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ORIGINAL ARTICLE

Temporal evolution of hurricane activity: insights from decades of category 1–5 analysis

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Abstract

This study conducts a comprehensive analysis of hurricane trajectories and their variabilities in categories 1–5 over several decades for the North Atlantic Basin. Utilizing HURDAT2 data from 1961 to 2021, the analysis categorizes hurricanes based on the rate of pressure drop within a 6-h interval, revealing distinct patterns of intensification and weakening among different categories. The K-means clustering method synthesizes hurricane trajectories into representative paths, illustrating significant variations across decades. The research indicates that hurricanes in categories 1 and 2 predominantly originate from tropical depressions, with this trend slightly intensifying in categories 3 and 4. In contrast, Category 5 displayed variation, revealing an increased frequency in the subsequent decades. Additionally, the study analyzes the monthly distribution of hurricanes, identifying September as the peak month across all categories. The analysis further detects significant interannual variability with a noticeable intensification in hurricane activity since the 1990s, albeit with some reductions in the early 2010s. The Accumulated Cyclone Energy (ACE) is used to summarize cyclonic activities, with results indicating a decrease from 1970 to 1995, followed by a consistent surge over the last 15 years. This aligns with previous research suggesting an approximately 60% increase in ACE since the 1980s. Furthermore, an analysis of North Atlantic Basin data reflects a progressive increase in the frequency of named storms (NS) and hurricanes, particularly from 1991 onwards. In conclusion, the study highlights not only an escalating frequency of hurricanes, but also increased variability and unpredictability, necessitating further research to comprehend the underlying causes and evaluate potential socioeconomic and environmental consequences.

Keywords Hurricanes · Climate change · Climate variability

Introduction

Tropical cyclones are devastating natural phenomena which are named as hurricanes in the North Atlantic and Northeast Pacific, typhoons in the Western Pacific, and cyclones in the Indian Ocean. When they hit land, hurricanes can cause massive loss of life. In addition, they are responsible for widespread damage due to high wind speeds, associated storms, and intense rainfall. Several studies, including Hellin et al. (1999), Seekins (2009), Pistrika et al. (2010), and others, confirm that these natural events have a significant impact on the affected communities. Upon landfall, hurricanes inflict significant casualties and widespread damage through high wind speeds, associated storms, and heavy rainfall, as affirmed by various studies, including Hellin et al. (1999), Seekins (2009), Pistrika et al. (2010), and others.

A hurricane is technically defined as a cyclone originating in the tropical oceans and primarily driven by heat transfer from the ocean (Emanuel 2003). They are classified according to the maximum wind speed reached. Hurricane classification is based on the wind speed measured at a height of 10 m and averaged over 10 min (Simpson and Saffir 1974). At the stage of formation, they can present sustained maximum winds of up to 17 m/s or less and are known as tropical

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depressions. When the wind speed is between 18 and 32 m/s, they are called tropical storms. When the maximum wind reaches 33 m/s, they are called hurricanes, which varies from category 1 to category 5, reaching wind speeds greater than 70 m/s.

Before the mid-twentieth century, the identification of hurricanes was primarily based on information obtained from reports from coastal stations, islands, and ships at sea. During this period, it is possible that many storms went unnoticed, and many others were sighted only once or a few times throughout their lives (Landsea 1993; Emanuel 2003). This was especially true in remote areas of the ocean and in storms that never reached the coast (Oouchi et al. 2006).

Since 1960, hurricane observation saw a significant leap with the transmission of the first image from a polar-orbiting satellite (Sadler 1962). By the 1970s, satellite observations became the primary method for recording hurricanes, offering precise tropical storm localization. These observations, combined with pattern recognition and infrared radiation measurements, are used to estimate storm intensity (Velden et al. 1992). Although there's debate about satellite-based wind estimates, they form the basis for most predictions, excluding specific cases in the Atlantic investigated by aircraft .

Operational forecasts play a crucial role in understanding hurricane formation and trajectory, focusing on predicting the cyclone's path and maximum surface wind intensity. Current forecasts incorporate representations of uncertainty in both path and intensity (Titley et al. 2019). Reducing these uncertainties is essential for improving local warnings, addressing threats from high wind speeds and the risks of heavy rainfall and coastal storms (Needham et al. 2015). The climatology of North Atlantic hurricanes is a topic of great importance for understanding cyclonic activity patterns in this region. According to analyses by Emanuel (2005a, b), Kossin et al. (2010), the North Atlantic is the most active region in terms of hurricanes worldwide, with an average of about 12–13 tropical storms and six to seven hurricanes each season. Tropical storms typically form between June and November, with August and September being the peak months of cyclonic activity (e.g., Mc Taggart-Cowan et al. 2008; Grondin and Ellis 2021). Ramsay (2017) mentions that there has been a significant increasing trend in the annual number of tropical cyclones in the North Atlantic from 1985 to 2014, at a rate of approximately 2.4 storms per decade.

The analysis and assessment of the intensity and impact of hurricanes often involve metrics grounded in physical and meteorological principles. The Accumulated Cyclone Energy (ACE) Index is one such metric, serving as a comprehensive measure of the kinetic energy of the wind associated with tropical storms and hurricanes during a specific season. This index takes into account the maximum wind intensity in each tropical storm or hurricane, along with the total duration of these events, providing a cumulative perspective of cyclonic activity (Emanuel 2005a, b; Murakami et al. 2014).

Furthermore, the scientific literature indicates that the climate of the North Atlantic is highly influenced by climatic factors such as the Atlantic Decadal Oscillation (ADO) and the El Niño-Southern Oscillation (ENSO). According to the analysis by Kossin et al. (2018), the increase in sea surface temperatures in response to global warming also plays a significant role in the increase in intensity and frequency of hurricanes.

Another important aspect of the climatology of North Atlantic hurricanes is the geographic distribution of cyclonic activity. According to the analysis by Mendes et al. (2023), most hurricanes develop in the western North Atlantic, especially off the east coast of the United States, Caribbean, and Gulf of Mexico.

Emanuel (2005a, b) identified that the intensity of hurricanes has been increasing significantly over the past three decades, both in terms of maximum sustained winds and in terms of minimum central pressure. According to the study, the increase in the intensity of hurricanes is primarily attributed to ocean warming, which provides more energy for the formation and intensification of these systems. The study also reveals that the total number of hurricanes has not increased significantly over the study period, but the proportion of category 4 and 5 cyclones (the most intense) has increased in all ocean basins studied. Additionally, the study highlights that hurricanes are moving more slowly, which increases their capacity to cause significant damage in affected areas.

Kossin et al. (2018) analyzed that there is a global trend in the increasing likelihood of occurrence of category 3, 4, and 5 hurricanes over the last four decades. The study concludes that the likelihood of occurrence of category 3, 4, and 5 hurricanes has been increasing significantly worldwide over the last four decades, with an average increase of about 8% per decade.

Thus, these events are extremely important to study and predict, but for that, it is necessary to study and analyze them, not only dynamically, but also in their variability, whether it is interannual, decadal, or secular.

The objective of this study is to analyze the climatology of cyclogenesis and the life trajectory of hurricanes in the North Atlantic Ocean, in order to evaluate the trajectory changes for different categories during the life cycle of hurricanes, presenting a climatology of cyclogenesis and standard trajectories for all hurricanes between 1961 and 2021. In this way, we can identify possible changes in hurricane behavior on a decadal basis.

In this article, we present a more comprehensive perspective in comparison to the existing literature, which typically addresses the variability of these systems in a general manner. Therefore, we categorize hurricanes by decades, spanning from 1960 to 2021, using cluster analysis (K-Means method). Our objective is to deepen the understanding of the variability among these categories and to examine their intensity based on ACE (Accumulated Cyclone Energy), revealing trends over the study period.

Data and methodology

Data

The HURricane DATabase (HURDAT) is a database maintained by the United States' National Hurricane Center (NHC), which contains information about the location, intensity, and trajectory of all hurricanes and tropical storms that have occurred in the Atlantic Ocean and the eastern Pacific region since the nineteenth century (Landsea et al. 2004, 2008, 2012, Hagen et al. 2012; Delgado et al. 2018). The HURDAT data have been used in numerous climatological studies, including analyses of hurricane intensity trends, changes in the frequency of tropical storms, and the relationship between hurricane activity and climate change (Landsea et al. 2004, 2008, 2012).

Another data source that we used was the International Best Track Archive for Climate Stewardship (IBTrACS 2013) (Knapp et al. 2010). The IBTrACS is an important data source for studies on hurricanes worldwide. Since its inception, IBTrACS has been widely used in a variety of climate, meteorological, and risk studies. IBTrACS has been widely used in a variety of climate and risk studies (Knapp et al. 2010).

Methodology

Cluster analysis

Hierarchical methods, with the ability to conduct cluster analysis, have as their main characteristic the ability to join clusters at each step of the algorithm, forming various groupings that are organized in a hierarchical structure based on the proximity of the elements. This results in a binary tree, known as a dendrogram, where the root represents the complete set of data, and the leaves represent the final individuals (Patel and Singh 2012).

There are two approaches to subdivision: agglomerative and divisive. In the agglomerative approach, each element starts in its own group, and over time, groups are formed based on the similarity between the elements until all possibilities are exhausted. In the divisive approach, one starts with a single group containing all elements and, over time, the group is divided into subgroups based on the distance between the elements present in each subgroup.

The criteria were:

I. Aggregating the latitudes and longitudes of the centers of hurricanes by decades;
II. Joining elements into groups;
III. Creating standard trajectories by intensity category.

Clustering the latitudes and longitudes of hurricane centers allows us to effectively track the movement and evolution of these systems. The formation of these groups is determined by the similarities among elements (latitude and longitude of the system's center), facilitating the identification of shared trajectories among hurricanes. .

Based on the clustered data, it is possible to establish standardized trajectories for each hurricane category.

K-mean

Some works use cluster methods to identify patterns, for example, Kossin et al. (2010) employed cluster analysis to identify seasonal variability, intensity, and data associated with tropical cyclones, demonstrating a strong relationship in diagnosing these events. On the other hand, Boudreault et al. (2017) used cluster analysis to identify hurricane trajectories, emphasizing the importance of this tool as a predictor of trajectory patterns. Kozar et al. (2012) went beyond the trajectory estimated by clusters, exploring the relationship between the quantity of events and their connections to state variables. They showed that cluster analysis extends beyond identifying pre-existing patterns. Finally, Corporal-Lodangco et al. (2014) used k-means to identify genesis regions and, notably, the decline of tropical cyclones.

In employing k-means in our analyses, we took care to choose the best cluster analysis for our study, and k-means proved to be effective. Our work with this method focuses primarily on the interdecadal variability of hurricanes, distinguishing it from the aforementioned studies.

One of the most well-known and recently used non-hierarchical methods is the k-means. K-means is a non-hierarchical data clustering method, where an iterative technique is used to position a dataset. This algorithm seeks to minimize the distance between the elements present in a dataset with k centers in an iterative manner, and in the current project aims to define the standard trajectory of hurricanes, dividing them by categories (Loyd 1982).

Thus, we have:

- The K-means clustering algorithm is used in the study.
- K-means is an unsupervised machine learning algorithm.
- The algorithm randomly selects K centroids from the dataset.

- The distance between each sample and the centroids is calculated.
- The samples are allocated to the nearest centroid to form K clusters.
- In each cluster, a new centroid is selected.

The process is iterated to update the centroids and clusters until there are few changes in the centroids.

In this research, distance is used to discern the similarity between the samples and the centroids of the clusters, allowing the algorithm to group the samples in the nearest cluster. Typically, the classic K-means algorithm uses Euclidean distance for this purpose.

The Euclidean distance is a measure of the distance between two points in a Euclidean space. It is calculated by the square root of the sum of the squares of the differences between the coordinates of the points in each dimension. The formula to calculate the Euclidean distance in a two-dimensional space between two points is:

$\left(X_1, Y_1\right)$ and $\left(X_2, Y_s\right) = D$, thus, the distance would be:

$$D = \frac{1}{n}\sqrt{[\left(X_2 - X_1\right)^2 + \left(Y_2 - Y_1\right)^2]}. \tag{1}$$

The amount of data in a sample is represented by n, while X_i and Y_i, where in our sampling, X_i is the longitude of the center of the hurricane and Y_i is the latitude, where i refers to the ith data in samples X and Y, respectively. Although Euclidean distance has been effective in previous studies that used grouped hurricanes trajectories, it is not suitable for three-dimensional environmental data, as it focuses only on the similarity of the values and ignores the global characteristics of the data.

Accumulated Cyclone Energy (ACE)

The Accumulated Cyclone Energy (ACE) for a season is calculated by summing the squares of the estimated maximum sustained wind speeds of hurricanes with winds of 35 knots (65 km/h; 40 mph) or higher, at 6-h intervals. These values are typically divided by 10,000 for data handling, making one unit of ACE equivalent to 10^{-4} knots^2. The ACE formula (2), where V_max represents the estimated maximum sustained wind speed in knots, reflects the kinetic energy of the storm system. Providing a measure of energy, ACE indicates that longer-lasting storms accumulate higher values than more powerful but shorter-duration storms. It is crucial to note that ACE is an approximation of the definite integral over time of the system's kinetic energy, not a direct calculation of energy, which would be influenced by the mass of air moved and the storm's size (Camargo and Sobel 2005; Bell and Chelliah 2006):

$$ACE = 10^{-4} \sum V_{max}^2. \tag{2}$$

Within the Atlantic Ocean, the National Oceanic and Atmospheric Administration of the United States and others use the ACE index of a season to classify the season into one of four categories: extremely active, above normal, near normal, and below normal. These categories are determined based on an approximate quartile division of the seasons, taking into account the ACE index over the 70 years between 1951 and 2020. In the period from 1951 to 2020, the median value of the ACE index is 96.7×10^4 kt^2 .

These conditions will be used as a reference in this research.

The categories are as follows:

- Extremely active—ACE above 159.6
- Above-normal—ACE above 126.1
- Near-normal—ACE 73 to 126.1
- Below-normal—ACE below 73.0

Named storm day and hurricane days

The acquisition of data on "Named Storm Days" and "Hurricane Days" is a crucial practice for monitoring and understanding tropical activity. The quantification of tropical cyclone days involves daily counting of the number of active storms throughout the year, with these totals subsequently summed. Storms are categorized into three groups based on their intensity. Named storm days encompass all tropical cyclones with winds of at least 39 mph. Hurricane days include storms with winds of at least 74 mph, and major hurricane days account for storms with winds exceeding 111 mph.

These counts are cumulative, meaning that a storm with major hurricane intensity is included in the counts of named storms, hurricanes, and major hurricanes. For instance, a storm that persists for three days as a tropical storm, two days as a category 1–2 hurricane, and one day as a major hurricane (category 3–5) is tallied as six named storm days, three hurricane days, and one major hurricane day. Taken together, these counts represent an integrated metric of the strength, duration, and frequency of tropical cyclones during a specific year. Major hurricanes are indisputably the most destructive tropical cyclones.

Results and discussion

Climatology of tropical cyclones: decadal variability

The analysis of the trajectories of hurricanes by decade, as shown in Fig. 1, is important for understanding the variations

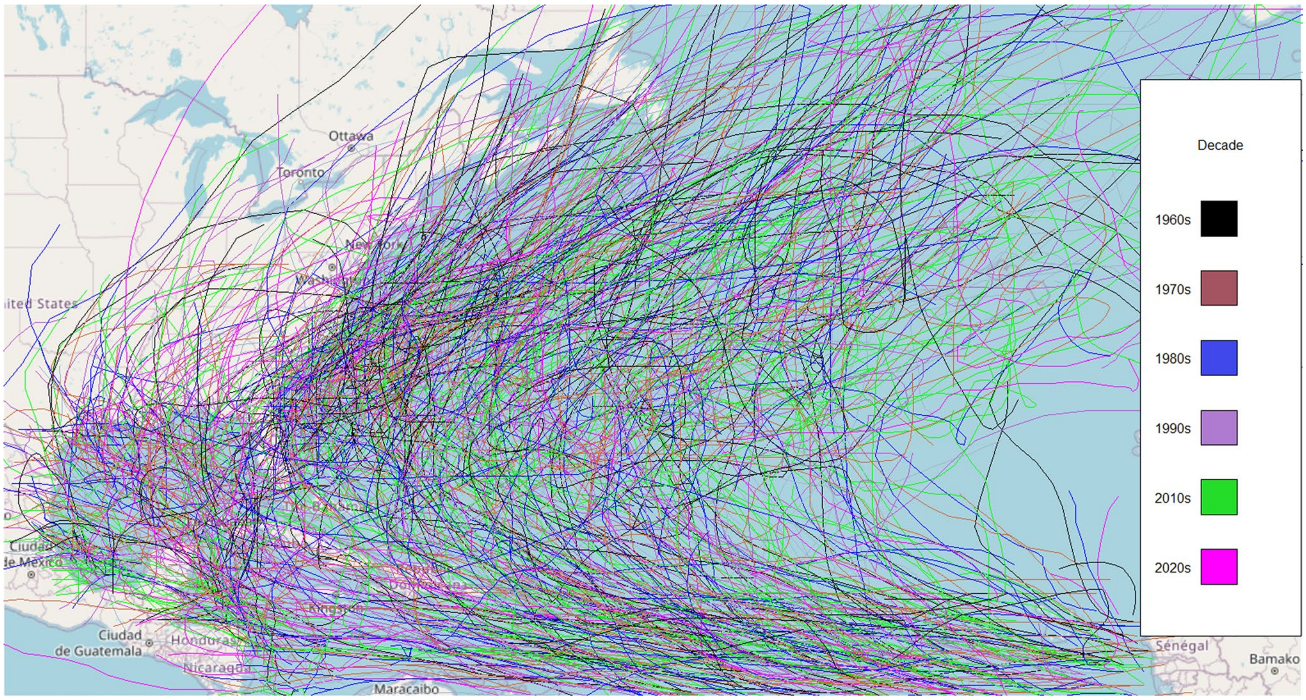

Fig. 1 Hurricane trajectories in the North Atlantic Basin between 1961 and 2021, by decades. The colors represent decades

and characteristics of these events over time. By grouping the events by decade, without specifying categories, we seek to evaluate the frequency of occurrences, with the purpose of identifying the variability of these events over the decades, providing insights into possible patterns and trends. Figure 1 reveals that the highest concentrations of events are located in the vicinity of the east coast of the United States, with values above 20 events for the decades. This observation is in accordance with the scientific understanding that this area is highly prone to hurricane impacts, owing to factors such as sea surface temperature and geographical configuration (Kossin et al. 2013; Landsea and Franklin 2013; Holland and Bruyère 2014).

It is important to emphasize that the number of events recorded for the 2020 decade is lower compared to other decades, due to the limited counting of events in only two years of this decade (2020 and 2021).

However, even in this short period, it is possible to identify the presence of up to 10 events in some areas. This finding emphasizes the spatial variability of hurricane activity and highlights the need for more comprehensive analyses to fully understand the patterns of occurrence of these extreme weather events.

In Fig. 2, we present the $\frac{Dp}{Dt}$ graph, which represents the rate of change of the central pressure of the systems over a 6-h period (Rezaee et al. 2016; Mendes et al. 2022). By observing the distribution of values on the graph, we can note that to the left of the graphs, there are values that indicate a decrease in central pressure, while to the right are values that indicate an increase in pressure, both measured in hectopascals (hPa).

When analyzing category 1 hurricanes (Fig. 2a), the majority of the studied hurricanes exhibited an average pressure decay of approximately 5 to 6 hPa over a 6-h period. Nevertheless, a substantial number of events showed an even more pronounced pressure decay, surpassing the 10 hPa threshold within the same time frame.

In Category 2 (Fig. 2b), the results indicate a similarity in events compared to the first category (Fig. 2a), suggesting a correlation in the number of occurrences related to this specific phenomenon. However, the pressure decays every 6 h is smaller, ranging between 2 and 3 hPa. This condition is crucial for understanding the intensification process of the phenomenon in question. The lower rate of pressure decay observed in Category 2 (Fig. 2b) compared to Category 1 (Fig. 2a) suggests greater stability in the formation and evolution of these phenomena. In Category 3 (Fig. 2c), we emphasize major hurricanes, which belong to the highest intensity category. These events are notable for their substantial destructive potential (Landsea 1993; Ellis et al. 2015). While the number of events in this category is fewer compared to lower categories of tropical cyclones, the rate of intensification for these major hurricanes is higher. In major cyclones, the deepening rate is particularly pronounced, with average values around 3 to 6 hPa in 6 h for lower hurricane categories (Fig. 1a, b). However, major cyclones can

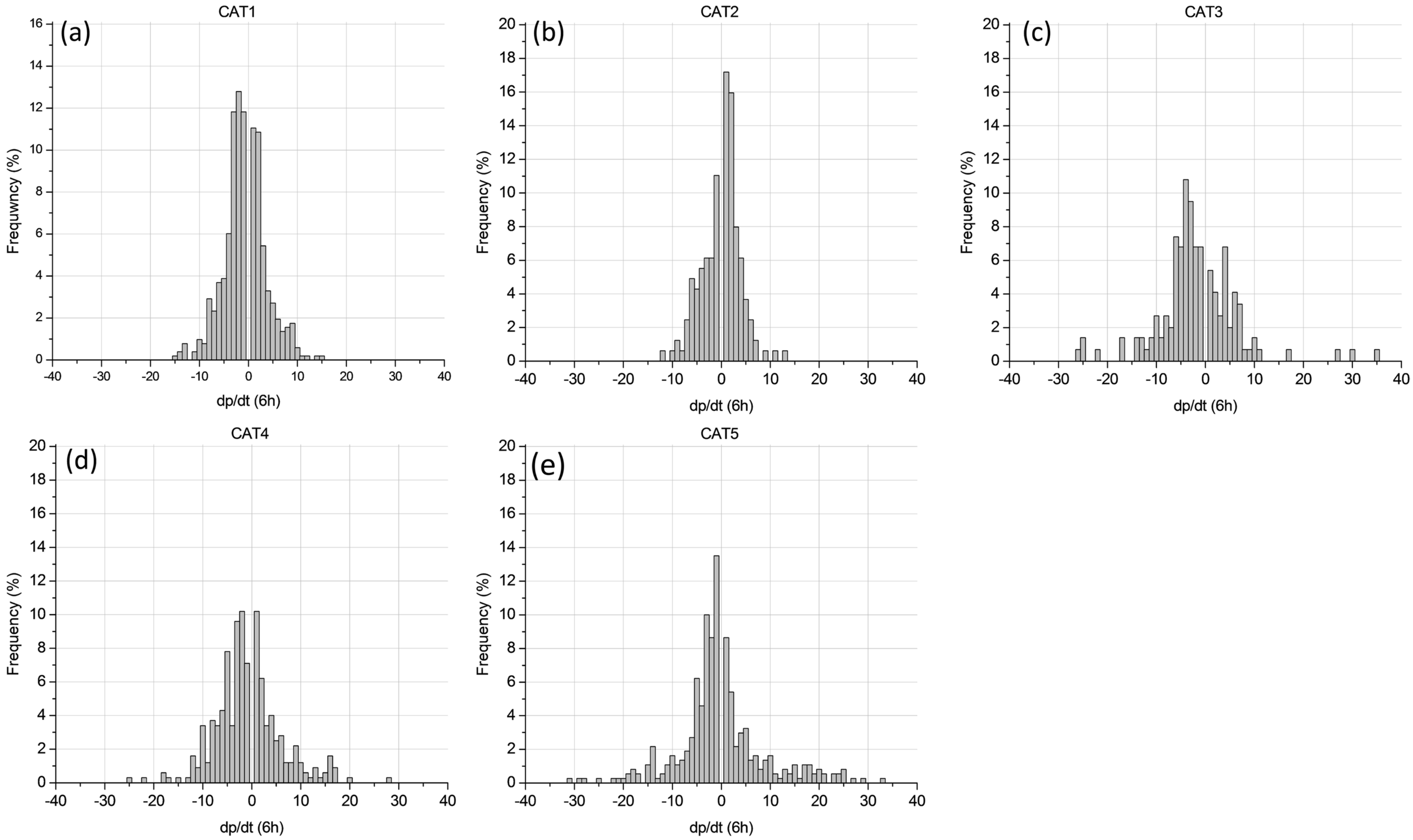

Fig. 2 DP/DT: rate of pressure changes over time, divided by hurricane category between the years 1961 and 2021, **a** category 1, **b** category 2, **c** category 3, **d** category 4, **e** category 5

exhibit a maximum deepening rate of up to 25 hPa in 6 h and an average of up to 8 hPa. Category 3 hurricanes, for instance, displayed pressure decay values reaching up to 25 hPa (Fig. 2c).

In the case of category 4 hurricanes (Fig. 2d), the intensification and deintensification rates follow a distribution resembling a Gaussian curve, with values ranging between -10 and 15 hPa. Approximately 50% of events are concentrated in the central region of the graph, indicating similar rates of intensification and deintensification, typically around 3 to 7 hPa every 6 h. Notably, similar to the previous category (Fig. 2c), there are events with values close to 25 hPa. In major cyclones, the deepening rate is particularly pronounced, with average values around 3 to 6 hPa in 6 h for lower hurricane categories (Fig. 1a, b). However, major cyclones can exhibit a maximum deepening rate of up to 25 hPa in 6 h and an average of up to 8 hPa. Category 3 hurricanes, for instance, displayed pressure decay values reaching up to 25 hPa (Fig. 2c).

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Trajectories and cluster analyses of hurricanes

In Fig. 3, the K-means algorithm was used to analyze hurricane trajectories, classified according to their category (CAT1 to CAT5) and by decades. This method was applied with the objective of joining the different trajectories for each hurricane category, until reaching a single representative trajectory for each category.

In Fig. 3a, we can observe the representation of Category 1, identified here as CAT 1, based on the Saffir–Simpson scale (Simpson 1974). When analyzing Fig. 3a, we notice a significant similarity between the trajectories in Category 1 over three distinct decades. However, the decade between 1981 and 1990 presents a different trajectory pattern. In the decade from 1961 to 1970, the trajectory begins near Cuba, passes through the southern part of the state of Florida, and then veers right towards the open sea. Between 1971 and 1980, it is observed that the origin of these hurricanes is located on the northeastern coast of the United States, and they move towards the continental region. These pieces of information reveal interesting patterns about the occurrence and movements of Category 1 hurricanes throughout the decades (Fig. 3a). The change in the origin and trajectory of these climatic phenomena may be related to various factors, such as variations in sea surface temperature (Bueti et al. 2014), atmospheric wind patterns, and other climatic aspects (Holland and Bruyère 2014).

For the period between 1981 and 1990, we identified a trajectory with a different pattern. Its initial positioning was identified in a region of the North Atlantic Ocean east of the Caribbean Sea, near a sequence of small islands, with a northwest direction trajectory towards Puerto Rico, then moving towards regions further away from the continents. This pattern may be directly related to the variability of oceanic conditions in this decade, such as an increase in sea surface temperature (SST) above 27 °C (Cione and Ulhorm 2003; Saunders and Lea 2008).

For category 2 (Fig. 3b), it is possible to observe a certain similarity to the trajectories of category 1 (Fig. 3a). The difference lies in the trajectories of this category, which are mainly concentrated within a latitudinal range between 20° and 30°N (Fig. 3b). With the exception of the 1961–1970 decade, which is located farther from the east coast of the United States, the remaining trajectories are close to the coastline, showing little variation among them (e.g., Bueti et al. 2014).

Regarding category 3 (Fig. 3c), representing the onset of the most intense hurricanes, it is possible to observe longer trajectories due to the amount of energy associated with these cyclones (Landsea 1993). All categories have in common the initiation of their trajectories to the east of the Caribbean Sea, as shown in Fig. 1. We can divide this analysis into two distinct groups. The first group consists of the decades 1961–1970 and 1981–1990, in which both presented a similar trajectory pattern. They start to the east of the Caribbean, passing through various islands in the region. However, in the first decade (1961–1970), the trajectory deviates northward, while in the other decade, the trajectory heads towards the United States coast.

The second group consists of the decades 1971–1980 and 1991–2000, which exhibit a significantly distant trajectory from the continent compared to the other two decades. This is mainly due to the frequent occurrence of hurricanes in oceanic regions, resulting in longer duration of systems in this period. This characteristic can be evidenced by the

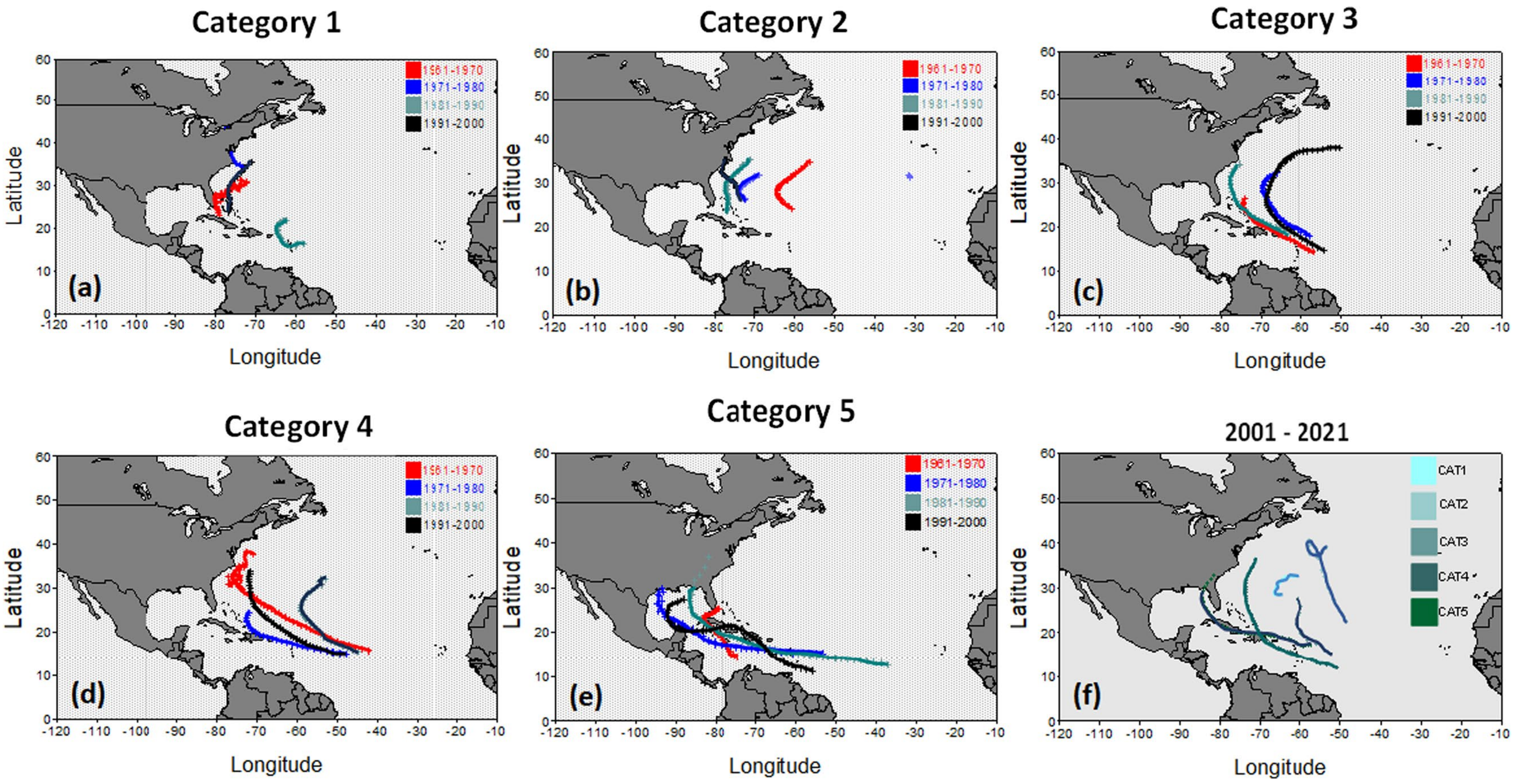

Fig. 3 Decade and category-based trajectories of hurricanes obtained through k-means. The colors represent the decades (**a**, **b**, **c**, **d**, **e**) and the categories (**f**)

longer and more distant routes that these hurricanes travel in relation to the continent, thanks to the exchange of energy between the surface and the atmosphere (Kozar and Misra 2014).

In category 4 (Fig. 3d), the trajectories show similarities both in terms of their shape and displacement. These trajectories are significantly longer compared to those in categories 1 and 2 (Fig. 3a, b). The genesis of these systems is confined between 40° and 50°W, with very close latitudinal positioning. In the 1981–1990 decade, the events presented shorter trajectories compared to the other decades, being more centralized in the North Atlantic. The 1961–1970 decade was the most extensive and had a dissimilarity in the final part of the trajectories because near the East Coast of the United States, there was an "appendage" of these trajectories. This was due to the larger cluster of events in this category in that decade, which were more confined to this region, especially during the peak intensity phase (Fig. 3d). The 1971–1980 decade shows a greater zonality in the trajectories, more confined to the Caribbean islands.

In category 5 (Fig. 3e), and as expected, the trajectories are larger compared to the other categories (Fig. 3a, b, c, d). Another common aspect among the different categories is that, in all the decades analyzed in this category (Fig. 3e), hurricanes enter the Gulf of Mexico region. In the 1961–1970 decade, we observe the shortest trajectory for the category, starting in the Caribbean Sea and passing through Cuban territory, where the trajectories of all decades intertwine, heading towards the southern part of the state of Florida. However, between 1981 and 1990, we identify the most extensive trajectory for hurricanes in this category. Their origin occurs between 40° and 30°W, crossing the Caribbean Sea, the Gulf of Mexico, and entering American territory (e.g., Mainelli et al. 2008).

When analyzing the first 20 years of the twenty-first century (Fig. 3f), by category instead of decades as in the previous figures (Fig. 3a, b, c, d, e), we observe a large variability among the categories. Category 1 continues to cover the shortest distance, while category 5 covers the longest distance, confirming the previously presented results.

An important factor is that category 5, the most intense one, shows a small variation in its trajectory compared to the decade trajectories shown in Fig. 3e, where the paths are more zonal and enter the Gulf of Mexico. However, this variation is not found between 2001 and 2021, as shown in Fig. 3f. This can be attributed to the fact that there were few events of this category in these two decades, although the year 2005 was anomalous for this specific category (see Fig. 4).

In Table 1, the process of formation, development, and transition of different phases of systems is presented, starting from their origin and determining the maximum category reached by the hurricane. Then, we return to the first detection point to determine which system originated each hurricane category, whether it formed from a Tropical Depression or Subtropical Storm.

Table 1 presents the relationship between the initial categories of systems that have the potential to become hurricanes. We classified them into two conditions: the first being systems that originated as tropical depressions and evolved into hurricanes, and the second being systems of subtropical, tropical, and extratropical origin that reached hurricane status. This approach aims to highlight the genesis of hurricanes based on these conditions, providing a comprehensive understanding of the diverse initial states that can lead to the development of these significant meteorological phenomena. Analyzing hurricane genesis through these conditions offers valuable insights into the patterns and factors influencing the formation of these impactful weather events. Upon analyzing each category, specific characteristics were identified. In Category 1, over 70% of Tropical Depressions evolved into hurricanes throughout the decades. In Category 2, this representation is very similar to Category 1, with the most remarkable fact being that in the decade between 1961 and 1970, 100% of Tropical Depressions evolved into hurricanes. In Category 3, there was a slight increase in the frequency of Tropical Depressions transforming into hurricanes compared to Categories 1 and 2, respectively. In the decades of 1971–1980 and 1991–2000, 100% of tropical depressions evolved into hurricanes, with a decrease in the decade between 2011 and 2020.

In Category 4, a pattern almost identical to Category 3 was observed, with values above 80% in almost every decade. Finally, in Category 5, a change in patterns was identified, where only 50% of tropical depressions developed into hurricanes in the 1961–1970 decade, with an increase over the subsequent decades.

When analyzing the subtropical, tropical, and extratropical conditions that lead to hurricane formation (lower part of Table 1), different peculiarities were identified compared to tropical depressions. Essentially, the vast majority of hurricanes in the North Atlantic originate from tropical depressions (Table 1—upper part). There is significant variability between decades and categories. In Category 1, in all decades, there was a transition from subtropical, tropical, and extratropical systems to hurricanes, which is not the case for the other decades. In the 1961–1970 decade in Category 2, there was no such transition, and over the subsequent decades, a gradual decrease is identified (Table 1—lower part). In the other categories, for example, there are decades where this transition did not occur, showing a multidecadal variability. An emblematic condition is seen in the 1961–1970 decade for Category 5, where 50% of the cases became hurricanes (Table 1—lower part).

A classic condition of these transitions was recorded in 2005, the year with the most system events in the North

Fig. 4 Percentage distribution of the number of tropical cyclone genesis occurrences each month, from May to December, divided by category based on the Saffir–Simpson scale, by decade, between the years 1961 and 2020

Atlantic until 2004 (Beven et al., 2005). Twenty-eight storms occurred, including 27 tropical storms and one subtropical storm. Fifteen of these storms became hurricanes, with seven of them reaching major hurricane status. Numerous records of activity in a single season were established, including the highest number of storms, the highest number of hurricanes, and the highest ACE index (NOAA 2005; Beven et al. 2008).

Table 1 Percentage breakdown of transitions leading to tropical cyclones (hurricanes) by decade from 1961 to 2020. (Top) From tropical storm to tropical cyclone. (Bottom) From subtropical to tropical, leading to tropical cyclone

	1961–70	1971–80	1981–90	1991–00	2001–10	2011–20
Tropical depression vs hurricanes						
CAT 1 (%)	80.0	87.5	73.1	77.8	78.9	78.5
CAT 2 (%)	100.0	70.0	71.4	81.3	81.9	83.2
CAT 3 (%)	78.6	100.0	85.7	100.0	91.5	89.8
CAT 4 (%)	88.9	100.0	87.5	100.0	84.3	75.2
CAT 5 (%)	50.0	66.7	100.0	100.0	98.8	91.0
Subtropical*–tropical*–extratropical* vs hurricanes						
CAT 1 (%)	20.0	12.5	26.9	22.2	21.1	21.5
CAT 2 (%)	0.0	30.0	28.6	18.8	18.1	16.8
CAT 3 (%)	21.4	0.0	14.3	0.0	8.5	10.2
CAT 4 (%)	11.1	0.0	12.5	0.0	15.7	24.8
CAT 5 (%)	50.0	33.3	0.0	0.0	1.2	9.0

In the analysis of North Atlantic basin hurricane formation, we found notable trends in the occurrence of Category 1 hurricanes. Over the decades, their concentration shifted, with July and August dominating in the 1961–1970 period, followed by a shift to September in the 1971–1980 decade. Subsequent decades witnessed a more evenly distributed occurrence, peaking in September. The latest decade (2011–2020) saw a significant concentration in July, August, and September, representing the highest throughout the study.

For Category 2 hurricanes, a concentration in August, September, and October was observed. The 1961–1970 decade saw October dominating, while September became prominent in the 1971–1980 period. The trend continued, with September consistently having the highest concentration, especially in the last two decades (2001–2021). However, the decade ending in 2021 saw occurrences in almost every month except May.

Category 3 hurricanes exhibited a pattern similar to other categories, with a shift in the 1971–1980 decade towards higher concentration in August and September. Notably, the 1981–1990 decade showed equal occurrences in September, August, and November, while October had none, differing from other categories.

Analyzing Category 4 hurricanes, the second most intense, revealed a consistent concentration in August, September, and October from 1961 to 1990. Subsequent decades showed variations, with September maintaining prominence. The last decade witnessed occurrences in the later months but excluded December.

For the most intense Category 5 hurricanes, a concentration in specific months was evident since the 1961–1970 decade. From 1981 onward, occurrences were limited to a single month, representing a significant risk despite lower frequency. The 1981–1990 decade saw all events in September, diverging from the 1991–2000 decade, where October dominated. It is noteworthy that September did not have the majority of Category 5 events in the latter decade.

The climatological analysis of these events is crucial for understanding their patterns and potential impacts on vulnerable regions. Unlike prior studies, our research not only delineates the historical trends, but also emphasizes the evolving nature of hurricane occurrences, necessitating ongoing scrutiny to inform preparedness and mitigation efforts.

Accumulated cyclonic energy

The combination of intensity, duration, and frequency creates the Seasonal Integrated Dissipation Index (PDI; Emanuel 2005a, b, 2007) and the ACE (ACE; Camargo and Sobel 2005; Bell and Chelliah 2006), which are metrics used to identify the activity of a tropical storm season. Both formulations are calculated taking into account the duration of storms and the maximum wind speed. The main difference between PDI and ACE is that PDI is calculated by raising the velocities to the power of three, while ACE raises the velocities to the power of two. Several studies have used these indices to examine past tropical storm activity, as well as potential changes in scenarios of climate warming (Emanuel 2005a, b, 2007; Camargo and Sobel 2005; Bell and Chelliah 2006).

Recent studies have focused on the statistical analysis of PDI variations and their relationship with sea surface warming in the Atlantic, both in observations (Walsh et al. 2015) and in future projections (Vecchi and Soden 2007).

When analyzing the decadal variability of ACE (Fig. 5), we identified a 25-year period, from 1970 to 1995, with lower values compared to other periods. During this interval, a decrease in global cyclonic activity was observed, reflecting a phase of lower intensity compared to previous decades (Landsea et al. 2006; Kossin 2018). This reduction may be associated with natural fluctuations in long-term

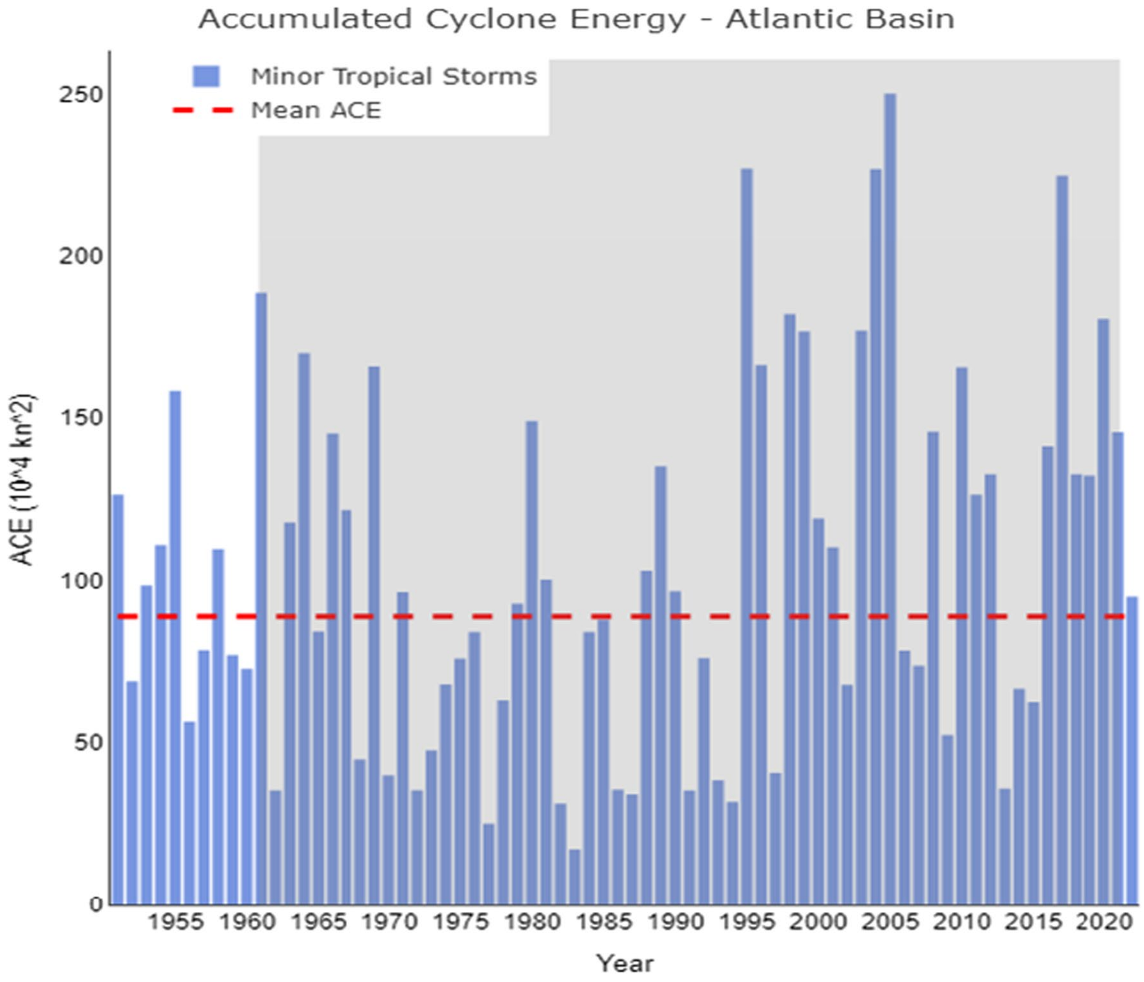

Fig. 5 Accumulated cyclone energy (ACE) of North Atlantic hurricanes, between 1950 and 2022. In gray, the period of study in this article (1961–2021)

climate patterns, as well as other atmospheric and oceanic factors that influence the formation and intensification of cyclones (Kossin et al. 2013). It is also observed that in the last 15 years, ACE indices have consistently doubled the average in most years. These results directly corroborate those identified by Kossin et al. (2018). The authors found evidence of an increase in ACE since the 1980s. According to the study, ACE has increased by about 60% since 1980, suggesting an increase in the intensity and frequency of tropical cyclones in the North Atlantic, very similar to the results found in this article.

The study by Wang and Lee (2009) emphasizes the variability of cyclonic activities across different time scales, encompassing both interannual and multidecadal periods. The authors highlight that this complex dynamic is linked to specific factors, with vertical wind shear and convective instability being two crucial elements that exert a direct influence on this relationship.

These results directly corroborate those identified by Kossin et al. (2018). The authors found evidence of an increase in ACE since the 1980s. According to the study, ACE has increased by about 60% since 1980, suggesting an increase in the intensity and frequency of tropical cyclones in the North Atlantic, very similar to the results found in this article.

The ACE is a direct representation of kinetic energy, where this energy is directly proportional to the square of velocity. By summing the energy over a specific time interval, accumulated energy is obtained. The longer the lifetime (duration) of a storm, the more values are summed, resulting in an increase in the ACE. This means that longer-lasting storms can accumulate a higher ACE than more intense but shorter storms.

Variability of hurricanes in the North Atlantic basin

When emphasizing variability, it becomes clear that we have discussed these conditions in previous sections while analyzing events over decades. This topic focuses on the variability of metrics related to storms in the North Atlantic basin. We chose to use the period between 1961 and 2021 because it demonstrates greater consistency in hurricane occurrences, with more precise observational data (Landsea and Franklin 2013). When examining the number of storms, we observe a mild global increase, more pronounced from 1961, with a significant peak in 2020 (Fig. 6a). Despite a slight decline in 2014, the trend suggests an overall increase, trends mentioned by Klotzbach and Landsea (2015), who note a global increase in storms between 1961 and 2021. The increase in the number of storms is reflected in storm days (Fig. 6b), possibly attributable to both the increased frequency of storms and the longer lifespan of systems.

When analyzing the number of hurricanes (Fig. 6c), we observe an upward pattern in the frequency of these events over the examined time series. This increase is most notable in the period between the years 1961 and 2021. A more detailed analysis of the data within this interval allows the identification of periods of faster growth, as well as moments of slight deceleration. This indicates that the increase in the number of hurricanes does not occur uniformly but rather exhibits certain fluctuations.

A precise manifestation of the growth in the number of hurricanes can be observed in the number of days these events occur, as shown in Fig. 6d. It is interesting to note that this series is not linear over time. Despite the overall increasing trend, there are periods where the fluctuation is more pronounced.

Regarding events categorized as intense hurricanes, as shown in Fig. 6e, we observe an increasing trend that becomes more pronounced as we analyze the progression of the time series. When studying the evolution of this series, it is noticeable that, in the last two decades, this increasing trend has become more significant (e.g., Klotzbach and Landsea 2015). This implies that the quantity and/or intensity of Intense Hurricanes recorded in the last 60 years are higher when compared to earlier periods within the series (Fig. 6e).

In Table 2, we present basic statistics such as mean, standard deviation, and trend of the conditions mentioned in Fig. 6. The number of Named Storms between the years 1961 and 2021 revealed some significant trends. When analyzing the data over this period, it is noticeable that there has been a notable increase in the frequency of these events compared to the entire available historical record, dating back to 1851.

From 1961 to 2021, there was an average increase of 2.42 Named Storm (NS) events compared to the average of the dataset from 1851 to 2021. This suggests that the events are becoming more frequent in recent times (Mei et al. 2019). Furthermore, an analysis of the data dispersion indicated that the variability in the frequency of NS has also changed. The standard deviation, a measure indicating how spread-out values are around the mean, increased by 0.41 during the period from 1961 to 2021 compared to the historical series from 1851 to 2021. This increase in standard deviation suggests an increase in the variability of events over the years, possibly indicating more instability and unpredictability.

Furthermore, when comparing the linear trend of the data between 1961 and 2021 with the linear trend from 1851 to 2021, an increase of 2.19 in the slope of the trend line was observed. This indicates that not only has the frequency of NS increased, but the rate of increase in this frequency has also become more pronounced in the more recent period (Table 2).

The period from 1961 to 2021 was marked by a notable intensification in the occurrence of NS, as observed earlier. During this interval, there was an increase of 9.18 days compared to the historical average of NS days, which refers to the number of days when NS were recorded (Table 2). This comparison takes into account the historical series extending from 1851 to 2021.

In addition, when evaluating the dispersion of the data, it is noticeable that the variability also increased in the period from 1961 to 2021. The standard deviation, a measure of dispersion, increased by 0.98 compared to the period from 1851 to 2021 (Table 2). This indicates that not only has the number of days with NS increased, but also the inconsistency over the years.

One of the most notable aspects is the significant upward trend in the number of days with NS. Between 1961 and 2021, this trend increased by an impressive 26.17 days compared to the period from 1851 to 2021 (Table 2). This suggests a substantial change in the dynamics of storms over the last six decades compared to the historical record from the mid-nineteenth century to the first half of the twentieth century.

Focusing on the period between 1961 and 2021, an average increase of approximately 0.91 hurricanes per year was detected (Table 2). Additionally, it is noteworthy that not only has the number of hurricanes increased, but also their variability. The standard deviation increased by 0.17 during the same period from 1961 to 2021 (Table 2). This suggests that hurricanes have not only become more frequent but also that there has been an increase in the irregularity of their annual occurrence.

Furthermore, it is interesting to compare this more recent 60-year period with a longer time frame to understand how trends behave on a broader time scale. When comparing the period from 1961 to 2021 with a more extensive range spanning from 1851 to 2021, an even

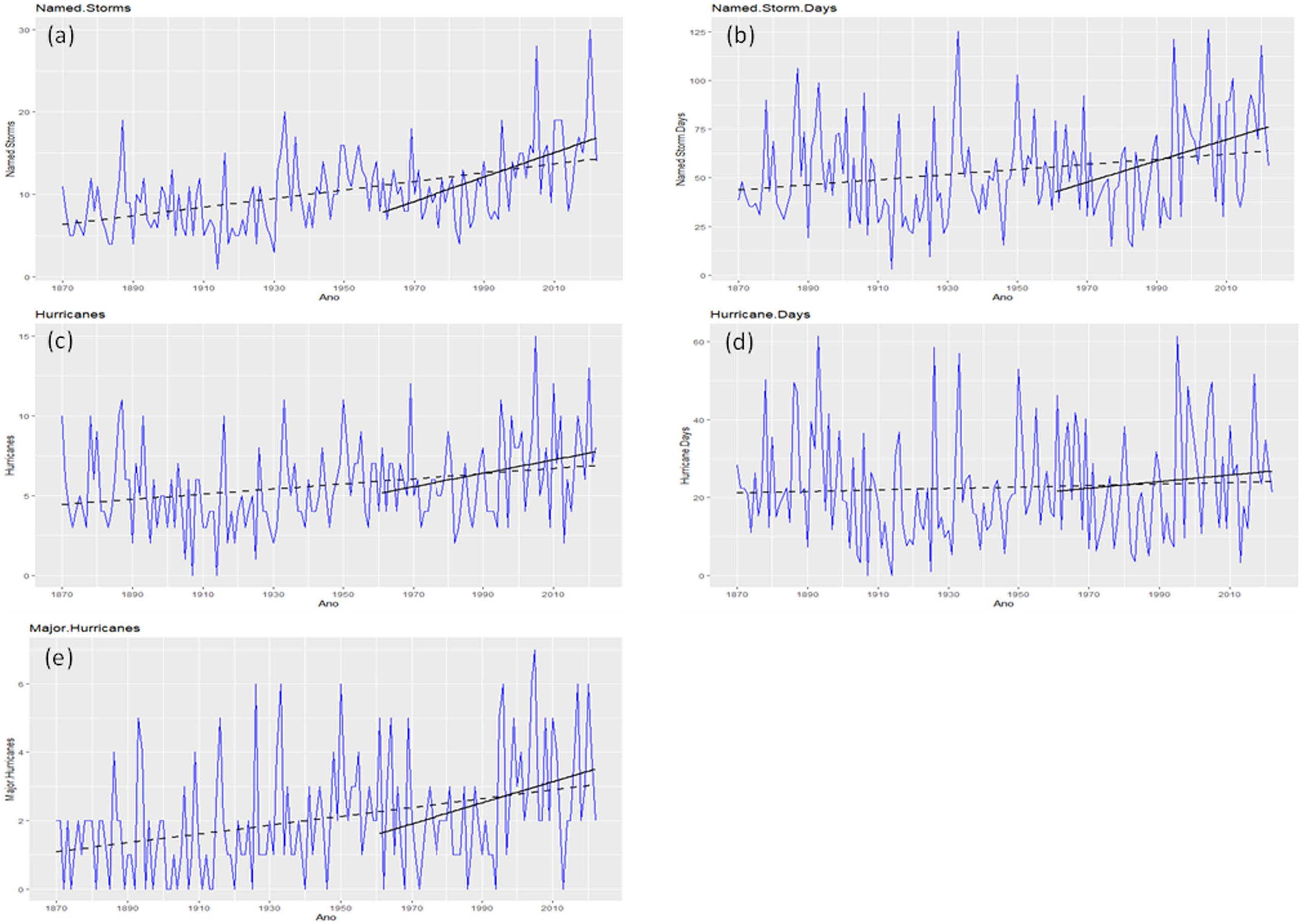

Fig. 6 Historical record of the number of days with events occurring in the Atlantic Ocean basin with trend calculation, from the beginning of records in 1851 until the year 2021, highlighting the period of the present study from 1960 to 2021. **a** Storms, **b** storm days, **c** hurricanes, **d** hurricane days, **e** major hurricanes

Table 2 Table with statistical analysis (mean, standard deviation, trend) between two different time series (1851–2021 and 1961–2021), for 5 different conditions (named storms, named storm days, hurricanes, hurricane days, major hurricanes)

	Named storms	Named storms days	Hurricanes	Hurricanes days	Major hurricanes
Mean					
1851–2021	9.93	50.34	5.54	21.66	1.92
1961–2021	12.35	59.52	6.45	24.15	2.56
STDEV					
1851–2021	4.53	25.47	2.58	13.28	1.63
1961–2021	4.94	26.45	2.75	13.99	1.77
Tendency					
1851–2021	5.67	31.69	3.31	10.92	0.62
1961–2021	7.86	57.86	8.27	30.80	4.78

more pronounced trend of increasing hurricane frequency is observed. Between 1961 and 2021, there was an average increase of 4.96 hurricanes per year compared to the average observed between 1851 and 2021 (Table 2).

When examining the hurricane activity over time, a significant increase in the duration of these phenomena stands out. Specifically, between 1961 and 2021, there was an average increase of 2.49 days in the so-called "hurricane days" compared to the period from 1851 to 2021 (Table 2). This suggests that, in the last six decades, hurricanes have lasted longer than in previous years.

It is worth noting that "Hurricane Day" is a term used to represent a full day during which a tropical cyclone/hurricane persists. This means that in recent years, there have been more days when hurricanes were active, possibly resulting in more significant damages and environmental impacts.

Furthermore, an increase in the variability of hurricane duration has been identified. The standard deviation, a statistical measure indicating how values in a sample vary around the mean, increased by 0.71 from 1961 to 2021, compared to the period from 1851 to 2021 (Table 2). This rise in standard deviation suggests that hurricanes not only have a longer average duration, but also exhibit more pronounced variations in the duration of these events.

Another significant aspect is the rise in the overall trend in the number of "hurricane days". The trend indicates the direction and rate at which something is changing over time. In the period from 1961 to 2021, the trend increased by an impressive 19.88 days compared to the period from 1851 to 2021 (Table 2). This means that the pace of increase in hurricane duration has been more accelerated in the last six decades than in the earlier period.

During the period from 1961 to 2021, a significant increase in the number of major hurricanes was observed compared to the longer historical period from 1851 to 2021. Over the past 60 years, there has been an average increase of 0.64 major hurricane events per year compared to the broader 170-year record.

It is important to note that not only has the quantity of major hurricanes increased, but also the variability of these events has shown growth. This can be illustrated by the increase in standard deviation. The standard deviation increased by 0.14 over the last 60 years (1961–2021) compared to the entire historical series (1851–2021). This increase in standard deviation may indicate that recent years have exhibited greater irregularity in the number of major hurricanes, which could be reflective of climate change and variations in oceanic and atmospheric conditions (Table 2).

In addition to the average increase, the overall trend shows a more substantial increment when analyzing the period between 1961 and 2021. During this time, there is an increase of 4.16 major hurricanes compared to the period from 1851 to 2021 (Table 2). This value represents a considerable growth.

These observations highlight a clear alteration in the conditions of hurricanes in the North Atlantic, especially in the last 60 years. Moon and Nolan (2010) provide evidence of significant changes in the characteristics of hurricanes in this region. The authors mention that the systems are moving more slowly at lower latitudes, resulting in an increase in the distance traveled and prolonging the duration of these events.

All these processes of hurricane variability in the North Atlantic Basin may be remotely linked to teleconnections, whether the ENSO (Shaman and Maloney 2012; Patricola et al. 2017), quasi-biennial oscillation (QBO) (Elsner et al. 1999), Atlantic multidecadal oscillation (AMO) (Tourre et al. 2010), significantly impacting the trajectories and intensities of these systems.

Conclusion

This study provides a detailed analysis of hurricane trajectories (categories 1–5) over different decades, highlighting variability in intensification rates and geographic concentrations, particularly along the East Coast of the United States. The study employs the K-means method to synthesize trajectories, revealing differences in hurricane life cycles. The majority of North Atlantic hurricanes originate from tropical depressions, potentially linked to changing climate conditions. The analysis also focuses on monthly and category distribution, showing a tendency for higher hurricane occurrence in September across all categories.

Examining interannual variability since the 1990s, the study notes an intensification of tropical storm activity, with concerns raised about its impact on coastal regions. The use of ACE as a metric reflects a 25-year period (1970–1995) with lower values, suggesting a decrease in global cyclonic activity. However, the last 15 years show consistently doubled ACE indices, indicating an increase in cyclone intensity and frequency, aligning with other studies. The North Atlantic basin exhibits a progressive increase in named storms and hurricanes, particularly from 1991 onwards. Major hurricanes show an upward trend in frequency and intensity in the last two decades.

Comparing data from 1961 to 2021 with historical records, the study reveals a significant intensification in the frequency and variability of named storms, hurricanes, and major hurricanes in the recent six decades. The results suggest not only an increase in the frequency of these events, but also greater variability and unpredictability, potentially indicating changes in climatic dynamics with implications for coastal communities and ecosystems. Further research is recommended to understand the underlying factors and assess potential socioeconomic and environmental impacts.

Based on the findings presented in this article, we emphasize the need for a comprehensive study of the influence of teleconnections on the physical and dynamic conditions of hurricanes in the North Atlantic Basin. It is clear, when analyzing decadal trends, that there is a remote influence that may be contributing to the variability between decades and the increase in hurricane activity.

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Data availability The datasets generated during and/or analyzed during the current study are available upon request on the corresponding author.

Declarations

Conflict of interest The authors declare no competing interests.

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Consent for publication Not applicable.

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