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Tropical disturbances in the southeastern North Atlantic. State of the art and future prospects

Perturbaciones tropicales en el Atlántico norte suroriental. Estado de la cuestión y perspectivas de futuro

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Abstract

This study analyzes tropical disturbances in a region usually not affected by these events, the southeastern North Atlantic. This is an extensive area between Macaronesia and the coasts of northwest Africa and the southwest of the Iberian Peninsula. In the context of climate change, a statistical analysis has been conducted of the main database of the National Hurricane Center for the Atlantic basin, as well as a bibliographical compilation, in order to analyze the temporal and spatial evolution of these phenomena. The starting hypothesis is to verify the existence of an increase in the risk of these situations in the region of study, through research that characterizes and charts these phenomena. The results indicate that, although with long periods of recurrence, some events with notable impacts had occurred before the first systematic records were kept. In addition, over the last fifty years, a much more reliable period from a scientific perspective, there has been an increase in their number, especially in recent decades. Furthermore, an approximate estimate is made of the population likely to be affected by tropical disturbances, which estimates that more than twenty million people are at risk.

Keywords: tropical cyclone; tropical storm; climate change, climate risk.

Resumen

Se presenta un estudio sobre las perturbaciones tropicales en una región habitualmente no afectada por estos eventos, el Atlántico norte suroriental. Se trata de una extensa área entre la Macaronesia y las costas del noroeste de África y suroeste de la península ibérica. En el contexto del cambio climático se hace un análisis estadístico de la principal base de datos del National Hurricane Center para la cuenca atlántica, así como una recopilación bibliográfica, con el fin de analizar la evolución temporal y espacial de estos fenómenos. La hipótesis de partida es comprobar la existencia de un incremento en el riesgo de estas situaciones en la región de análisis, para lo que se elabora un estudio que las caracteriza y contabiliza. Los resultados señalan que, aunque con periodos de recurrencia largos, se han dado algunos eventos con destacados impactos antes del comienzo sistemático de su registro. Además, en los últimos 50 años, periodo

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mucho más fiable desde una perspectiva científica, se constata un aumento en su número, especialmente en las últimas décadas. Asimismo, se hace una aproximación a la población susceptible de ser afectada por las perturbaciones tropicales, la cual se estima en más de 20 millones de personas en riesgo.

Palabras clave: ciclón tropical; tormenta tropical; cambio climático, riesgo climático.

1. Introduction

The different genesis of atmospheric instability between temperate and tropical regions is well known. In the middle latitudes, rain and wind events are linked to the arrival of storms or extratropical cyclones. Although, in general, they do not have a great impact, the formation of an Isolated Depression at High Levels (DANA) can produce episodes of floods, which are more serious in coastal areas, especially in spaces with mountains near the sea, such as large sectors of the Mediterranean (Llasat et al., 2010; Faccini et al., 2021). This is the case of the Spanish Mediterranean coast, the Ligurian coast in Italy, the French *Côte d'Azur* or the archipelagos of Madeira and the Canary Islands. The latter are outside the aforementioned basin, but with a pluviometric regime with similar features, both in terms of temporal distribution, as well as their interannual irregularity, and intensity of precipitation (Dorta, 2007; López-Díez et al., 2019).

Instability in the intertropical world has its genesis in the presence and latitudinal oscillation of the Intertropical Convergence Zone (ITCZ). This gives rise to depressive convective systems generating easterly waves, which in turn organize the primary tropical cyclone structure and origin of markedly varied low pressure systems such as depressions, storms and, in the most extreme cases, tropical cyclones, called hurricanes in the Atlantic basin[6], which are the most destructive weather systems on a planetary scale (Walsh et al., 2019). The intensity of these events depends, to a large extent, on the pressure in the core, from depressions to category 5 tropical cyclones on the Saffir-Simpson scale, with winds that can exceed 300 km/h and torrential precipitation that leads to large-scale damage. These disturbances have been widely analyzed from many different perspectives (Elsner et al., 2008; Vecchi et al., 2021; Webster et al., 2005).

All mentioned phenomena, as well as the ITCZ itself, are usually delimitated by the tropics, especially on the eastern fronts of the oceans, such as the area studied in this work, in which the presence of cold waters and the direction of the easterly winds, within the anticiclone of the Azores, hinder the development of atmospheric instability. Apart from these three categories (depressions, storms and cyclones) there are also the so-called subtropical storms, hybrid phenomena which have only recently become the subject of research, so they have probably been underestimated in the databases (Evans & Guishard, 2009). Finally, there are mixed systems capable of developing in waters with temperatures above 26°C, which can start as non-tropical disturbances that turn into tropical systems (Mauk & Hobgood, 2012).

Unstable tropical phenomena are concentrated in the oceans, affecting insular spaces and continental coasts, especially in the intertropical world, although they sometimes travel along temperate coastlines located in the east of the continents, as is the case of the southeastern United States or southern Japan on the East Asian coast. In addition, some tropical cyclones can reach the western fronts of Europe, but in the form of extratropical cyclones or storms, thus becoming part of the temperate circulation (Liu et al., 2017). Most of all these events affect a large sector from the northern coast of Portugal to the British Isles. However, the lower latitudes, below about 40°N, are regions that are not affected by these phenomena or their frequency is markedly low.

In general terms, the latest report of the Intergovernmental Panel for Climate Change (IPCC) (2021) refers to numerous meteorological milestones with markedly severe impacts on a planetary scale, partially or totally attributed to climate change. This is the case of the appearance of the first tropical cyclone in the South Atlantic (2004), Hurricane Sandy (2012) on the eastern coast of the United States, Super Typhoon Haiyan (2013) around the Philippines, or the extraordinary hurricane season in 2014 in the eastern and central Pacific around Hawaii, as well as the exceptional 2005 and 2020 seasons for the number and intensity of North Atlantic hurricanes.

6 In this article we talk about tropical cyclone when the database used indicates that the episode reaches the category of hurricane, thus differentiating it from lower category low pressures that are also cyclones (tropical depressions and storms, as well as subtropical storms), following the definition of Viñas (2019).

According to the evolution of temperatures, reported in all the main climate research centers (NOAA, Climatic Research Unit, Berkeley Earth, etc.) as well as the IPCC, the global thermal rise in temperature was not particularly pronounced until the 1970s. It is from then when the increase in temperatures begins to be much more noticeable, especially in the second half of the decade, not only on a planetary but also on a local scale (Martín-Esquivel et al., 2012) as well as the rise in sea level (Knutson et al., 2021), a crucial aspect in terms of the damage caused by these phenomena. Along the same lines, although there are numerous problems derived from the homogenization of the series (Kossin et al., 2007), some authors also mark these years as a turning point in terms of the increase in the intensity of tropical cyclones (Kossin et al. al., 2013) with the highest frequency being observed in those of higher categories, especially in cyclones 4 and 5 on the Saffir-Simpson scale (Webster et al., 2005; Knutson et al., 2020). In addition, the systematic use of meteorological satellites began at that timeproviding greater precision and which have been an indisputable advance in the detection and monitoring of tropical disturbances (Kossin et al., 2007).

In this context, tropical phenomena have hardly affected coastal zones of the southeastern Iberian Peninsula, the African coast between Morocco and Senegal and the archipelagos of Cape Verde, Madeira and the Canary Islands. The latitude of these regions and the cold waters of the Canary Current have ensured that these areas have not been affected by these events, since one of the main factors influencing their course is the high temperature of the ocean surface. Furthermore, this entire region is basically marine, so in addition to these phenomena being scarce, they usually move in oceanic waters, and the probability of making landfall is extremely low, and as such, in many cases, they appear and disappear in the ocean. In other words, they are not only scarce, but the exposed surfaces are also relatively small.

The main objective of this research work is to find out whether this situation can change in this sector of the southeastern North Atlantic as a result of global warming and, based on what has happened in recent years, whether climate change may be beginning to modify this behavior. In order to fulfil this aim, a spatial-temporal analysis of unstable phenomena with a tropical origin was performed in this region, where their incidence is usually very low. The evolution of the number of tropical storms and cyclones is analyzed according to official databases to verify whether there has been an increase in these phenomena in the region and, therefore, if climate change may be favoring a transformation in the distribution of these tropical disturbances in this area of the Atlantic. Finally, there is an estimate of the exposure in terms of the affected population in a future scenario of the arrival of these markedly unstable situations.

2. Methodology

2.1. Sources

To develop a solid background this work is based on a bibliographic review, which includes a broad analysis of many specific publications on disturbances with a tropical origin. The spatial-temporal context is part of a broader content on the behavior and evolution of storms and tropical cyclones on the planet and, specifically, in the North Atlantic, with climate change always being a determining condition. It is not possible to address such a complex issue without presenting a solid current state of affairs, which is why a specific section has been prepared, which will be described below.

The National Oceanic and Atmospheric Administration (NOAA) has been used as the main source for spatial analysis and exploration. The National Hurricane Center (NHC), dependent on the sNOAA, has a database that has been compiling all the tropical disturbances in the North Atlantic since 1851 in terms of their trajectory and, since 1958, has prepared an individual report for each one. This is the HURDAT2 (Hurricane Data 2nd generation) database (https://www.nhc.noaa.gov/data) which is widely used by researchers (Vecchi, et al., 2021). However, it is important to point out that it is highly likely that not all episodes are included in these databases, which negatively affects its reliability (Elsner et al., 2008; Kossin, et al., 2007). In addition, it should also be taken into account that the records, especially the oldest ones, have a significant statistical heterogeneity (Kossin et al., 2020). The further back we go in time, the more the information loses quality and, furthermore, it is highly likely that there are unrecorded events (Vecchi & Khnutson, 2011). Although there is abundant bibliography in the area of paleotempestology, in which tropical phenomena of the pre-instrumental past are reconstructed (Chenoweth & Divine, 2008; Vaquero et al., 2008; Burn & Palmer, 2015), it is clearly not possible to have the level of precision that is available nowadays, especially from the use of meteorological satellites.

In the first decades of the series, these phenomena could only be detected by direct observation from the land or the sea, which means that some of them have not been counted, either because they only had an oceanic route, both in their cyclogenesis and cyclolysis, or due to their small size and impact on sparsely populated territories. Proof of this are the events classified in the database as unknown, commonly found in the first decades and which, in most cases are tropical depressions, with an annual mean average of almost seven unknown events between 1851 and 1900. In addition, the unknown events do not have a specific file (1958-2020) in the database. As of 1901, the percentage of unknown events is statistically insignificant and statistically significant percentages only appear again in 1967. On the other hand, named tropical depressions only begin to appear after 1966 and from then until the present there have been numerous events but these have appeared in a highly irregular manner. The same can be seen in the case of subtropical storms, although in this case there have been hardly any (1.2%). For all of the above, the analysis for this research has focused on subtropical storm, tropical storm and tropical cyclone categories as well as their subsequent evolution to extratropical episodes and tropical depressions have been ignored due to the problems mentioned above. Therefore, the total number of events in the Atlantic is 1,662, with a clear majority of recorded storms and tropical cyclones occurring between 1851 and 2020.

2.2. Method

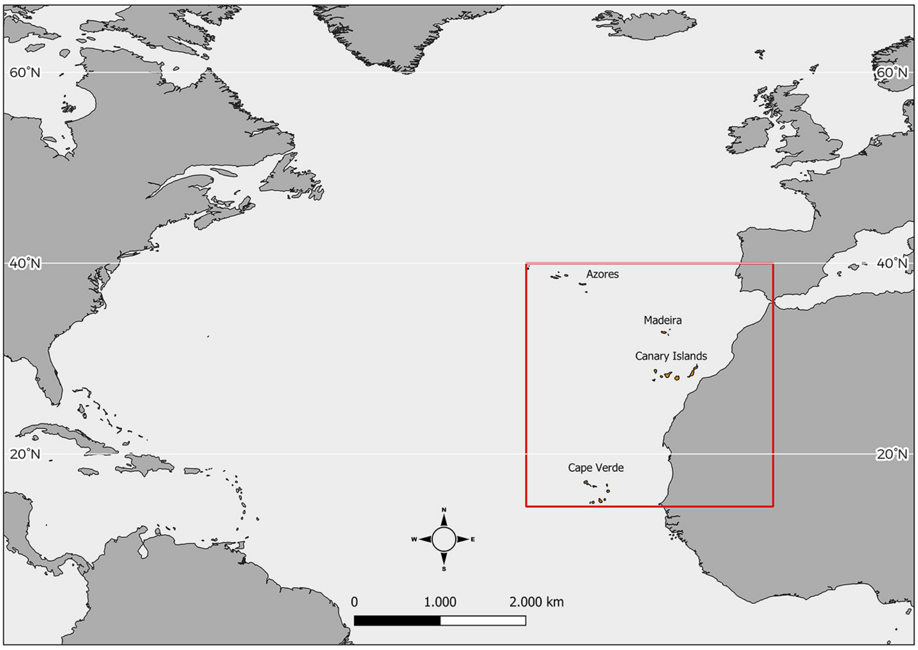
In order to perform the spatial-temporal analysis of the cyclonic phenomena in the study region, the methodological sequence used is as follows:

1. Delimitation of the study area.
2. Spatial classification of the Atlantic basin according to cyclone frequency.
3. Analysis of the spatial-temporal evaluation of the phenomena in the study area.
4. Simple analysis of exposed populations in the study area.

2.2.1. Delimitation of the study area

The study area is an area of just over 7.2 million km² corresponding to a projected rectangle with its northern limit on the 40º N parallel, coinciding with the northwest coast of the island of Corvo in the archipelago of the Azores. The western limit of the region is the western end of Ilha das Flores, also belonging to the Azores. The eastern limit is the Strait of Gibraltar, around the 5º W meridian, and finally, the southern limit is the southern coast of Ilha Brava in Cabo Verde at 14º N.

Figure 1. Location of the study area



Own elaboration

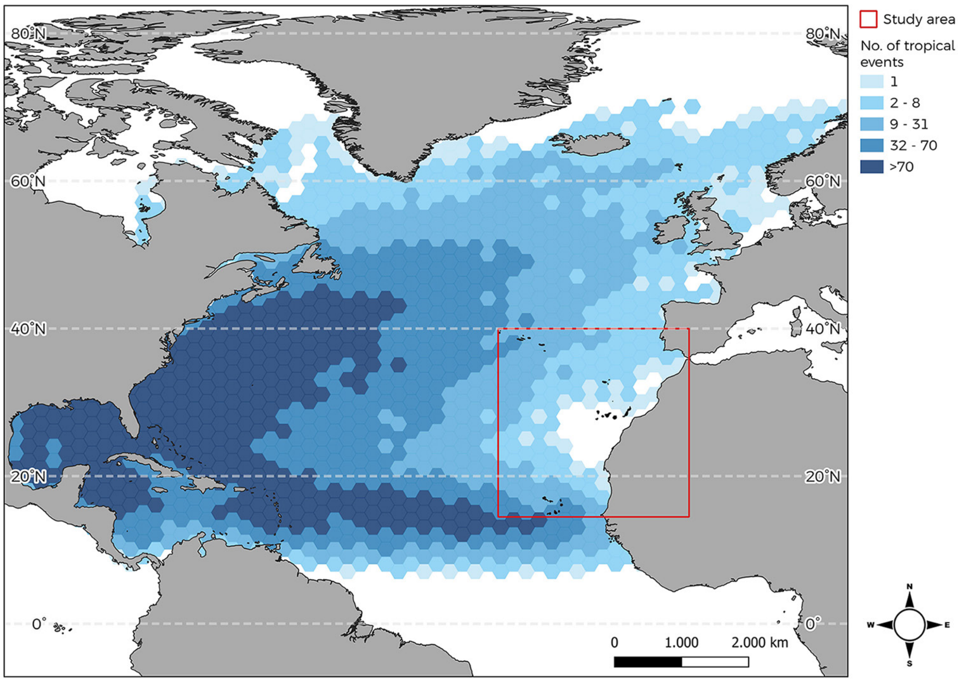
The study area includes all the archipelagos that are part of the Macaronesia region, the Azores, the Madeira Islands, the Canary Islands and Cape Verde. Territory on the southeastern coast of the Iberian Peninsula is also included, as well as a strip of the northwestern African coast (Figure 1). Despite the geographical similarities in the territories that make up this area, there are climatic nuances that should be mentioned. Most of the region is characterized by a Mediterranean pluviometric regime whose features are defined, on the one hand, by a marked rainfall seasonality, where the warm months are markedly dry and, on the other hand, these regions are subject to episodes of torrential precipitation (Máyer & Marzol, 2014; Mayer et al., 2017). Only the southernmost sectors of Senegal, Cape Verde and the southern half of Mauritania have typically tropical features, with maximum summer-autumn rainfall.

The northern end of the study region is made up of the Azores archipelago, the only space in which the arrival of unstable tropical phenomena is not uncommon. Even Cape Verde, in the extreme south, despite being very close, slightly to the north of one of the main sources of origin of the formation of storms and tropical cyclones in the Atlantic Ocean basin, is not affected by them since their usual trajectories consist of a displacement from the south of the aforementioned Cape Verde archipelago towards the central and eastern Atlantic with easterly or southeasterly directions.

2.2.2. Spatial classification of the Atlantic basin according to cyclone frequency

An initial analysis for the entire Atlantic basin was performed to characterize the study area with respect to the incidence of tropical cyclones. To do this, a vectorial grid of regular hexagonal polygons of approximately 37,000 km^2 was constructed, which occupies the entire area of the Atlantic where, according to the records, any tropical cyclone had passed between 1851 and 2020 (Figure 2).

Figure 2. Spatial frequency of tropical disturbances in the North Atlantic basin (1851-2020)



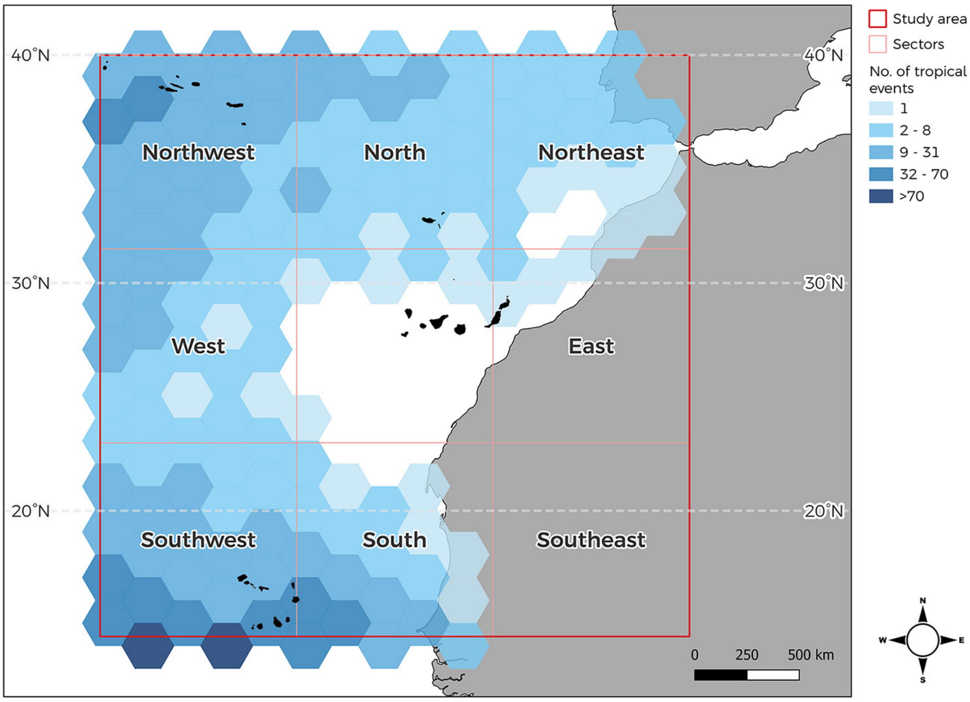
Source: NHC. Own elaboration

A summation was made of all the tropical cyclonic trajectories intersecting with each of the hexagons of the grid for the time period. The observed result is a tropical cyclone density map (1851-2020), classified into five categories grouped into quintiles, which characterize the entire Atlantic basin according to the frequency of passage of cyclone trajectories, but above all to contextualize the study area regarding this criterion within the entire Atlantic space affected by these phenomena (Figure 2). In this way, one can see that although the frequencies of tropical cyclone incidence on the coasts of the Gulf of Mexico are high (more than 70 records per hexagon), the study area is characterized by moderate and low frequencies with respect to the passage of tropical cyclones, with fewer than 8 per hexagon.

2.2.3. *Analysis of the spatial-temporal evaluation of the phenomena in the study area*

A series of analyses, for a series of 170 years between 1851 and 2020, were carried out using the database to evaluate the evolution of the phenomenon in the study area. However, the most exhaustive statistical analysis focuses on the last fifty years, between 1971 and 2020, where the reliability of the information and detection of events is scientifically valid, unlike the period beforehand due to the problems described above for the older data.

Figure 3. Spatial frequency and grids for the study of tropical disturbances (1851-2020)



Source: NHC. Own elaboration

The next step involved selecting only the episodes that had their path in the work grid. The final result of this profuse procedure was the discrimination of 149 events in the analyzed period. In addition, a further four events found in the bibliography were added (Vaquero et al., 2008; Bethencourt & Dorta, 2010; Domíngez-Castro et al., 2013), resulting in a total of 153 episodes. The study area is also divided into nine sectors, according to their location (Northwest, North, Northeast, etc.) in order to facilitate the writing and reading of the research results (Figure 3). The interannual and monthly frequency, seasonality and trends are analyzed in this spatial framework, as well as the development of a diagnosis on the historical evolution of tropical disturbances/pertubations in the area, with all the available information.

2.2.4. *Simple analysis of exposed populations in the study area*

Finally, without attempting an exhaustive analysis of exposure and vulnerability, a simple analysis was conducted of the population that may be affected by the foreseeable arrival of these disturbances. In order to do this, a public source of community license data stored in the public.opendatasoft.com repository called GEONAMES was used, which in turn is based on multiple official sources (http://www.geonames.org/data-sources.html).

3. Results

Having described the methodology and context, it should be noted that, in general, the entire study sector, as mentioned, has a low number of tropical disturbances, with a maximum in the northwestern and southwestern sectors and a minimum in its central and eastern sector, where the colder waters of the Canary current are.

Based on all of the above, it is necessary to analyze the historical evolution of tropical disturbances, with all the information available, and to be able to verify whether these phenomena are really new and whether there is any trend in their frequency, thus confirming if there is any relationship with climate change.

This section analyzes the evolution of unstable tropical situations of tropical origin in the study area from the first references, at the end of the 18th century, until the 2020 hurricane season. The evolution of tropical phenomena is analyzed by using a fragmented chronological division into the following three periods: before 1970, from 1971 to 2020 and future projections. Finally, there are some questions about the urban population exposed to this type of threat.

3.1. 18th century to 1970

As mentioned above, data prior to the satellite era may be biased and may not represent all events that occurred. Thus, according to the information from the NOAA-NHC and the specific bibliography, the presence of tropical disturbances in the study area in the past, as expected, is scarce; although it is true that there are some episodes of great intensity with serious damage and many victims.

Among the 1,662 tropical disturbances detected in the North Atlantic (1851-2020) and according to the sources consulted, sixty-five occurred in the study area between 1851 and 1970 (subtropical storms, tropical storms and tropical cyclones). If three previous episodes are included in the list that do not appear in the NOAA database but are verified in the bibliography, the total number rises to sixty-eight. These refer to the historical events recorded in November 1724, November 1826 and October 1842 (Domínguez-Castro et al., 2013; Vaquero et al., 2008; Bethencourt & Dorta, 2010) (Table 1). In these cases, although the time elapsed since their occurrence means that it is not possible to know what their intensities, the specific spaces affected or the precise trajectories were, there is enough information to verify their tropical origin, their approximate intensities, as well as the more general damage.

Table 1. Historical tropical disturbances prior to 1851 not recorded by the NHC

Date	Category	Affected sectors
18-19 Nov 1724	Tropical cyclone	Madeira and W of Portugal
7-8 Nov 1826	Tropical cyclone	The Canary Islands
27-28 Oct 1842	Tropical cyclone	South-east of the Iberian Penisula

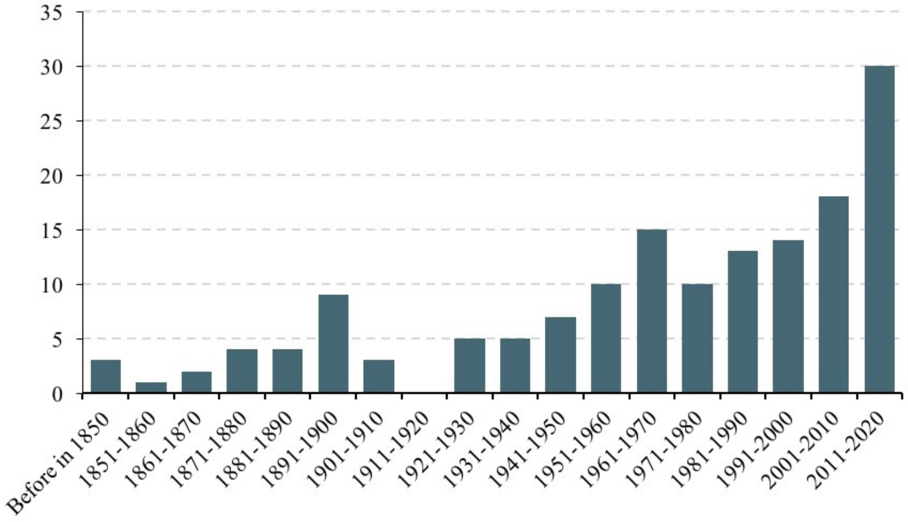
Source: Vaquero et al., 2008; Bethencourt & Dorta, 2010; Domínguez-Castro et al., 2013. Own elaboration

Therefore, the episode of November 18th and 19th, 1724, is the oldest known event and which affected, with significant damage, especially Madeira and the sector around Lisbon (Domínguez-Castro et al., 2013). Its main meteorological feature was the pronounced decrease in pressure in the measurements of the time.

In second place is the event recorded between November 7th and 8th, 1826. Among its main effects were flooding and the dragging of materials generated by torrential rainfall (Criado et al., 2018). The number of deaths, mainly due to the floods, was around 300 only on the island of Tenerife (Bethencourt & Dorta, 2010), although the entire archipelago was affected, even reaching the easternmost islands such as Lanzarote (Criado et al., 2013). The damage was of an unprecedented magnitude and, according to current knowledge of the region's climate, never seen again to date. All the evidence regarding damage and the few direct or indirect meteorological parameters shows that, in all probability, this was the first tropical cyclone, and the only one reported in the Canary Islands (Bethencourt & Dorta, 2010). Furthermore, as in the case of 1724, a sharp drop in atmospheric pressure was recorded.

Finally, the hurricane of October 1842 was the only one documented in Europe (Vaquero et al., 2008) until the publication of the research on the storm of 1724, causing considerable damage in Cádiz (Spain) (Domínguez-Castro et al., 2013). As in the previous cases, the proxy data and some marginal meteorological information, especially related to pressure, facilitate its reconstruction, even allowing its trajectory to be traced, which suggests this event in 1842 was similar to Tropical Cyclone Vince, which occurred in October 2005.

Figure 3. Evolution by decades of the number of tropical disturbances in the study area (1724-2020)



Source: NOAA-NHC. Own elaboration

Figure 3 shows the total number of episodes between 1724, when the first one was detected, and 2020. A clear increase in their number can be seen, indicating an upward trend. However, as has already been pointed out, it is possible that not all episodes are recorded and some are missing in the first decades and as such the last fifty years are the most reliable and will be discussed in the following section.

3.2. 1971 to 2020

The data from recent decades is much more reliable, especially since the generalization of meteorological satellites. The GOES geostationary satellite program began in the United States in 1975 (NASA, 2022). Therefore, this is the period with the most reliable data and as such is the period when the most exhaustive statistical analyzes were conducted for the present article.

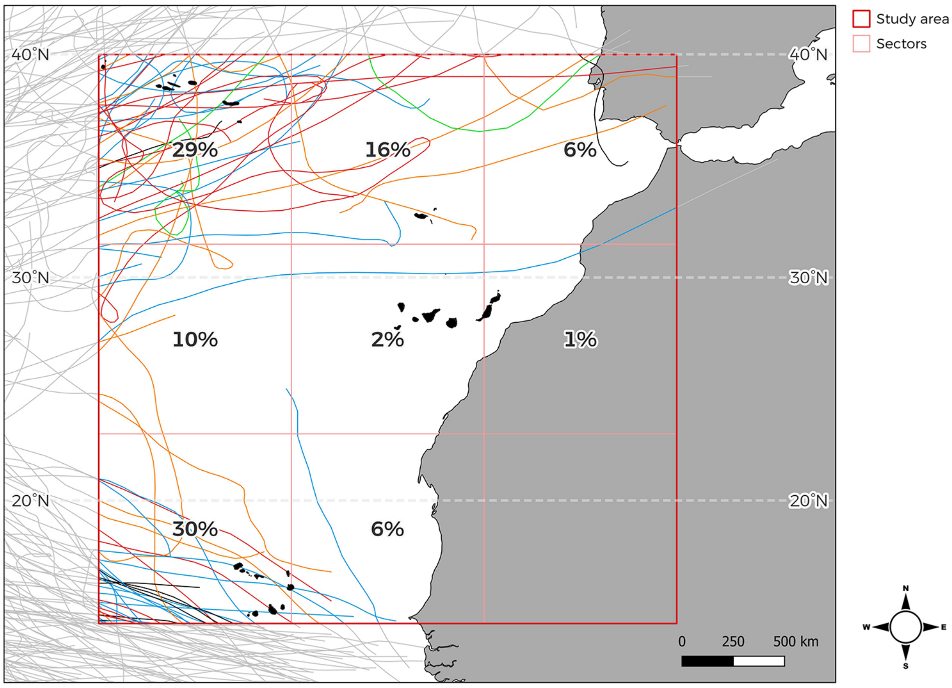
In the field of study, the analysis of the trajectories of unstable tropical phenomena shows, as hypothesized here and as some authors have begun to point out, an extension towards the central and eastern Atlantic (Zelinsky, 2019). The first of the events is that of December 1975, an important tropical disturbance in the Canary Islands, classified as a subtropical storm causing serious damage (Bethecourt & Dorta, 2010), although, in this case, the wind was much more notable than the rain. Another important milestone was Hurricane Arlene, in 1987, which mainly affected the Portuguese coast, although now considered an extratropical cyclone (Capel-Molina, 1988). The most recent episode occurred in September 2020, which was a subtropical storm called Alpha, that affected the central coast of Portugal.

The distribution, as expected, was concentrated in the northwestern and southwestern corners of the study area with a marked minimum in the central and eastern sectors (Figure 4).

In the NHC series, between 1851 and 2020, there were 149 or 152, if those prior to 1851 are counted, disturbances of tropical origin (tropical storms, subtropical storms, tropical cyclones) in the study area, with eighty-four events between 1971 and 2020. Therefore, over the last 170 years the mean average number of events was 0.87 events/year, compared to 1.68 in the last fifty years. However, the decade with the highest frequency is clearly 2011-2020, accounting for just over three events/year. Although without statistical significance, due to the small number of phenomena, and as Figure 3 shows a clearly upward trend in the number of events, the trend has been confirmed over the last fifty years (Figure 5)[7]. Even assuming the difficulty in accounting for the phenomena prior to the 1970s, and especially in the first decades of the series, it seems that there is both a clear the upward trend and that the invasion of the eastern Atlantic is a reality.

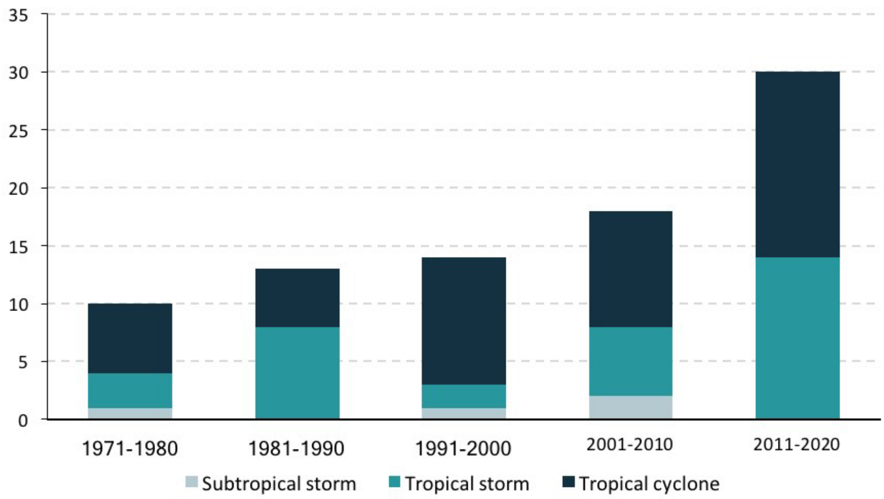
7 During the editing of this article, the passage of tropical storm Hermine, in September 2022, has occurred in the study area, which corroborates the increase in the number of episodes in the Southeastern North Atlantic.

Figure 4. Percentage distribution of tropical disturbance trajectories in the study area (1971-2020)



Source: NOAA-NHC. Own elaboration

Figure 5. Decadal evolution and type of tropical disturbance in the study area (1971-2020)



Source: NOAA-NHC. Own elaboration

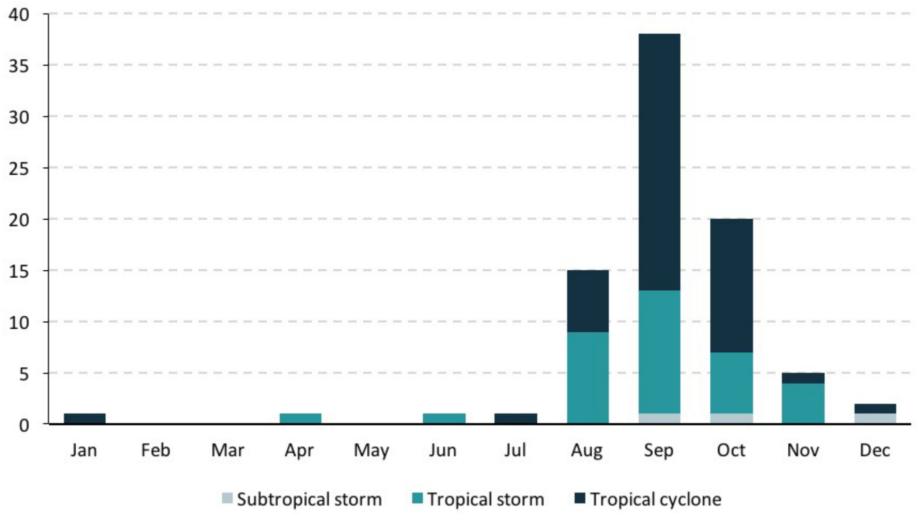
In addition, it should be mentioned that the number of disturbances in the period 1971-2020 classified as tropical cyclones or stronger also increased and was highest in the last decade of this period with sixteen hurricanes and there had been a clear increase since 1991 (Figure 5).

In this context, it is worth highlighting Hurricane Vince in 2005, which was the first scientifically verified hurricane to reach the Iberian Peninsula, although it had reduced its intensity to that of a tropical storm on arrival. However, although there were others in the pre-instrumental era, which have been mentioned above, such as the one in 1842, without exhaustive numerical data, that had reached the Iberian Peninsula (Vaquero et al., 2008). In the case of Vince, with regard to rainfall, the totals recorded in the southwest of Andalusia were important, although the torrential rainfall was much more significant, with nearly 90 mm/h in 10 minutes in some points and with maximum wind gusts close to 80 km/h (Instituto Nacional de Meteorología [INM], 2005).

The monthly distribution of the episodes shows a clear maximum in the month of September, followed with a notable difference by October and August. The former accounts for just over 45% of the total and, together with August and October, account for 87% of all events (Figure 6).

The extension of the unstable phenomena of tropical origin towards the center and east of the Atlantic, and demonstrated in the study area, may be related to the thermal increase of the Atlantic Ocean around the analyzed area, as corroborated by different researchers (Kossin, 2008; Guijarro et al., 2014), since, as has been pointed out, there is a close relationship between the sea surface temperature (SST) and the activity of tropical cyclones (Knutson et al., 2010).

Figure 6. Monthly distribution and by type of tropical disturbance in the study area (1971-2020)



Source: NOAA-NHC. Own elaboration

3.3. *Socioeconomic aspects: exposure*

Before describing some socioecomic and vulnerability aspects regarding the study area, the 2005 and 2020 seasons should be noted in terms of the great interannual irregularity stand out. These two years registered the highest number of storms and tropical cyclones since records began, more than doubling the annual mean average of twelve (Table 2). In both cases, about thirty events were recorded, including seven tropical cyclones with a category of more than three, and were the only two years when such a number of events was reached.

Table 2. Mean average values and seasons of greater intensity in terms of storms and tropical cyclones in the North Atlantic (1971-2020)

	Storms	Cyclones	Total
Mean average	5.6	6.4	12
Maximum	15	15	29
Minimum	1	2	3
2005	12	15	27
2020	15	14	29

Source: NHC. Own elaboration

The damage caused by these phenomena is well known, and fall into three categories of major threats: the winds, which can reach sustained wind speeds of over 250 km/h and cause very severe damage to all types of infrastructure; river floods, which lead to serious economic losses and many victims and, finally, the storm surge causes serious damage to the coastline as a result of flooding by waves and the sudden rise in sea level.

Rainfall can exceed 500 mm in twenty-four hours in some cases, as occurred with Tropical Cyclone Harvey (NOAA) with recent research reporting a global increase of around 14% (Knutson et al., 2020). Attribution studies now show that some specific cases of extraordinary rainfall in some hurricanes would not be possible without the influence of climate change, as is the case of Hurricane Harvey in 2017 or Florence in 2018 (Trenberth et al., 2018; Kunkel & Champions, 2019).

From a socioeconomic point of view, the analyzed region presents significant demographic pressure in coastal regions, especially in the case of Morocco, Madeira, the central Canary Islands and the entire southeastern Iberian Peninsula of Portuguese and Spanish coastal areas. The main economic activity in the European case in these places is tourism, which further increases the level of exposure.

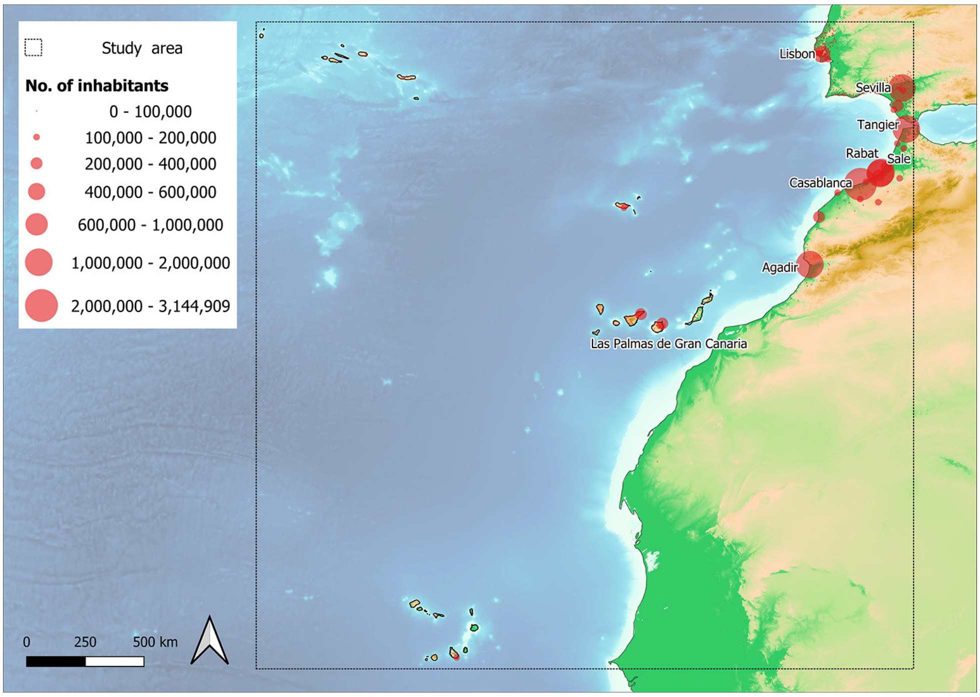
The estimated calculation of the foreseeable affected population in the insular area and its immediate continental surroundings suggests that more than twenty million inhabitants will be affected (Table 3 and Figure 7). This population is distributed to a large degree in a wide coastal strip of Morocco, Spain, and Portugal, as well as in the insular territories, whether they are states, such as the case of Cape Verde, or in European outermost regions, such as the case of Azores, Madeira and Canary Islands. The possibility of tropical disturbances such as storms and tropical cyclones reaching the Saharawi, Mauritanian and Senegalese coasts is extremely low, due to their geographical location, although they are in the study area. In fact, no case has been recorded to date, so populations in these areas have been ruled out as potentially exposed populations. Even so, if the coastal population of this African sector were counted, more than ten million people living on the coast would be added to the foreseeable affected population.

Table 3. Estimated population that may be affected by tropical disturbances in the study area

Country	Population	Population centres	Cities > 500.000 hab.
Morocco	10,407,346	79	5
Spain	5,327,482	243	1
Portugal	4,509,319	342	1
Cape Verde	309,511	25	0
Total population	20,244,147	689	7

Source: GEBCO and Geonames in https://public.opendatasoft.com. Own elaboration

Figure 7. Main cities likely to be affected by tropical disturbances in the study area



Source: GEBCO and Geonames en https://public.opendatasoft.com. Own elaboration

In the European countries of Spain and Portugal, the population in potentially affected areas is mostly concentrated in small towns, with less than 100,000 inhabitants. However, two medium-sized cities of much economic importance are located in the geographical area analyzed here, one of them is Lisbon, with a clear Atlantic coastal orientation and the other Seville, somewhat further inland, but not free from the possible effects of floods caused by extraordinary tropical phenomena. Cadiz, despite being a smaller urban nucleus, is also particularly exposed to problems related to the cyclone tide.

Morocco has a large concentration of population in coastal cities, most of them on the Atlantic coast. There are five cities with more than 500,000 inhabitants (Rabat, Tangier, Agadir, Casablanca, Rabat and Salé) with Morocco being the country with the largest exposed population in the analyzed region of more than ten million inhabitants. All the above cities are of considerable importance from the national economic point of view.

The effect of the concentration of the population in cities and in specific points of the coast is a phenomenon that is also found in insular regions, as is the case of Santa Cruz de Tenerife, Las Palmas de Gran Canaria in the Canary Islands, Funchal in the case of Madeira and Praia in Cape Verde.

4. Discussion

Despite the abovementioned difficulty of using the data, and the cyclical variations, both interannual and multidecadal, of these phenomena, the increasing number of investigations on tropical cyclones reveal a series of clear conclusions for the entire planet and, specifically, for the Atlantic Ocean basin, although only 12% of the total occurs in this region (Emanuel, 2021). The most important ones that have been identified are listed below:

- Firstly, the data show that there is a clear increase in episodes of greater intensity, those that fall into categories 4 and 5 of the Saffir-Simpson scale, known as Major Hurricanes (MH) with a broad scientific consensus, (Bhatia et al., 2018; Knutson et al., 2021), especially in the Atlantic Ocean basin (Elsner et al., 2008; Vecchi et al., 2021), where the number of these has been increasing by more than 40% per decade, with respect to the total, since 1980 (Kossin et al., 2020).
- Although an increase in the number of phenomena has been demonstrated in the study area, in general, there does not seem to be an upward trend in the Atlantic basin in the number of disturbances according to some authors (Knutson at al., 2021). However, there is great interannual variability in the Atlantic basin depending on multiple factors. In this context, although there is no absolute consensus, some very recent publications report a general increase in the number of events, not only of the higher categories (Emanuel, 2021), although this increase does not seem in all probability to exceed the natural variability observed in the last millennium (Burn & Palmer, 2015).
- There is a clear relationship between SST and the number of tropical events, although the correlation is much more significant if it is made with higher category hurricanes (MH) (Elsner et al., 2008).
- In relation to the above, an increase in floods has been detected due to the aforementioned increase in higher category cyclones (Paerl et al., 2020), which is consistent with an increase in precipitation per event (IPCC, 2021).
- As the path of tropical cyclones slows down (Knutson et al., 2019) their damage capacity increases, in terms of total precipitation (Gori et al., 2022), since it has been shown that this is inversely proportional to the speed of movement (Kossin, 2018).
- There is an extension in the latitude at which tropical cyclones are at maximum intensity in both hemispheres, especially in the North Pacific (Kossin et al., 2014; Knutson et al., 2019; Knutson et al., 2021). In other words, their trajectories are ascending latitudinally, thus affecting regions that were either previously unaffected or where the effects of these phenomena were uncommon.
- There is a recorded increase in the frequency of out of season tropical cyclones, especially after the 1970s, as a consequence of an increase in SST (Hernández-Ayala & Méndez-Tejeda, 2020). Thus, the appearance of the first tropical disturbance is earlier and earlier while the last one is appearing gradually later and later in the year (Kossin, 2008).
- In the case of the North Atlantic, the surface extension of the paths of these phenomena is expanding, so that they are now invading the center of the ocean. In addition, in this regard, events with

extreme intensities are also beginning to travel across the central Atlantic. The best example of this is Hurricane Lorenzo in 2019, which reached a scale of category 5, and was one of the easternmost maximum category hurricanes recorded since records began (Zelinsky, 2019).

- Finally, the most recent research shows that the multidecadal variations related to the Atlantic Multidecadal Oscillation (AMO), which is used to explain the cycles in the appearance of tropical cyclones, with positive and negative phases, could be explained by aerosols, whether of volcanic or anthropogenic origin (Mann et al., 2021). Therefore, the role that AMO would have in explaining the increase in tropical disturbances in recent years, attributed in part to a positive AMO, remains a matter of debate and, in reality, global warming would be responsible for these interannual changes in tropical cyclones. (Vecchi et al., 2021).

Having exhaustively analyzed the evolution of tropical disturbances in the southeastern North Atlantic, it is now necessary to explain what the future situation will be. Among the main conclusions shown in the most recent publications are that the number of tropical cyclones will remain stable or even decrease, although their intensity and precipitation will increase (Knutson et al., 2021; Walsh et al., 2019; IPCC, 2021). As regards the first question, there will be an increase in the highest category cyclones (Bhatia et al., 2018; Knutson et al., 2021). Wind speeds will increase as a consequence of the increase in the proportion of category 4 and 5 cyclones (Knutson et al., 2021). It is estimated that the rainfall increase could be, according to some authors, of the order of 20% by the end of the century (Knutson et al., 2010), although this varies depending on the future thermal increase, from 11% to 28% for values of global increase in temperatures of 1.5º C and 4º C, respectively (IPCC, 2021). In addition, it should be noted that as the sea level rises, the impact of the floods, both fluvial and derived from the storm surge, will have very serious impacts, especially in coastal areas (Woodruff et al., 2013).

The latest publications clearly present the main features of the relationship between climate change and tropical cyclones (Knutson et al., 2021; Liu, et al., 2019). Despite the difficulty in preparing future projections and the need to continue adjusting the simulation models, the results are conclusive.

- Although the number of tropical disturbances will remain or may more likely decrease slightly, there will be a clear increase in MH, which will result in more damage from wind, floods and more intense rainfall.
- This increase in MH is expected to be between 24% and 35% by the end of the century depending on the greenhouse gas (GHG) emissions scenario (Knutson et al., 2021). With a thermal increase of 1.5º C, the rise will reach 10%, but it may reach 30% with 4º C of warming (IPCC, 2021)
- MH will also last longer.
- Regarding the above, the wind speed will also increase, depending on the GHG emission scenarios.
- The increase in atmospheric humidity is likely to cause greater volumes of rain, thus increasing the risk of flooding, which is expected to increase as warming continues. In the case of the Atlantic, this increase is estimated at between 8% and 24% depending on the emissions scenario.
- In this respect, according to the thermal rise of the ocean surface, the increase could reach 29% (Lui et al., 2019).
- Under the higher emissions scenarios, the risk of tropical cyclones is likely to continue to rise at increasingly higher latitudes, especially in the western North Pacific.
- The rise in sea level will cause more serious coastal flooding. In addition, in a context of increased MH, the intensity of the storm surges added to the increase in precipitation could cause very severe damage much higher than the damage caused to date (Gori et al., 2022).

The data presented in the present article and for the study area analyzed indicate that the number of tropical disturbances is increasing, so it is foreseeable that the impact risk of this type of situation will continue to grow in the future as a consequence of the increase in oceanic temperatures and the arrival of disturbances with serious consequences in coastal regions cannot be ruled out. It is foreseeable, therefore, that hitherto unheard-of phenomena may be recorded causing damage never before recorded, especially in a scenario of sea level rise, as stated by other researchers.

On the other hand, it has been suggested that an increase in the intensity of tropical cyclones will also increase the risk of extratropical cyclones on western European coastlines (Haarsma et al., 2013; Baatsen et al., 2015). This has been made clear by the IPCC (2021) as was the case of Tropical Cyclone Ophelia in October 2017, which reached category 3 as it passed through the southwest of the Azores and led to considerable damage, especially in Ireland, when it reached Ireland as an extratropical cyclone.

The rise in the sea level in the study area, as a consequence of climate change, may generate considerable damage in some sectors of the coasts. In the case of Spain, a good example is the large stretch of the Andalusian Atlantic coast, and especially worrying in the Bay of Cádiz, where it is foreseeable that by the end of the century the sea level could rise by more than 80 cm (Fraile & Fernández, 2016). In the abovementioned area, the floodable areas could increase almost threefold by the end of the 21st century (Fraile & Ojeda, 2012). In the case of the Canary Islands, although it is true that, in general, its coasts are different to those in the Gulf of Cádiz, there is a trend of a rise in sea level of 0.56 cm/year (1992-2013) (Gobierno de Canarias, 2020), and it is estimated that by the end of the 21st century the rise will be between 70 and 131 cm in the central islands; this will depend, as is the case of most meteorological parameters, on the emission scenarios, the higher the GHG emissions, the greater the rise in sea level (Fraile et al., 2014).

Such a situation, with a sea level higher than the current one, means that storm surges, which accompany tropical cyclones, will have a marked increasingly greater impact in highly exposed and vulnerable areas; most of which are heavily dependent on tourism, both in the case of Andalusia and in the Canary Islands and Portugal.

Finally, different researchers even suggest a decrease in disturbances in the western Atlantic and an increase in the eastern Atlantic (Liu et al., 2017). In this respect, although there are few available studies in this regard, there are already indications that point to an increase in the number of unstable phenomena of tropical origin in Western Europe, especially by the end of this century, a time when hurricanes, even when they turn into extratropical cyclones, could pose a serious threat to this region (Haarsma et al., 2013; Baatsen et al., 2015). Thus, there would be a foreseeable extension of severe storm seasons in Europe, currently concentrated in and around winter and which would also extend into autumn (Baatsen et al, 2015).

5. Conclusions

In the current context of climate change, with a thermal increase in the oceans and, specifically in the Atlantic, the present work shows the relevance that unstable phenomena of tropical origin are starting to have in a geographical area where the risk of these has always been very low. The extensive bibliography referring to tropical disturbances and, above all, to tropical cyclones in the Atlantic basin, is starting to report important changes in their intensity, seasonality and distribution. The increase in tropical disturbances in the study area of the southeastern North Atlantic is clear. As a consequence, the coasts of this environment are beginning to be threatened by the foreseeable presence, more and more frequent, of these situations.

Among the most serious effects associated with these events are floods, both river and sea, and extreme winds. There have already been cases of torrential rainfall with the effect of flooding and the models indicate an increase in the volume of rainfall associated with hurricanes in the near future. With the rise in sea level, the risk of flooding due to waves increases exponentially, increasing exposure in a region with a high population density, and as has been seen, with several tens of millions of people exposed to the dangers of tropical cyclones.

In Spain, from the perspective of management, various territorial and sectoral plans have been developed in recent years in relation to floods, most of them thanks to the European directive 2007/60, incorporated into the Spanish legal system by Royal Decree 903/2010. The hydrographic district authorities drew up the flood management plans and flood risk management plans for the hydrographic basins in mainland Spain and similar plans have been drawn up in the Spanish archipelagos. In addition, in the field of civil protection, action plans have been developed to deal with the risk of flooding. All these documents are based on the premise that floods are related to typical phenomena of what could be called Mediterranean climatology. However, it is foreseeable that these rains of a temperate origin could be added to the abovementioned plans, although it is true that there is infrequent intense precipitation caused by tropical phenomena such as storms and tropical cyclones in late summer and early autumn. Coastal flooding due to storm surges should also be taken into account, with a predictable higher sea level, as well as strong winds capable of causing serious damage to all kinds of infrastructure, which could reach speeds never before recorded in the said geographical area. All this at a time of year when unstable phenomena are infrequent, so the seasonality of risk due to rain, sea storms and wind would be longer.

The sum of the increase in wind, precipitation and waves of cyclones in a context of higher sea levels than now means that coastal risks will be markedly exacerbated. The increased risk of disturbances of tropical origin exists not only because of the increase in the threat itself but also because of the increasingly marked coastalization of socioeconomic activities, especially in reference to tourism.

Consequently, it is necessary to continue researching to gain better knowledge of the dangers of tropical origin, but also to contribute to a territorial and sectorial planning much more in line with the future conditions that the necessary, urgent and enormous task of the adaptation to climate change demands.

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References

Baatsen, M., Haarsma, R.J., Van Delden, A.J., & de Vries, H. (2015). Severe Autumn storms in future Western Europe with a warmer Atlantic Ocean. *Climate Dynamics* 45, 949–964. https://doi.org/10.1007/s00382-014-2329-8

Bethencourt-González, J., & Dorta-Antequera, P. (2010). The Storm of November 1826 in the Canary Islands: possibly a tropical cyclone? *Geographisca Annaler*, *92 A*(3), 329–337. https://doi.org/10.1111/j.1468-0459.2010.00398.x

Bhatia, K., Vecchi, G., Murakami, H. Underwood, S., & Kossin, J. (2018). Projected Response of Tropical Cyclone Intensity and Intensification in a Global Climate Model. *Journal od Climate, 31*(20), 8231-8303. https://doi.org/10.1175/JCLI-D-17-0898.1

Burn, M., & Palmer, S. (2015). Atlantic hurricane activity during the last millennium. *Scientific Reports*, 5, 12838. https://doi.org/10.1038/srep12838

Capel-Molina, J.J (1988). Trayectorias de las gotas frías en el flanco sur europeo: Archipiélagos Ibéricos, Mediterráneo y Mar Negro. In A. Blanco (Coord), *Avances sobre la investigación en Bioclimatología* (pp. 489-505). C.S.I.C.

Chenoweth, M., & Divine, D. (2008). A document-based 318-year record of tropical cyclones in the Lesser Antilles, 1690-2007, *Geochemistry, Geophysics, Geosystems*, *9*(8). https://doi.org/10.1029/2008GC002066

Criado, C., Dorta, P., Bethencourt, J., Navarro, J.F., Romero, C., & García, C. (2013). Evidence of historic infilling of valleys in Lanzarote after the Timanfaya eruption (AD 1730-1736, Canary Islands, Spain). *The Holocene, 23*(12), 1786-1796. https://doi.org/10.1177%2F0959683613505342

Criado, C., Dorta, P., Casanova, H., González-Reimers, E., Arnay, M., & Soler, V. (2018). Debris flow triggering on Teide stratovolcano, Tenerife. A growing process?. *Cuaternario y Geomorfología, 32*(3-4), 23-38. http://dx.doi.org/10.17735/cyg.v32i3-4.67068

Domínguez-Castro, F., Trigo, R.M., & Vaquero, J.M. (2013). The first meteorological measurements in the Iberian Peninsula: evaluating the storm of November 1724. *Climatic Change,* 118, 443–455. https://doi.org/10.1007/s10584-012-0628-9

Dorta, P. (2007). Catálogo de riesgos climático en Canarias: amenazas y vulnerabilidad. *Geographicalia,* 51, 133-160. https://doi.org/10.26754/ojs_geoph/geoph.2007511118

Elsner, J., Kossin, J., & Jagger, T. (2008). The increasing intensity of the strongest tropical cyclones. *Nature,* 455, 92–95. https://doi.org/10.1038/nature07234

Emanuel, K. (2021). Atlantic tropical cyclones downscaled from climate reanalyses show increasing activity over past 150 years. *Nature communications,* 12, 7027. https://doi.org/10.1038/s41467-021-27364-8

Evans, J.L., & Guishard, M.P. (2009). Atlantic subtropical storms. Part I: Diagnosis Criteria and Composite Analysis. *American Meteorological Society,* 137, 2065-2080. https://doi.org/10.1175/2009MWR2468.1

Faccini, F., Luino, F., Paliaga, G., Roccati, A., & Turconi, L. (2021). Flash Flood Events along the West Mediterranean Coasts: Inundations of Urbanized Areas Conditioned by Anthropic Impacts. *Land, 10*(6), 620. https://doi.org/10.3390/land10060620

Fraile, P., & Fernández, M. (2016). Escenarios de subida de nivel medio del mar en los mareógrafos de las costas peninsulares de España en el año 2100. *Estudios geográficos*, *77*(280), 57-79. https://doi.org/10.3989/estgeogr.201603

Fraile, P., & Ojeda, J. (2012). Evaluación de la peligrosidad asociada al aumento de la superficie inundable por la subida del nivel medio del mar en la costa entre Cádiz y Tarifa. *Geofocus*, 12, 329-348.

Fraile, P., Sánchez, E., Fernández, M., Pita, Mª.F., & López, J.M. (2014). Estimación del comportamiento futuro del nivel del mar en las Islas Canarias a partir del análisis de registros recientes. *Geographicalia*, 66, 79-98. https://doi.org/10.26754/ojs_geoph/geoph.2014661066

Gobierno de Canarias (2020). *Plan especial de Gestión del Riesgo de Inundación de la Demarcación Hidrográfica de Tenerife (PGRI)*.

Gori, A., Lin, N., Xi, D., & Emanuel, K. (2022). Tropical cyclone climatology change greatly exacerbates US extreme rainfall–surge hazard. *Nature Climate Change,* 12, 171–178. https://doi.org/10.1038/s41558-021-01272-7

Guijarro, J.A., Conde, J., Campins, J., Picornell, Mª.A., & Orro, Mª.L. (2014). In S. Fernández, & F. Sánchez (Eds.), *Cambio climático y cambio global* (pp. 315-324). Asociación Española de Climatología.

Haarsma, R., Hazeleger, W., Severijns, C., De Vries, H., Sterl, A., Bintaja, R., Van Olddenborgh, & van den Brink, H. (2013). More hurricanes to hit western Europe due to global warming. *Geophyscal Research Letters*, *40*(9), 1783-1788. https://doi.org/10.1002/grl.50360

Hernández Ayala, J.J., & Méndez-Tejeda, R. (2020). Increasing frequency in off-season tropical cyclones and its relation to climate variability and change. *Weather Climate Dynamics, 1*(2), 745-757. https://doi.org/10.5194/wcd-1-745-2020

Instituto Nacional de Meteorología (2005). Consideraciones sobre el ciclón tropical "Vince". http://www.aemet.es/es/conocermas/recursos_en_linea/publicaciones_y_estudios/estudios/detalles/Consideraciones_sobre_el_ciclon_tropical_Vince

Intergovernmental Panel for Climate Change. (2021). Climate Change 2021: The Physical Science Basis. In V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (Eds.), *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* . Cambridge University Press. In Press

Knutson, T. R., Chung, M. V., Vecchi, G., Sun, J., Hsieh, T-L., & Smith, A. J. P. (2021). Climate change is probably increasing the intensity of tropical cyclones. In C. Le Quéré, P. Liss, & P. Forster (Eds), *Critical Issues in Climate Change Science*. https://doi.org/10.5281/zenodo.4570334

Knutson, T., Camargo, S.J., Chan, J.C., Emanuel, K., Ho, C.H., Kossin, J., Mohapatra, M., Satoh, M., Sugi, M., Walsh, K., & Wu, L. (2019). Tropical Cyclones and Climate Change Assessment: Part I: Detection and Attribution. *Bulletin of the American Meteorological Society, 100*(10), 1987-2007. https://doi.org/10.1175/BAMS-D-18-0189.1

Knutson, T., Camargo, S.J., Chan, J.C., Emanuel, K., Ho, C.H., Kossin, J., Mohapatra, M., Satoh, M., Sugi, M., Walsh, K., & Wu, L. (2020). Tropical Cyclones and Climate Change Assessment: Part II: Projected Response to Anthropogenic Warming. *Bulletin of the American Meteorological Society, 101*(3), E303-E322. https://doi.org/10.1175/BAMS-D-18-0194.1

Knutson, T., McBride, J., Chan, J., Emanuel, K., Holland, G., Landssea, C, Held, I., Kossin, J.P., Srivastacva, A.K., & Sugi, M. (2010). Tropical cyclones and climate change. *Nature Geoscience,* 3, 157–163. https://doi.org/10.1038/ngeo779

Kossin, J., Emanuel, K., & Vecchi, G. (2014). The poleward migration of the location of tropical cyclone maximum intensity. *Nature,* 509, 349–352. https://doi.org/10.1038/nature13278

Kossin, J.P. (2008). Is the North Atlantic hurricane season getting longer?. *Geophysical Research Letters*, 35. https://doi.org/10.1029/2008GL036012

Kossin, J.P. (2018). A global slowdown of tropical-cyclone translation speed. *Nature,* 558, 104–107. https://doi.org/10.1038/s41586-018-0158-3

Kossin, J.P., Knapp, K.R., Olander, T.L., & Velden, C. (2020). Global increase in major tropical cyclone exceedance probability over the past four decades. *PNAS, 117*(22), 11975-11980. https://doi.org/10.1073/pnas.1920849117

Kossin, J.P., Knapp, K.R., Vimont, D.J., Murnane, R.J., & Harper, B.A. (2007). A globally consistent reanalysis of hurricane variability and trens. *Geophysical Researh Letters*, 34, L04815. https://doi.org/10.1029/2006GL028836

Kossin, J.P., Olande, T.L., & Knapp, K.R. (2013). Trend Analysis with a New Global Record of Tropical Cyclone Intensity. *Journal of Climate, 26*(24), 9960-9976. https://doi.org/10.1175/JCLI-D-13-00262.1

Kunkel, K.E., and Champion, S.M. (2019). An Assessment of Rainfall from Hurricanes Harvey and Florence Relative to Other Extremely Wet Storms in the United States. *Geophysical Research Letters*, 46, 13500-13506. https://doi.org/10.1029/2019GL085034

Liu, M., Vecchi, G.A., Smith, J.A., & Knutson, T.R. (2019). Causes of large projected increases in hurricane precipitation rates with global warming. *npj Climate and Atmospheric Science,* 2, 38. https://doi.org/10.1038/s41612-019-0095-3

Liu, M., Vecchi, G.A., Smith, J.A., & Murakami, H. (2017). The Present-Day Simulation and Twenty-First-Century Projection of the Climatology of Extratropical Transition in the North Atlantic. *Journal of Climate*, *30*(8), 2739-2756. https://doi.org/10.1175/JCLI-D-16-0352.1

Llasat, M.C., Llasat-Botija, M., Prat, M.A., Porcú, F., Price, C., Mugnai, A., Lagouvardos, K, Kotrono, V., Katsanos, D., Mirchaelides, S., Yair, Y., Savvidou, K., & Nicolaides, K. (2010). High-impact floods and flash floods in Mediterranean countries: the FLASH preliminary database. *Advances in Geosciences*, 23, 47-55. https://doi.org/10.5194/adgeo-23-47-2010

López-Díez, A., Máyer, P., Díaz-Pacheco, J., & Dorta, P. (2019). Rainfall and flooding in coastal tourist areas of the Canary Islands (Spain). *Atmosphere*, *10*(12), 809. https://doi.org/10.3390/atmos10120809

Mann, M.E., Steinman, B.A., Brouillette, D.J., & Miller, S.K. (2021). Multidecadal climate oscillations during the past millenium driven by volcanic forcing. *Science*, *371*(6533), 1014-1019. https://doi.org/10.1126/science.abc5810

Martín-Esquivel, J.L., Bethencourt, J., & Cuevas-Agulló, E. (2012). Assessment of global warming on the island of Tenerife, Canary Islands (Spain). Trends in minimum, maximum and mean temperatures since 1944. *Climatic Change*, 114, 343-355. https://doi.org/10.1007/s10584-012-0407-7

Mauk, R.G., & Hobgood, J.S. (2012). Tropical Cyclone Formation in Environments with Cool SST and High Wind Shear over the Northeastern Atlantic Ocean. *American Meteorological Society*, *27*(6), 1433-1448. https://doi.org/10.1175/WAF-D-11-00048.1

Máyer, P., & Marzol, Mª.V. (2014). La concentración pluviométrica diaria y las secuencias lluviosas en Canarias: factores de peligrosidad. *Boletín de la Asociación Española de Geografía*, 65, 231-247. https://doi.org/10.21138/bage.1751

Máyer, P., Marzol, Mª.V., & Parreño, J.M. (2017). Precipitation trends and a daily precipitation concentration index for the mid-Eastern Atlantic (Canary Islands, Spain). *Cuadernos de Investigación Geográfica, 43*(1), 255-268. https://doi.org/10.18172/cig.3095

NASA (2022). https://www.nasa.gov/content/goes

Paerl, H.W., Hall, N.S., Hounshell, A.G. Rossignol, K.L., Barnard, M.A., Luettich Jr, R.A., Rudolph, J.C., Osburn, C.L., Bales, J., & Harding Jr, L.W. (2020). Recent increases of rainfall and flooding from tropical cyclones (TCs) in North Carolina (USA): implications for organic matter and nutrient cycling in coastal watersheds. *Biogeochemistry,* 150, 197–216. https://doi.org/10.1007/s10533-020-00693-4

Trenberth, K.E., Cheng, L., Jacobs, P., Zhang, Y., & Fasullo, J. (2018). Hurricane Harvey Links Ocean Heat Content and Climate Change Adaptation. *Earth Future*, *6*(5), 730-744. https://doi.org/10.1029/2018EF000825

Vaquero, J. M., García Herrera, R., Wheeler, D., Chenoweth, M., & Mock, C.J. (2008). A historical analog of 2005 Hurricane Vince. *Bulletin of the American meteorological society, 89*(2), 191-201. http://dx.doi.org/10.1175/BAMS-89-2-191

Vecchi, G. A., & T. R. Knutson. (2011). Estimating annual numbers of Atlantic hurricanes missing from the HURDAT database (1878-1965) using ship track density. *Journal of Climate, 24*(6), 1736-1746. https://doi.org/10.1175/2010JCLI3810.1

Vecchi, G.A., Landsea, C., Zhang, W., Villarini, G., & Knutson, T. (2021). Changes in Atlantic major hurricane frecuency since the late-19th century. *Nature communications*, *12,* 4054. https://doi.org/10.1038/s41467-021-24268-5

Viñas, J.M. (2019). Conocer la Meteorología. Diccionario ilustrado del tiempo y el clima. Alianza Editorial.

Walsh, K.J.E., Camargo, S.J., Knutson, T.R., Kossin, J., Lee, T.-C., Murakami, H., & Patricola, C. (2019). Tropical cyclones and climate change. *Tropical Cyclone Research and Review*, *8*(4), 240-250. https://doi.org/10.1016/j.tcrr.2020.01.004

Webster, P.J., Holland, G.J., Curry, J.A., & Chang, H.R. (2005). Changes in Tropical Cyclones Number, Duration, and Intensity in a Warming Environment. *Science, 309*(5742), 1844-1846. https://doi.org/10.1126/science.1116448

Woodruff, J.D., Irish, J.L., & Camargo, S.J. (2013). Coastal flooding by tropical cyclones and sea-level rise. *Nature*, 504. https://doi.org/10.1038/nature12855

Zelinsky, D.A. (2019). *Hurricane Lorenzo (AL132019)*. National Hurricane Center Tropical Cyclone Report.