataset developed at the University of Berlin (available at https://www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/index.html). This dataset is constructed from radiosonde observations of zonal winds from several equatorial stations (Canton Islands, Maldives Islands, and Singapore) (Camargo & Sobel, 2010).

We decided on area of study based on METEOALERTA, a plan with the objective to provide actualized information on adverse meteorological phenomena within a range of 1000 km radius around the Canary Islands. This radius gives us approximately a surface area defined between the coordinates 24º N to 38º N and 30º W to 3º W.

To perform our analysis on tropical cyclones, we used the best track-data provided by the National Hurricane Center (Atlantic), as well as the more recent developed International Best Track Archive for Climate Stewardship (IBTrACS). Our analysis only considers tropical/subtropical cyclones inside the area described above, between 1970 and onwards, due to a lack of information on previous years.

We treated all of our data either through the Climate Reanalyzer website (available at https://climatereanalyzer.org/), platform designed to visualize climate and weather datasets, supported by the University of Maine or through a spreadsheet on Excel.

3. Results and Discussion

3.a. Characterization of the area

The study zone is located on the east side of the basin of the North Atlantic Ocean, in Macaronesia, next to the African coast of Morocco and Western Sahara, with a population of 2.15 million people. The climate is considered to be warm subtropical and semi desertic, with a large presence of microclimates. According to the Köppen climate classification, the main groups in which the climate of the Canary Islands fall, are BWh, referring to hot desertic climate, and CSb, referring to temperate with dry and warm summers (Martín-Carrillo et al., 2021).

Being an archipelago, the climatic conditions are moderated by the sea, especially because of the Canary Current, and the trade winds. This current is a wind-driven surface current that is about 500 m deep, belonging to the North Atlantic Gyre, it flows along the African coast from the north towards the south, between 30º N and 10º N. It is a wide (100 km) and slow (10-30 cm s^{-1}) current (Wooster et al. 1976) characteristics belonging to an eastern boundary current, flowing all year long towards the equator while entraining upwelled water from the coast, making the surface water relatively cool (Mittelstaedt, 1991). Seasonal patterns on the behavior of the Canary Current have been discovered, strengthening during summer when the trade winds are at their peak. This produces a core velocity of 75 cm s^{-1} as it passes through the Canary Islands, moving parallel to the coastline until 20º N, point after which the current starts to flow west due to the influence of the Equatorial Countercurrent (Fedosev 1970). The seasonal variation of the coastal upwelling is coupled with the meridional shift of the Azores High. The stronger the trade winds are, the stronger the upwelling is, and, depending on the position of the Azores High, the upwelling occurs at one latitude or another. In the summer, we find the Azores High at its northernmost position, further strengthening of winds between 32º N and 20º N and intensifying the upwelling north of Cape Ghir (32º N) spreading the filaments outwards from the coast (Hernández-Guerra et al., 2002). As the seasons change, the Azores High moves southwards, and the Upwelling intensifies at lower latitudes (25º N-10º N), losing strength in the 25º N to 32º N latitudes and causing a strong upwelling all year long in the 20º N- 25º N latitudinal band (Hernández-Guerra et al., 2002).

The Trade Winds also referred as easterlies, are a permanent east-to-west prevailing wind that flows around the equator (Azorin-Molina et al., 2017), created by the cooling air descending from the Hadley cell, around subtropical latitudes. In the

Canary Archipelago, the presence of north-east trade winds, which is the return component of the anti-trades arriving from the equatorial region blowing throughout the year, are driven by the Azores high pressure system (Azorin-Molina et al., 2017). They maintain stable conditions throughout the year, allowing lower temperatures than those at the same latitude.

Hot dry dusty winds coming from the Sahara also bring dry weather with low visibility known as "calima" over the archipelago, due to the influence of the Saharan Air Layer (SAL) (Barreto et al., 2022). The Saharan Air Layer is an extremely hot, dry and sometimes dust-filled layer of the atmosphere that often moves and overlaps the cooler, more humid surface of air, over the Atlantic Ocean (Prospero et al., 1970). SAL outbreaks normally happen from late spring to early fall and cover extensive portions of the Atlantic Ocean, from the coast of Africa to the Caribbean coast, affecting our study zone directly.

SAL effects air temperature, turning the 800-900 hPa layer between 5º C and 10º C warmer than the typical moist tropical sounding, and affecting the humidity of the air simultaneously, becoming 50 % dryer than the moist tropical atmosphere (Dunion, 2011). It also has an effect on vertical shear wind, increasing it between 25-75 kt in the North Atlantic by a mid-level jet normally located in the 600-800 hPa layer. (CIMSS Tropical Cyclones - Saharan Air Layer (SAL), n. d.). SAL-TC interaction can either mitigate TC activity by affecting TC genesis and intensification, or, if overrun by the faster moving SAL, TCs remain insulated from the inhibiting effects of SAL and intensify, making every TC interaction unique depending on its climate conditions.

(a) (b)

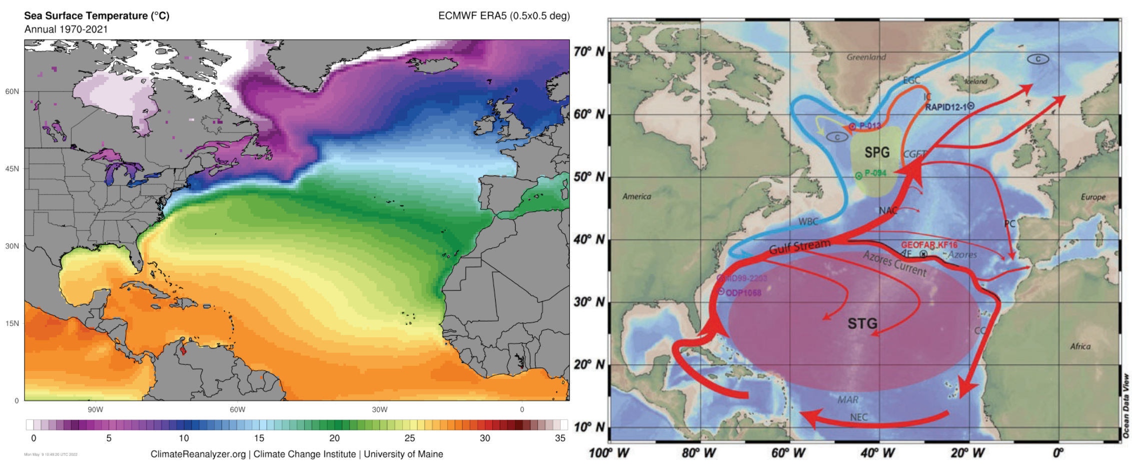


Fig. 1 – SST maps of the North Atlantic Ocean. a) Annual mean SST 1970-2021 b) Modern surface water hydrography of the North Atlantic currents (Repschläger et al., 2017) – from *Climate Reanalyzer (https://ClimateReanalyzer.org), Climate Change Institute, University of Maine, USA.*

If we observe the fig. 1a. where annual mean Sea Surface Temperature (SST) values of the North Atlantic are represented from 1970 to 2021, we can see that the mean value of our study zone is that of around 20º C, being colder from Azores to Lanzarote and along the African Coast, due to the presence of the Canary Current. SST values in our study zone are colder compared to the ones in the east side of the basin at the same latitude, where we can observe mean temperatures of around 25º C or even higher.

The North Atlantic Current (NAC), governs the water circulation in the North Atlantic, transporting warm saline water to higher latitudes (Roessler et al., 2015). This current branches off several times on its way to polar latitudes, creating several currents, such as the Azores Current and Irminger Current between others (Fig. 1b.). Irminger Current, goes through the Labrador Sea on the Southwestern coast of Greenland feeding warm saline water into the counterclockwise-rotating subpolar gyre, fueling deep-water convection and returning to the NAC as cold water that helps cooling the Gulf Stream and in consequence, the Azores Current (Repschläger et al., 2017). The eastward-flowing Azores Current, separates from the NAC between 30º N and 40º N, forming the northern boundary of the subtropical gyre. It then rotates clockwise circulating cold water into the coast of Africa via the Canary Current, which transitions to saline warm water nearing the equator. It later recirculates warm water between 10º N and 40º N (Repschläger et al., 2017).

Throughout the atmosphere, the wind conditions vary in intensity and direction at different pressure levels. In TC activity the difference of the values between layers is important. If this difference is too big, tropical cyclonic activity can't survive. This is difference is called wind shear, defined as

$$Wind\ Shear = (Zonal\ Wind_{850hPa} - Zonal\ Wind_{250hPa})$$

To calculate and analyze the wind shear of our study zone, we used the 850 hPa and 250 hPa pressure levels due to them being the most common used levels to calculate the shear wind variable. (Rhome et al., 2006)

(a) (b)

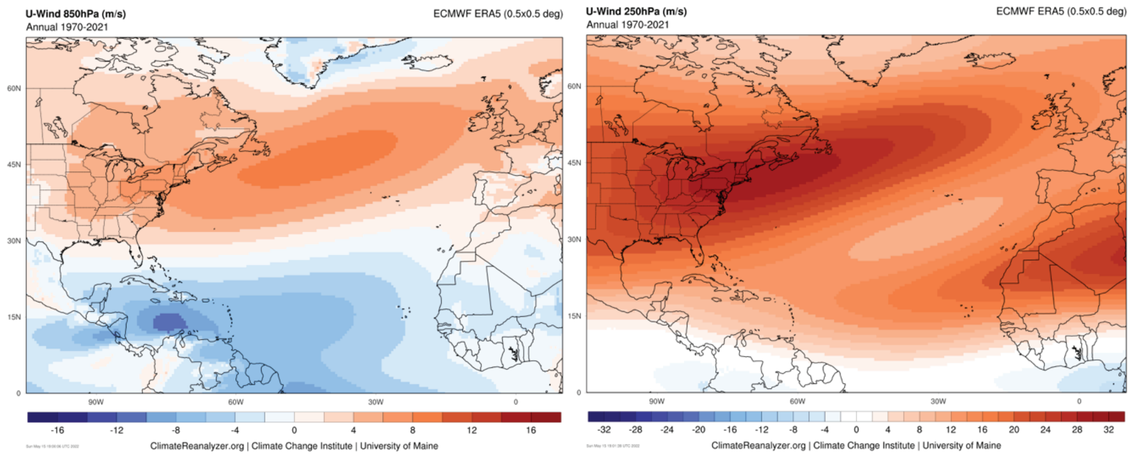


Fig. 2 – u-wind annual mean component reanalysis map from 1970-2021-a) at 850 hPa, b) at 250 hPa- *from Climate Reanalyzer (https://ClimateReanalyzer.org), Climate Change Institute, University of Maine, USA.*

Here (fig. 2) we have the u-wind annual mean values from 1970-2021 at different pressure levels, so we can observe which winds predominate overall in our study area.

On one hand, positive values in fig. 2 are attributed to winds coming from the west, or westerlies. On the other hand, negative values represented in blue indicate winds coming from the east, also known as easterlies or trade winds. If we look at 850 hPa variables (fig. 2a.) in a radius of 500 nautical miles from the Canary Archipelago, we can divide the surface in two. The southwestern part of the surface seems to be dominated by easterlies with low intensity values, ranging circa 0 m s^{-1} to 2 m s^{-1}, while the northeastern part of the study area seems dominated by westerlies with low intensity values here as well of around 0 m s^{-1} to 2 m s^{-1}. Meanwhile, the values at the 250 hPa pressure level are in their majority positive over the North Atlantic Ocean, implying that westerlies dominate this pressure level throughout the years, with values ranging from circa 6 m s^{-1} to 20 m s^{-1} in our study area. As we move further into Central Atlantic, a decreasing intensity gradient seems to appear, indicating stronger winds on the African Coast.

(a) (b)

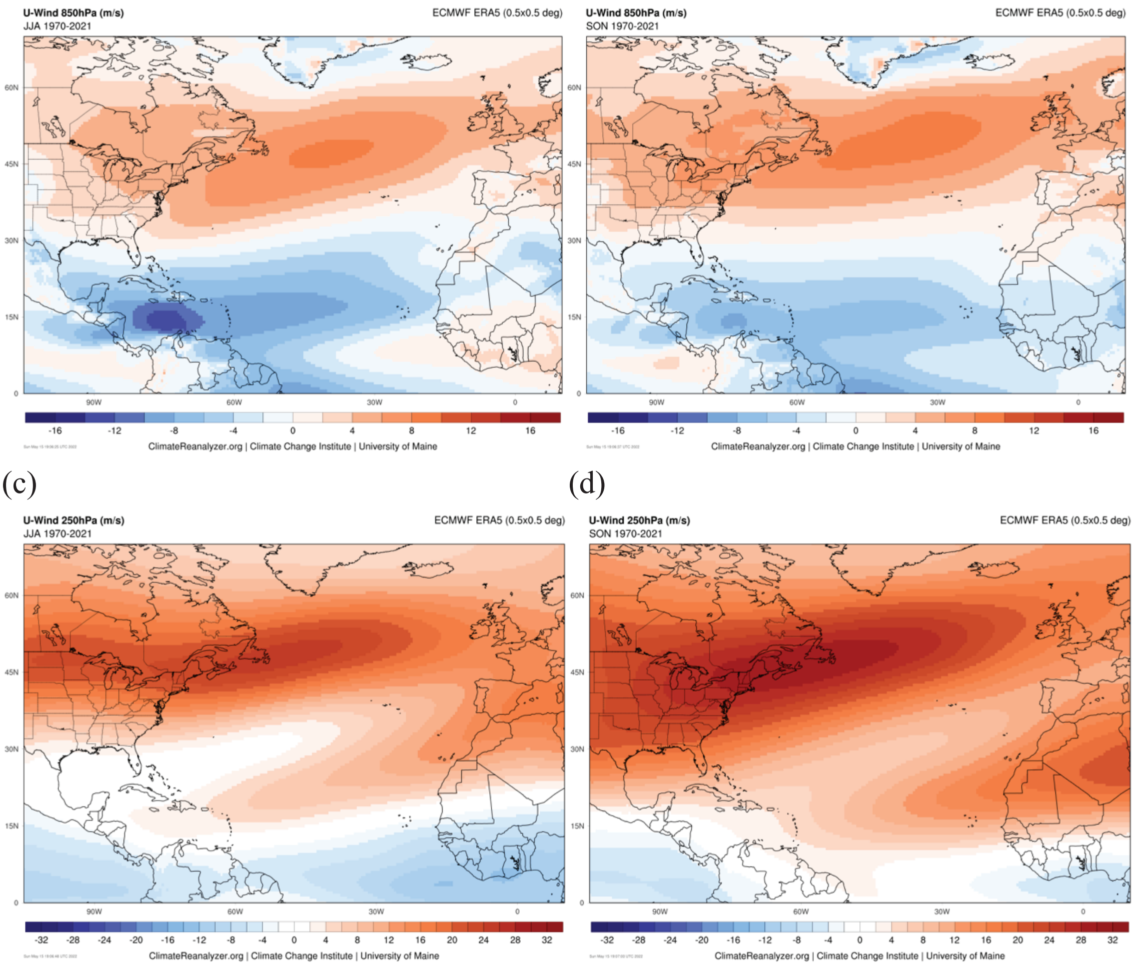


Fig. 3 – u-wind monthly mean component reanalysis maps for (a) JJA (b) SON seasons at 850 hPa, (c) JJA (d) SON seasons at 250 hPa from 1970-2021- *from Climate Reanalyzer (https://ClimateReanalyzer.org), Climate Change Institute, University of Maine, USA.*

We then have u-wind values representing only the cyclonic season going from June to November (JJASON) at both pressure levels. Due to the reanalysis model used, we can only represent these values divided by trimesters, 1st one is from June to August (JJA) (fig. 3a.) and the 2nd one is September to November (SON) (fig. 3b.). During the JJA season, our study zone seems to be predominately dominated by the presence of easterlies. The intensity of the u-winds during this period of time is very low, ranging from 0 m s^{-1} to -2 m s^{-1} and decreasing as we move towards the western part of the Atlantic basin, reaching their peak intensity over the Caribbean Sea. During the SON season, the u-wind conditions change. As we can observe that the surface in our study area that was dominated before by easterlies is now dominated by westerlies of low intensity values, here again ranging from 0 to 2 m s^{-1}. While the most western part of the study area remains predominated by easterlies. During the JJASON season, the westerlies predominate the Northern Atlantic Ocean at 250 hPa, but compared to annual values, the intensities seem to have diminished. As we can see a division appearing (fig. 3c. & 3d.) through the Atlantic Ocean, leaving lower values on the southeastern part of the basin and higher values on the northwestern part, while a trough with values circa 0 m s^{-1} appears in the middle, form the Caribbean Sea towards the center of the Atlantic. If we focus on our study zone, we observe that in JJA (fig. 3c.), the westerlies present a value of around 12 m s^{-1} and around 16 m s^{-1} during SON (fig. 3d.)

The 25 kt (12,5 m s^{-1}) wind shear value is considered the maximum intensity at which TC can suffer intensification (Elsberry & Jeffries, 1996). After such conditions, the TC will quickly dissipate as explained by Emanuel (2018). Knowing the general state of wind and SST, as well as other conditions cited before, the area doesn't seem to have optimal conditions for TC presence and would only support a decaying cyclones or dissipating systems. But as we will see hereafter, this is not the case for all the TC present near the Canary Archipelago.

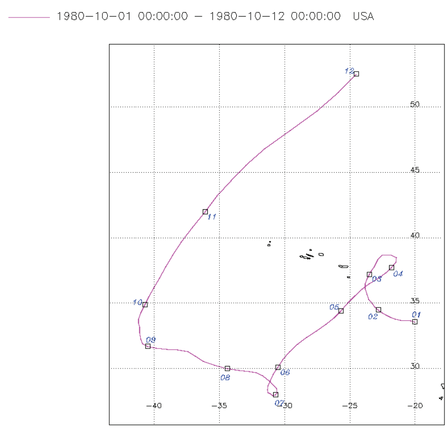
3.b. Retrospective synoptic analysis of the region´s cyclones

All the individual cases of Tropical and Subtropical cyclonic activity that appear in our study zone are represented in Table. 1. Every cyclone has been categorized by their maximum intensity overall and their maximum intensity in our study zone. We have also described the state of ENSO in El Niño and La Niña phases during the existence of every TC. Here under, we will analyze every individual cyclone synoptically; describing their characteristics, including their intensities and directions of the systems while they lived. Since we can only obtain accurate data from 1970 and onwards, we will study the TC that are present after this date.

Year	Name	Category in Study Zone	Max Category attained	Origin	ENSO Stage
1980	Ivan	Extratropical	Hurricane	East Atlantic	Neutral
2005	Vince	Hurricane	Hurricane	East Atlantic	Neutral
	Delta	Tropical Storm	Tropical Storm	Central Atlantic	La Niña
2010	Otto	Disturbance	Hurricane	West Atlantic	La Niña
2012	Nadine	Tropical Storm	Hurricane	East Atlantic	Neutral
2018	Leslie	Hurricane	Hurricane	Central Atlantic	El Niño
2020	Paulette	Tropical Storm	Hurricane	Central Atlantic	La Niña
	Theta	Tropical Storm	Tropical Storm	Central Atlantic	La Niña

Table. 1 – Particular cases of TC affecting the region

(a)



(b)

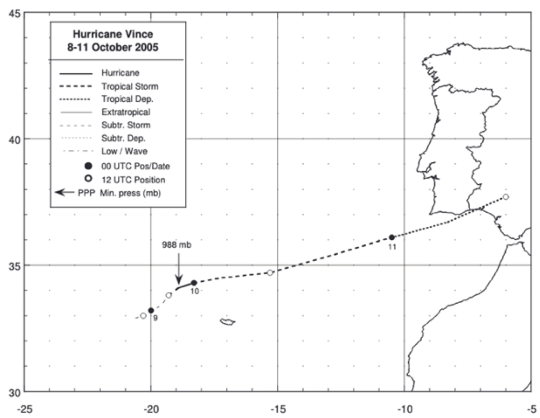


Fig. 4 – (a) Best track of Hurricane Ivan, October 1980- (Knapp, 1981), (b) Best track of Hurricane Vince, October 2005 (Franklin & National Hurricane Center, 2006), (c) Best track of Hurricane Delta, November 2005 (Beven & National Hurricane Center, 2006), (d) Best track of Hurricane Otto, October 2010 (Cangialosi & National Hurricane Center, 2010), (e) Best track of Hurricane Nadine, September-October 2012 (Brown & National Hurricane Center, 2013), (f) Best track of Hurricane Leslie, September-October 2018 (Pasch et al., 2019), (g) Best track of Hurricane Paulette, September 2020 (Latto & National Hurricane Center, 2020), (h) Best track of Hurricane Theta, November 2020 (Beven II & National Hurricane Center, 2021)

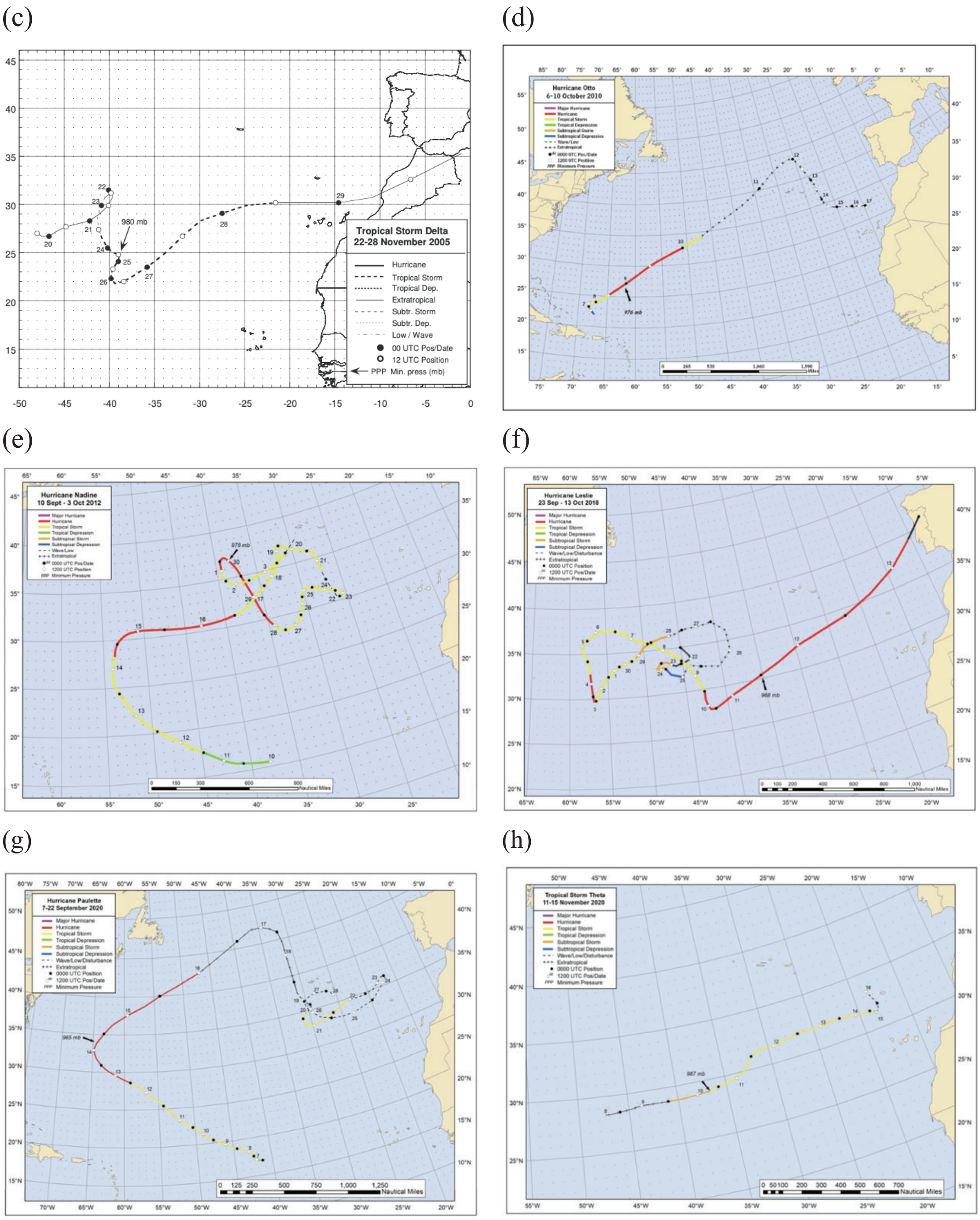


Fig. 4 – continued.

Hurricane Ivan (fig. 4a.) develops in an atypical way, in September 1980, a cold low was detected in the coast of Portugal, it extended itself from the surface to the troposphere, creating a cold nucleus system. On the 5th of October, the center of circulation was clearly defined in a zone of concentrated convection as it started to gain strength along its movement towards the southwest, finally achieving the strength of a hurricane. Changing its trajectory again at the height of the Canary Islands, turning towards the northwest and loosing strength until it dissipated. (National Hurricane Center, 1981)

Vince (2005) was the hurricane coming from the Atlantic Ocean that has reached the farthest into the east (fig. 4b.). It originated after an occluded deep-layer frontal low that was moving southeastward through Azores the 6th of October. Gaining organized convection around the center of circulation, allowing us to designate the cyclone as a subtropical storm on the 8th of October. The system had a very prominent cold core on the upper part of the troposphere, hence categorized as subtropical. As it moved northeastward, it acquired a warm-core on the mid-upper troposphere level, giving Vince the conditions to be categorized as a TS. That same day on the 9th of October, a cloud band started to form around, presenting an eye pattern, converting the TS into a category 1 hurricane, but it almost immediately started to debilitate, regaining its TS condition due to high vertical wind shear, dissipating over the Iberic Peninsula. (Franklin & National Hurricane Center, 2006)

Delta storm (fig. 4c.) was a Tropical storm (TS) that appeared at the end of the cyclonic season, turning into an extratropical storm that caused high speed winds that damaged the Canary Islands. The system started as a non-tropical system that moved towards northeast and started to develop a central convection, forming an upper-level warm core. On the 23rd of November the convection consolidated, and Delta became a TS, reaching maximum wind intensities of 60kt. An increase of vertical wind shear caused the system to debilitate, but just after, due to an intensification of the deep layer over eastern Europe, Delta accelerated towards east-northeast, accompanied by a re-intensification of the maximum winds. On the 28th of November, the cyclone turned northeastward into a zone where vertical wind shear and cold air made the system lose its tropical properties, loosing strength approaching Morocco and dissipating over Argelia. (Beven & National Hurricane Center, 2006)

Otto (2010) developed from a well-defined circulation next to San Juan, Puerto Rico (fig. 4d.). The genesis of hurricane Otto started as a subtropical depression that began to gain strength moving towards the northwest. Once the necessary intensity was gained, it converted into a subtropical storm and changed direction northeastwards. On the night of the 7th of October, a deep-convection started to form, which indicated the presence of a warm-core that developed vertically, turning Otto into a Tropical Storm. The cyclone then intensified and became a Hurricane on the 8th of October, reaching a maximum wind speeds of 75 kt. But due to vertical shear winds, it debilitated as it moved, losing TC characteristics. The system then changed direction towards the south and acquired the intensity of a Tropical Depression (TD), dissipating a bit after over the Canary Islands. (Cangialosi & National Hurricane Center, 2010)

Hurricane Nadine (fig. 4e.) formed after a tropical wave that developed a broad area of low pressure on the 9th of September 2012 near Cape Verde Islands. A day later, the deep convection started to become more organized and the low better defined, leading to the formation of a tropical depression. Because a deep convection redeveloped the next day, the cyclone started to strengthen gradually making the depression transition into a tropical storm. When the system was over a zone with warm waters and low wind shear, Nadine quickly intensified. But the strengthening episode came to an end when the cyclone entered a region with moderate southwesterly shear, despite this, the inner-core convective structure developed gradually, and Nadine became a hurricane. Due to strong westerly shear, the system decelerated, and the associated deep convection became less symmetric and separated from the low-level center causing Nadine to weaken. Dry air then wrapped into the circulation and caused the deep convection to diminish, losing TC status and becoming a non-tropical low-pressure area near Azores. But, as it moved over warm waters, gradual strengthening ensued and Nadine became a hurricane for a second time, but quickly weakened into a tropical storm due to upwelled cooled waters. Finally, an increase in vertical shear wind weakened the storms intensity, dissipating into a post-tropical low. (Brown & National Hurricane Center, 2013)

Leslie (2018) (fig. 4f.) originated after a non-tropical system, moving slowly and erratically. The cyclone then lost frontal features as its outer cloud bands became sufficiently defined to designate the system as a subtropical storm. Dry air and a moderated vertical wind shear debilitated the system until it was considered a subtropical depression. The same day, Leslie merged with a front, and the system reverted itself into the state of an extratropical cyclone, moving and gaining speed, while intensifying due to baroclinic processes until it started to produce hurricane winds on the 27th of September. It then regained its state of Subtropical storm for a day, after which the system evolved into a Tropical storm due to a deep convection that formed near the center. On the 2nd of October, the system became almost stationary while it was intensifying slowly and, on the 3rd, it finally became a hurricane that debilitated quickly due to it moving at high speeds over low temperature waters. Leslie was considered a TS the next day, and as its core structure became better defined while it moved towards the southeast, Leslie regained its hurricane state on the 10th of October. The system continued to gain strength while it moved east-northeastwards to finally lose it, and transition into a tropical storm that dissipated over Portugal. (Pasch et al., 2019)

Paulette (fig. 4g.) formed after a tropical wave that departed from the west coast of Africa and a low-pressure area that was moving slowly to its west. By the 5th of September, both systems merged, better defining the associated surface low and by the 7th, the convection increased sufficiently to designate the system as a tropical depression. The system slowly strengthened because of a moderate southwesterly vertical wind shear and surrounding dry air that limited its intensification. After a period of weakening due to strong wind shear, Paulette turned northwest increasing its speed and intensifying at the same time, until the system attained the conditions to be categorized as a hurricane. It then began to accelerate towards the northeast, to then transition to extratropical as a baroclinic zone approached from the northwest, decreasing peak winds and expanding its wind field. Due to the system reaching cold waters of the northern Atlantic, and interacting with the baroclinic zone, the hurricane completed its transition to an extratropical cyclone. When it reached Azores, it regained intensity attaining Tropical Storm characteristics but quickly dissipated due to strong wind shear. (Latto & National Hurricane Center, 2020)

Finally, Theta a cyclone of subtropical origin (fig. 4h.), appeared due to an upper-level trough that developed over the central Atlantic Ocean in November 2020. A non-tropical surface low pressure formed along a weak frontal zone about 1130 nautical miles west-southwest of Azores, while the low moved eastward. An increase of winds to gale forces and a better organized convection made the system non-frontal, becoming a subtropical storm while approaching Azores. Shortly after, the cyclone transitioned to a tropical storm as it entered a light-shear region and from then on, the system generally moved eastwards, until it dissipated due to dry air entrainment that caused the convection to be sporadic and in consequence exposed the low-level core. (Beven II & National Hurricane Center, 2021)

3.c. Climatic conditions in situations with cyclonic activity in the area

When looking into the conditions for TC formation, we assume that the most important variables that contribute to their life are, SST and vertical wind shear, with a threshold of 26º C and 12.5 m s^{-1} respectively (Emanuel, 2018). In exceptional cases as described before, CT do present themselves in the area, this is why we are intrigued to evaluate the climate conditions during those episodes.

As we can see in fig. 5a., the number of cyclones has risen in the last years. Knowing that SST has a big relevance in TC activity, we observe the monthly values of this variable from 1970 onwards using data from ERA5 dataset.

The SST values vary according to seasonal change, solar radiation exposure as well as surface turbulence induced by the winds. They are at their lowest during January and increase until attaining their maximum around August or September (fig. 5c.), the temperatures then decrease until January, closing a cycle. TC activity season spans between June and November, time period where sea surface temperatures are at their highest. In our study region, the maximum value of SST we attain is 24,4º C in August 2004, while the lowest temperature is attained in March 1972, at 16,9º C. Knowing that the necessary minimum value for TC formation is 26ºC (Emanuel, 2018), we would assume that these conditions are unfavorable for TC presence due to their low temperatures and would only present almost dissipated systems that are reaching their end life. Since, TC present in the area appear with maximum temperatures of 24,3º C (September 2012), and minimum values of 21,3º C (November 2005). This data makes us believe that other climatologic conditions are responsible for TC presence in the area.

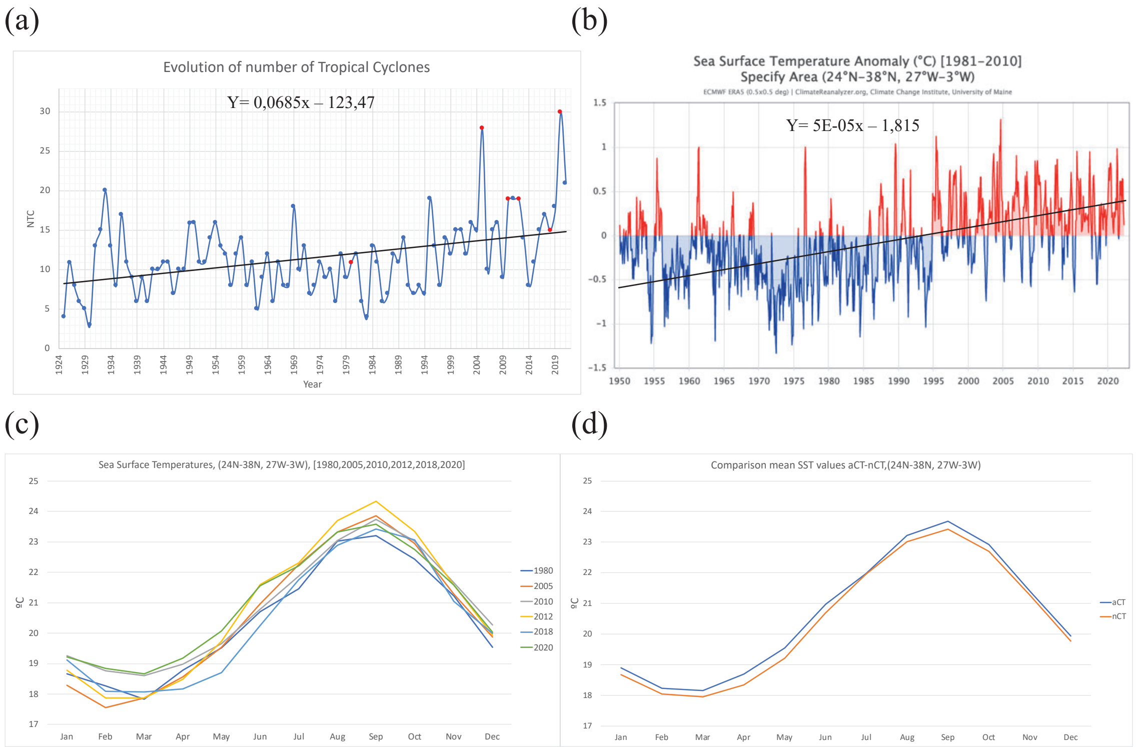


Fig. 5 – (a) Evolution of number of Tropical Cyclones over the Atlantic Ocean through the last century, (b) Sea Surface Temperature Anomaly (ºC), (24ºN-38ºN, 27ºW-3ºW), [1950-2022] (c) SST temporal variation (ºC) for aTC years, (24N-38N, 27W-3W), [1980, 2005, 2010, 2012, 2018, 2020], (d) Sea Surface Temperature mean (ºC) aTC-nTC, (24ºN-38ºN, 27ºW-3ºW)]- ERA5, *from Climate Reanalyzer (https://ClimateReanalyzer.org), Climate Change Institute, University of Maine, USA.*

If we shift our focus on SST anomaly (SSTA) values instead of mean values, we can understand the changes suffered by the SST that might have led to the presence of TCs. The SST anomaly values give us information on an increase or decrease of temperatures compared to normal conditions. Those normal conditions have been defined as the mean value of temperatures of every month individually, over the span of our study. If we look at fig. 5b., we can see an increase in temperature values shifting from mostly negative to positive after the year 2000. Century in which we also start to appreciate more TC activity in our study zone. Overall, it appears that TC activity is present when the anomaly values are positive, implying that an increase in SST the month of TC activity might be necessary. This isn't absolute, as an increase in SST does not imply presence of TC. We can observe negative values in some cases of TC presence, like in October 1980, November 2005 and September 2018 (Fig. 5b.) ranging from -0,3º C to -0,03º C, as well as positive values without presence of TC. SSTA seem to be more influent on TC activity than SST mean values, as observed TC appear in cold waters per se, but not in waters that are much colder than usual.

The difference of SST values between the years with TC activity (aTC) and the years with no activity at all (nTC) (fig. 5d.) are relevant to confirm the conditions for TC presence. Observing the data from the ERA5 database, we see that the SST mean values for aTC are higher than the ones for nTC, implying that the presence of TC might have been due to higher mean values in those years, dictated by a positive SSTA.

As explained before, wind shear is one of the most essential variables in TC existence, a difference of high wind speeds and direction in different altitudes amounting to a wind shear over 25 kt (12,5 m s^{-1}) (Emanuel, 2018) will mitigate the cyclone until dissipation. This shear wind can be better observed comparing u-wind (or Zonal Wind) values between the 850 hPa and 250 hPa layers (Rhome et al., 2006), that we will analyze hereafter.

We have represented in fig. 6 the u-wind maps at 850 hPa for every SON period with TC activity near the Canary Archipelago. During Hurricane Ivan (fig. 6a.) the conditions of the u-winds were divided, as we can see that the surface area is split in two parts. The northeastern part dominated by westerlies and the southwestern part dominated by easterlies. Even though two different directions are presented, their values a very close to 0. Calculating the mean u-wind value of the area using Climate Reanalyzer data obtained after ERA5 dataset, gives us a mean value of 0,24 m s^{-1}, which corresponds to the values seen in the map and explains that even though we see easterly and westerly winds, the westerly winds dominate the area overall.

During existence of Vince and Delta in 2005 (fig. 6b), Otto in 2010 (fig. 6c.) as well as Paulette and Theta in 2020 (fig. 6f), we can observe that the study area is mostly dominated by mild intensity westerlies. With values between 0 and 2 m s^{-1} according to the map, as well as little to no presence of easterlies on the most western part of the area. If we look into the data from Climate Reanalyzer obtained after ERA5 dataset, we find that the u-wind values at 850 hPa for the SON trimester in those years, were, 0,75 m s^{-1}, 1,11 m s^{-1} and 0,32 m s^{-1} respectively.

In fig. 6d. we can observe that the study area is completely dominated by westerlies with values between 0 and 4 m s^{-1} according to the map. If we look into the data from Climate Reanalyzer obtained with ERA5 dataset, we find that the u-wind value at 850 hPa for the 2012 SON trimester in presence of Nadine were 2,26 m s^{-1}. Implying the complete domination of higher intensity westerly winds in our study area for this period of time compared to other years.

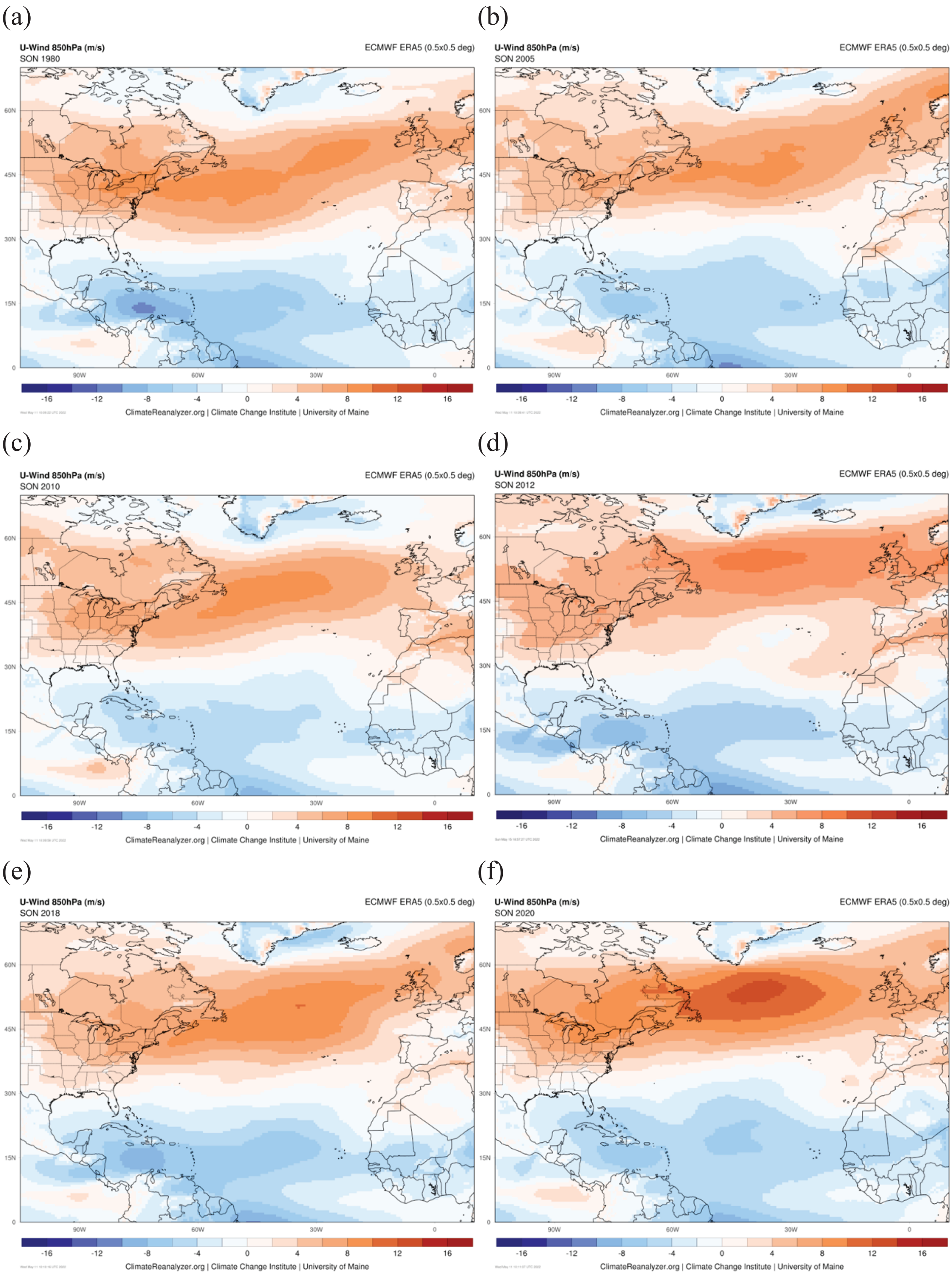


Fig. 6 – u-wind component at 850 hPa for SON season, (24ºN-38ºN, 27ºW-3ºW), a) 1980, b) 2005, c) 2010, d) 2012 e) 2018, f) 2020 - *from Climate Reanalyzer (https://ClimateReanalyzer.org), Climate Change Institute, University of Maine, USA*

In 2018, Hurricane Leslie appears. During this SON season (fig. 6e.), the u-wind conditions at 850 hPa became polarized again in our study area. The division between easterlies and westerlies shows again very low intensity values ranging circa 0 m s^{-1} for both directions of the wind. The data from Climate Reanalyzer obtained after ERA5 dataset, gives us the following SON value 0,64 m s^{-1}. Similar to SON 2005 conditions (fig. 2a.), the polarized wind conditions in the area present a stronger influence of westerlies, with a slight intensity difference between 2005 and 2018. This is seen in the map of fig. 9e. with a bigger influence of the positive values compared to fig. 9a.

An observation of the zonal wind conditions at 250 hPa will help us calculate and understand the conditions of wind shear during TC activity. Their intensity values range from 8,9 m s^{-1} to 21,3 m s^{-1}, indicating a strong presence of westerly winds.

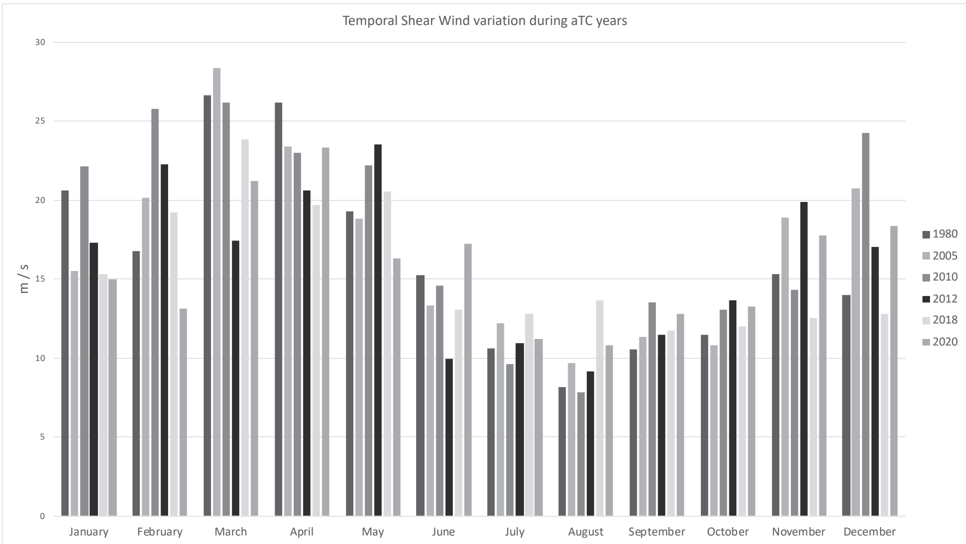


Fig. 7 – Temporal wind shear intensity variation during aTC years, (24ºN-38ºN, 27ºW-3ºW), [1980, 2005, 2010, 2012, 2018, 2020] - *from Climate Reanalyzer (https://ClimateReanalyzer.org), Climate Change Institute, University of Maine, USA.*

Looking at fig. 7, we observe a pattern on the intensity of the shear wind in aTC years. It seems that from January to March/April the shear wind increases generally. From then, it decreases until August, when the trade winds are at their peak. And from then on, the intensity increases a bit to reach similar values to the ones from January, completing a cycle. Of course, we can see values that do not follow the normal tendency from one month to the other, but generally speaking they all follow the same pattern. The intensity values range from 7,9 m s^{-1} to 28,3 m s^{-1} attaining them in August 2010 and March 2005 respectively. Looking at the data from the aTC years (fig. 7), we observe that during the JJASON season several wind shear values have come close and even surpassed the 12,5 m s^{-1} threshold. Implying that the wind shear conditions where not always favorable during these years for TC activity in our study area.

During the presence of the TCs, the values of wind shear were 11,5 m s^{-1} for Ivan (1980), 10,8 m s^{-1} for Vince and 18,9 m s^{-1} for Delta in 2005. Otto (2010) had values of 13,1 m s^{-1}, followed by Nadine (2012) with intensities of 11,5 m s^{-1} in September and

13,7 m s^{-1} in October. In 2018, Leslie suffered shear wind intensities of 11,7 m s^{-1} and 12 m s^{-1} in September and October respectively. Finally, in 2020, Paulette suffered a wind shear of 12, 8 m s^{-1} and Theta suffered values of 17,7 m s^{-1}. We can see that TC Delta, Otto, Nadine, as well as Paulette and Theta went through our study zone under unfavorable shear wind conditions for TC intensification, leading to their dissipation over time, as we can see in the synoptical analysis done beforehand (fig. 4). However, the other TCs (Ivan, Vince and Leslie) maintained their intensity and even increased, like in the case of Leslie (2018), showing the influence that wind shear has over TC activity and how wind shear values over the threshold are one of the main reasons of low activity in our study zone.

After having seen the climatologic conditions of the study area during TC activity, we want to understand how they are influenced by global oscillations and how the atmospheric conditions can alter the characteristics of our study zone increasing the probability of TC activity in it.

3.d. Effects of Atmospheric Oscillations on Tropical Cyclonic activity; relation with ENSO, variation in the presence of El Niño and La Niña and influence of QBO

TC activity is influenced by the large-scale environment and so by different modes of climate variability (Camargo & Sobel, 2010). Gray (1984a) pointed out in his paper, that one of the main inter-seasonal phenomena that influenced their activity in the North Atlantic is the El Niño-Southern Oscillation (ENSO). As well as hypothesize that seasonal hurricane frequency in the Atlantic basin and the stratospheric Quasi-Biennial Oscillation (QBO) are associated with the trade-wind nature of Atlantic cyclone formation.

ENSO is a recurring 3-to-7-year period climate pattern involving water temperatures in the central and eastern tropical Pacific Ocean. The surface waters warm or cool from 1º C to 3º C, depending on the phase of the ENSO cycle (Wang, 2001). It affects rainfall and temperature distribution in the tropics and can have a large influence on weather around the world due to its ability to change the global atmospheric circulation. The 3 phases that characterize ENSO are two extremes, called El Niño and La Niña, as well as a neutral one called ENSO-neutral.

El Niño is the hotter phase of ENSO, where the temperatures of the sea surface are above average. The hotter they are, the stronger El Niño is considered. The rainfall over Indonesia tends to reduce, while it increases over the central and eastern Pacific Ocean. The low-level surface winds considered easterlies along the equator, weaken or even switch in some cases to westerlies (Hanley et al., 2003).

La Niña phase presents a cooling of the SST to below-average conditions over the central and eastern Pacific Ocean. Easterly winds become stronger over the equator and the rainfall over Indonesia increases, while the eastern Pacific turns dryer (Hanley et al., 2003).

Neither El Niño nor La Niña conditions appear sometimes, turning ENSO-neutral. SSTs are considered close to average, and while the sea conditions can seem to belong to one phase or the other, the atmospheric conditions do not play along (Hanley et al., 2003).

QBO is a quasi-periodic oscillation of the tropical winds in the stratosphere. It dominates the interannual variability of the equatorial stratosphere, by alternating periods of westerly and easterly zonal winds that descend with time (Camargo & Sobel 2010). The full QBO cycle takes 28 months more or less, alternating the direction of the winds every 14 months, affecting stratospheric dynamics.

Gray (1984 a, b) pointed out an influence of QBO on TC activity over the Atlantic Ocean. He stated that when QBO was in a westerly phase, TC activity was greater than when QBO was in its easterly phase. But Camargo & Sobel (2010) found out that somewhere between the 1980s and the 1990s the QBO relationship with TC activity seemed to change. Apparently, they didn't present significant correlation between both of them to state a clear influence of the QBO phase over TC activity over the Atlantic Ocean in later periods, opposed to Gray (1984 a, b) results.

ENSO and QBO have similar time scales (Camargo & Sobel, 2010). So, we will evaluate the relationship between the TC studied in our paper and the different phases of both oscillations. We want to determine if there is an atmospheric and stratospheric influence over the presence of TC near the Canary Islands.

(a) (b)

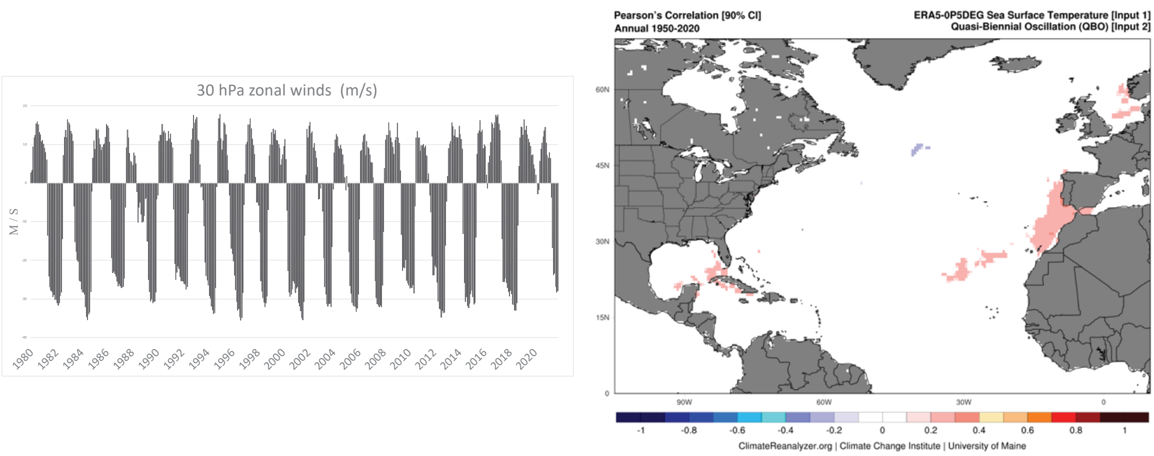


Fig 8 –(a) Zonal wind values at 30 hPa, [1980-2021] - *from Freie Universität Berlin (https://www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/index.html#access), Department of Earth Sciences, Institute of Meteorology, University of Berlin, Germany.* (b) QBO index and SST correlation map, (24ºN-38ºN, 27ºW-3ºW), [1950-2020] - *from Climate Reanalyzer (https://ClimateReanalyzer.org), Climate Change Institute, University of Maine, USA.*

Figure 8a. represents the zonal wind values at 30 hPa attributed to QBO index. Using the same data as in Camargo & Sobel (2010), we use the values at 30 hPa because this pressure level is where we find statistically significant stronger relationship between QBO and TC activity as well the method used by Gray (1984 a, b). Since QBO descends with time, we will only evaluate u-winds at one pressure level as using others could alter the results.

We observe the westerly (W) and easterly (E) phases in QBO changing every fourteen months approximately. With maximum wind speeds of 17,4 m s^{-1} for westerly values, and speeds of 35,5 m s^{-1} for easterly values. There is no existence of apparent relation between QBO phases and winds affecting TC activity in our study area. We can observe some cyclones as Ivan (1980), Otto (2010), Leslie (2018), Paulette and Theta (2020) present during a QBO westerly phase (fig. 8a.). While Vince (2005), Delta (2005), Nadine (2012) and Leslie (2018) once again, are present during an easterly (E) QBO phase (fig. 8a). The perfect example that QBO phases don't affect TC presence by influence of winds in our study zone is TC Leslie (2018), as it went through both easterly and westerly (W) phases during its lifetime. The only difference that we observe is that westerly phases are more present during TC activity, taking place in 5 cases whereas the easterly phase was present 4 times.

However, in fig. 8b., we observe that contrary to the u-wind correlation, the SST-QBO correlation is positive in some parts of our study zone. More specifically, in the northeastern part, compared to the southwestern part where no correlation exists. This implies that the SST conditions near the Canary Islands are hotter with the existence of a QBO westerly phase. As we have explained before, positive QBO values imply a dominance of westerly W winds in the stratosphere. In Huang et al. (2011), a significant correlation between QBO and tropical SST anomalies (SSTA) is found, due to the influence of ENSO and its relationship with QBO. These positive correlation values exist when the NINO3.4 index leads the QBO index by 8-10 months. However, they suggested that the interaction between QBO and SSTA needs further investigation because it is not fully understood.

Contrary to QBO-TC relationship, observing the conditions of ENSO in which TC cases occur, we find that TC activity in the North Atlantic Ocean has a total of 2264 storms, from which 352 correspond to La Niña conditions, 255 correspond to El Niño conditions, 541 correspond to Neutral conditions, while the rest are unknown (Historical Hurricane Tracks, 2022). The presence of Neutral and La Niña phases during most of the TC activity in our study area might be due to pure probability, as we can see that during those phases, more TC activity exists over the North Atlantic, in consequence increasing the probability of TCs striking the Canary Islands. Since 1970, only one TC appeared during El Niño conditions, Leslie (2018). Three cases occurred during a Neutral phase and 4 during La Niña. We will hereunder evaluate the effect of ENSO in our study zone and determine if ENSO has a direct impact in its TC activity.

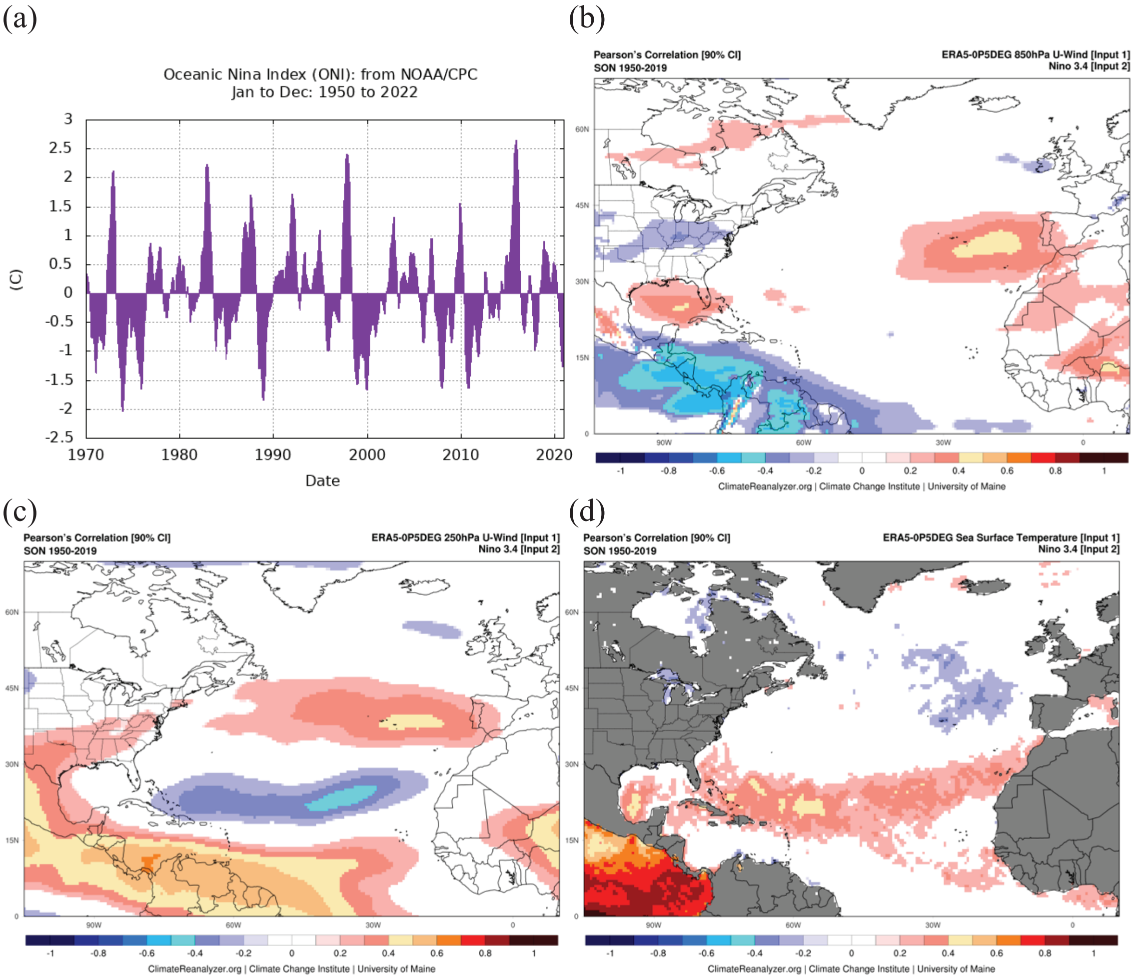


Fig. 9 – (a) Oceanic Nino Index, [1970-2021]- *from NOAA Climate Prediction Center (CPC) (https://www.cpc.ncep.noaa.gov/data/indices/), National Weather Service.* (b) Nino3.4 index and u-wind at 850 hPa correlation map during SON season, (c) Nino3.4 index and u-wind at 250 hPa correlation map during SON season, (d) Nino3.4 index and SST correlation map during SON season, (24ºN-38ºN, 27ºW-3ºW), [1950-2020], - *from Climate Reanalyzer (https://ClimateReanalyzer. org), Climate Change Institute, University of Maine, USA.*

Figure 9a. shows the variation of temperatures in the central and eastern Pacific, that determine the ENSO phases. When the values are positive, ENSO is in El Niño phase, and the higher they are, the stronger is El Niño. Values near 0º C represent neutral ENSO, while negative values indicate the presence of La Niña conditions. Just like with El Niño, the lower the temperature, the stronger is La Niña.

In fig. 9 we can observe the different variables concerning the climatological environment of our study zone and their correlation to ENSO during the SON trimester. In fig. 9b., we see that the effect of Nino3.4 on the u-wind variable at 850 hPa is positive, showing a correlation value around 0.4. This indicates, that when ENSO is in El Niño phase, wind speeds at that pressure level will increase. Observing the correlation between Nino3.4 and u-wind values at 250 hPa will tell us the effect ENSO has on wind shear. In fig 9c., we observe that ENSO does not seem to influence the u-wind values at 250 hPa inside most part of the 500 nautical mile radius of the Canary Islands. From these observations, we understand that during El Niño phase, the wind shear intensity, will increase. An increase in shear wind would hinder the presence of TC activity, as it would mitigate intensification of the cyclones. While during La Niña, those conditions would be the opposite, decreasing the wind shear value, and presenting environmental conditions that would allow the intensification of the cyclones. During ENSO-neutral stages, the conditions would be similar to La Niña phases. In fig 9d., we observe a positive correlation of 0,3 between Nino3.4 and SST values in our study area. This implies an increase in SST temperatures in our study zone while in El Niño phase, and colder temperatures in La Niña phase. The higher the intensity of El Niño or la Niña, the hotter or colder the SST will be. But we can see that the influence on SST values is not very large, so, the SST temperatures in our study zone shouldn't change much. Allowing TC presence during La Niña phases, even if SST becomes a bit colder with La Niña.

While SST might decrease with the presence of La Niña, an upward tendency of SST values has been observed (fig. 5c.) and we would like to know if it's influenced by Climate Change. Bringing us to the next part of this work, the changes in TC related variables with an increase of CO_2 concentration.

3.e. Effects of Climate Change on TC activity

First of all, let's take a look into the past. Atlantic Hurricane activity has shown an increase over the last century. Although much of it has been attributed to a lack of observations throughout the early years due to absence of material able to record TC activity. Emanuel (2021) used a tropical downscaled model driven by three global climate analyses (NOAA v.2c, NOAA v.3 and CERA-20C) mostly based on SST and surface pressure data to see if it was true. In this study (Emanuel, 2021) the results support the statement that storms were undercounted in the 19th century. Although his result shows an undercounted number of storms before 1900s, they also present a pronounced upward trend of TC activity over the Atlantic Ocean over the 1900s. But he finds the existence of a prominent hurricane depression occurring in the 1970s and 80s, attributed to anthropogenic aerosols. Making us to ask the question: Will the increase in anthropogenic aerosols make TC activity increase or decrease? In his paper, he concludes that while global measures of the number of TC activity and wind intensity show small changes in the variability of upward TC tendency, increasing temperatures do present an increase of TC rainfall. So, in response of Climate Change and global warming, an increase of TC activity might occur in the future, particularly in the northern hemisphere (Emanuel, 2021).

Through different methods, several researchers (Fedorov et al. 2010b; Emanuel & Sobel, 2013; Korty et al. 2017; Studholme et al. 2021) have tried to find a way to predict and understand future TC tendencies. Either comparing the current climate conditions with older hotter conditions, like in the Pliocene where global mean temperatures were 4º C higher than today in the early stage, and 2-3º C higher in the mid-Pliocene (Fedorov et al., 2010b). Or via modeling of future cyclone-related variables in response to an increase of CO_2 (Emanuel & Sobel, 2013). Or even via downscaled simulations of TC with high CO_2 levels (Korty et al., 2017)

A set of environmental variables have been identified to be essential to sustain storms and observe their evolution under global warming conditions. Korty et al. (2017) thinks that one the main parameters that present changes in TC climatology when exposed to an increase of CO_2 is Potential Intensity (PI). This variable predicts an upper bound for intensity, based on the thermodynamic environment in the sea surface and column of the atmosphere. Implying an involvement of SST and enthalpy flux. Their results show an increase of PI with warmer climates due to a higher transfer of energy from the sea surface to the atmosphere through thermodynamic transfer. Since its value is only large in zones where deep convection is possible, it helps to identify regions with high TC activity.

High levels of mid-tropospheric humidity help with TC formation, as high values reduce the necessary moisture flux to saturate the environment and maintain moist convection. Because relative humidity is invariant with climate change, and specific humidity does increase with temperature, following the Clausius-Clapeyron relation, the moisture fluxes that are required to saturate the atmospheric column, must fill an exponentially increasing gap that grows with temperature. This introduces an inhibition of TC formation with warming (Korty et al., 2017).

Through a study on wind shear intensity variation with warmer climate, it is shown that the magnitude decreases through most of the tropics. When coupled with the thermodynamic variables, Tang and Emanuel (2010, 2012) introduced a normalized wind parameter called ventilation parameter. When subsaturated environmental air is entrained through deep-tropospheric shear and the intensity that a cyclone can a achieve is reduced.

Using some of these parameters, Korty et al. (2017) use a downscaling method in simulations with different levels of CO_2. They use extremely hot ocean surfaces simulating Miocene and Eocene epochs. Introducing 3 models, M-Ctrl, M-3 and M-5, containing different levels of carbon dioxide among them. These contents are 355 ppm, 2240 ppm and 8960 ppm, respectively. The values correspond to late-twentieth century levels for M-Ctrl, 2^3 times the pre-industrial CO_2 values in M-3 and 2^5 times for M-5.

On the other hand, Fedorov et al. (2010b) uses a downscaling method to compare the TC activity in two models. One with modern climatological SST, and the other with early Pliocene STT. He uses this to produce a global climatology for vertical profiles of temperature, atmospheric humidity and winds to help him simulate synthetic TC tracks.

What's interesting from these papers (Fedorov et al. 2010b; Emanuel & Sobel, 2013; Korty et al. 2017; Studholme et al. 2021) is, that even if they simulated possible future conditions through different methods and using different variables, they find a common tendency in TC activity.

With the increase in temperatures, there is a tendency for the TCs area of formation to expand poleward. Korty et al. (2017) results show an increase in TC genesis between 20º and 40ºN in hotter climates. While Fedorov et al. (2010b) finds an expansion of warm pool waters that allow Power Dissipation Index (PDI) to increase towards Central Atlantic and poleward (Fig. 28).

Korty et al. (2017) indicates an increase of the cyclonic activity under an increased CO_2 concentration exposure during the second semester of the year, while the activity decreases in the first semester of the year, from January to July. Korty et al. (2017) analysis of the data shows that during M-5 conditions, the number of tropical storms is 121% larger than in M-Ctrl. He attributes this increase in numbers to the activity in subtropic latitudes as well as midlatitudes and polar latitudes. (Korty et al., 2017) also finds a decrease in the frequency of category 2-4 storms (64%) and category 5 storms (40%). But, the most severe storms, those that exceed 190 kt, become 2.4 times more frequent. Polarizing the TC activity, increasing the severe cases while mitigating the milder ones. Here under we will see how the different TC related variables change with different CO_2 concentrations at a global scale, and how this could maybe affect our area.

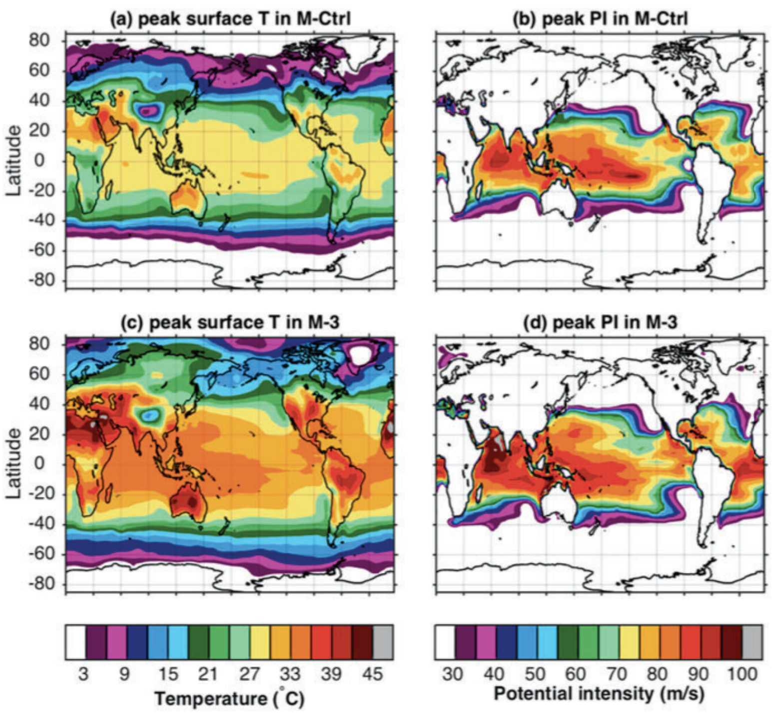


Fig. 10 – (left) Annual peak surface temperature, (a) M-Ctrl, (c) M-3, (e) M-5 and (right) Annual PI, (b) M-Ctrl, (d) M-3, (f) M-5 - (Korty et al. 2017)

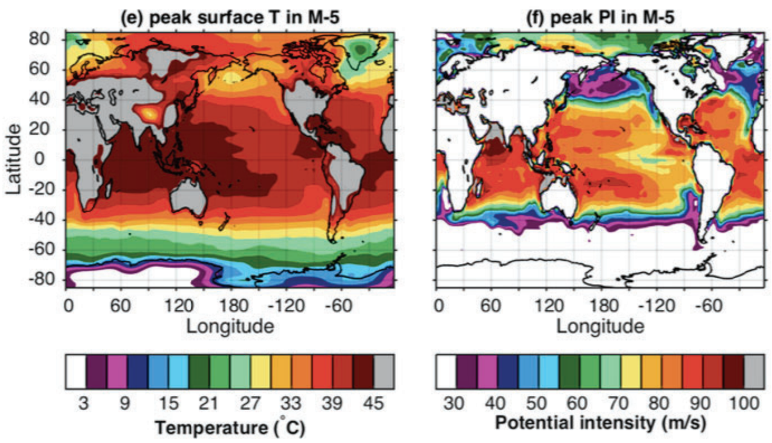


Fig. 10 –continued

In fig. 10, we observe the peak surface temperatures for every model of Korty et al. (2017) paper compared to their PI. We can see a gradual intensification of the temperatures throughout the models, reaching very high temperatures near the poles in M-5. Compared to the temperatures, the PI doesn't increase as much until we attain the M-5 values. In both fig. 10b. & 10d., a low PI of 30 m s^{-1} over the eastern part of the Atlantic basin can be seen along the African coast between latitudes 20º N to 40º N. If we now look into figures a & c, we see that the surface temperature values in this zone are lower than average at that latitude, due to the presence of the Canary Current. Making an increase in PI difficult in the study zone at CO_2 levels of 2240 ppm. On the other hand, in M-5 conditions, where CO_2 levels achieve 8960 ppm values, the Canary Current seems to increase its temperature, imposing an upward tendency in PI values, now reaching over 50 m s^{-1}. Still low values compared to the ones at the same latitude in the North Atlantic.

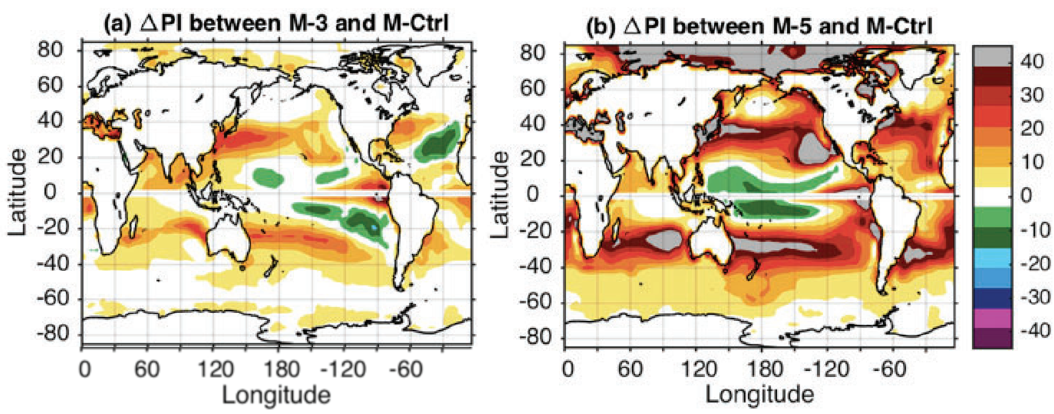


Fig. 11 – Difference in storm-season mean (July - October for Northern Hemisphere; January - April for Southern Hemisphere) of PI (m s^{-1}) (a) between M-3 and M-Ctrl (b) between M-5 and M-Ctrl, (Korty et al. 2017)

For M-3 conditions, the PI seems to have increased in the most western part of the North Atlantic basin, while decreasing in the eastern part, near the Canary Islands (fig.

11a). Presenting a negative difference indicating that the M-3 conditions present lower PI values than the ones from M-Ctrl. While implying a reduction of potential TC cases in the eastern part of the North Atlantic Ocean. The difference of PI between M-5 and M-Ctrl (fig. 11b) present very different conditions to the ones with lesser increase in CO_2 (fig. 11a), as we can observe that in M-5 conditions the values represented in that same area are much higher. Switching form negative values to positive ones near the Canary Archipelago. We could argue that with much higher concentrations of CO_2, TC activity could increase in our study area, just like PI has increased in the model of fig. 11b.

Observing the differences genesis densities between M-Ctrl and M-3 (fig. 12a), as well as M-Ctrl and M-5 (fig. 12c), we find a significant difference in the increase of cyclonic genesis with M-5, where the genesis density is bigger throughout the central Atlantic in subtropical latitudes.

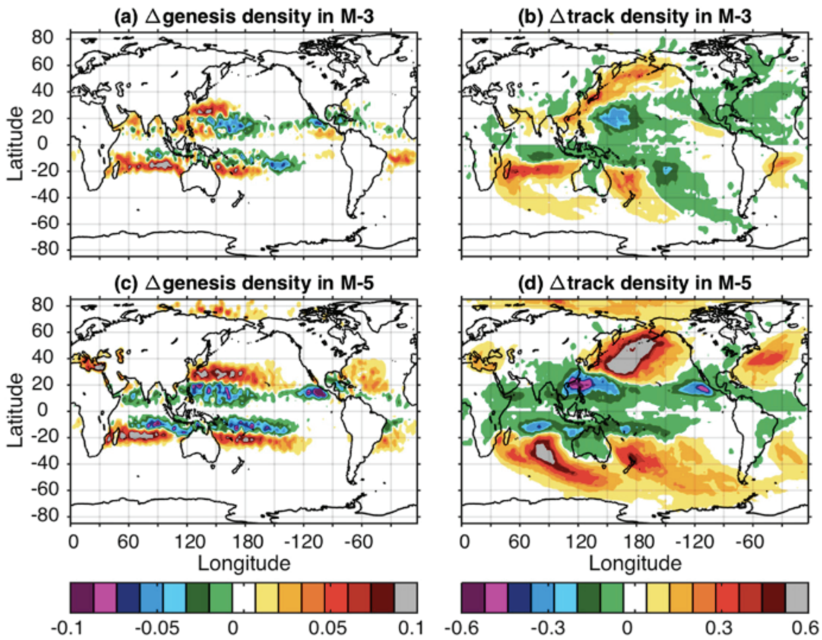


Fig. 12 – (a) Difference in genesis density between M-3 and M-Ctrl, (b) difference in track density between M-3 and M-Ctrl, (c) as is (a) but between M-5 and M-Ctrl, (d) as in (b) but between M-5 and M-Ctrl - (Korty et al. 2017)

This causes a shift in special distribution towards the north pole in the Atlantic Ocean. The difference in track density in M-3 (fig. 12b) shows a decrease of TC activity over most of the North Atlantic, compared to M-Ctrl conditions, while the differences with M-5 conditions show an increase of TC activity, as we see a positive difference over most of the North Atlantic Ocean. The positive values appear over the 20º N latitude, increasing TC activity from subtropical to almost polar latitudes, while negative values appear over tropical latitudes, implying a decrease in TC activity in the tropics. Our study area doesn't seem influenced by any of these conditions, if so, the densities seem to decrease over part of our area.

M-Ctrl (fig. 13a) presents wind shear values of around 18 m s^{-1} over a big part of the Atlantic Ocean, along the American Coast from Florida (20º N) to Greenland (60º N) and expanding throughout the east. Our study zone seems affected by weaker wind shear, presenting values of around 16 m s^{-1} at the center and even lower values as we move outwards, into the Ocean.

In M-3 (fig. 13b), we observe a shift of shear wind over the North Atlantic. What was before an 18 m s^{-1} magnitude that spanned diagonally northeastwards, now spans horizontally towards the coast of south Europe, even affecting our study zone. The area near Azores is affected by stronger magnitude values of around 18 m s^{-1}, increasing lightly the wind shear near the northern part of the Canary Archipelago, while the southern part seems to stay almost the same as in M-Ctrl.

In M-5 (fig. 13c) the wind shear over the tropical and subtropical latitudes seems to have weakened while strengthening over the Northeastern part of the basin at midlatitudes (40º N- 60º N). We observe values of around 6 m s^{-1} over our study zone and subtropical latitudes, presenting favorable wind shear conditions for TC activity.

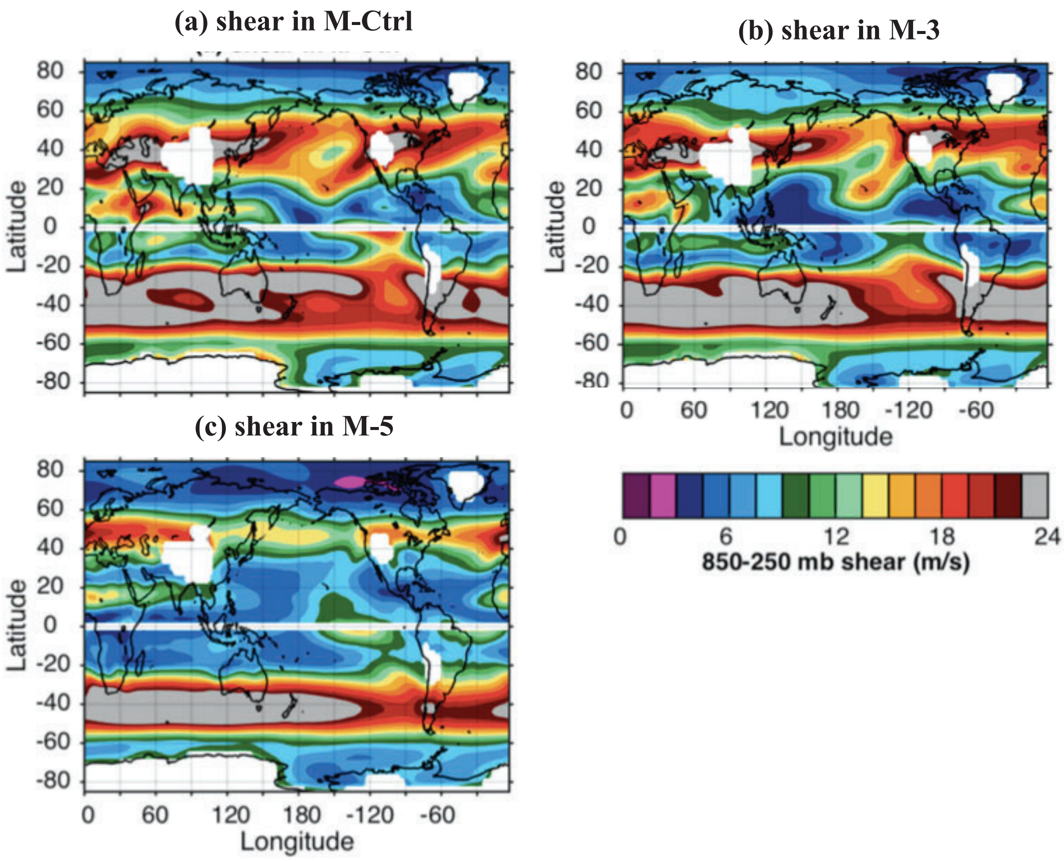


Fig. 13 – Storm-season mean values of magnitude of 850-250 hPa wind shear vector (1 mb = 1 hPa) in (a) M-Ctrl, (b) M-3, (c) M-5- (Korty et al. 2017)

We have observed a poleward tendency of the variables related to TC activity. The tropical zone seems to weaken with CO_2 concentration while higher latitudes seem to gain strength and allow TC activity to occur. Studholme et al. (2021) conclude their work on the topic of poleward tendency by saying that in the North Atlantic, TC genesis and vertical wind shear will be controlled by a polar amplified ocean warming, which would create a poleward TC activity shift, while weakening an equatorward TC activity. Studholme et al. (2021) suggests that the genesis and intensification of TC will occur over the 30º N to 40º N latitudes, thus occupying a broader range of latitudes in TC activity as CO_2 concentration increases by the end of the 21st century.

We can't exactly predict how the conditions near the Canary Islands will vary, but we can estimate what will happen with massive increases on CO_2 concentrations. Due to the importance of the Canary Current and its influence in the area, we can suppose that while TC genesis will shift to subtropical latitudes, this won't affect the Canary Islands in M-3 conditions (fig. 12b.). Of course, this is not a fact, and TC activity will probably still occur as it increases over the Atlantic Ocean. Random TC that are exposed to suitable conditions at the right moment might approach the Canary Islands, just like some have approached until now. With extreme CO_2 concentrations like in M-5, global warming might have an impact on the Canary Current, elevating SST. This increase coupled with a reduced wind shear (fig. 13c.) will probably create suitable conditions for TC activity in a further future.

4. Conclusions

The main aim of this study has been to try and identify the relationship between TCs near the Canary Islands and the local environmental conditions, influenced by different climatic indices. We have concluded the following:

- There has been an increase of SST and TC activity in the past two decades in the area of study.
- TC activity in the area of study is determined by a decrease in wind shear and an increase in SST.
- During La Niña phases, the environmental conditions near the Canary Islands are more favorable to TC activity.
- QBO doesn't seem to affect the atmospheric winds, however it influences the increase of SST during its westerly phase.
- In the future, we suspect that a moderate increase of CO_2 (M-3 conditions) will reduce TC activity in the area. On the other hand, a higher increase of CO_2 (M-5 conditions) will increase activity, due to the rise in SST and decrease of wind shear.

In order to improve this study and obtain more accurate results, we would need to look at other TC related variables, such as Relative Humidity, and use daily based data rather than monthly. We could also subdivide the area into smaller areas of study, avoiding misleading results.

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1. Descripción detallada de las actividades desarrolladas durante la realización del TFT

Lo primero que hice fue informarme sobre el tema de la Actividad ciclónica tropical. Una vez obtuve el suficiente conocimiento, realicé un análisis sinóptico de los ciclones que pasaban cerca de las Islas Canarias, catalogando todos los ciclones que aparecían por la zona. Una vez descritos, empecé mi análisis sobre la zona de estudio, comentando los diferentes procesos meteorológicos que ocurrían y como influenciaban la actividad ciclónica tropical. Recopilé datos sobre las condiciones climáticas de la zona y los estudié. A continuación, estudié la relación entre dichas condiciones y diferentes índices climáticos. Para finalizar realicé un análisis de la evolución de diversas variables, que sufriría la zona en consecuencia de un calentamiento global y en consecuencia la actividad ciclónica en ella.

2. Formación recibida (cursos, programas informáticos, etc.)

Al principio, se me facilito información relacionada con el tema de estudio. A lo largo de la elaboración del trabajo, se me han proporcionado diferentes webs para la recopilación de datos, al igual que programas y paginas webs con el propósito de representar y analizar dichos datos.

3. Nivel de integración e implicación dentro del departamento y relaciones con el personal.

He encontrado el trato con mis tutores muy agradable, nos comunicábamos a través de e-mails y video llamadas. Realice mis practicas el año pasado y debido a la situación del Covid-19 no se podía asistir presencialmente. Este año, he realizado todo el proyecto a distancia, ya que no me encontraba en las Islas Canarias. Mis tutores han estado siempre a mi disposición y han contestado siempre rápidamente a mis preguntas. Me he reunido con mi cotutor todas las semanas a través de Teams.

4. Aspectos positivos y negativos más significativos relacionados con el desarrollo del TFT

Por una parte, he descubierto el mundo de la meteorología, en concreto el mundo de la actividad ciclónica tropical. Un tema muy interesante y complicado, del cual se desconoce mucho. Y he tenido un gran apoyo por parte de mis tutores a lo largo del trabajo, lo cual agradezco.

Por el lado negativo, he encontrado en ciertos casos una falta de accesibilidad a cierta documentación, como puede ser el caso de algunos “papers” a los cuales la Universidad no tenia acceso.

5. Valoración personal del aprendizaje conseguido a lo largo del TFT.

A lo largo de este trabajo, he aprendido a buscar y analizar información por mi cuenta, además de relacionarla a contenido aprendido a lo largo de mis estudios en la facultad de Ciencias del Mar.