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CYCLONE SYSTEMS OVER THE AEGEAN SEA. A STATISTICAL REPRESENTATION OF THEIR MAIN CHARACTERISTICS.

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Abstract

The Aegean Sea is a closed basin where a significant part of the cyclonic activity of the Mediterranean takes place. Furthermore, it is surrounded by densely populated cities rich in assets, so being able to track and examine the characteristics of the intense meteorological phenomena such as cyclones can prevent natural hazards that result in human losses and economical damages.

This study deals with the main characteristics of the low-pressure systems that occurred in the Aegean Sea from 1979 to 2020 based on a cyclone's tracking dataset. Specifically, it is a statistical analysis of the characteristics such as the average number of occurrence for each month of the year, their speed of propagation, their duration, the distance covered from the moment of their formation to the point of their dissipation, the displacement between the position of formation and dissipation as well as their spatial distribution in the 4 seasons. What has been observed is a significant cyclonic activity that takes place in the Aegean Sea which is one of the places in the Mediterranean with not negligible cyclonic activity.

A quantitative comparison has been made between cyclones and more generally the cyclonic activities that pass or form in the Aegean Sea with cyclones that take place in the Mediterranean and what has been found is that the Aegean Sea is a region of the Mediterranean with significant cyclonic activity, and similar characteristics with the cyclones occurring in the Mediterranean Region.

***Keywords**: Cyclones, climatology, Aegean Sea, low/pressure systems, cyclonic activity, ERA5.*

SISTEMI CICLONICI NEL MAR EGEO. UNA RAPPRESENTAZIONE STATISTICA DELLE LORO CARATTERISTICHE PRINCIPALI

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Dicembre 2021

Abstract

Il Mar Egeo è un bacino chiuso dove ha luogo una parte significativa dell'attività ciclonica del Mediterraneo. Inoltre, è circondato da città densamente popolate e ricche di risorse, quindi essere in grado di tracciare ed esaminare le caratteristiche degli intensi fenomeni meteorologici come i cicloni può prevenire i pericoli naturali che provocano perdite umane e danni economici.

Questo studio tratta le caratteristiche principali dei sistemi a bassa pressione avvenuti nel Mar Egeo dal 1979 al 2020 ed è basato sul dataset di ERA5. Nello specifico, si tratta di un'analisi statistica delle loro caratteristiche come il numero medio di occorrenza per ogni mese dell'anno, la loro velocità di propagazione, la loro durata, la distanza percorsa dal momento della loro formazione fino al punto della loro dissipazione, lo spostamento fra la posizione di formazione e di dissipazione nonché` la loro distribuzione spaziale nelle 4 stagioni. Quello che è stato osservato è un'attività ciclonica rilevante che ha luogo nel Mar Egeo che costituisce uno dei posti del Mediterraneo con attività ciclonica non trascurabile.

Si è fatto un confronto quantitativo tra i cicloni e più in generale le attività cicloniche che passano o nascono nel Mar Egeo con i cicloni che hanno luogo nel Mediterraneo nel suo complesso e quello che è stato trovato è che il Mar Egeo è un'area del Mediterraneo con attività ciclonica rilevante, e con caratteristiche simili dei cicloni che avvengono nel Mar Mediterraneo.

Parole chiavi*: Cicloni, Climatologia, Mar Egeo, sistemi a bassa pressione, attività ciclonica, ERA5*

SUMMARY

1. INTRODUCTION

At mid-latitudes, the atmospheric dynamics are governed by exchanges of heat, humidity, and precipitation between the poles and the equator. Despite several well-known atmospheric teleconnections acting on annual and multidecadal scales, the cyclonic systems are a key player in driving meteorology and climate in these regions, daily shaping the meso-to-synoptic-scale patterns of the main atmospheric variables (Aragão and Porcù, 2021). These structures are often responsible for hydrometeorological hazards, such as heavy and persistent rain and strong winds (Porcù and Carrassi, 2009; Messmer *et al.*, 2015). The Mediterranean basin is one of the main cyclogenetic regions in the world (Ulbrich *et al.*, 2009; Neu *et al.*, 2013), where the most intense cyclones often produce high impact weather such as floods and windstorms (e.g., Jansa *et al.*, 2000; Kotroni *et al.*, 2006; Kysely and Picek, 2007; Nissen *et al.*, 2010; Pfahl and Wernli, 2012). The Mediterranean Region (MR) is a peculiar environment characterised by a closed sea ecosystem, relatively warm and surrounded by mountain chains. In addition, there are several densely populated cities in coastal areas, rich in assets and heritage (Aragão and Porcù, 2021).

The spatial distributions and general cyclogenesis mechanisms in the northern hemisphere have been firstly described by Peterssen (1956). According to Trigo *et al.* (2002), in the MR, the western part has a much more marked seasonality than the eastern basin, and the frequency of occurrence should not be simply equated with strength. An example is the Gulf of Genoa, where, although cyclones are a constant feature over the whole year, they are generally deeper and have more severe weather in winter than during the summer when they are more frequent (Trigo *et al.* ,2002).

The MR is one of the most active regions of the Northern Hemisphere in terms of cyclone activity, displaying a distinct regional maximum of cyclone numbers (Trigo *et al.*, 1999; Ulbrich *et al.*, 2009). The MR favours a wide variety of cyclogenesis mechanisms, such as the deepening of mid-latitude perturbations at the lee of the Pyrenees and the Alps triggered by low-level moisture sources and low-level baroclinicity along the coasts and by the formation of thermal lows over warm inland regions (McGinley, 1982; Radinovic, 1986; Michaelides *et al.*, 1999). Consequently, the MR is prone to the occurrence of cyclones with a broad range of characteristics, from synoptic to mesoscale, and a variety of intensities and depths (Lionello *et al.*, 2006; Ulbrich *et al.*, 2012).

In meteorology, a cyclone is defined as a large-scale air mass system that rotates around a strong centre of low atmospheric pressure counterclockwise in the northern hemisphere and clockwise in the southern hemisphere (Wallace and Hobbs, 2006). There are many common structural characteristics in all cyclones, such as the dimension of the low-pressure area and its gradient regarding the surrounding areas, the vertical alignment and the layer thickness between the surface and the upper-air depressions, and the dynamical support induced by temperature contrasts or convective activities. Near the centre, the pressure gradient force and the force from the Coriolis effect must be in balance. Otherwise, it would collapse on itself due to the difference in pressure (Holton, 2004). Cyclogenesis is defined as the stage of development or strengthening of cyclonic circulation in the atmosphere. On the other hand, cyclolysis is defined by the dissipation or weakening of a cyclonic circulation (Holton, 2004). Usually, a cyclonic activity rises from a thermal low, defined as an area of atmospheric low-pressure near the surface resulting from heating of the lower troposphere and the subsequent lifting of isobaric surfaces and divergence of air loft. The thermal lows generally present a weak, but organised, cyclonic circulation and it is often associated with surface troughs extending from the low-pressure centre (Rowson and Colucci, 1992). Although the modern meteorology restricts the use of the term cyclone to the so-called synoptic-scale cyclonic circulations, it is popularly still being wrongly applied to other small-scale and strong wind circulations such as tornadoes, waterspouts, dust devils, etc. (which may in fact exhibit anticyclonic rotation). The first use of this term was in the very general sense as the generic term for all circular or highly curved wind systems. Because cyclonic circulation and relative low-pressure usually coexist, in common practice the terms cyclone and low-pressure are used interchangeably (AMS, 2012).

Cyclogenesis over the Aegean Sea is a quite rare phenomenon, occurring mostly in the cold period of the year, and the current available CDTMs (Cyclone Detection and Tracking Methods) often underestimate the cyclogenesis due to its subsynoptic-scale nature (Flocas and Caracostas, 1996). However, recent studies have shown that a significant cyclonic activity takes place over the Aegean Sea, as it is one of the main cyclogenesis areas in the MR (Aragão and Porcù, 2021). According to Papagiannaki *et al.* (2013) in the period 2001-2011, about 84 people lost their lives in Greece due to weather events, and the largest part of the victims were caused by flash flood events and lightning. In the period 1970-2010, other 151 people lost their lives in Greece due to flood events (Diakakis and Deligiannakis, 2017). According to the Elinda Labropoulou and Euan McKirdy, CNN (2017) in the 16th of November 2017, 16 people died close to Athens due to floods. Thus, it is clear that having a better knowledge about the characteristics of the cyclonic systems can help in the direction of preventing those hazards that lead to human losses as long as severe economic damages.

The Aegean Sea is a closed basin surrounded by several high altitude mountain ranges as Pindus (summit at 2637 meters) and Rhodope (summit 2191 meters), despite Prezerakos and Flocas (1996) suggests that topography plays a minor role in surface cyclogenesis over the Aegean Basin. Furthermore, the presence of a multiplicity of islands (around 3,000) in the Aegean basin may play a significant role in the formation of low-pressure atmospheric systems as the accentuated contrast land-sea is one of the most important topographical factors that can contribute to the formation of cyclonic systems in some areas of the Mediterranean like southern Tunisia to western Libya as reported by Almazroui and Awad (2016). Moreover, according to Trigo et al (2002), topographic barriers like the Alps as well as the mountain ranges over the Balkan peninsula may influence cyclonic activity in the Aegean Sea.. A big part of the studies (Neu *et al.*, 2013; Lionello et al, 2016; Aragão and Porcù, 2021) that have analysed and examined the characteristics of the cyclones have assessed a minimum duration of at least 24 hours to consider the candidate cyclone, in order to eliminate artificial low-pressure cores, short-living thermal-lows or too weak cyclones as much as possible.

The present's study scope is to analyse and detect the cyclone's characteristics as duration, frequency, propagation velocity and distance covered in monthly basis. An ulterior intention of this study is to investigate the spatial distribution of the cyclones and the cyclonic activities in general that take place over the Aegean Sea. Being able to study the nature and the behavior of intense phenomena like cyclones is crucial, as a lot of densely populated cities and areas surround the Aegean Sea so a deeper knowledge of their characteristics may contribute to the prevention of natural hazards that may provoke human losses.

2. DATA AND METHOD

2.1. STUDY OF THE CYCLONES

According to Aragão and Porcù (2021) the idea to extensively study hydrometeorological hazards and climate change through the structure and dynamics of extra-tropical cyclones claims the availability of automatic tools, working on given meteorological field to detect and track such systems, and able to estimate their relevant characteristics. An effective cyclone tracking system has numerous applications in weather and climate studies: revisit notable past events exploiting the enhanced capabilities of modern data assimilation systems (e.g. Liberato *et al.*, 2011; Marra *et al.*, 2019); (2) establish continuity between different decades, which is the key to understand changes in cyclonic activity (e.g. Trigo 2006; Priestly *et al.* 2020); and (3) evaluation of climate model outputs to evidence the expected modification in cyclone structures (e.g. Pinto *et al.*, 2007; Catto *et al.*, 2019), assessing possible increase of their impact on society (e.g. Leckebusch *et al.*, 2007).

Since the late 80s, many algorithms for identifying extratropical cyclones into large atmospheric datasets (reanalysis and climate projections) have been contributed to a better understanding of precipitation associated with frontal weather systems affecting the regional climate and, in particular, the water cycle and the weather extremes (Blender *et al.* 1997). Typically, these algorithms follow the standard two-step approach proposed by Lambert (1988): (1) the identification of possible cyclone centre position through the local minimum or maximum of a given atmospheric parameter within the study domain at each available timestep; and (2) the definition of cyclone's trajectory based on the nearest-neighbour search procedure, where a candidate identified in the previous timestep possibly travels the shortest distance to reach the position of the candidate identified in the current timestep.

In general, the main differences among CDTMs are the choice of the meteorological parameter under analysis (e.g. mean sea level pressure, geopotential height or vorticity), the data optimisation method applied to filter candidates in each timestep (e.g. terrain filtering or atmospheric variable limits), and the definition of a distance threshold for the cyclone's displacement between consecutive timesteps (Neu *et al.* 2013). Although summarised, a wide range of combinations and variations of these parameters define not only the advantages and disadvantages of each method but also the cyclone typology under investigation. The recent availability of the high-resolution ERA5 reanalysis dataset (Hersbach *et al.* 2020) for a climatologically significant period (from 1950 to present) offers the possibility to perform a long-term detailed study of cyclonic structures and dynamics (Aragão and Porcù ,2021).

2.2. DATASET ASSIMILATION AND THE AEGEAN SEA

This study explores the climatological cyclone tracking dataset developed by Aragão and Porcù (2021), which they proposed a new tracking and detecting method for the cyclones occurring in the Mediterranean Region based on a high-resolution reanalysis dataset, named ERA5, the fifth generation European Center for Medium-Range Weather Forecasts (Hersbach *et al.*,2020). The same data have been used for the purpose of this study, with the only difference that also low-pressure systems that last less than 24 hours have been taken into account. From now on, for the purpose of this study, we will be referring to cyclonic activities for all the low-pressure systems that last at least 6 hours, and the term cyclone will be used for all the low-pressure systems that have a minimum duration of 24 hours.

ERA5 is designed to provide hourly estimates of a big number of atmospheric, land and oceanic climatological variables. The data cover the earth on a 30 km grid and resolve the atmosphere using 137 levels from the surface up to 80 km of height (ECMWF website). The dataset used is from a 42 year window (1979-2020) and the variable examined in order to detect the cyclones/cyclonic activities was the geopotential height at the 1000 hPa level. Geopotential height approximates the actual height of a pressure surface above mean sea-level. Therefore, a geopotential height observation represents the height of the pressure surface on which the observation was taken Furthermore the higher spatial and temporal resolution of ERA5 upon its precursors help significantly in the process of identifying the cyclones in a small domain box like the one we used, and the sub-synoptic scale phenomena that occur in the Aegean Sea. Furthermore, one of the main advantages regarding its precursor ERA-Interim concerns the data resolution equally distributed in a 0.25º x 0.25º spacing grid that provides data in hourly basis.

The climatological cyclone tracking dataset used in the present study contains the geographic coordinates of each cyclone detected from 1979 to 2020, from its cyclogenesis location up to its cyclolysis location in hourly basis. For each timestep also the value of the geopotential height was reported and the propagation velocity was estimated. Furthermore, the total displacement of every single cyclone was available. By total displacement we intend the distance along a straight line (km) between the point of formation of the cyclone and the point of where its dissipation took place. By taking into account the temporal coordinates of the cyclogenesis and the cyclolysis, the total duration of each cyclone/cyclonic activity was calculated. By summing the propagation velocity, we obtained the total distance covered by its cyclone/cyclonic activity.

Figure 1: The domain box

The domain used for the purposes of this study covers the Aegean Sea and its geographic coordinates are from 21.5° to 29.5° E and from 34° to 42° N. The domain box is presented in Figure 1.

Furthermore, in order to be able to compare the results that we obtained with other literature studies that assume cyclones with durations over the 24 hours mark (Neu *et al.*, 2013; Lionello *et al.*, 2016), a further analysis of the cyclones that had duration greater than 24 hours was made for the entire domain box.

It has to be clarified the fact that the cyclones/cyclonic activities tracked and examined were not necessarily formed inside the domain box but just passed over it.. This means that each cyclone/cyclonic activity detected, had at least one point inside the domain box in its lifetime. This implies that the cyclones/cyclonic activities examined were not necessarily generated inside the domain box, nor were dissipated inside it.

3. CHARACTERIZATION OF CYCLONES OVER THE AEGEAN SEA

3.1. FREQUENCY

According to other studies, the mean number of cyclones per year in the Mediterranean is 62 to 474 cyclones per year (Lionello *et al.*, 2016), and 285 to 390 cyclones per year (Aragão and Porcù, 2021). Like it was mentioned before, these studies have taken in consideration only the cyclonic activities with duration greater than 24 hours, so what we experienced is a significant overestimation of the number of the observed cyclonic activities in the Aegean Sea since we took into account also the cyclonic activities that last less than 24 hours. In this study we have found a total of 4584 cyclonic activities in the 1979-2020 period that equals to 109.1 cyclonic activities per year that passed over the Aegean Sea. Though if we take to account only the cyclones, we found that there were 1363 cyclones that equal to 32.5 cyclones per year.

As far as it regards the monthly distribution of the cyclones over the year we've found that the maximum cyclonic activity occurs from November to April and the maximum cyclonic activity for the all the cyclonic activities occurs principally from May to September. The mean number of cyclones and cyclonic activities by month occurred in the period 1979-2020 can be seen in the next table (Table 1).

Month	Aegean Sea		Mediterranean*
	Dur. > 6h	Dur. > 24h	Dur. > 24h
January	7.74	3.48	22
February	7.66	3.66	24
March	8.38	3.05	27
April	8.42	3.00	35
May	11.45	2.55	36
June	11.33	1.83	33
July	10.24	1.48	30
August	11.98	1.33	31
September	10.29	1.93	29
October	8.14	2.14	26
November	6.31	2.79	23
December	7.19	3.69	20

*Table 1: Monthly means of the total number of cyclones and cyclonic activities crossing the Aegean Sea (1979-2020) and the Mediterranean region (1979-2018). *Source: Aragão & Porcù (2021).*

From the previous table (Table 1), we observe that the monthly distribution between cyclones and the cyclonic activities is very different. In fact, we see that the cyclones of the Aegean Sea happen less frequently in the summer and do not follow the same trend as the cyclones of the Mediterranean Region. The cyclonic activities follow the opposite trend than the cyclones of the Aegean Sea occurring more frequently in the summer and less frequently in the summer.

Hence, we can observe that the formation of the cyclones/cyclonic activities is strictly correlated with the season. The distribution of the formation of the cyclones in monthly basis for cyclonic activities (Figure 2), and for the cyclones (Figure 3).

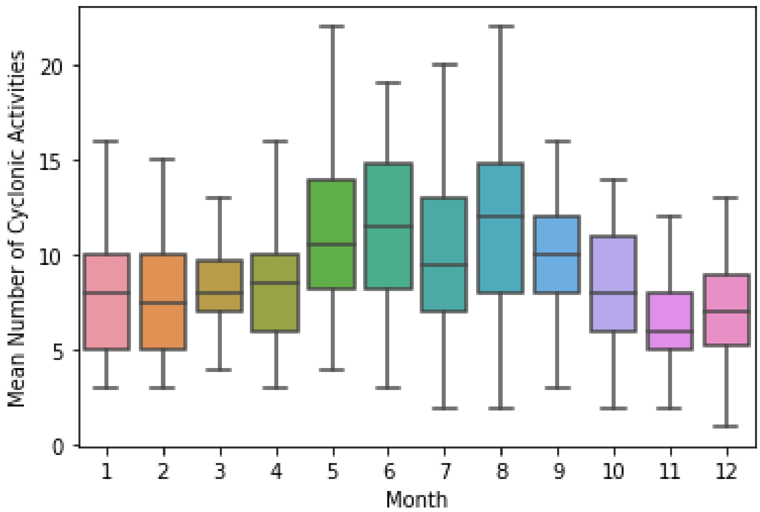

*Figure 2: Monthly mean of the total number of the cyclonic activities in the Aegean Sea (1979-2020), the respective 1st, 2nd and 3rd quartiles (bars of the box) and the external bars that have values respectively Q3+1.5*IQR and Q3-1.5*Q1*

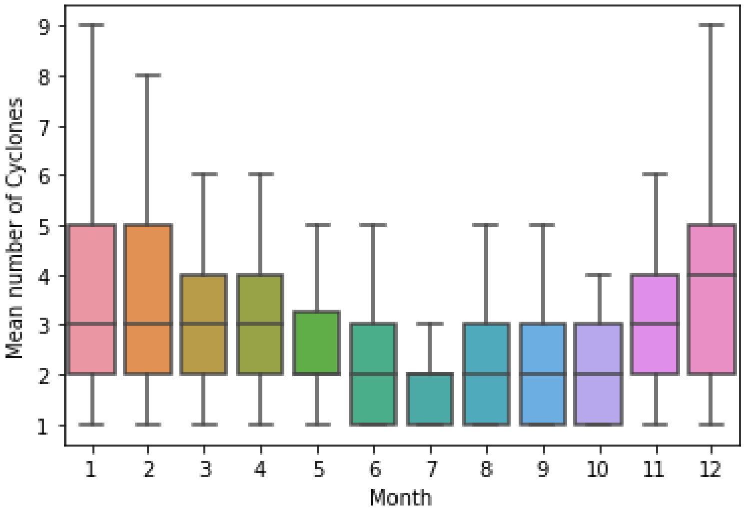

*Figure 3: Monthly mean of the total number of the cyclones in the Aegean Sea (1979-2020), the respective 1st, 2nd and 3rd quartiles (bars of the box) and the external bars that have values respectively Q3+1.5*IQR and Q3-1.5*IQR where IQR=Q3-Q1*

From the previous figures, we observe that from May to September the cyclonic activities present the higher mean values, but also the higher degree of uncertainty (Figure 2). For the cyclones, on the other hand we observe the higher mean numbers of occurrence from November to April with the highest degree of uncertainty being placed in December and January (Figure 3).

3.2. Duration

A very important parameter that was also analysed is the duration of the cyclones. Most studies referring to cyclones in the Mediterranean Region impose a minimum duration of 24 hours in order to consider a cyclonic activity as a cyclone (Neu et al, 2013; Lionello et al, 2016). As far as it regards the cyclones (duration greater than 24 hours), we have found 1366 cyclones. This equals, comparing this number with the total number of the cyclonic activities, to 29.8% of the cyclonic activities that last more than 1 day. Considering only those, we've found that they have a mean duration of 48.18 hours. Comparing this value with the mean duration of the cyclones in the whole Mediterranean Region found in other studies (Trigo,2006; Lionello et al ,2016), those studies place this value to be 42 hours, we can observe that the mean duration of the cyclones of the Aegean Sea is higher than those of the whole Mediterranean Region. As far as it regards the cyclones of the Aegean Sea, we observed that 25% of them present durations lower than 31 hours, 50% of them lower than 41 hours and 75 % lower than 58 hours.

Taking all the cyclonic activities longer than 6 hours, we found that their mean duration is 22.43 hours. That denotes the sub-synoptic nature of the phenomena occurring in the Aegean Sea and that is the reason why the cyclogenetic activity of this area has been underestimated. Moreover from the analysis of the data we have obtained that only 25% of the cyclonic activities have durations greater than 28 hours, only 10% above 50 hours and only 5 % above 68 hours.

In the next figure, the density of probability of finding a certain cyclone and a certain cyclonic activity in a certain duration range can be seen (Figure 4).

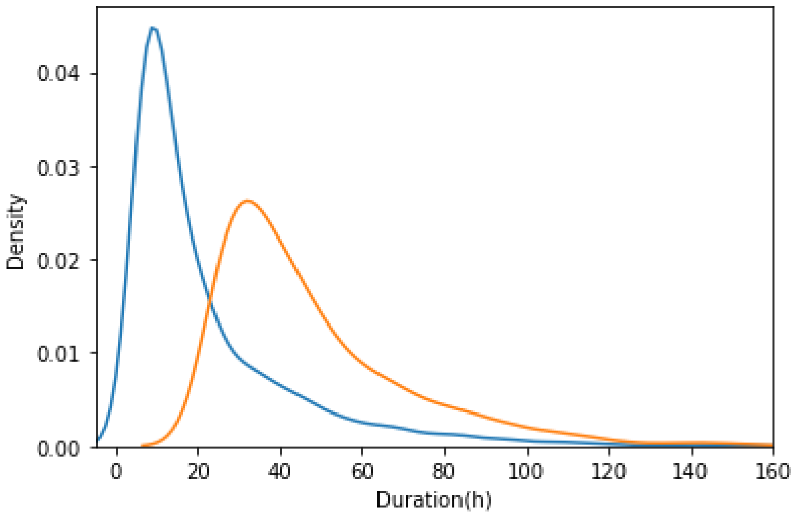

Figure 4: Density of probability in relation to duration for cyclonic activities (blue line) and for cyclones (orange line) in the Aegean Sea (1979-2020)

Duration is a key parameter for the cyclones/cyclonic activities and we observed that does not remain stable over the annual cycle but is presents a strong seasonal dependence as also other studies confirm (Aragão and Porcù, 2021). The mean duration of the cyclones and the cyclonic activities by month can be seen in Table 2.

Month	Aegean Sea	
	Dur. > 6h	Dur. > 24h
January	30.23	49.18
February	31.40	50.83
March	25.39	46.22
April	23.55	44.46
May	19.28	44.25
June	16.95	42.32
July	14.94	38.92
August	13.93	37.72
September	18.19	48.11
October	24.06	54.66
November	31.46	54.44
December	34.48	54.01

Table 2:Monthly Mean Duration for all the cyclones(>24h) and the cyclonic activities(>6h) crossing the Aegean Sea (1979-2020)

From the previous table, we observe that both cyclones and cyclonic activities have longer durations in the late autumn and throughout the winter, and much shorter durations in the summer.

In the next figure (Figure 5), it is shown how duration varies in monthly basis for all cyclonic activities

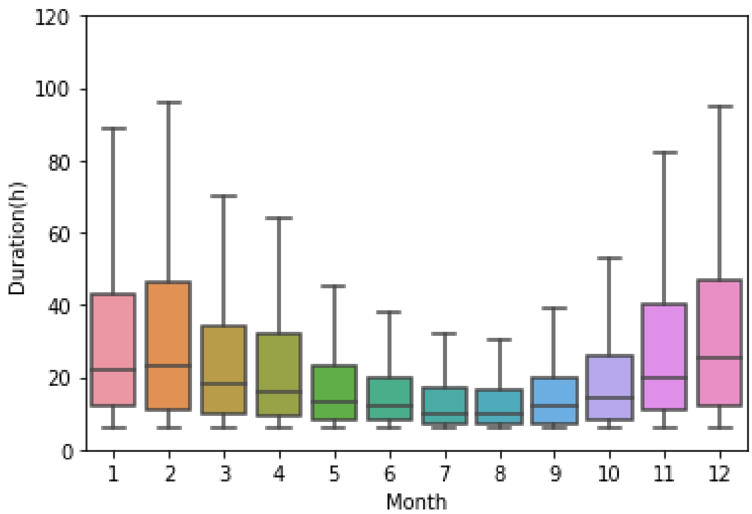

*Figure 5: Monthly Mean Duration for the cyclonic activities in the Aegean Sea (1979-2020), the respective 1st, 2nd and 3rd quartiles (bars of the box) and the external bars that have values respectively Q3+1.5*IQR and Q3-1.5*IQR where IQR=Q3-Q1*

From the previous figure, we observe that when the mean duration of the cyclonic activities is higher, also the degree of uncertainty increases. In the next figure (Figure 6),_it is shown how duration changes in monthly basis for the cyclones

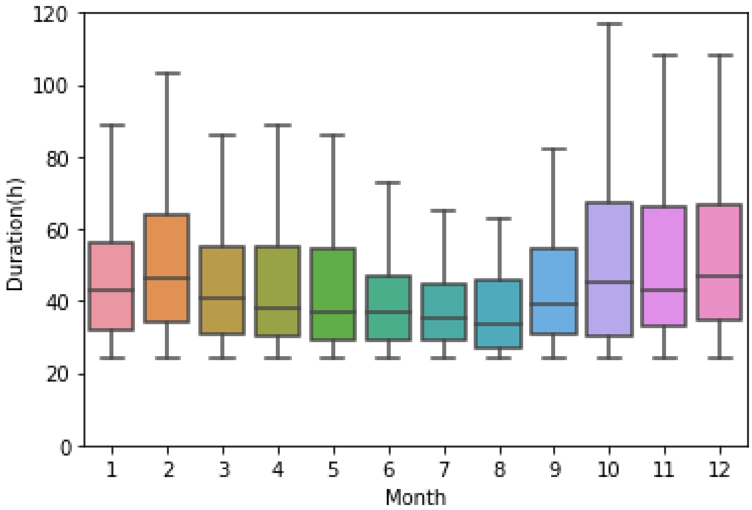

*Figure 6: Monthly Mean Duration for the cyclones in the Aegean Sea (1979-2020), the respective 1st, 2nd and 3rd quartiles (bars of the box) and the the external bars that have values respectively Q3+1.5*IQR and Q3-1.5*IQR where IQR=Q3-Q1*

We observe that even if the seasonal dependance of duration in the cyclones is clear, also the degree of uncertainty is high especially for higher values of duration.

Finally in the next figure (Figure 7), we can observe that the trend of the seasonal variability of duration for the cyclones, and for the cyclonic activities is pretty similar.

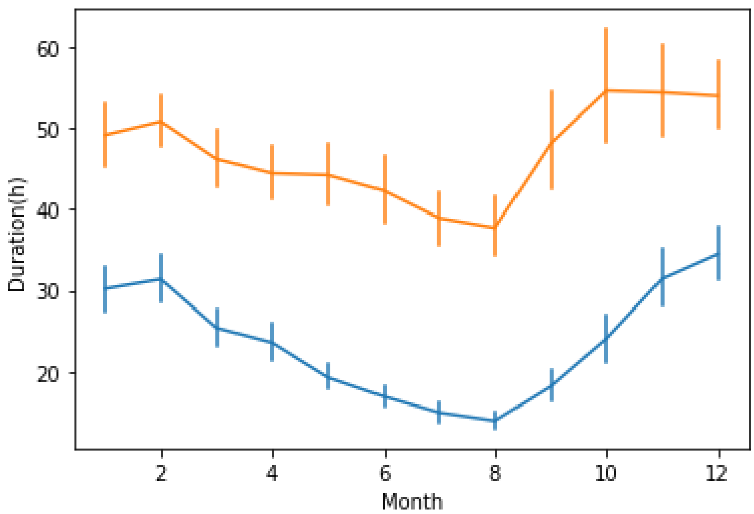

Figure 7: Mean Duration by month for cyclonic activities (blue line) and for cyclones (orange line) in the Aegean Sea (1979-2020) with error bars for each month representing the error in the 95% confidence interval

From the previous, we see that both cyclones and cyclonic activities follow the same trend in terms of duration over the year (higher durations in the winter and lower durations in the summer)

3.3. VELOCITY

The propagation velocity of the cyclones is one of the most important and interesting characteristics to be examined as it presents a strong seasonal variability. According to other studies (Aragão and Porcù ,2021) the mean velocities in the Mediterranean Region are between 32 and 36 km/h. Some other studies (Trigo ,2006; Lionello *et al.* ,2016) place this value a little bit lower (24- 32 km/h). By the analysis of the data that regard this study, we 've found that the mean velocity of the cyclones is 45.83 km/h. This value is higher than the values found for the Mediterranean Region, so we can suppose that the mean propagation velocity of the cyclones that pass over the Aegean Sea is higher than those that occur in the entire Mediterranean Region. Furthermore, it has been seen that 75 % of the cyclones have velocities lower than 55.45 km/h ,50 % have velocities lower than 44.34 km/h and 25% have velocities lower than 35.30 km/h.

Having a look to the cyclonic activities, we see that the mean propagation velocity assumes the value of 38.55 km/h. 75% of the cyclonic activities have mean velocities lower than 51.44 km/h, 50% of them have mean velocities lower than 36.97 km/h and 25% lower than 22.64 km/h.

The density of probability in relation to the mean velocity for the cyclonic activities and the cyclones is shown in the next graph (Figure 8)

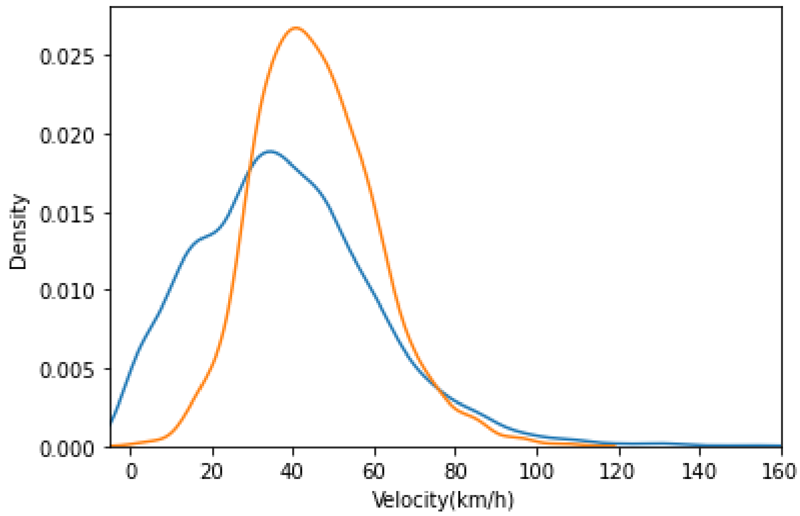

Figure 8: Density of probability by mean propagation velocity for cyclones (orange line) and cyclonic activities (blue line) in the Aegean Sea (1979-2020)

The propagation velocity of the cyclones is one of the characteristics of the cyclones that are subjected to a very net seasonal variability. As it is known from other studies (Aragão and Porcù,2021) the higher propagation velocities in the Mediterranean Region are registered between April and June with the peak registered in May. The present study shows that the cyclonic activities and the cyclones that pass over the Aegean Sea follow the same tendency as the cyclones in the Mediterranean Region. We've found that both cyclones and cyclonic activities present their maximum velocities in this period of the year and present also a secondary peak in October, more pronounced for the cyclones. In addition, both of them have their peak mean velocities registered in May. If we take a closer look to the cyclonic activities we assume that there are mainly 2 different seasons. We note that from October to May the mean velocities are higher, with the peak in April and May. From June to September the cyclones present the lowest mean propagation velocities with the lowest point in August. The mean velocities for each month can be seen in the next table (Table 3)

Month	Aegean Sea	
	Dur. > 6h	Dur. > 24h
January	39.85	43.17
February	42.49	45.21
March	43.05	48.81
April	44.07	48.73
May	44.77	50.99
June	36.21	46.38
July	31.13	41.87
August	28.20	38.36
September	34.77	44.87
October	42.78	50.00
November	42.61	46.28
December	39.92	42.16

Table 3:Monthly Mean propagation velocity(km/h) for cyclonic activities and cyclones crossing the Aegean Sea(1979-2020)

In the next graph (Figure 9), we can see how propagation velocity varies in monthly basis for the cyclones.

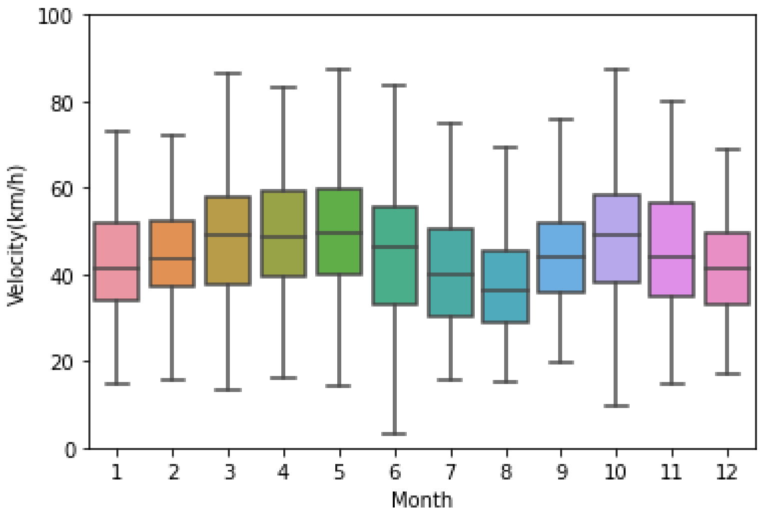

*Figure 9: Monthly Mean Velocity for the cyclones in the Aegean Sea (1979-2020), the respective 1st, 2nd and 3rd quartiles (bars of the box) and the external bars have values respectively Q3+1.5*IQR and Q3-1.5*IQR where IQR=Q3-Q1*

In the next one (Figure 10), we can see how velocities changes by month for the cyclonic activities.

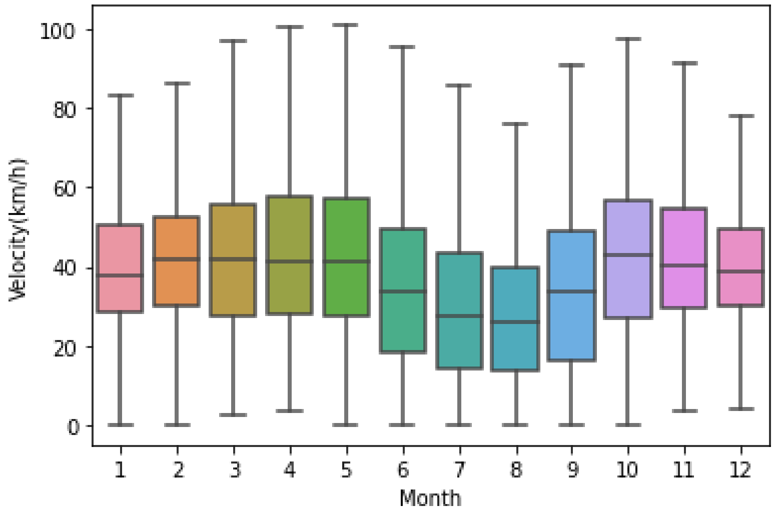

*Figure 10: Monthly Mean Velocity for the cyclonic activities in the Aegean Sea (1979-2020), the respective 1st,2nd and 3rd quartiles (bars of the box) and the external bars have values respectively Q3+1.5*IQR and Q3-1.5*IQR where IQR=Q3-Q1*

From the previous figures and tables we observe that the mean propagation velocity for both cyclones and cyclonic activities is subjected to a net seasonal dependance. For both cases, the highest mean velocities are registered from April to June with the peak registered in May. For the cyclones we also can observe that there is a secondary peak in October, lower though than the peak registered in May. Another valuable information we can get from the graphs is that there is a high range of velocities in the same month and thus a high level of uncertainty in the values registered.

4. AREAS OF CYCLONIC ACTIVITIES IN THE AEGEAN SEA

4.1. DISTANCES

The distance covered by cyclones is an important parameter to be taken in consideration in order to examine their nature and behavior. In this section, we separated both cyclones and the cyclonic activities on the condition if they passed over the Aegean Sea or they were formed inside it. Moreover, the displacement of a cyclone, the distance in straight line between its cyclogenesis position and the cyclolysis position has been taken into consideration. In addition, being able to see the correlation between these two parameters can tell us a lot about the trajectory and the stationary or not nature of the cyclone.

According to (Aragão and Porcù,2021) a large part of the cyclones in the Mediterranean Region (46%) cover distances between 800 and 1600 km. From the analysis of the dataset, we found that 30% of the cyclones that pass over the Aegean Sea cover distances in this range of values. The mean distance covered is 2167 km. 90% of the cyclones cover distances smaller than 3620 km and 50% cover distances between 1333 and 2738 km. As far as it regards the cyclones that were formed inside the domain box, we see that in the period we examine (1979-2021), from the 1366 cyclones that passed over the Aegean Sea, 684 of them (50%) were formed inside the considered domain box. Those have covered mean distances equal to 1750 km.90% of them covered distances smaller than 2835 km and 50% of them covered distances between 1146 and 2230 km

In the next graph, it is shown the density of probability in relation to the distance for all the cyclones and for the cyclones formed inside the domain box (Figure 11)

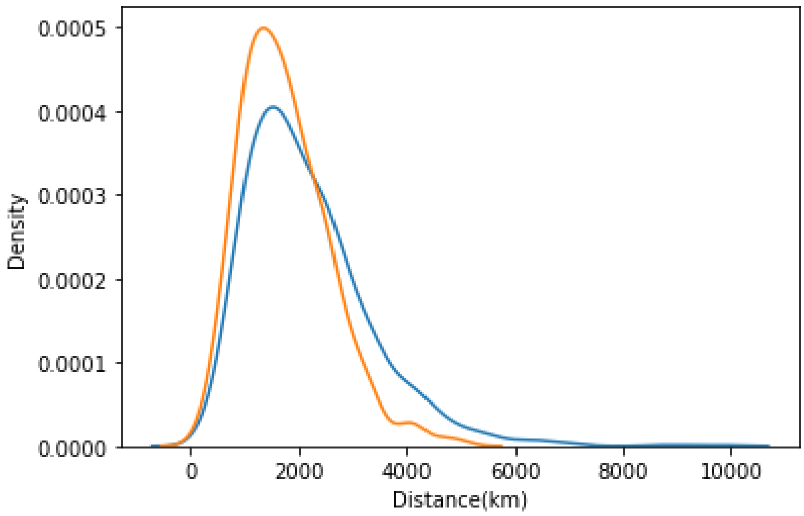

Figure 11: Density of probability by distance for all the cyclones (blue line) and the cyclones formed inside the domain box (orange line) in the Aegean Sea (1979-2020)

Taking in consideration the cyclonic activities that passed over the Aegean Sea, we observe that the mean distance covered is 948 km. 50% of these cyclones cover distances lower than 550 km, and 25% cover distances larger than 1287 km. If we consider only the cyclonic activities that were formed inside the domain box we notice that they have mean distances equal to 669 km.50% of them cover distances lower than 414 km and 25% of them cover distances larger than 895km. In the next figure it is shown the density of probability of the cyclonic activities and the cyclonic activities formed inside the domain box in relation to the distance (Figure 12)

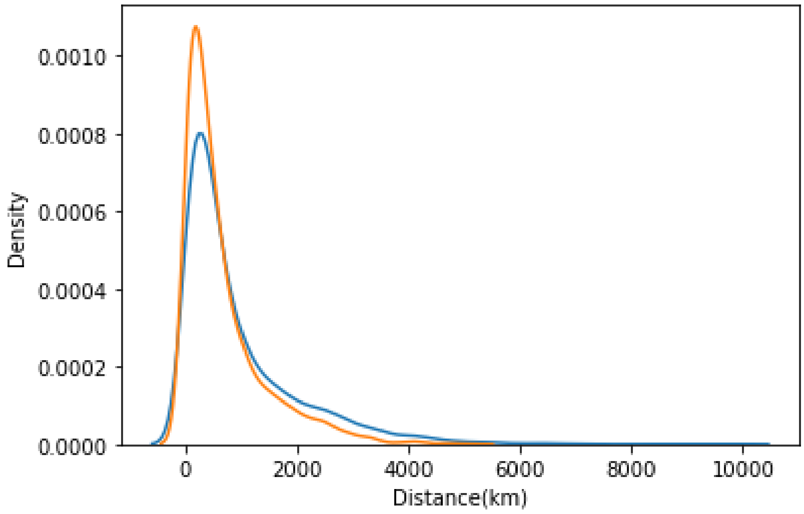

Figure 12: Density of probability for all the cyclonic activities (blue line) and those formed inside the domain box (orange line) (1979-2020) in the Aegean Sea (1979-2020)

4.2. DISPLACEMENT

Displacement, for the purpose of the present study, is defined as the distance in straight line between the position of cyclogenesis and the position of cyclolysis. The cyclones that just passed over the Aegean Sea have a mean displacement of 964 km. As it can be easily intuited the displacement is always equal or smaller than the distance covered, and the ratio between those is an important information that was also examined. It has also been found that half of the cyclones have displacement values lower than 841 km, 75% lower than 1321 km and 90% lower than 1823 km. If we take only the cyclones that were formed inside the domain box, we see that those have a mean displacement of 728 km, half of them have displacement values lower than 629 km, 75% lower than 1018 km and 90% lower than 1406 km. In the next graph, we can see the density of probability of the displacement of the cyclones that passed over the Aegean Sea and those who were formed inside it (Figure 13).

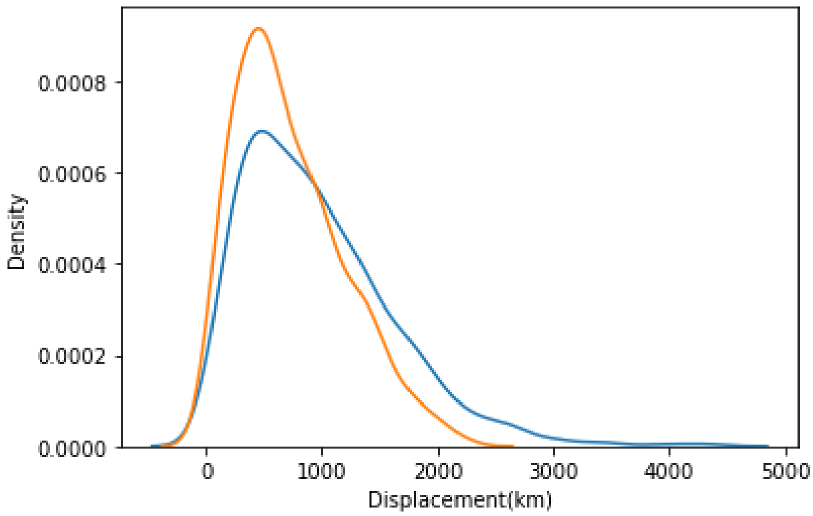

Figure 13: Density of probability by displacement for all the cyclones (blue line) and those formed inside the domain box (orange line) in the Aegean Sea (1979-2020)

As far as it concerns the cyclonic activities, those have a mean displacement of 434 km, 50% of them present displacements lower than 248 km, 75% lower than 515 km and 90% lower than 1138 km. For the cyclonic activities that were formed inside the domain box we' ve found that they have mean displacement equal to 299 km, 50% of them present displacements lower than 186 km, 75% lower than 372 km and 90% lower than 714 km. In the next graph it can be seen the density of probability of the total cyclonic activities and those formed inside the domain box in relation to the displacement (Figure 14).

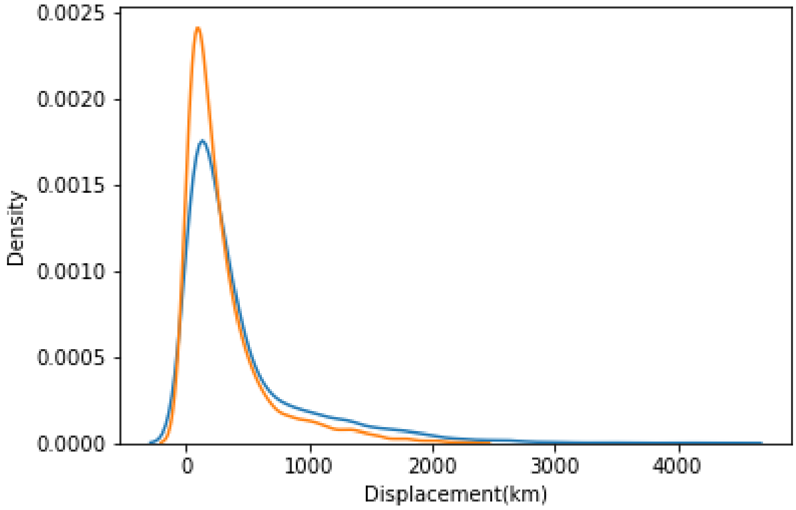

Figure 14: Density of probability by displacement for all the cyclonic activities (blue line) and for the cyclonic activities formed inside the domain box (orange line) in the Aegean Sea (1979-2020)

The displacement of the cyclones does not remain constant over the year. In the late autumn and in the winter they tend to move much more from their initial position and in the summer they tend to remain close to it. The mean minimum displacement of the year takes place in August and the maximum in February (Figure 15)

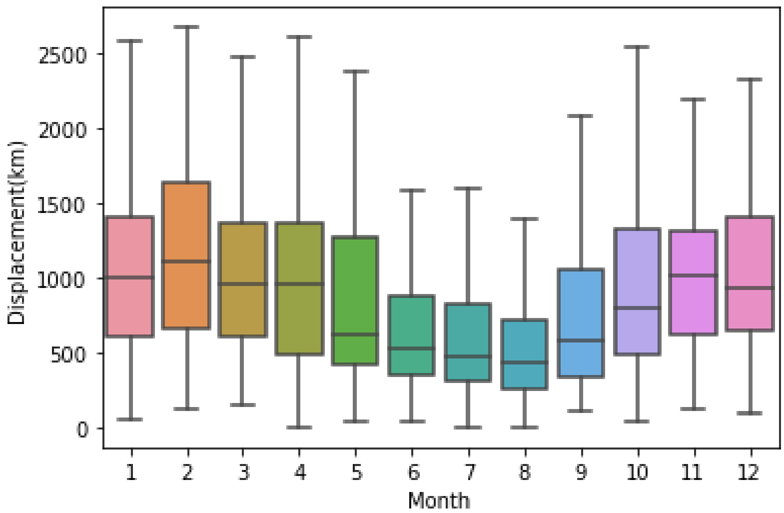

*Figure 15: Monthly Mean Displacement for the cyclones in the Aegean Sea (1979-2020), the respective 1st,2nd and 3rd quartiles (bars of the box) and the external bars have values respectively Q3+1.5*IQR and Q3-1.5*IQR where IQR=Q3-Q1*

The same trend is also verified for the cyclonic activities, with maximum mean displacements in the winter and the minimums in the summer, even though as the displacement values become bigger also the uncertainty becomes more significant. In the next graph it is shown how displacement varies in monthly basis for all the cyclonic activities (Figure 16).

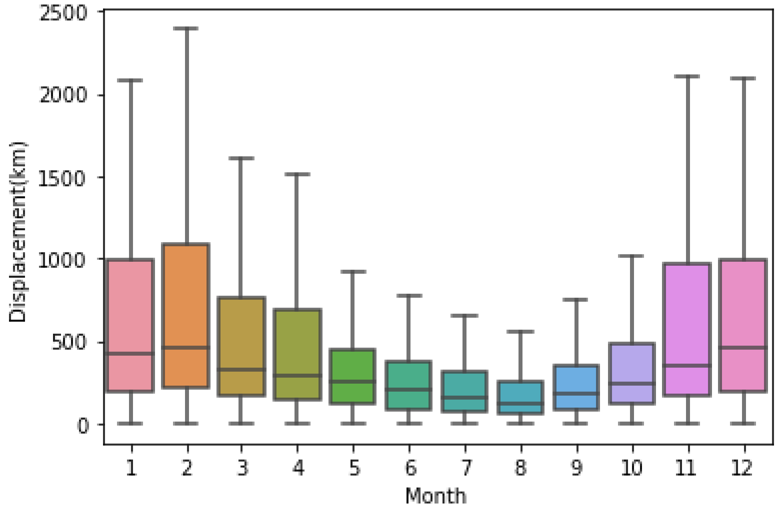

*Figure 16: Monthly Mean Displacement for all the cyclonic activities in the Aegean Sea (1979-2020), the respective 1st,2nd and 3rd quartiles (bars of the box) and the external bars have values respectively Q3+1.5*IQR and Q3-1.5*IQR where IQR=Q3-Q1*

Another important feature of the cyclones is the relation between the distance covered and the total displacement. The ratio between those two features can show a lot about how stationary a cyclone is. The higher the ratio, the more stationary a cyclone is. According to (Aragão and Porcù, 2021), the median ratio for the cyclones occurring in the Mediterranean Region is equal to 2.6. In addition, they suggest this value to be equal to 4.5 in order to characterise a cyclone stationary. As far as it regards the Aegean Sea, we 've found that the mean ratio is 3.26 and that half of the cyclones present ratios lower than 2.22. Furthermore only 15 % of the cyclones present ratios higher than 4.5 and they can be classified as stationary. Taking a closer look also to the cyclonic activities we observe that they have mean ratios equal to 2.80, 50% present ratios lower than 1.86 and only 12.5% present ratios higher than 4.5 and they can be classified as stationary. In the next graph it is shown the density of probability of the cyclones and the cyclonic activities in relation to the distance/displacement ratio (Figure 17).

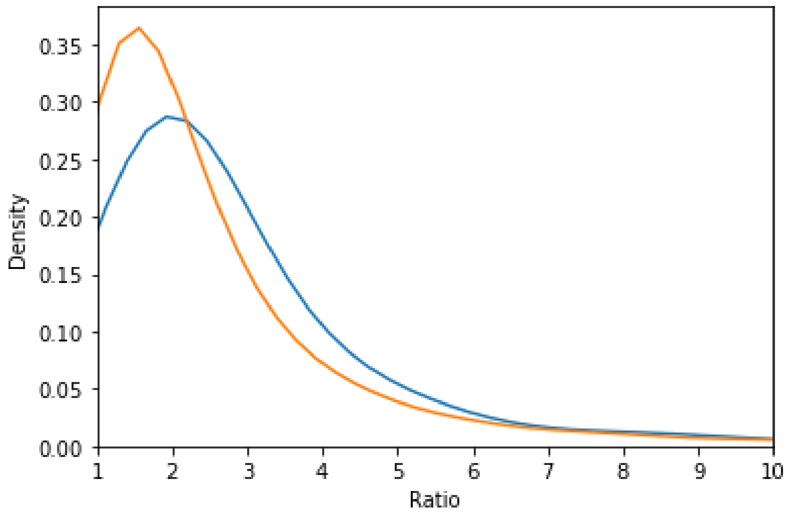

Figure 17: Density of probability by ratio for the cyclones (blue line) and for the cyclonic activities (orange line) in the Aegean Sea (1979-2020)

From the previous figure we observe that the cyclones tend to be more stationary than the cyclonic activities as they present higher distance-to-displacement ratios. So even if they cover larger distances than the cyclonic activities as it has been shown previously, we can suppose their trajectory is more curved than the trajectories of the cyclonic activities who tend to move more in a straight line.

The distance-displacement ratio does not though remain constant throughout the year but it presents strong seasonal changes. In the next figure (Figure 18), we can see how the distance/displacement ratio varies in monthly basis.

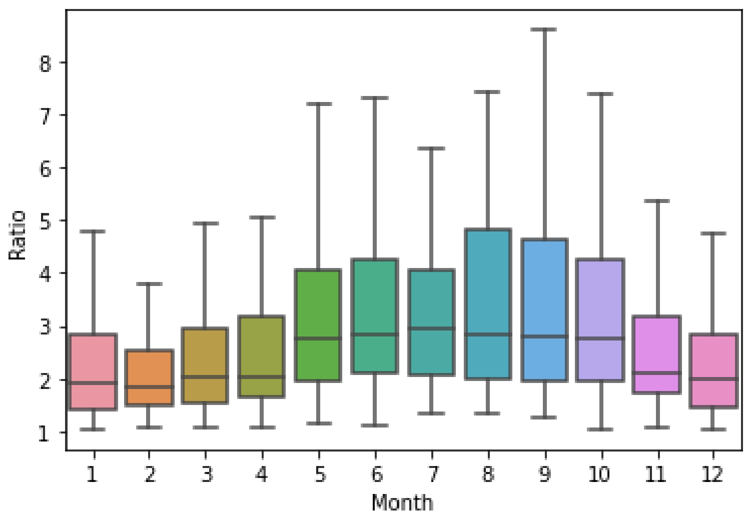

*Figure 18: Mean monthly ratio for all cyclones in the Aegean Sea (1979-2020), the respective 1st,2nd and 3rd quartiles (bars of the box) and the external bars have values respectively Q3+1.5*IQR and Q3-1.5*IQR where IQR=Q3-Q1*

As we observed the lower ratios are registered from November to April, and the higher from May to October. For the cyclonic activities the minimum mean ratio is verified in January and the maximum mean ratio in October. The mean ratios for all the months of the year for the cyclonic activities is shown in the next graph (Figure 19)

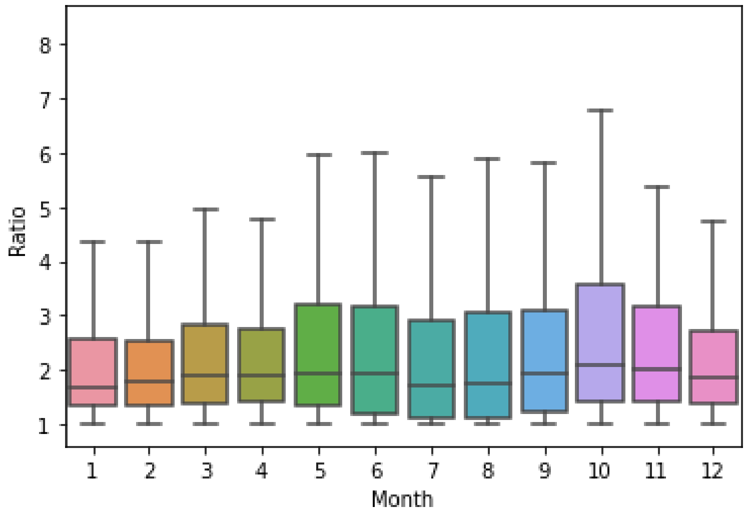

*Figure 19: Monthly Mean Ratio for the cyclonic activities in the Aegean Sea (1979-2020), the respective 1st,2nd and 3rd quartiles (bars of the box) and the external bars have values respectively Q3+1.5*IQR and Q3-1.5*IQR where IQR=Q3-Q1*

From the previous graph we observe that the distance-to-displacement ratio for the cyclonic activities is not subjected to a strong seasonal variability as it happens with the cyclones. In addition, we can assume that the cyclonic activities are less stationary than the cyclones as they present ratios lower than the cyclones.

4.3. CYCLOGENESIS AREAS

The cyclones that we have taken in consideration do not happen with equal frequency in all the area covered by the domain box. This behavior is susceptible to variations along the annual cycle. For this part of the analysis we excluded the cyclones born outside of the domain box. In the next figure (Figure 20) one can observe the spatial distribution of cyclogenesis for the cyclones and for the cyclonic activities that last less than 24 hours formed inside the domain box

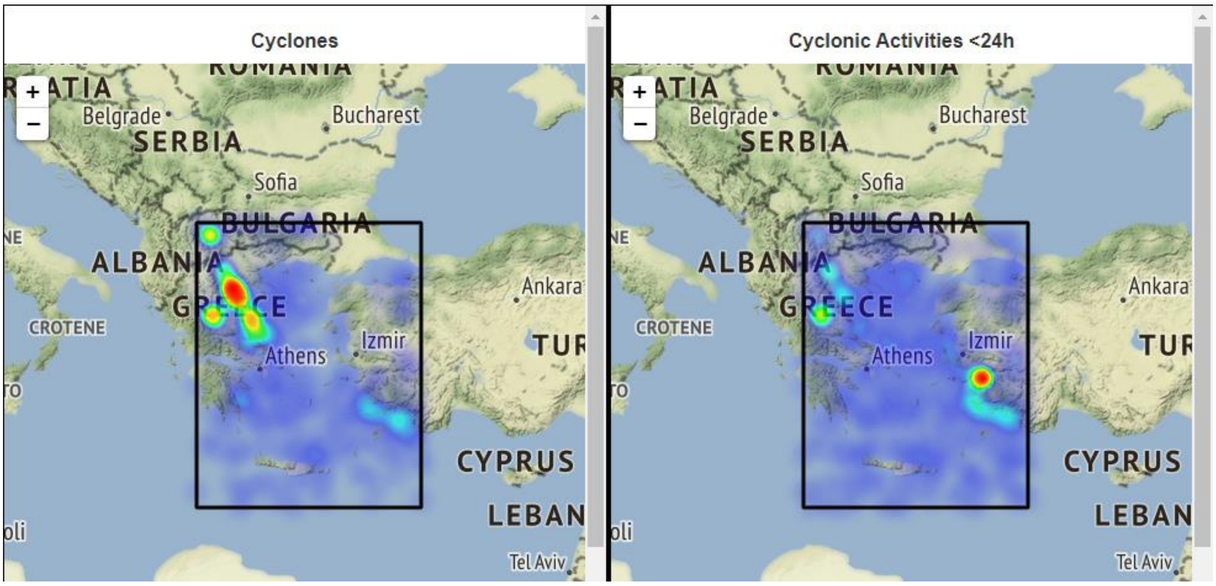

Figure 20: Spatial distribution of cyclogenesis for the cyclones (left) and for the cyclonic activities that last less than 24 hours (right), formed inside the domain box (1979-2020)

From the previous figure we observe that the cyclonic activities lasting less than 24 hours are equally distributed in the domain box, with their main cyclogenetic activity to be concentrated on the south-west coasts of Turkey. Looking only at the spatial distribution of the cyclones we see that there is an intense cyclogenetic activity in the north-west area of the domain that is not relevant if we look the spatial distribution of the cyclonic activities lasting less than 24 hours.

Furthermore, an ulterior analysis of the spatial distribution of the cyclogenesis of the cyclones by every season was made. In the next figure we can see how cyclones are distributed in the domain box in the 4 seasons of the annual cycle (winter DJF, spring MAM, summer JJA, autumn SON)(Figure 21).

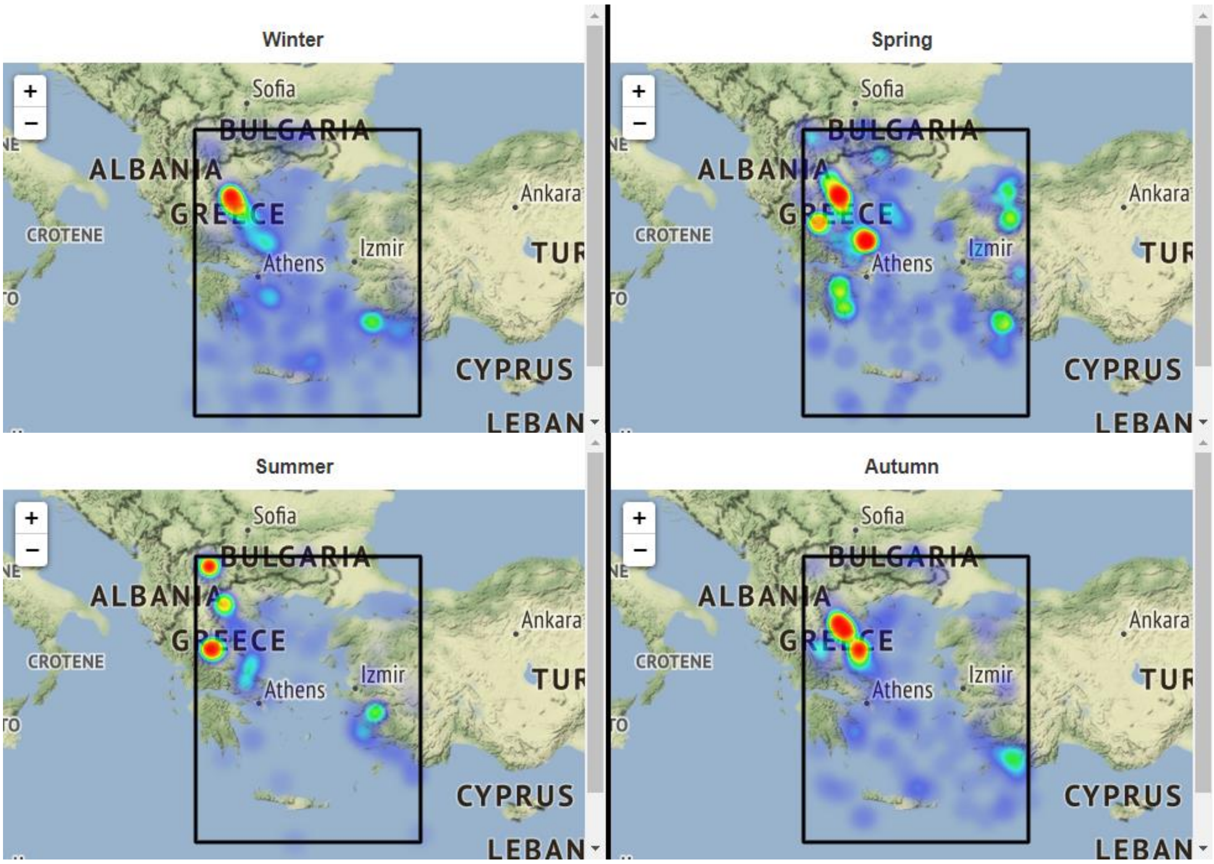

Figure 21: Spatial distribution of cyclogenesis for the cyclones formed inside the domain box (1979-2020) for all seasons (winter top left, spring top right, summer bottom left, autumn bottom right)

From the previous figure and from the data analysis we did, we observed that the winter is the season when the largest part of the cyclones occur in the domain box (35.7 %), followed by spring (25.4 %) and by autumn (20.2 %). Finally in the summer occurs the 18.7 % of the cyclones formed inside the domain box. Furthermore, we notice that also the spatial distribution of the cyclogenesis changes. In the winter, the spatial distribution is more homogeneous and covers the entire domain box, in the summer the cyclogenesis occurs mainly close to the coastlines of Greece and south-west Turkey. The spring and the autumn can be considered as mid-seasons in terms of cyclogenesis, when indeed cyclogenesis occurs both over land and over sea and is less intense than the winter but more intense than the summer. Another important observation we can make is that throughout the year, there is a specific region in the north-west of the Aegean that presents consistent cyclogenetic activity.

In this section, we analysed the spatial distribution of the cyclogenesis for the cyclones and for the cyclonic activities that last less than 24 hours and we observed that the spatial distribution of the cyclonic activities results more homogenous and equally distributed over the domain box. For the cyclones we saw that there is a specific area over the north-western Aegean where cyclogenesis takes primarily place. In that area, the cyclogenetic activity of the cyclones is relevant through the whole annual cycle.

5. CONCLUSIONS

The scope of the present study was to examine, analyse and observe the behavior and the main characteristics of the cyclones and the cyclonic activities that pass over the Aegean Sea, and how those vary throughout the annual cycle.

This was done through the analysis of data that came from the application of several filters that (Aragão and Porcù, 2021) applied in their study on the cyclones of the Mediterranean Region of the ERA-5 dataset for a period of 42 years (1979-2020). The first characteristic that was examined is the frequency of cyclones/cyclonic activities and comparing our results with what is known for the cyclones of the Mediterranean, we found that a large part of the cyclones occurring in the Mediterranean Region occurs in the Aegean Sea. In addition, we observed that the frequency of cyclones/cyclonic activities vary in the year, with higher frequencies to be observed in the winter for the cyclones and in the summer for the cyclonic activities.

As far as it regards the duration of the cyclones, we found that the mean duration of the cyclones 48.18 hours, higher than the mean duration of the cyclones occurring in the Mediterranean. Taking into account the cyclonic activities we found that their mean duration is much lower (22.43 hours) and that the largest part of the cyclonic activities last less than 1 day. This is one of the characteristics that denotes the subsynoptic nature of the phenomena occurring in the Aegean Sea. We observed that the duration varies significantly over the year with the peak registered in late autumn and in the winter and the lower values registered mostly in the summer.

Moreover, the propagation velocity has been taken into consideration and what was found is that the cyclones of the Aegean Sea have slightly higher mean propagation velocities than those of the whole Mediterranean Region. Their mean velocity does not remain constant throughout the annual cycle with the peak velocities being registered for both cyclones and cyclonic activities in May.

As far as it concerns the distance and the displacement we saw that the cyclones of the Aegean Sea tend to cover larger distances and to displace more from their cyclogenesis position in the winter and the opposite happens in the summer.

Also, the ratio distance-displacement has been taken into account in order to examine the stationary or not nature of the cyclones and the cyclonic activities in general. It was found that a small part of them can be considered stationary and the mean ratio is very close for the cyclones of the entire Mediterranean Region. This ratio though changes over the year with higher ratios observed from May to October, when the cyclones tend to be more stationary and the lowest in the winter where the cyclones cover also larger distances.

Finally, the spatial distribution of the cyclogenesis of the cyclones and the cyclonic activities that last less than 1 day, formed in the domain box, was taken in consideration and we observed a more homogenous distribution of the cyclonic activities lasting less than 1 day in the entire domain box and one specific area over the north-west part of the Aegean to be the most cyclogenetic region for the cyclones of the domain. Furthermore, we examined the spatial distribution of the cyclogenesis only for the cyclones for the 4 seasons of the annual cycle. What we experienced is that the cyclones occurring in the winter are more frequent and takes place all over the domain, in the summer the cyclones are less frequent and they occur mostly on the coastlines and the land.

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