ISTANBUL TECHNICAL UNIVERSITY ★ EURASIA INSTITUTE OF EARTH SCIENCES

TRAJECTORIES OF CYCLONES AFFECTING TURKEY: NCEP 2 VERSUS ERA-INTERIM

M.Sc. THESIS

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Climate and Marine Science Department

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ AVRASYA YER BİLİMLERİ ENSTİTÜSÜ

TÜRKİYE'Yİ ETKİLEYEN SİKLON YÖRÜNGELERİ: NCEP 2 - ERA-INTERIM

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Date of Submission : **4 May 2018**
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To my family and friends,

FOREWORD

The purpose of this thesis is to identify the trajectories of cyclones affecting Turkey using two different data sets: NCEP2 and ERA-Interim. I would like to thank my advisor Prof. Dr. Ömer Lütfi ŞEN for guiding me and Dr. Yasemin EZBER for helping me in my study. I hope, this study inspires and guides other researchers in this field. Finally, I am grateful to my friend Adem Gürkan TÜRK and my family for helping me all the time.

June 2018 Merih BOZBURA

TABLE OF CONTENTS

Page

ABBREVIATIONS

CTS	: Cyclone Tracking Scheme
DOE	: Department of Energy
ECMWF	: European Center of Medium Range Weather Forecast
ERA	: European Reanalysis
MSLP	: Mean Sea Level Pressure
NEAT	: Neighbour Enclosed Area Tracking
NPT	: Neighbour Point Tracking
PS	: Polar Stereographic
UTC	: Coordinated Universal Time

SYMBOLS

ξ_{850}	**:** Relative Vorticity at 850 hPa
Z_{1000}	**:** Geopotential Height at 1000 hPa
ρ	**:** Density
f	**:** Coriolis Parameter
$\nabla^2 p$	**:** Laplacian Operator
p	**:** Pressure
t	**:** Time

LIST OF TABLES

LIST OF FIGURES

Page

**TRAJECTORIES OF CYCLONES AFFECTING TURKEY:
NCEP 2 VERSUS ERA-INTERIM**

SUMMARY

Cyclones are low pressure atmospheric systems that control weather conditions every day in many places of mid-latitudes. Any systematic change in the density, frequency or location of cyclones has a wide range of influence on the local climate. When they arise it takes time to evolve and become a mature cyclone and fade away after a cyclone exists. So, lifetime of a cyclone is about a week or so. As it is known from the polar front theory, this strong horizontal temperature gradient results from the cold air from the Polar cell and the warm air from Ferrel cell moving towards each other and this movement develops a transition zone. If there is a convenient environment in the upper atmosphere, the pressure begins to drop, developing a low center at the surface, so cyclogenesis starts. The cold air moves to south and starts to rotate around warm air, forming a cold front, and the warm air moves north into the cold air, developing a warm front. While the system moves to the east, the central pressure keeps reducing and the cold front approaches to the warm front. Ultimately, the cold front cuts off the connection between the warm front and surface and goes under the cooler air ahead of the warm front, thus occluded front forms. This mature system covers a large area and vigorous weather events generally occur in the occlusion stage. The huge warm sea surface of the Mediterranean Basin immensely triggers cyclogenesis and evolutions of the cyclones. These cyclones can bring rain and snow in the form of flooding, snow storms and severe thunderstorm with hail. For instance, a long-running snowstorm hit Turkey on January 22^{nd}, 2004 and it lasted until January 25^{nd}. There were a lot of accidents, the power outage, and one of the rope of Bosphorus Bridge was broken. Shortly, life stopped in İstanbul and nearby cities for a few days. Purpose of this thesis is to identify the trajectories of cyclones affecting Turkey from two different reanalysis data sets.

Detection of cyclone is achieved by The University of Melbourne automatic cyclone tracking scheme (CTS) using 6 hourly NCEP Reanalysis 2 and ERA-Interim mean sea level pressure field respectively at 2.5 x 2.5 and 1.0 x 1.0 spatial resolution for a region between 15°W - 60°E and 20°N - 60°N for 38 years (1979 - 2016). The first step is to transform latitude and longitude data into 101 x 101 polar stereographic (PS) array via bicubic spline interpolation. Smoothing is applied to ERA-Interim pressure field, however it is not preferred for NCEP 2 data because of its low spatial resolution. The local maxima of relative cyclonic geostrophic vorticity (ξ) value via the Laplacian of pressure is sought through comparing each grid point with surrounding eight grid points. If there is no closed depression reasonable distance (*diflt1*), scanning for minimum pressure gradient begins to find an open depression in closest allowable space (*diflt2*). There is no need to integrate the *diflt1* parameter to ERA-Interim case after smoothing. Each cyclone is followed from the first moment of its formation to

its perish. This procedure involves three steps. First one is estimating the subsequent positions of the centres. Second is looking for probability of a relations between the estimated position and the current position. The subsequent positions are predicted via prediction velocity (u_{pred}). Positions were estimated using u_{pred}. Final step is choosing most probable candidate for matching.

Thus, this study shows that the most of the cyclones affecting Turkey are generally westerly and they follow a southerly trajectory in winter, however their trajectory shifts northward towards summer. Cyclones affecting Turkey generally originate in Gulf of Genoa, northern Italy, and the Black Sea, but there are other regions such as the Aegean Sea, Cyprus, and Sahara. However, some changes are seen season to season. Gulf of Genoa and northern Italy regions play major role for all seasons. In winter seasons, Turkey is also affected by southern Italy, the Aegean Sea and the Black Sea cyclones other than Gulf of Genoa and northern Italy cyclones. Sahara, Cyprus, the Aegean Sea, and the Black Sea are cyclogenesis regions in spring seasons. While winter cyclones traverse, summer cyclones are more stationary. Cyclones of Cyprus and the Black Sea have high intensity in summer season. In autumn seasons, cyclones of Sahara, Cyprus, and the Black Sea become pronounced.

The results of NCEP2 and ERA-Interim are generally similar, however there are several differences between them. There are approximately 31% more tracks in the result of NCEP2 than ERA-Interim. In all seasons, there are more tracks in North Africa in ERA-Interim results than NCEP2. While there is a few tracks around Syria, Iraq, and Persian Gulf in ERA-Interim results, NCEP2 results has more tracks than ERA-Interim in these regions in the spring, summer, and autumn seasons. The average central pressure of cyclones is around 1010 hPa for ERA-Interim and 1009 hPa for NCEP2. While the mean cyclone intesity is 0.68 $hPa(^{\circ}lat)^{-2}$ for ERA-Interim, it is obtained to be 0.53 $hPa(^{\circ}lat)^{-2}$ for NCEP2. Also, the mean radius of the cyclones is around 4.10 $^{\circ}lat$ for ERA-Interim and it is found to be 4.08 $^{\circ}lat$ for NCEP2.

TÜRKİYE'Yİ ETKİLEYEN SİKLON YÖRÜNGELERİ: NCEP 2 - ERA-INTERIM

ÖZET

Siklonlar, orta enlemlerin birçok yerinde her gün hava koşullarını kontrol eden atmosferik sistemlerdir. Siklonların yoğunluğu, frekansı veya konumundaki herhangi bir sistematik değişiklik, yerel iklim üzerinde geniş kapsamlı bir etkiye sahiptir. Siklonlar doğdukları zaman gelişmeleri ve sönümlenmeleri biraz zaman alır. Yani, bir hafta kadar uzun bir süre dayanabilirler. Polar cephe teorisinden bilindiği gibi, güçlü bir yatay sıcaklık gradyanı, Polar hücresindeki soğuk havanın ve Ferrel hücresindeki sıcak havanın birbirine doğru hareket eder ve bu hareket bir geçiş bölgesini oluşturur. Yukarı atmosferde uygun bir ortam varsa, basınç yüzeyde düşerek bir alçak basınç merkezi oluşturmaya başlar, böylece siklojenez başlar. Soğuk hava güneye ve sıcak hava kuzeye doğru hareket ederek cepheleri oluşturur. Sistem doğuya doğru hareket ederken, merkezi basınç düşmeye devam eder ve soğuk cephe sıcak cepheye yaklaşır. Nihayetinde, soğuk cephe, sıcak cephenin yüzey ile bağlantısını keser ve sıcak cephenin önündeki serin havanın altına girerek oklüzyon cephesini oluşturur. Bu olgun sistem geniş bir alanı kaplar ve genellikle oklüzyon aşamasında şiddetli hava olayları meydana gelir. Akdeniz Havzası'nın büyük sıcak yüzeyli denizi, siklojenezi ve siklonların gelişimine büyük bir katkı sağlar. Bu siklonlar yağmur ve karı, kar fırtınası ve oraj haline getirebilir. Örneğin, uzun süren bir kar fırtınası 22 Ocak 2004'te Türkiye'yi vurdu ve 25 Ocak'a kadar sürdü. Çok sayıda araba kazası oldu, elektrikler kesildi ve Boğaz Köprüsü'nün halatlarından birisi koptu. Kısaca, hayat İstanbul ve çevresindeki şehirlerde birkaç günlüğüne durdu. Bu projenin amacı, Türkiye'yi etkileyen siklonların yörüngelerini iki farklı veri setinden belirlemektir.

Siklonlar Melbourne Üniversitesi tarafından geliştirilen otomatik siklon izleme yazılımı ile 38 yıllık (1979- 2016) 6 saatlik 2.5 x 2.5 NCEP Reanalysis 2 ve 1.0 x 1.0 ERA-Interim ortalama deniz seviyesi basınç yüzeyi kullanılarak 15° W - 60° E ve 20° N - 60° N arasındaki alan için yürütülmektedir. İlk olarak, bicubic spline interpolasyon ile enlemler ve boylamlar 101 x 101 polar stereografik projeksiyona dönüşürülmüştür. ERA-Interim basınç yüzyeni yüksek çözünürlüklü olduğu için yumuşatma uygulanmıştır. Yumuşatma NCEP 2 basınç yüzeyi düşük çözünürlüğe sahip olduğu için tercih edilmemiştir. Alçak merkezleri bulmak için, çevredeki sekiz grid içerisinde nispi siklonik jeostrofik vortisitinin (ξ) maksimum olduğu yer arandır. Eğer belirli bir yarıçap (*difIt1*)içinde bir kapalı depresyon bulumaz ise izin verilen uzaklıkta (*difIt2*) minimum basınç gradyanı aranır. ERA-Interim veri yumuşatıldığı için *difIt1* parametresine ihtiyaç duyulmamıştır. Siklonlar bulunduktan sonra bazı güç kriterleri belirlenerek güçlü siklonların seçilmesi sağlanır. Her siklon doğduğu andan sönümlendiği ana kadar takip edilir. Takip işlemi üç adımda gerçekleşmiştir. İlk olarak, bir zaman adımı ilerideki alçak basıncın pozisyonu tahmin edilir. Bu pozisyonu bulmak için tahmin hızı (u_{pred}) hesaplandı. Pozisyonlar u_{pred} kullanılarak

tahmin edildi. İkinci olarak, tahmin edilen ve gerçek olan siklon arasında olabilcek ilişkinin olasığılı hesaplandı. Son olarak, olma olasılığı yüksek olan aday siklon bir, zaman adımı önceki siklon ile birleştirilmek için seçildi.

Sonuçlar Türkiye'yi etkileyen siklonların ağırlıklı olarak batılı olduklarını ve kış mevsiminde daha güneyli bir yörünge izlediklerini ancak yaza doğru yörüngelerinin kuzeye kaydığını ortaya koymuştur. Türkiye'yi etkileyen siklonlar genellikle Cenova Körfezi, kuzey İtalya, Ege Denizi, Karadeniz, Kıbrıs ve Sahra bölgesinde oluşurşlar. Fakat, bunlar mevsimden mevsime değişiklik gösterirler. Cenova Körfezi ve Kuzey İtalya bölgelerinde oluşan siklonlar her mevsim için büyük rol oynar. Türkiye kışın, Cenova Körfezi ve Kuzey İtalya dışında, Ege ve Karadeniz siklonlarından da etkilenir. Bahar mevsimindeki siklojenez bölgeleri Sahra, Kıbrıs, Ege Denizi ve Karadeniz'dir. Kış siklonları hareket ederken, yaz siklonları daha sabittir. Kıbrıs, Sahra ve Karadeniz siklonları yaz mevsimlerinde baskındır. Sonbahar mevsimlerinde, Sahra, Kıbrıs ve Karadeniz'in siklonları belirgindir.

NCEP2 ve ERA-Interim'in sonuçları genellikle benzerdir, ancak aralarında birkaç farklılık vardır. NCEP2 sonuçlarında ERA-Interim'e göre yaklaşık %31 daha fazla yörünge vardır. Kuzey Afrika'da bütün mevsimlerde ERA-Interim sonuçlarında NCEP2'ye göre daha çok yörünge vardır. İlkbahar, yaz ve sonbahar mevsimlerinde ERA-Interim verisine göre Suriye, Irak ve Basra Körfezi'nde daha az yörünge bulunurken, NCEP2 verisi sonuçlarına göre bu bölgelerde daha fazla yörünge bulunmaktadır. Siklonların ortalama merkez basıncı ERA-Interim için 1010 hPa, NCEP2 için 1009 hPa civarındadır. Ortalama siklon şiddeti ERA-Interim için 0.68 $hPa(^{\circ}enlem)^{-2}$ iken NCEP2 verisi için 0.53 $hPa(^{\circ}enlem)^{-2}$ olarak elde edilmiştir. Ayrıca siklonların ortalama yarıçapı ERA-Interim verisi için 4.10 $^{\circ}enlem$ ve NCEP2 verisi için 4.08 $^{\circ}enlem$ olarak bulunmuştur.

1. INTRODUCTION

Mid-latitudes cyclones, also called extratropical cyclones are basically synoptic-scale vortices and they are responsible for local weather patterns including extreme and severe weather of the mid-latitude regions of the Earth. When they arise it takes time for them to evolve and become mature cyclones and it takes time to fade away. So, they tend to last quite a while, about a week or so. Mid-latitude cyclones are the systems with winds blowing around them and they blow counterclockwise in the Northern Hemisphere. These cyclones tend to follow the jet stream from below and move along with it from west to east. A strong horizontal temperature gradient causes a sharp change in pressure in the upper atmosphere, and as a result, the jet stream forms. The position of the jet stream indicates the location of the temperature gradient at the Earth's surface. As it is known from the polar front theory, this strong horizontal temperature gradient results from the cold air from the Polar cell and the warm air from Ferrel cell moving towards each other and this movement develops a transition zone. This transition zone is a stationary front between two different air masses in terms of their temperature. If there is a convenient environment in the upper atmosphere, the pressure begins to drop developing a low center at the surface, so cyclogenesis starts. The cold air moves south and starts to rotate around warm air forming a cold front and the warm air is moving north into the cold air developing a warm front. While the system moves to the east, the central pressure keeps dropping and the cold front approaches the warm front. At this stage, this is a fully developed mid-latitude cyclone. Ultimately, the cold front cuts off the connection between the warm front and the surface and goes under the cooler air ahead of the warm front, thus occluded front forms. This mature system covers a large area and vigorous weather events generally occur in the occlusion stage. At this point, there is no more rising warm air to sustain the system as an energy source, the cold air occupies the large area and causes the decay of the cyclone.

The large warm sea surface of the Mediterranean Basin immensely encourages cyclogenesis and evolutions of the cyclones. Nearly confined Mediterranean Sea has quite impact on weather events of surrounding lands and provides a huge amount of energy and moisture for the development of cyclones [3]. Extreme weather events, hydrological cycle, and regional climates are especially influenced by the mid-latitude cyclones related to rain bringing frontal systems [4]. These cyclones can bring rain and snow in the form of flooding, snow storms and severe thunderstorm with hail. For instance, a long-running snowstorm hit Turkey on January 22^{nd}, 2004 and it lasted until January 25^{th}. There were a lot of car crashes, the power went out, and one of the rope of Bosphorus Bridge was broken. Shortly, life stopped in İstanbul and nearby cities for few days. Increasing sea surface temperature in late summer and autumn and precipitation bringing Mediterranean cyclones give rise to an excessive amount of rainfall ending up with floods [5] [6], for instance the flood events on September 8^{th} and September 9^{th}, 2009 in Marmara region of Turkey. It is recorded as the worst heavily rainfall event in Istanbul which has not been observed for 80 years in Turkey and it caused the death of 31 people. In addition, Schröter et al. (2015) state that low pressure systems in the upper atmosphere awaken the cyclones which were amplified by nonstop humid and warm air. As a result, Austria, the Czech Republic, Poland, Hungary, Croatia, Switzerland, Serbia, Slovakia, and especially Germany were affected by extensive flooding in June 2013 [7].

1.1 Purpose of Thesis

The source of precipitation in Turkey is characterised by cyclones that occur in the Mediterranean Basin. The way to understand the source of precipitation in Turkey is to examine climatology of the Mediterranean cyclones. Therefore, the main purpose of this study can be stated as identifying cyclones affecting Turkey and finding their trajectories using a numerical scheme called The University of Melbourne automatic cyclone tracking scheme (CTS) [8] [9] from two different reanalysis data sets.

1.2 Literature Review

Accurate and robust identification of cyclones is crucial for certainty of subsequent operations such as tracking and statistics. To remove collected artificial and weak troughs, the result of high resolution data, thresholds of cyclone identifying stage were obtained experimentally [3]. These kind of artificial centres can lead misunderstanding of cyclone frequency and lifetime. Using high resolution data in terms of temporal and spatial is important for credibility of the algorithm [4]. Also, it is very important to make the right choice with regard to meteorological variables as some fields can be inconvenient for including in calculations like vorticity. Vorticity field requires smoothing since it is very detailed in high spatial resolution data, but it detects the systems in their early stages [10]. On the other hand, [11] [12] [13] applied smoothing to vorticity field to eliminate artificial vorticity centres even tough they used low resolution data. Several different variables have been used to search for low centres as 1000 hPa geopotential height (Z_{1000}), mean sea level pressure (MSLP), and 850 hPa vorticity (ξ_{850}) fields. While [4] [3] [14] searched the low centres with Z_{1000} filed, MSLP field was used by [8] [15] [16] [17] [18] [19]. Besides, [11] [20] studied with both Z_{1000} and ξ_{850} fields. Finding the location of the low centres was generally carried out by comparing 8 or more neighbouring and surrounding grid points with each other. Whereas looking for maximum ξ_{850}, minimum of MSLP and Z_{1000} were searched between the grid points. A detected local minima or maxima is defined as a cyclone. According to Wernli and Schwierz (2006), finding local minimum of MSLP is not enough for identifying the cyclones. The closed isobar around the local minima of MSLP is considered as cyclone field (c) as the second stage of identification. Also, one isobar is enough for assigning [16]. Tracking is matching the cyclones at time t with the predicted ones at time t+dt and typically nearest neighbour search method is applied. According to Serreze (1994), firstly each center at time t is assigned to a number and each center at time t+dt is set on the center of 3 x 3 array. When a system at time t is found in determined 3 x 3 array at time t+dt, the number of the center is designated to the matching center. The numbers of the unmatched centres are appointed to the closest centres at time t+dt if a few conditions are meet like travelling less then 1400 km and 10° south or having less than 40 mb sea level pressure tendency. The remaining unfollowed centres are considered as nascent centres [18]. Alternatively, the matching cyclones are searched in an elliptic area and the equation of the ellipse is calculated by [14] using 700 hPa wind vector.

Inatsu and Amada (2013) states that a Neighbour Enclosed Area Tracking (NEAT) algorithm is simpler than conventional neighbour point tracking (NPT) algorithm which is searching the local-minimum points. This algorithm includes both identification and tracking procedures. A binary image is created from integer relative vorticity values using NEAT. Several relative vorticity thresholds are used to label the binary image to obtain enclosed surfaces like genesis, lysis, merge or split. Selected values are labelled to 1 and the remaining are labelled to 0. After labelling tracking procedure starts. If an enclosed surface with the threshold overlaps with a subsequent enclosed surface, these surfaces are linked. To illustrate this, if an enclosed area labelled to 1 does not overlap with an area (area labelled to 0) in the next time step, they cannot be linked and this represent lysis. Features of enclosed areas are obtained and tracked like this using NEAT algorithm [21].

2. DATA AND METHODOLOGY

2.1 Data

Reanalyses data are hybrid data sets which are generated from combination of observations and model forecasts through data assimilation and they are one of the most preferred data sets since they are very neat over long periods of time [22]. The cyclone identifying and tracking procedures are conducted by using the University of Melbourne automatic cyclone tracking scheme [8] [9] and 2 reanalysis data sets. These are European Center of Medium Range Weather Forecast (ECMWF) ERA-Interim Reanalysis and The National Centers for Environmental Prediction (NCEP) the Department of Energy (DOE) Reanalysis 2 data sets. Both data sets are downloadable on their websites for free and they are available from 1979 to present. MSLP field for the period 1979-2016 (38 years) having 6-hourly (0, 6, 12, 18 UTC) temporal resolution is used in this study. While the spatial resolution of NCEP/DOE Reanalysis 2 data set is 2.5° x 2.5°, the resolution of ERA-Interim data set is 1.0° x 1.0° (interpolated from 0.75° x 0.75°).

2.2 Cyclone Identification

The nature of the mid-latitude cyclones are described objectively by CTS [23]. This scheme finds the locations of meteorological low and high centers on the both hemispheres. In this study, low centres are searched in the Mediterranean Basin between 15°W - 60°E and 20°N - 60°N which represents almost Med-CORTEX region [24]. The first step is transforming latitude and longitude data into 101 x 101 polar stereographic (PS) array via bicubic spline interpolation and these PS grids are centred on the North Pole. For certainty of the results at high latitudes, projection transformation is applied to the data to remove anisotropy in the grids [25]. This is an unalterable step of the algorithm since it continues through PS projection data. Also, smoothing (*rdiff* and *rdifz*, Table 2.1) is applied to ERA-Interim data to diminish spurious systems. Smoothing is not preferred for NCEP 2 data because of its low spatial resolution. Identification of the extratropical cyclones is defined better through the relative vorticity than local minima of pressure [8] . The local maxima of relative cyclonic geostrophic vorticity (ξ) value via the Laplacian of pressure (Equation 2.1) is sought through comparing each grid point with surrounding grid points (*nshell*) in the second step. In order to assign a cyclone to a closed or an open depression, the minimum pressure is scanned around maximum value of the Laplacian of pressure. If a minimum pressure is detected, this low pressure is designated as a closed depression. If there is no closed depression reasonable distance (*difltl*), scanning for minimum pressure gradient begins to find an open depression in closest allowable spacing (*diflt2*). There is no need to integrate the *difltl* parameter to ERA-Interim case after smoothing. Finally, cyclones must meet certain strength criteria in order to be considered as meteorologically important event. Basically, this step is a compatibility test that examines whether the cyclones belong to the Mediterranean Basin and removes the cyclones that do not belong.

$$\xi = \frac{1}{\rho . f} \nabla^2 p \tag{2.1}$$

Open systems generally occurs around orography and frontal areas around great cyclones and the closest allowable spacing is selected 3 degree latitude for removing these kind of insignificant open systems [26]. Spurious lows generally occur as a result of lows values of the Laplacian of pressure. Several thresholds are set for removing these kind of lows and keeping the strong systems. Mediterranean cyclones are in between mesoscale or sub-synoptic scale [3]. The averaging radius (*cvarad*) and minimum area averaged laplacian for closed and open systems (*cmnc1, cmnc2*) are set so that small-scale systems can be kept. Minimum area averaged laplacian parameters are set to small values since the strong mature systems are generally weak in their early life [3]. However, the minimum central value of Laplacian (*cmncw*) is set to a high value, thereby the systems must reach *cmncw* at least once in its lifetime to not to be eliminated and to be considered as strong. Thus, the cyclone is considered strong. Topography can lead occurance of spurious lows [27]. The search domain and the topography of it are displayed in Figure 2.1. Systems are found at locations where the elevation is greater than *zsmax* are not considered. If *ftopeq* is set, the calculated strength is decreased by an amount proportional to the absolute value of the topographic Laplacian. Lastly, an averaging radius (*rdpgrd*) is set to derive the steering velocity for tracking procedure around the center of the cyclone with averaged pressure gradient.

Table 2.1 : Instruction parameter definitions and settings for cyclone identification.

Parameter	ERA-Interim	NCEP 2	Description
rdiff	2	0	smoothing radius of pressure
rdifz	2	0	smoothing radius of topography
nshell	8	8	number of surrounding gird points for searching
diflt1	0	3	minimum distance between 2 systems (grid units)
diflt2	0	6	minimum separation of starting grid point closed system position for allowing a parallel search for an open depression (grid units)
cvarad	2	4	Radius around centre over which average the Laplacian of the pressure is found (deg.lat.)
cmnc1	0.1	0.1	minimum area averaged Laplacian for closed depressions ($hPa/deg.lat^2$)
cmnc2	0.2	0.2	minimum area averaged Laplacian for open depressions ($hPa/deg.lat^2$)
cmncw	0.6	0.6	minimum central value of Laplacian ($hPa/deg.lat^2$)
zsmax	1000	1500	maximum topographic height for finding cyclones (meters)
rdpgrd	5	4	averaging radius for MSLP derived steering

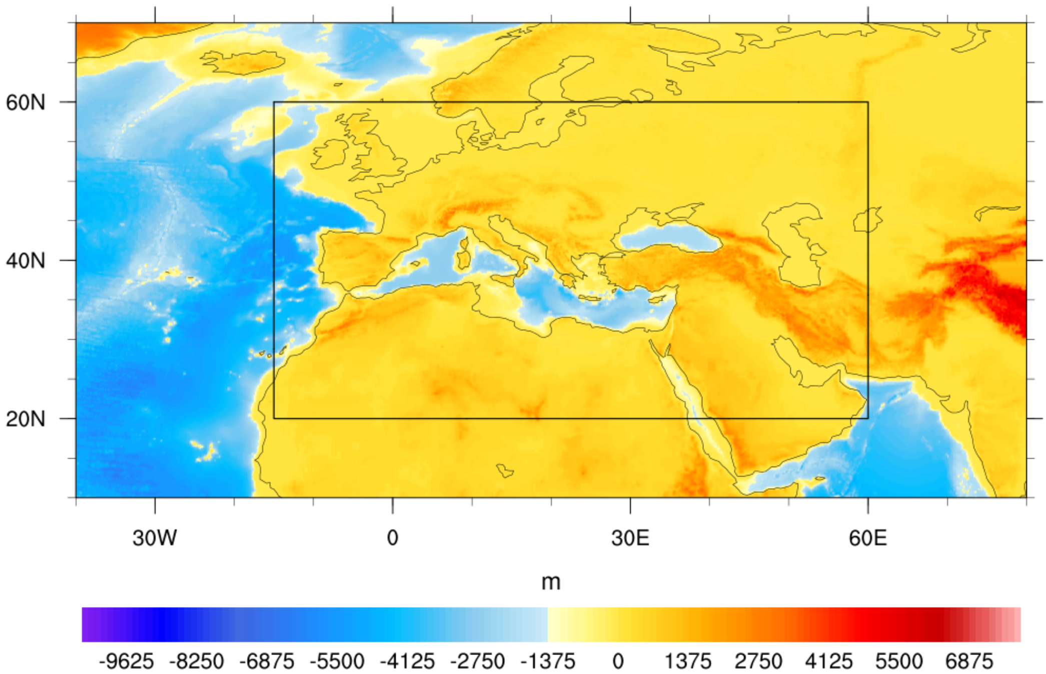


Figure 2.1 : Elevation map of the search domain.

2.3 Tracking

Each cyclone is followed from the first moment of its formation to its perish and tracking procedure is based on cyclone identification. According to Murray and Simmonds (1991), instead of just searching a center within a certain area of the preceding center, a new procedure is developed to obtain more convenient results. This procedure involves three steps which are:

1. Estimating the subsequent positions of the centres
2. Looking for probability of a relations between the estimated position and the current position
3. Choosing most probable candidate for matching [8].

The first step is predicting subsequent position and core pressure for every cyclone that detected in Section 2.2. As it is seen from Equation 2.2, the subsequent positions are predicted via prediction velocity (u_{pred}) whose equation is compose of geostrophic steering velocity (uS), weighting factor (*wsteer*, Table 2.2) for steering velocity, scaling factor (*fsteer*) for steering velocity, and displacement of the cyclone (uM) in previous time step [26]. As it is mentioned in Section 2.2, calculation of the steering velocity is achieved by averaged pressure gradient around the center over 5 and 4 degree latitude (*rdpgrd*) for ERA-Interim and NCEP2 respectively.

$$u_{pred} = (1 - wsteer).uM + wsteer.(fsteer.uS) \tag{2.2}$$

Predicted position and central pressure is calculated as they are stated respectively in Equation 2.3-2.4:

$$r_{est}(t+\delta t) = r(t) + w_M.(r(t) - r(t-\delta t)) + (1-w_M).v_{av}(\phi(t)).\delta t + r_k \tag{2.3}$$

$$p_{est}(t+\delta t) = p(t) + [w_P.(p(t) - p(t-\delta t))] \tag{2.4}$$

where

r_{est}: the predicted position

δt: one time interval

t: current time

w_M: weighting factor for movement (*wmotn*, Table 2.2)

$v_{av}(\phi)$: the averaged cyclone velocity (u_{pred}), for the latitude, ϕ

r_k: a small magnitude term for replicating the acceleration implied by u_{pred}

p_{est}: the predicted central pressure

w_P: weighting factor for pressure tendency (*wpten*).

In the second step, a probability function (Equation 2.5) is defined to find maximum probability. First, the distance (Equation 2.6) between the estimated position and the current position including the pressure difference (δp) between them are calculated to use in the probability function. Normally, maximum probability (P_{max}) is equal to 1, however P_{max} is set to smaller than 1 for open, weak, and new cyclones (qmxopn, qmxwek, and qmxnew, Table 2.2) [8].

$$P = \frac{P_{max} - r\prime^2}{rpbell + (1 - rpbell).r\prime^2} \tag{2.5}$$

$$r\prime = (\frac{1}{rcprob}).\sqrt{r^2 + (\delta p.dequiv)^2} \tag{2.6}$$

Finally, the matching is attempted by selecting most likely pair of the successor cyclone and the subsequent cyclone.

Table 2.2 : Instruction parameter definitions and settings for cyclone tracking.

Parameter	ERA-Interim and NCEP 2	Description
wsteer	0.4	weighting factor for steering velocity
fsteer	2.25	scaling factor for steering velocity
wmotn	0.85	weighting factor for movement
wpten	0.8	weighting factor for pressure tendency
qmxopn	0.75	maximum probability for open depression
qmxwek	0.5	maximum probability for weak depression
qmxnew	0.75	maximum probability for new depression
rpbell	0.4	shape factor of the probability function
rcprob	12.5	pass radius for the probability function
dequiv	0.4	degree latitude equivalent to 1 mb pressure difference

3. RESULTS

3.1 Track Analysis

The most of the cyclones affecting Turkey are generally westerly and they follow a southerly trajectory in winter, however their trajectory shifts northward towards summer. When the cyclones originated in the Gulf of Genoa, the Adriatic Sea, and northern Italy come to Turkey's western border, they divide into two main branches. In one of the branches, some of the cyclones move to the north and pass through the Aegean Sea and reach Russia. The second branch travel to the south to the Aegean Sea and reach the Mediterranean Sea and extend to the Syrian border in the other branch. Meanwhile, there are quite a few cyclones that arise from the Aegean Sea arriving in Turkey. Also, The Black Sea and Cyprus are the other cyclone sources and these influence The Black Sea and The Mediterranean regions of Turkey respectively. In addition to these, Saharan cyclones reach up to Turkey from the south.

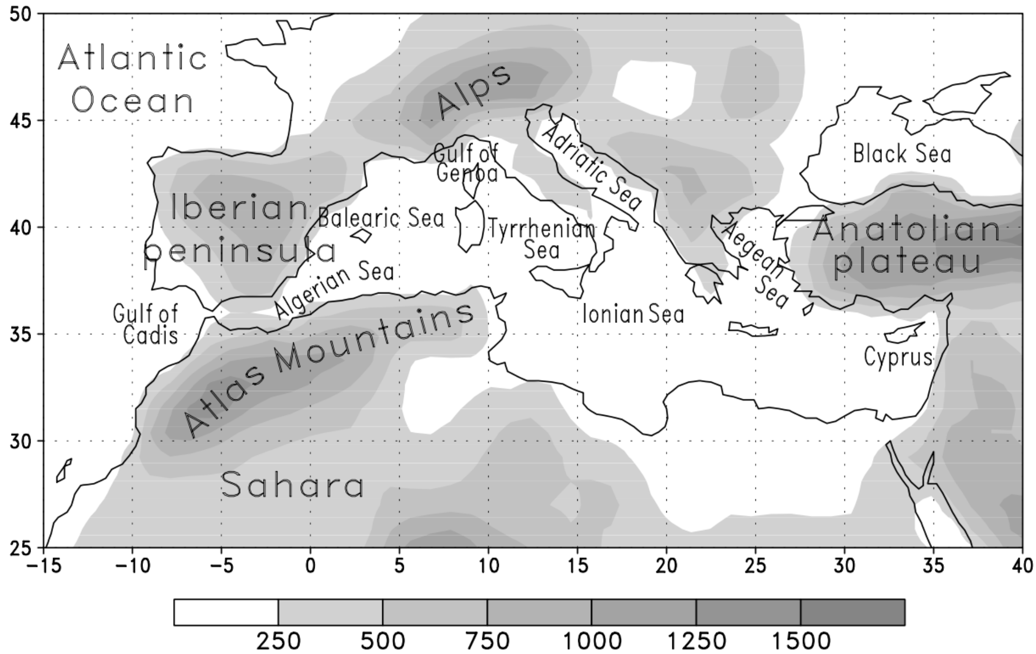
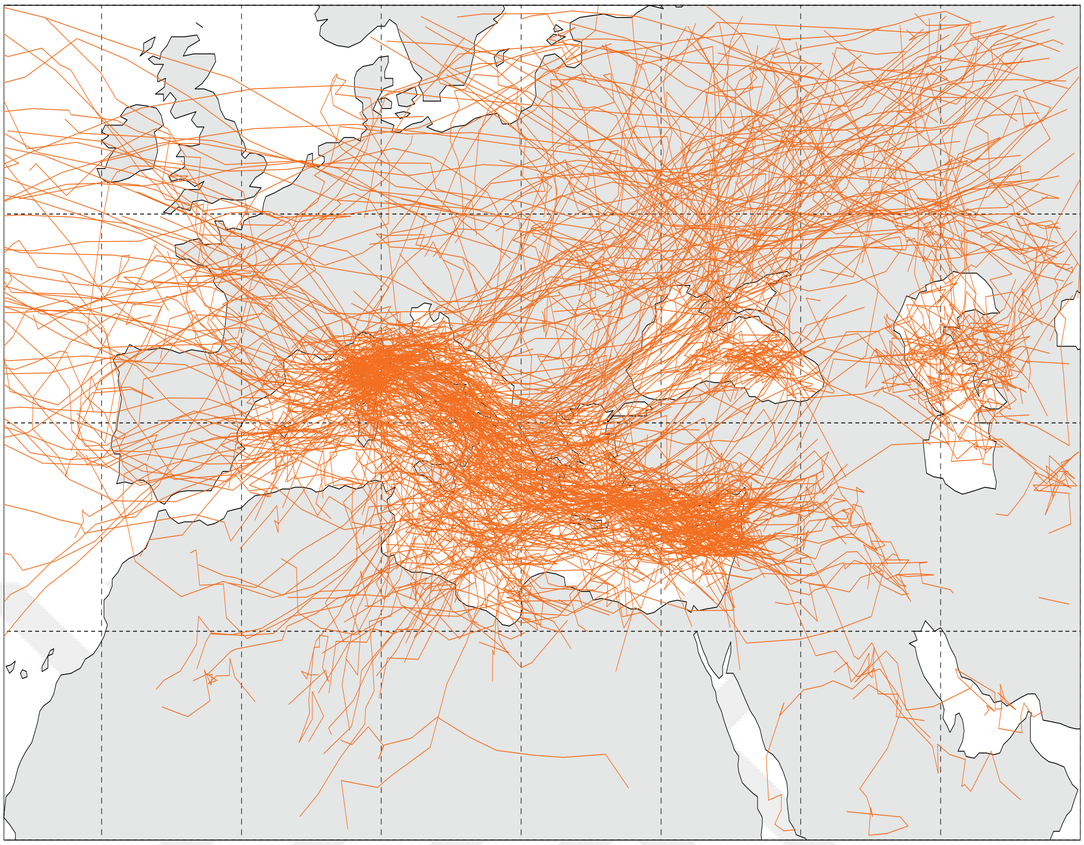


Figure 3.1 : Western and Eastern Mediterranean Region with geographical names and the orography (ERA-40 in meters) [1].

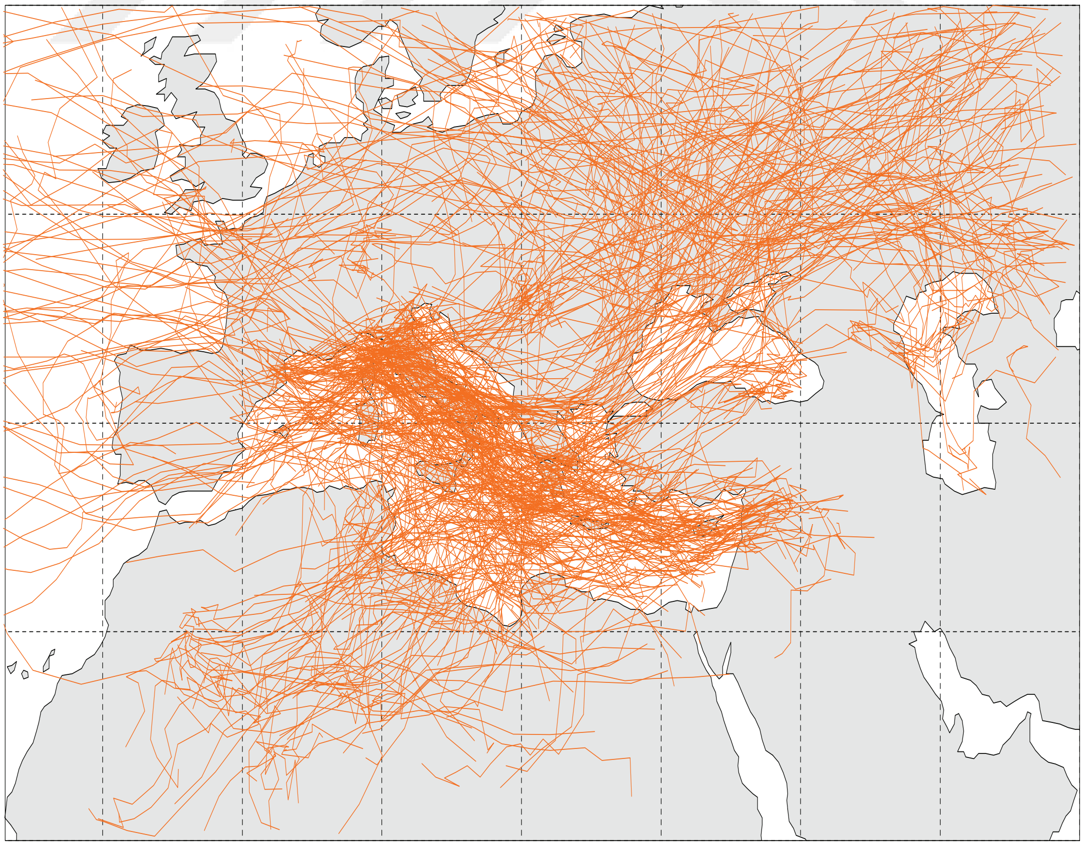
Although there are a few cyclones originated from the Iberian Peninsula, very few of them reach Turkey. Figure 3.1 represents the regions mentioned. As it is shown in Figure 3.2 - 3.5, some of these regions are the major source of cyclones for Turkey. Nevertheless, several seasonal shifts and differences based on resolution of the data sets are seen in these trajectories of cyclones. From now on, these differences and all cyclone paths will be comprehensively perused.

3.1.1 Winter season

Almost all of the trajectories are mainly eastward in the winter season according to Figure 3.2a. Cyclogenesis is very intense in the Gulf of Genoa, northern Italy, and the Adriatic Sea regions. Some of these cyclones pass over Croatia and Slovenia and enter to Central Europe and interior parts of it. Also, another branch of them move parallel to Croatia along the Adriatic Sea and make land from Albania to northern Greece, Macedonia, and Bulgaria. A large and remaining part of these cyclones merging with the cyclones originated from the Iberian Peninsula, the Algerian Sea, and the Balearic Sea following the road of Sardinia and Sicily islands arrives around southern Greece. These western cyclones split into two main branches (northern and southern)and merge with the Aegean Sea cyclones before arrving Turkey. The northern branch begins to travel from southern Greece to Marmara and northern Agean regions of Turkey and come to the Black Sea. In addition, a small amount of them reaches to Ukraine and Russia over the Black Sea. The southern branch again starts to invade around southern Greece and reachs to Crete and Cyprus. They combines with the cyclones arising from Cyprus and extend to Syria, Iraq and Lebanon. The cyclones stemming from Atlas Mountain and Sahara regions come around southern Greece and disperse over Turkey. Also, a part of them directly comes to Cyprus arriving Syria, Iraq, and Lebanon. Besides, a couple of cyclones occur around eastern Black Sea that surrounded by the Eastern Black Sea region of Turkey and Georgia. While there are mobile cyclones in western Black Sea, eastern Black Sea is a cyclogenesis region. A few of the Black Sea cyclone reaches to Georgia. Some of these cyclones survive overcoming the orography of Tukey and they proceed into the interor parts of Turkey. Therefore, as it is seen form Figure 3.2a, the major cyclones that affect Turkey originated from the Gulf of Genoa, northern Italy, and the Adriatic Sea, Sahara region, the Aegean Sea, the Black Sea, and Cyprus.



(a) NCEP 2



(b) ERA-Interim

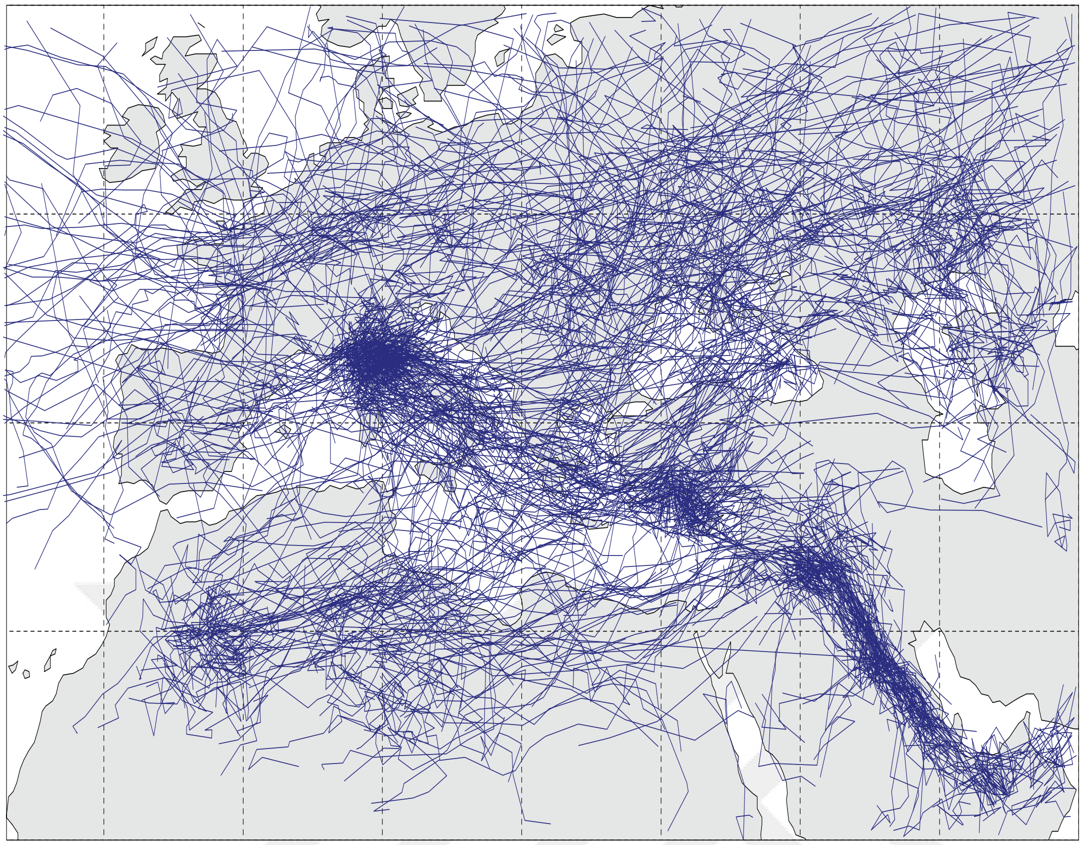
Figure 3.2 : Winter cyclones that survived 3 and longer than 3 days.

The intense cyclogenesis area around Gulf of Genoa, northern Italy, and the Adriatic Sea regions is larger in Figure 3.2b than Figure 3.2a. This area spread to coasts of France from the Gulf of Geona. In 3.2b, these cyclones split into four branches and move along these branches. They make land to around Croatia, Albania, and northern and southern Turkey and reaches Cental Europe and the Balkans. Atlas Mountain and Sahara regions and Cyprus contribute to southern Turkey branch like in 3.2a. There are more tracks around Atlas Mountain and Sahara regions in Figure 3.2b than Figure 3.2a. Nearly, there are no tracks that occured in Eastern Black Sea coast of Turkey while there are tracks in eastern Black Sea in 3.2a. However, there are tracks that occurs both around the Black Sea coast of Turkey and eastern Black Sea in 3.2b. Moreover, eastern Black Sea is a cyclone source and western Black Sea is a frequent destination like in Figure 3.2a. Transition rate from eastern Balck Sea to Georgia is lower in Figure 3.2b than Figure 3.2a. Generally, there are more tracks in 3.2a than Figure 3.2b. This excess in cyclone tracks can be spurious systems as a result of a low resolution of NCEP2 data set. The dominant cyclone source region that affect Turkey is around the Gulf of Genoa, northern Italy and the Adriatic Sea in the winter.

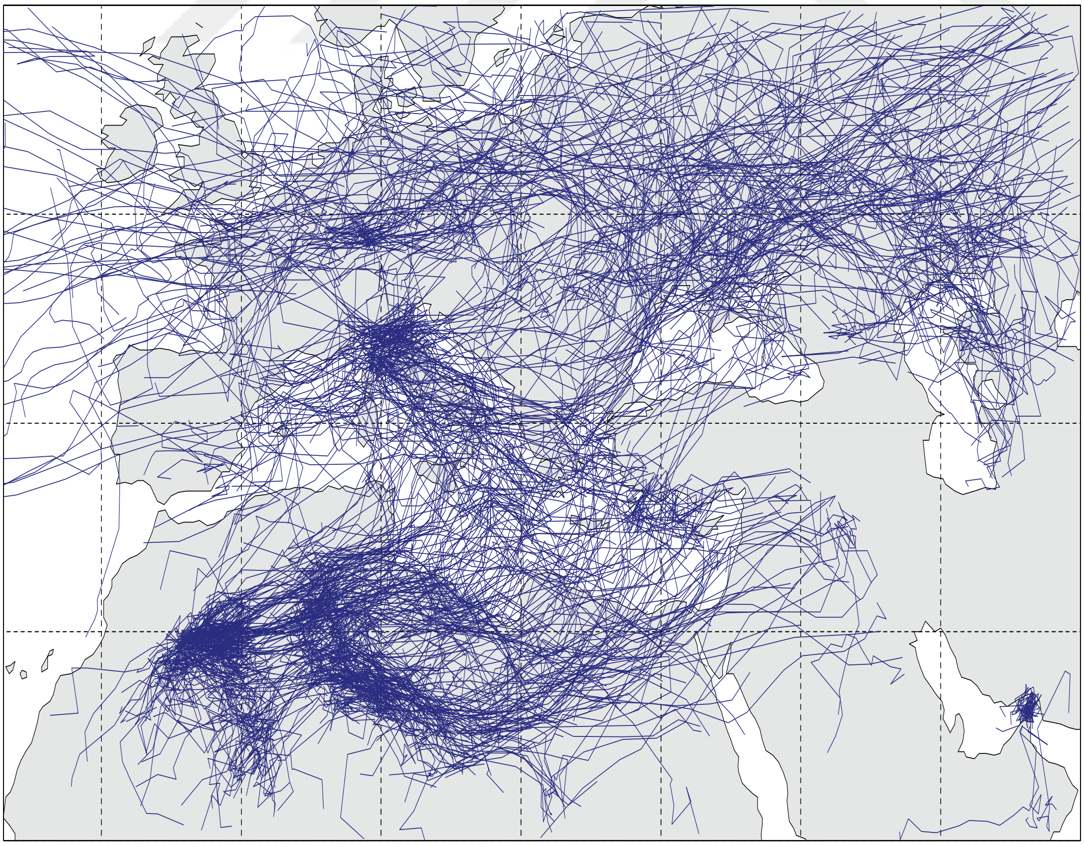
3.1.2 Spring season

The Gulf of Genoa, northern Italy, and the Adriatic Sea regions draw attention as a fundamental cyclogenesis region, as it is shown in Figure 3.3a. A number of cyclones of this fundamental region move over Slovenia and Croatia and hit Central Europe and interior parts of it. Some of them travel along the Adriatic Sea to Croatia and reach to Bosnia and Herzegovina and interior parts of the Balkans. A few of them passes over the Adriatic Sea and Albenia and proceeds to Macedonia and Bulgaria. Also, a certain part of these cyclones begin to traverse from the Gulf of Genoa, northern Italy, and the Adriatic Sea combining with the Iberian Peninsula, the Algerian Sea, and the Balearic Sea to southern Greece. After that, they enter Marmara, Aegean, and western Central Anatolia region of Turkey with the cyclones formed in the Aegean Sea. These cyclones reach to the Black Sea and some of them move to Ukraine and Russia. While cyclones use western part of the Black Sea as a transit point, cyclone are born in eastern side of the Black Sea. Some of eastern Black Sea cyclones pass over Georgia and enter Russia and the Caspian Sea. Besides, there are several tracks around the Caspian Sea. Other part of the cyclones around southern Greece first stop by Crete, and then invade Cyprus. Also, Cyrpus is a vigorous cyclogenesis region and these cyclones merge with Cyprus cyclones extending to Syria, Iraq, and Lebanon. There are a lot of cyclones come from Cyprus and they hit Mediterranean and Central Anatolia region of Turkey. In addition to these, the Persian Gulf is intensely dominated by the cyclones that originated from Syria and Iraq. The increase in the North African tracks attract the attention in the spring season. Other cyclone generating regions for Turkey are Atlas Mountain and Sahara. These cyclones move to southern Greece and support this area, and then enter Turkey. Another trajectory for them is going directly to Cyprus and around of it and Lebanon. According to Figure 3.3a, cyclones of the Gulf of Genoa, northern Italy, and the Adriatic Sea, Sahara region, the Aegean Sea, the Black Sea, and Cyprus influnce Turkey.

Cyclones arising from Atlas Mountain and Sahara regions are very noticeable and a lot more in Figure 3.3b than Figure 3.3a. Some of these cyclones follow northern costs of Arfica and they enter to Israel, Jordan, Lebanon, Syria, and Iraq from Egypt. However, in Figure 3.3b, the cyclones of Syria and Iraq do not appear in the spring season like in the Figure 3.3a, so there is no tracks around the Persian Gulf. The rest of them travels through the Mediterranean Sea, Italy, Greece, and Cyprus. The track intensity is lower in Figure 3.3b than Figure 3.3a for Cyprus. Therefore, less cyclones entering to Cenrtal Anatolia region of Turkey is represented by Figure 3.3b. The other noticeable cyclogenesis regions are the Gulf of Genoa, northern Italy, and the Adriatic Sea. A part of them cross from these places to Slovenia and Croatia. A branch of these cyclones go to Albenia, and then enter Greece, Bulgaria, and northern Marmara region of Turkey. Also, very few of them passes over Marmara region and reachs the Black Sea, and then Ukraine and Russia. This path is a distinctive characteristics between Figure 3.3b and Figure 3.3a since it is apparent in Figure 3.3a. Interior parts of Turkey is very emptier in results of ERA-Interim spring season comparing to NCEP2 in terms of tracks. There are some tracks from Croatia to Bosnia and Herzegovina and interior parts of the Balkans, nevertheless tracks are quite less in outcome of ERA-Interim springs. Cyclones occured in the Iberian Peninsula, the Algerian Sea, and the Balearic



(a) NCEP 2



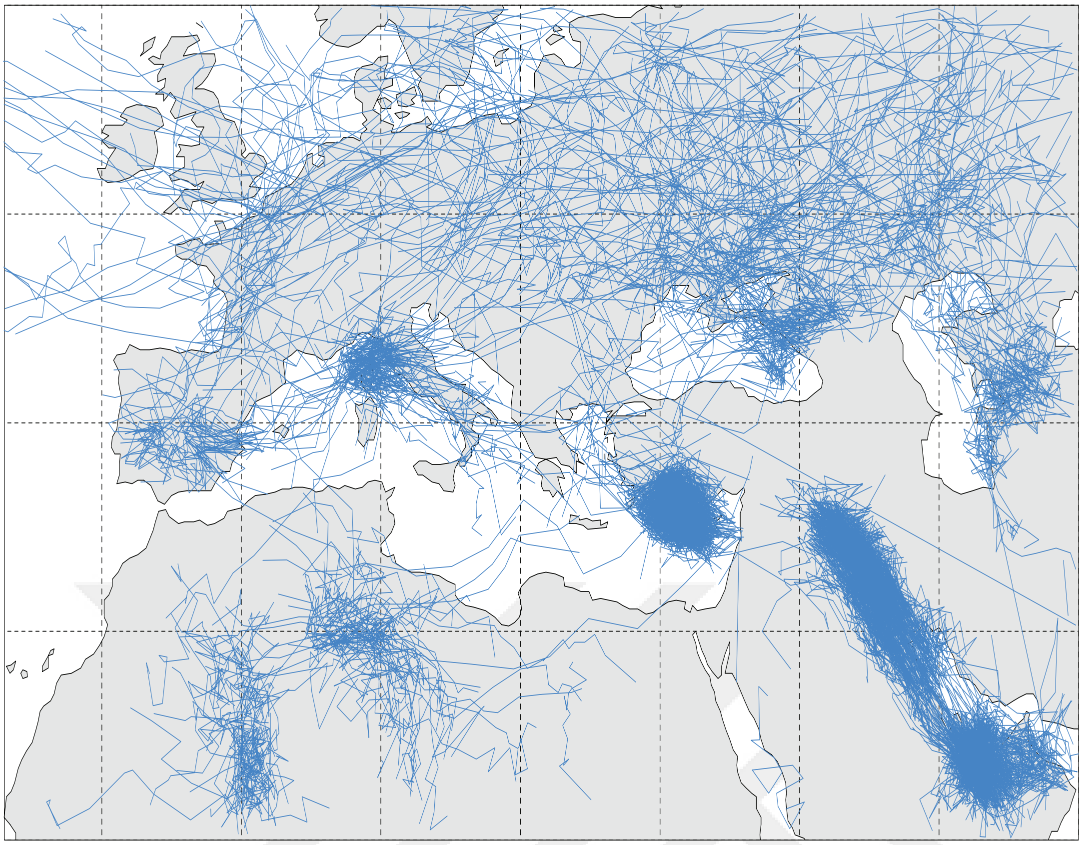
(b) ERA-Interim

Figure 3.3 : Spring cyclones that survived 3 and longer than 3 days.

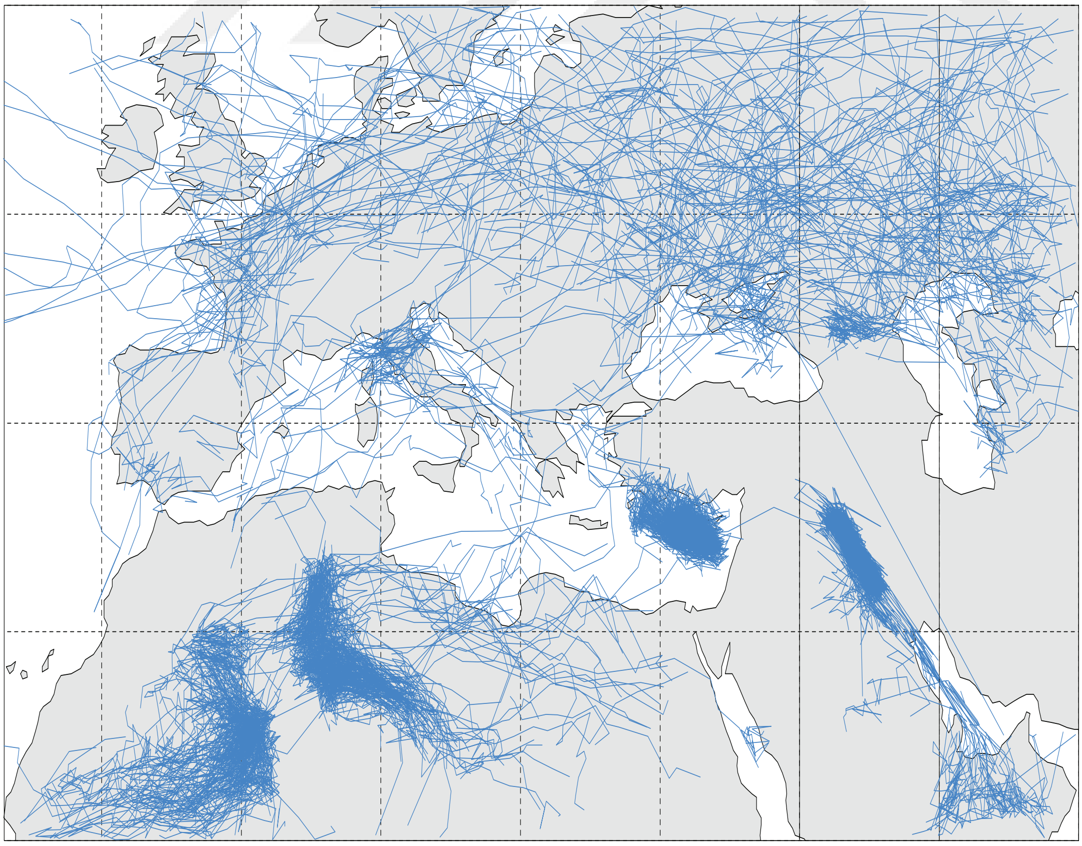
Sea come around the Gulf of Geona and reach southern Italy and Greece. They arrive to Crete and Cyprus and they hit the Mediterranean coast of Turkey with the cyclones of Cyprus. Also, the intensity of tracks is not as much as they are in the result of NCEP2. The cyclones affecting Turkey stem from the Gulf of Genoa, northern Italy, the Aegean Sea, the Black Sea, and Cyprus with noticeable increased in the Adriatic Sea, and Sahara region.

3.1.3 Summer season

The Mediterranean Basin has clear sky during the summer season comparing the other seasons. The increase in the Iberian Peninsula tracks attracks the attension in the summer season, as it is represented by Figure 3.4a. There are few tracks around the Balearic Sea and there is hardly no tracks around the Algerian Sea. Again, the Gulf of Genoa and northern Italy are existing place of the cyclones. However, the decrease in the Adriatic Seacyclones draws attention. very few of the cyclones of the Iberian Peninsula and Balearic Sea moves to northern parts of Italy. The tracks draw circles around the Iberian Peninsula. It can be said that they are stationary in the summer season. The stationary cyclones are the result of relatively warm land during the summers. Some cyclones aried from the Gulf of Genoa and northern Italy invade to Slovenia and Croatia and reach to Central Europe and interiors of it, but the amount of them is less comparing to the other seasons. Similarly, these cyclones come to southern Italy, but very few of them reaches to Greece, Marmara and Aegean regions of Turkey. Also, the decrease in the Aegean Sea cyclones is seen in Figure 3.4a. Hence, the cyclones merely enter Turkey. Tracks in western Black Sea is also less, however the rise in eastern side of the Black Sea. A number of eastern Black Sea cyclones hit Russia and northern Georgia. Besides, these cyclones recah to Sea of Azov and Ukranie. The tracks gathered around east of the Caspian Sea. When looking to Cyprus, it is not possible to see that the rise of the tracks around Cyprus. Again, a lot of them are also stationary during the summer. Consequently, there is almost no transition of the cyclones to Syria and Iraq from Cyprus. Massive increase in Iraq and eastern Syria cyclone tracks is seen and they heavliy dominate the Persian Gulf. The impact of Atlas Mountain and Sahara regions reduced since the intensity of the tracks



(a) NCEP 2



(b) ERA-Interim

Figure 3.4 : Summer cyclones that survived 3 and longer than 3 days.

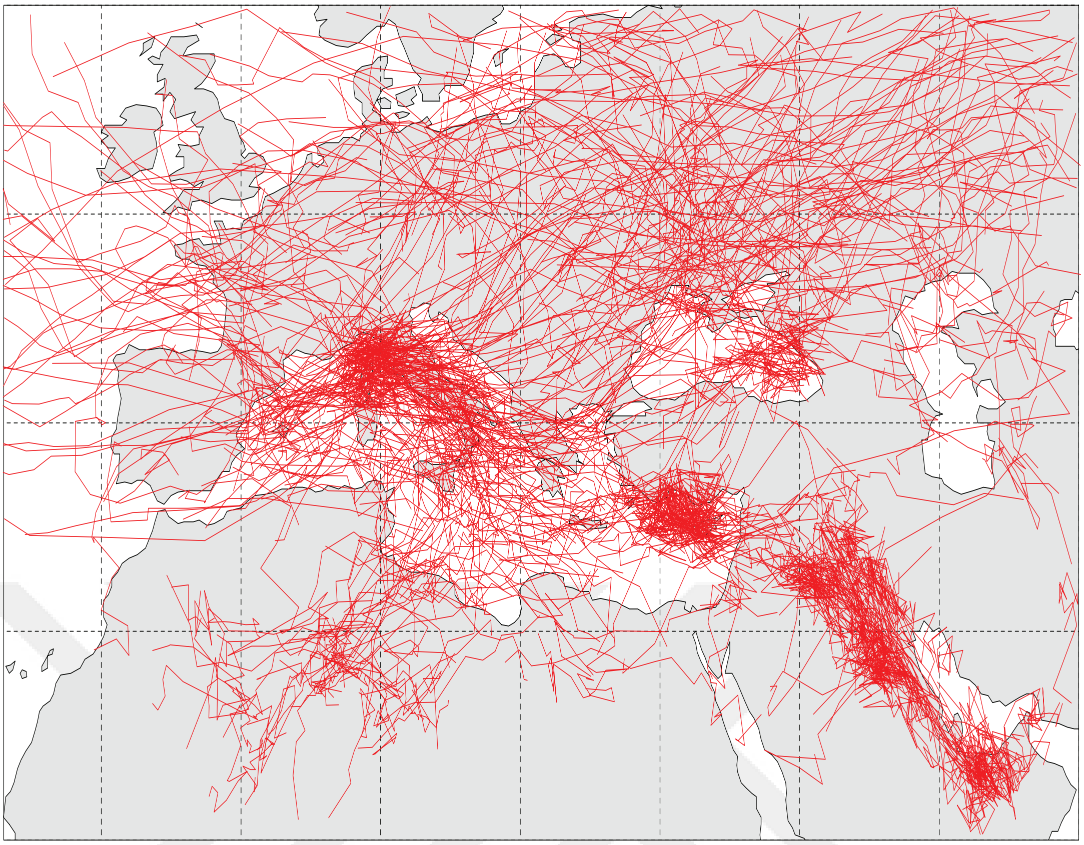
decreased, as it is seen in Figure 3.4a. A few of these cyclones move to Cyprus. Isreal, Jordan, Lebanon and cyclones from Nprth Africa do not reach Syria and Iraq. In addition to these, the Aegean Sea and Sahara cyclones have reduced impact on Turkey towards summer seasons. Therefore, Turkey is nearly affected by them. Mainly, the Gulf of Genoa and northern Italy, Cyprus, and eastern Black Sea have impac on Turkey in the summer season according to the Figure 3.4a.

There is pretty much no track around the Iberian Peninsula. Unlike in Figure 3.4a, a few Algerian cyclones is seen in the Figure 3.4b. The decrease in the tracks around the Gulf of Genoa, northern Italy, and the Adriatic Sea is getting attention. A few amount of them cross over Slovenia and Croatia and reach Central Europe. Also, the decrease in the tracks around the Balkans is seen in Figure 3.4b. Practically, there is one or two cyclones come to Turkey through Greece. So, the amount of transition from the Black Sea to Ukraine and Russia is less comparing to other seasons. Cyclones in eastern Black Sea are less in the results of ERA-Interim data set than NCEP2. Some tracks are seen around east of Georgia and Azerbaijan. Also, the Caspian Sea has less tracks in Figure 3.4b than Figure 3.4a. In addition to these, the number of tracks of the Aegean Sea are less than the other seasons. Hence, western Turkey is hardly impacted by them. Even though Cyprus could not reach the amount of tracks in the result of NCEP2, the rise in the tracks are seen. This cyclones are also stationary. The cyclones around Cyprus could not get in interior parts of Turkey during the summer season. However, there are much more tracks in Atlas Mountain and Sahara regions in Figure 3.4b comparing to Figure 3.4a. Again, these do not reach Israel, Jordan, Lebanon, Syria, and Iraq. The number of tracks reduced around Syria and Iraq, so they do not dominate the Persian Gulf. In short, the cyclones affecting Turkey is same as in Figure 3.4a, except the reduce in eastern Black Sea.

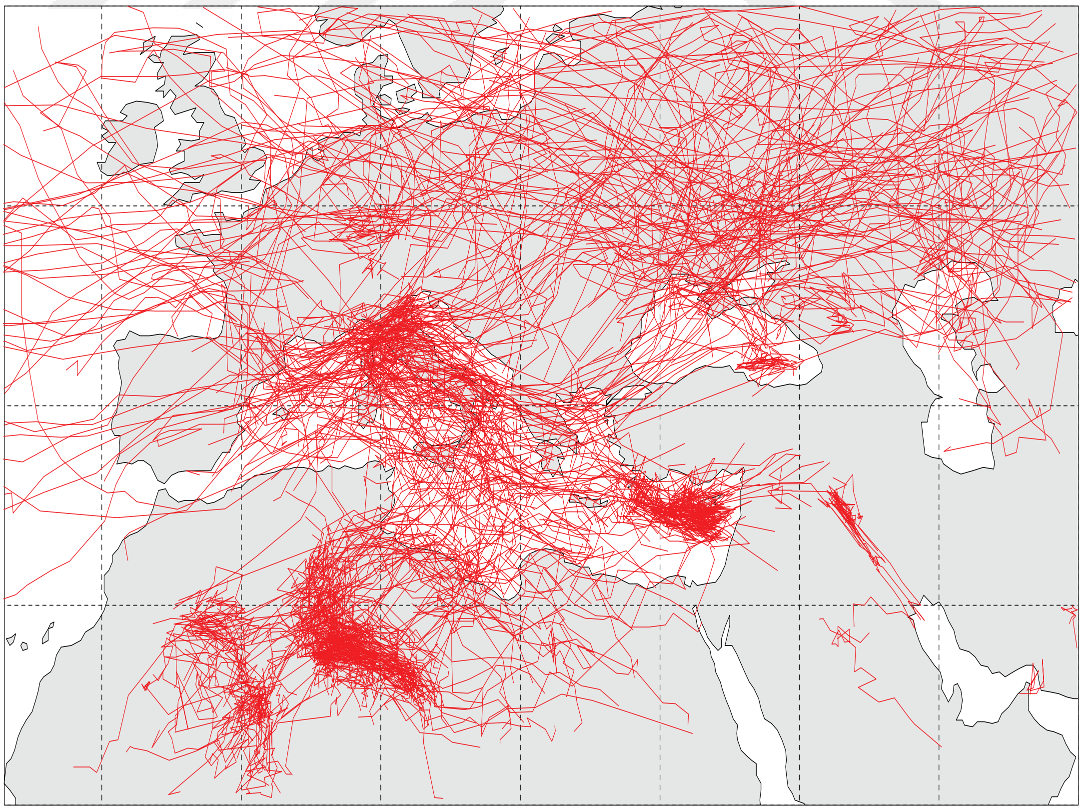
3.1.4 Autumn season

Northern Italy, Cyprus, the Black Sea, Syria, Iraq, and Saharan tracks leap out in the autumn season, as it is shown in Figure 3.5a. They cyclones in the Gulf of Geona, northern Italy, and the Adriatic Sea are the major cyclogenesis regions as they are in the other seasons. The Iberaian Peninsula, the Balearic Sea, and the Algerian Sea cyclones move northern Italy and make there even more dense in terms of existing cyclone amount. These cyclones travel along the Adriatic Sea coasts and enter Central Europe and the Balkans and some of them reach Ukraine and Russia. A part oh them come to Albania and northern Greece and reach northern parts of Marmara region of Turkey, and the Black Sea and they reach out from these regions to Ukraine and Russia. Eastern side of the Black Sea is richer than western side of it in terms of cyclogenesis. Some of them cross over Georgia and Azerbaijan. A number of northern Italy cyclones also move to Greece, Crete, and Cyprus. Cyprus is also a powerful cyclogenesis region. The cyclone of Cyprus and the Aegean Sea enter Turkey and a few of them come to the Black Sea. Besides, Cyprus cyclones invade Syria and Iraq. Cyclones originated from Syria and Iraq dominate around the Persian Gulf coasts of Saudi Arabia. Cyclones originated from Atlas Mountain and Saharan generally exit North Africa through Tunisia and Libya and reach out south of Italy and Greece and Cyrups. In the autumn season, cyclones of Sahara, Cyprus, and the Black Sea become pronounced other than northern Italy region, as it is illustrated by Figure 3.5a.

Atlas Mountain and Saharan cyclones are more pronounced in Figure 3.5b than Figure 3.5a. These cyclones travel from North Africa to south of Italy and Greece and some of them directly hit around Cyprus. As it is represented by Figure 3.5b, Gulf of Geona, northern Italy, and the Adriatic Sea regions have more tracks than Figure 3.5a. A number of cyclones travel here via France and the Iberian Peninsula. Also, cyclones from the Balearic Sea and the Algerian Sea move to northern Italy. A branch of northern Italy cyclones invade Slovenia and Croatia and enter Central Europe. The other appearent branch of cyclones travel to Albania and Greece, and then enter Marmara and Aegean regions of Turkey with the cyclones of the Aegean Sea. They reach out the Black Sea, Ukranie, and Russia. A cyclogenesis region is seen in the middle of eastern Black Sea. Besides, cyclones come to south of Greece, Crete and Cyprus. With Cyprus cyclones, they enter Syria and Iraq. Also, cyclones of Syria and Iraq are not dominant around the Persian Gulf coasts of Saudi Arabia in ERA-Interim result. Briefly, The Black Sea, Cyprus, and Saharan cyclones are prevailing regions in the autumn season for Tukey.



(a) NCEP 2



(b) ERA-Interim

Figure 3.5 : Autumn cyclones that survived 3 and longer than 3 days.e

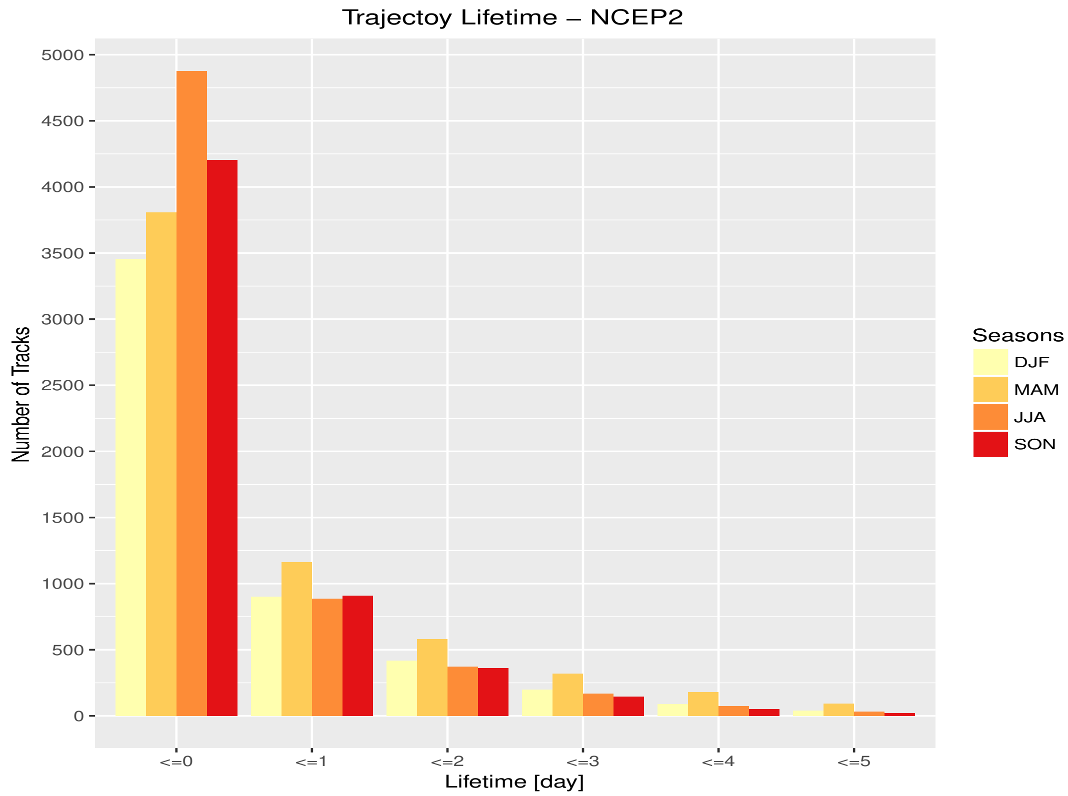
3.2 Interseasonal Variations and Cyclone Characteristics

The Gulf of Genoa, northern Italy, and the Adriatic Sea and the Black Sea regions are the continuous cyclogenesis regions for all seasons in the Mediterranean Baisn. The number of tracks of the Aegean Sea, Atlas Mountains and Sahara, and Cyprus, Syria, and Iraq change more than northern Italy and the Black Sea regions season to seasons. Figure 3.6 represents tracks numbers in area between 26°E - 47°E and 35°N - 43°N which corresponds to Turkey. As it is illustrated by Figure 3.6, the change in the number of tracks and their lifetimes can be seen.

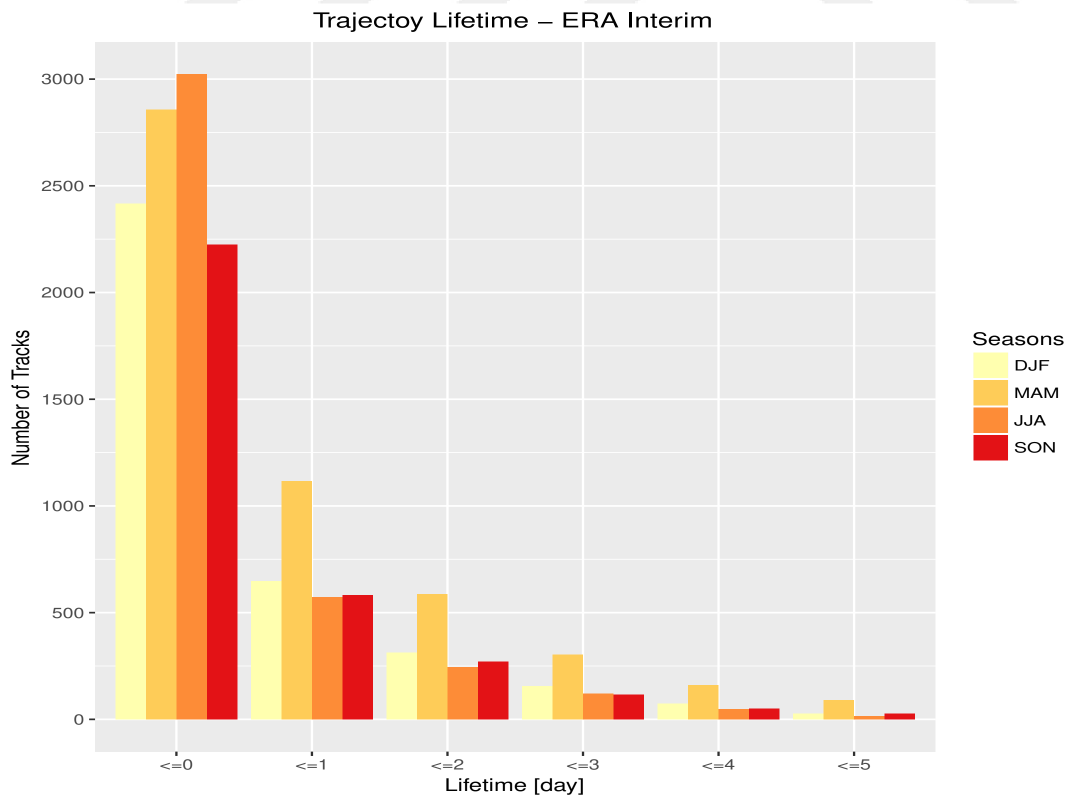
According to Figure 3.2 - 3.5, northern Italy around the Gulf of Genoa region generates more cyclones, their contribution on the number of cyclone Turkey is more in the winter the other seasons. These cyclones split into three different subsections as it mentioned. Two of them affetct Turkey and they are more southerly in the winter. The Black Sea region starts to produce more cyclones towards the summer. The increase in the amount of tracks are seen in NCEP2 results, however they are not seen in ERA-Interim results. The cyclones are much more shallower towards the summer and this can be the result that not appearing in results of ERA-Interim. It needs to be specified that these tracks are the tracks that survive 72 hours or more. So, they need to be strong to appear. The Aegean Sea is also more dominant in the winter. Besides, the winter cyclones are more southerly than the other seasons as it seen from Figure 3.2 - 3.5. The number of Sahara resgion traks are less in the winter than the other seasons. The Middle East (Syria and Iraq) tracks do not appear in this season.

Apart from northern Italy and the Black Sea tracks, the Aegean Sea, Atlas Mountains and Sahara, and Cyprus tracks become evident in the spring seasons. Three branch structure of the Gulf of Genoa, northern Italy, and the Adriatic Sea begins to fall apart. Also, the tracks of Syria and Iraq become pronounced in the spring season. The tracks of the Aegean Sea is still dominant.

The amount of Saharan cyclones increase towards the summer as it is shown in Figure 3.2 - 3.5. In addition to this, lifetime of the cyclones that originated from Cyprus, Syria, and Iraq increases towards the summer. The number of the tracks increases for the Iberian Peninsula towards the summer. Even though their quantity is not as much as the Gulf of Genoa region has, however, a considerable amount of tracks are seen in the summer. However, they cannot reach out the Adriatic Sea, they stuck around the Gulf of Genoa.The tracks of the Aegean Sea lose their dominance in the summer season while Cyprus enhances its dominance. The summer low centers are more permanent than the other seasons especially around Sahara and Cyprus.



(a) NCEP 2



(b) ERA-Interim

Figure 3.6 : Number of tracks and trajectory lifetime.

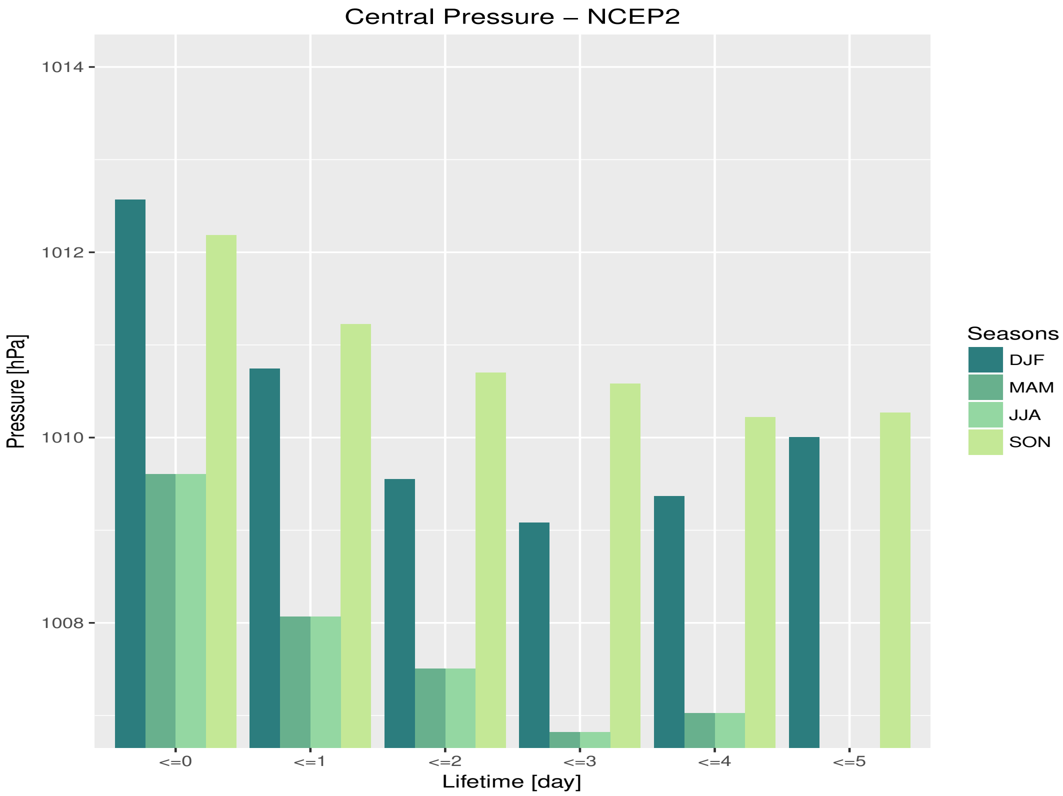
They do not travel so much. The three brach of the Gulf of Genoa, northern Italy, and the Adriatic Sea completely disapper in the summer season. Moreover, the tracks in the study domain are more northerly than the other seasons.

The increase in the Iberian Peninsula diminished in the autumn season. The tracks of Cyprus is still pronounced. The three branch structure of Gulf of Genoa, northern Italy, and the Adriatic Sea starts to appear again in the autumn season as it is illustrated in Figure 3.5. Also, tracks are southerly than the summer season. While the tarcks of Syria and Iraq are pronounced in Figure 3.5a, they are less in Figure 3.5b. Also, the number of are less North Africa tracks are less in Figure 3.5a while Saharan cyclones are dominant in Figure 3.5b.

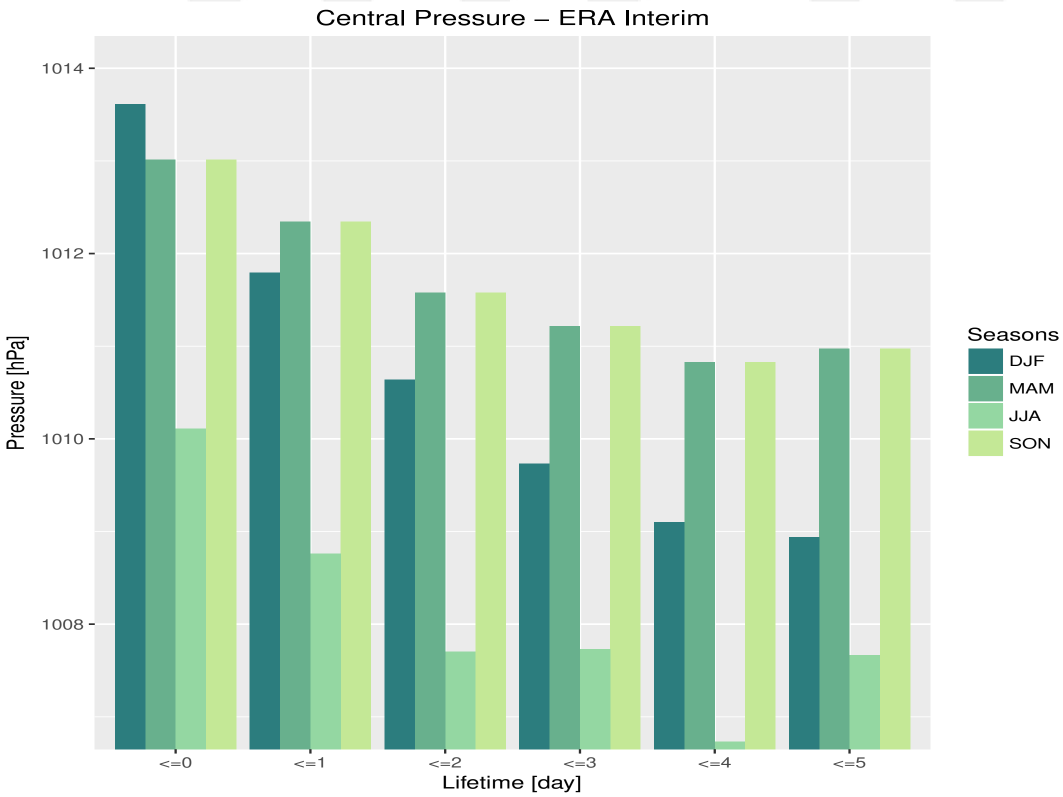
Consequently, at first glance, the pattern in the winter season disappears, tracks shifts to the north towards the summer as it is seen in Fugure 3.2 - 3.5. This pattern begins to disappear in the spring season, it compeletely disappears in the summer, and it become apparent in the autumn season again. While summer cyclones are stationary, the cyclones are moving in the other seasons. The cyclones affecting Turkey mainly come from the Gulf of Genoa and northern Italy and this broad branch splits into two. One of them affects northen Turkey and the other one influences southern parth of Turkey. Also, the Black Sea from the north and Cyprus and Sahara region from the south are minimum cyclone source regions for Turkey.

In the Figure 3.6, the x-axis shows trajectory lifetime in days while y-axis shows the number of tracks. The cyclones that survive 24 hours or less constitute 65% and 70% of the total number of cyclones in ERA-Interim and NCEP2 results resprectively, according to Figure 3.6. Seasonal distribution of the number of cyclones from winter to autumn are around 23%, 25%, 20%, and 32% for ERA-Interim and 22%, 28%, 24%, and 26% for NCEP2 results around Turkey. The results of the seasonal distribution are consistent between ERA-Interim and NCEP2. As a result of low resolution, there is approximately 31% more tracks in the result of NCEP2.

Central pressure, cyclone intensity and radius, and the number of tracks are obtained from The University of Melbourne CTS. The radius represents the distance between cyclone center and the point where the Laplacian of the pressure is zero.



(a) NCEP 2



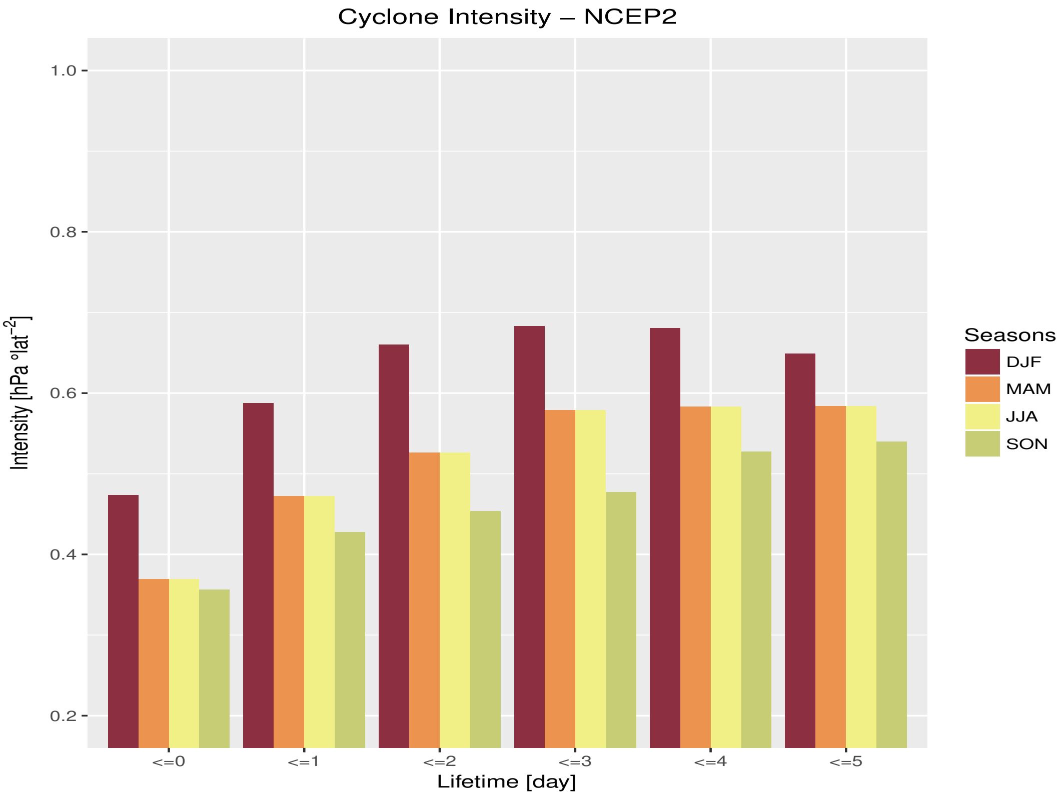
(b) ERA-Interim

Figure 3.7 : Mean central pressure of the cyclones.

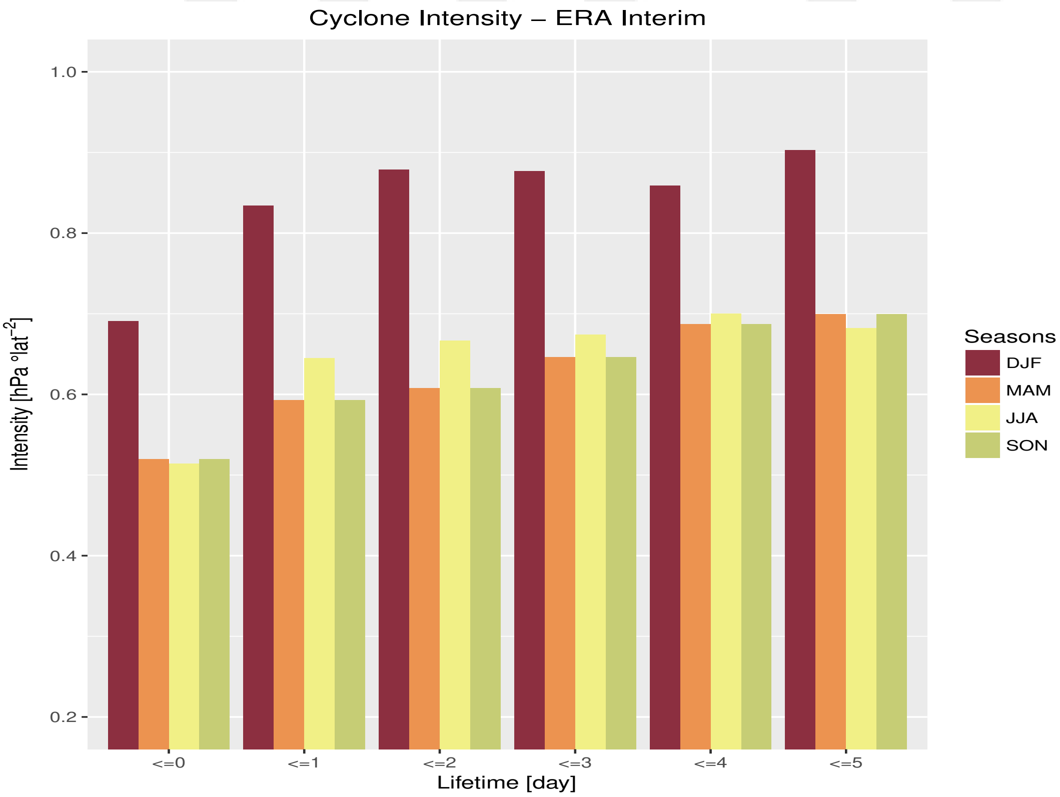
In the Figure 3.7, the x-axis stands for trajectory lifetime in days while y-axis stands for mean central pressure of the cyclones in hPa. It seems that cyclones with long lifetime have gradually decrease their central pressures according to Figure 3.7. The average central pressure is around 1010 hPa for ERA-Interim and 1009 hPa for NCEP2. Also, it approximately changes in the range of 1007 hPa - 1014 hPa for ERA-Interim and 1006 hPa and 1013 hPa for NCEP2 as it is shown in Figure 3.7.

In the Figure 3.8, the x-axis represents trajectory lifetime in days while y-axis represents mean cyclone intensity in $hPa(^\circ lat)^{-2}$. The intensity of the center increases as lifetime incereases as it is illustrated by Figure 3.8. The mean cyclone intesity is 0.68 $hPa(^\circ lat)^{-2}$ for ERA-Interim and 0.53 $hPa(^\circ lat)^{-2}$ for NCEP2 and it shows a change in the range of 0.51 - 0.90 $hPa(^\circ lat)^{-2}$ for ERA-Interim and 0.36 - 0.68 $hPa(^\circ lat)^{-2}$ for NCEP2.

In the Figure 3.9, the x-axis shows trajectory lifetime in days while y-axis shows mean radius of the cyclones in $^\circ lat$. As it is exptected, the cyclone radius also increases as lifetime incereases according to Figure 3.9. The mean radius is around 4.10 $^\circ lat$ for ERA-Interim and 4.08 $^\circ lat$ for NCEP2. The cyclone radius is between 3.67 $^\circ lat$ and 4.49 $^\circ lat$ ERA-Interim and 3.71 $^\circ lat$ and 4.39 $^\circ lat$ for NCEP2.

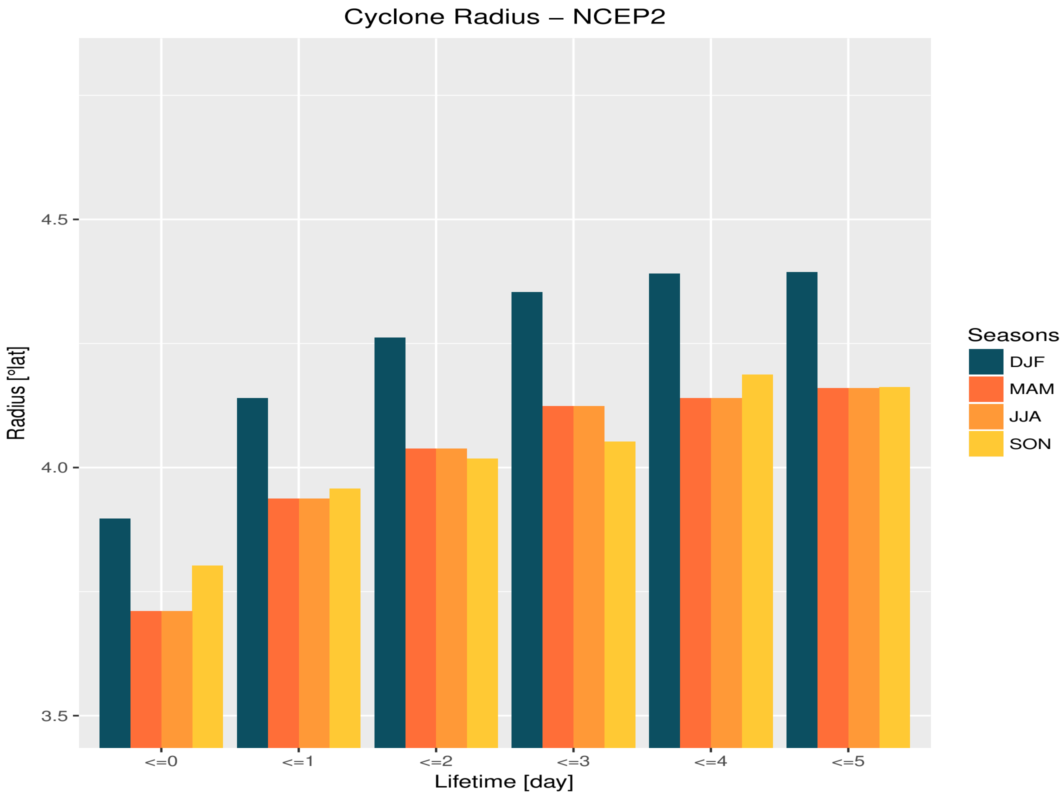


(a) NCEP 2

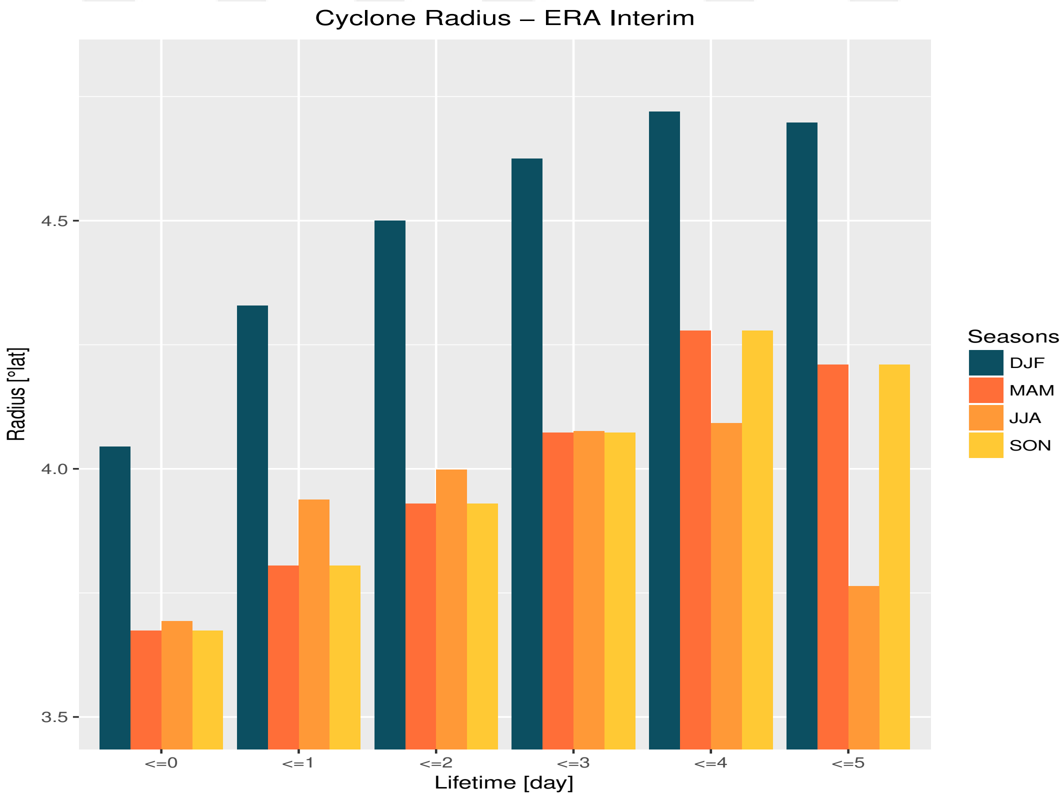


(b) ERA-Interim

Figure 3.8 : Mean cyclone intensity.



(a) NCEP 2



(b) ERA-Interim

Figure 3.9 : Mean radius of the cyclones.

4. DISCUSSION

Turkey is affected by the cyclones originated from the Gulf of Genoa, northern Italy, the Adriatic Sea, Sahara region, the Aegean Sea, the Black Sea, and Cyprus. All of these regions are influential in the winter and this is shown very nicely in Figure 4.1, but it is majorly influenced by northern Italy cyclones . The cyclones that come to Turkey from the west (around northern Italy), they split into three branhes before entring Turkey and two of them reach out northern and western Turkey. According to Alpert et al. (1990), there are three main branches in January. First one invades among Swiss and Dinaric Alps (aroud Slovenia, Croatia, Bosnia and Herzegovina, and Kosovo). Second one reaches the Balkans, mountains of Turkey, and then the Black Sea. The last one travels between mountains in southern Turkey and Syria/Lebanon mountains stopping by Cyprus [14].

The number of the tracks that arised from North Africa increases towards the spring and the summer. The number of Atlas Mountains and Saharan cyclones increase towards summer [3] [14]. The number of tracks around the Iberian Peninsula are pronounced in the summer seasaon and they move to northern Italy, however they generally cannot reach the Adriatic Sea. Also, the cyclones in the whole domain tend to be stationary. The tracks of the Iberian Peninsula fade away around the Gulf of Genoa and the Adriatic Sea [3]. Despite being a cyclogenesis place in the summer, the cyclones die away in the way of the Adriatic Sea as they get close [28]. The atmosphere is fair and cyclones are semi-steady in July [14].

The cyclones influencing Turkey mainly divide into two major regions which are west of Turkey and around Turkey. According to Trigo et al. (1999), main cyclogenesis regions are divided into 2 groups which are western and eastern Mediterranean Basins. While western Mediterranean Basin involves the Gulf of Genoa, Sahara and Iberian regions, the Aegean Sea, the Black Sea, Cyprus, Syria, and Iraq dominate eastern part of the Mediterranean Basin [3]. Also, cyclone source regions are in agreement with [29], [30], and [28]. While cyclogenesis in the Gulf of Genoa, northern Italy, and the Balck Sea region does not disappear in any seasons, Atlas Mountains and Sahara region, the Aegean Sea, and Cyprus do not exist dominantly in all seasons. Sometimes the number of tracks intensifies and sometimes they diminish. The Gulf of Genoa and the Black Sea regions stay as cyclogenesis regions for entire year [3].

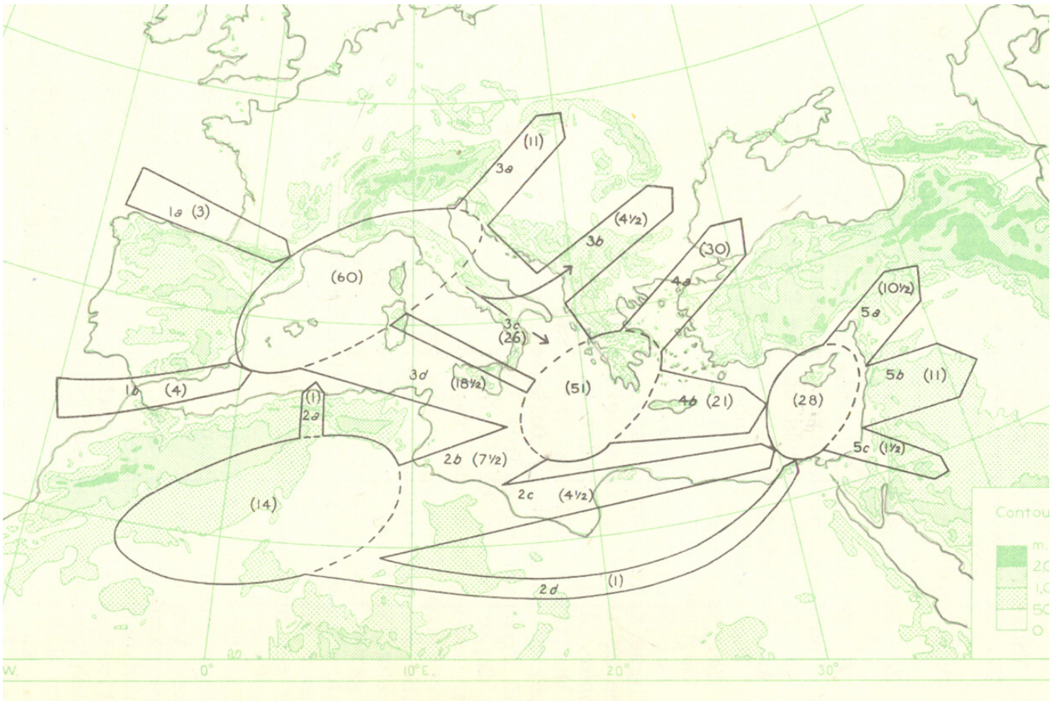


Figure 4.1 : Major cyclone tracks in the winter season [2].

65% and 70% of the total number of tracks in order of ERA-Interim and NCEP2 consist of the cyclones that survived 24 hours and less according to Figure 3.6. The mean survival time for the cyclones in the Mediterranean Basin is 28 hours and the cyclones that live 12 hours or less constitute more than 60% of the all cyclones [3].

For the area covering Turkey, the central pressure of the cyclones changes between 1007 hPa - 1014 hPa for ERA-Interim and 1006 hPa and 1013 hPa for NCEP2. These cyclones are weak and moderate cyclones in terms of strength, as it is stated by [30]. Mediterranean cyclones are weak and they have shorter lifetime comparing to the other cyclones in the Northern Hemisphere [3]. Also, the cyclone radius changes in the range of 3.67 $^\circ lat$ and 4.49 $^\circ lat$ for ERA-Interim and 3.71 $^\circ lat$ and 4.39 $^\circ lat$ for NCEP2 having average 4.10 $^\circ lat$ and 4.08 $^\circ lat$ respectively. Mediterranean cyclones are between mesoscale and sub-synoptic scale and their mean radius is less than 500 km [3]. 0.68 $hPa(^\circ lat)^{-2}$ and 0.53 $hPa(^\circ lat)^{-2}$ are the mean cyclone intensity for ERA-Interim and NCEP2. Also they respectively shift between 0.51 $hPa(^\circ lat)^{-2}$ -

0.90 $hPa(^{\circ}lat)^{-2}$ and 0.36 $hPa(^{\circ}lat)^{-2}$ - 0.68 $hPa(^{\circ}lat)^{-2}$ in this study. According to Iordanidou, Koutroulis, and Tsanis (2014), the cyclone intensity changes in the range of 0.3 $hPa(^{\circ}lat)^{-2}$ - 1.1 $hPa(^{\circ}lat)^{-2}$ with average intensity 0.86 $hPa(^{\circ}lat)^{-2}$. The average central pressure is 1010 hPa and it changes between 1002 hPa and 1008 hPa [31].

5. SUMMARY AND CONCLUSION

Cyclones are low pressure systems that dominate weather conditions in the mid-latitudes every day. In this thesis, we have analysed the cyclones affecting Turkey as part of the Mediterranean Basin. The main purpose of this thesis is to find the trajectories of the cyclones that affect Turkey. So, the study is achieved with two steps. The cyclones are determined using the Laplacian of pressure in the first step. The subsequent positions of the centres are predicted, and a relationship is sought between the estimated positon and the cuurent position. In the end, the cyclones are linked with choosing the best candidate for matching. These cyclones are detected and tracked by The University of Melbourne automatic cyclone tracking scheme (CTS) using ERA-Interim with 1.0° x 1.0° horizontal resolution (interpolated from 0.75° x 0.75°) and NCEP/DOE Reanalysis 2 with 2.5° x 2.5° horizontal resolution data sets. After the algorithm is adapted and several criteria are set for the Mediterranean Basin, major cyclogenesis regions are obtained. Cyclones affecting Turkey generally originate in Gulf of Genoa, northern Italy, the Adriatic Sea, the Aegean Sea, the Black Sea, Cyprus, and Atlas Mountains, and Sahara.

The Gulf of Genoa, northern Italy, the Adriatic Sea cyclones divide into three main branches before reaching Turkey. One of the branch stops by southern Greece, the Aegean Sea, Aegean and Marmara regions of Turkey, the Black Sea, Ukraine and Russia respectively. The other branch travels to Aegean and Mediterranean regions of Turkey and Cyprus. Cyprus is also a cyclogenesis region and the cyclone exdends Syria and Iraq. In addition to these, Atlas Mountains and Saharan cyclones depart from Tunisia, Libya, and Egypt and they reach out around Cyprus. The third branch enter from Slovenia and Croaita and reaches Central Europe and it does not travel to Turkey. Also, the Aegean Sea cyclones participate to the two braches that affect Turkey.

Cyclone trcaks changes season to seasons. The Black Sea, the Gulf of Genoa, northern Italy, and the Adriatic Sea regions are nearly steady cyclogenesis regions and they appear and play major role in all of the seaons. In winter seasons, Turkey is affected by southern Italy, the Aegean Sea and the Black Sea cyclones other than Gulf of Genoa and northern Italy cyclones. Sahara, Cyprus, the Aegean Sea, and the Black Sea are cyclogenesis regions and their cyclones have impact on Turkey in the spring season. While winter cyclones traverse, summer cyclones are more stationary. The number of tracks of Cyprus and the Black Sea increases towards the summer season. Also, the number of tracks of the Iberian Peninsula increase in the summer, however its cyclones exists in this region do not reach to Turkey. In autumn seasons, cyclones of Sahara, Cyprus, and the Black Sea become pronounced.

The results of NCEP2 and ERA-Interim are generally similar, however there are several differences between them. There are approximately 31% more tracks in the result of NCEP2 than ERA-Interim. In all seasons, there are more tracks in North Africa in ERA-Interim results than NCEP2. While there is a few tracks around Syria, Iraq, and Persian Gulf in ERA-Interim results, NCEP2 results has more tracks than ERA-Interim in these regions in the spring, summer, and autumn seasons. The average central pressure of cyclones is around 1010 hPa for ERA-Interim and 1009 hPa for NCEP2. While the mean cyclone intesity is 0.68 $hPa(^{\circ}lat)^{-2}$ for ERA-Interim, it is 0.53 $hPa(^{\circ}lat)^{-2}$ for NCEP2. Also, the mean radius of the cyclones is around 4.10 $^{\circ}lat$ for ERA-Interim and 4.08 $^{\circ}lat$ for NCEP2.

Consequently, the major sources of precipitation and path of the cyclones are revealed in this study. In the future studies, it is planned to examine the relationship of the determined cyclones with the amount and distribution of the precipitation.

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APPENDICES

APPENDIX A.1 : The R script that is used to make graphichs of tracking analysis results.

APPENDIX A.1

```
library(dplyr) library(stringr) library(tidyr) library(splitstackshape)

path1<- "/Users/merihbozbura/Documents/THESIS RELATED/WinSCP/DJF/track-/NCEP"

loaddata <- function(path1) files <- dir(path8, pattern = '-', full.names = TRUE) tables <- lapply(files, read.table, sep="", stringsAsFactors=FALSE) do.call(rbind, tables)

NCEP<- loaddata("/Users/merihbozbura/Documents/THESIS RELATED/WinSCP/DJF/track/NCEP")

NCEP= NCEPfilter(!grepl('=', NCEP$V1))

NCEP= NCEPfilter(!grepl('HISTORY', NCEP$V1))

NCEP= NCEPfilter(!grepl('& ', NCEP$V1))

NCEP= NCEPfilter(!strdetect( NCEP$V1, 'iop'))

NCEP=cSplit( NCEP,"V1"," ") names( NCEP)<-c("t","da","hr","stat","k","iop","q","x","y","p","c","dp","rd",

path2 <- "/Users/merihbozbura/Documents/THESIS RELATED/WinSCP/DJF/track-/ERA"

loaddata <- function(path2) files <- dir(path, pattern = '-', full.names = TRUE) tables <- lapply(files, read.table, sep="", stringsAsFactors=FALSE) do.call(rbind, tables)

ERA<- loaddata("/Users/merihbozbura/Documents/THESIS RELATED/WinSCP/D-JF/track/ERA")

ERA= ERAfilter(!grepl('=', ERA$V1))

ERA= ERAfilter(!grepl('HISTORY', ERA$V1))

ERA= ERAfilter(!grepl('& ', ERA$V1))

ERA= ERAfilter(!strdetect( ERA$V1, 'iop'))

ERA=cSplit( ERA,"V1"," ") names( ERA)<-c("t","da","hr","stat","k","iop","q","x","y","p","c","dp","rd","up"

meanERA<-colMeans(ERA) meanNCEP<-colMeans(NCEP)

# # # # # FOR AREA COVERING TURKEY FOR 3 LONGER THAN 3 DAYS

DJF.E3<-subset(DJF.ERA.3, x > 26 & x < 47 & y > 35 & y < 43)

DJF.N3<-subset(DJF.NCEP.3, x > 26 & x < 47 & y > 35 & y < 43)

MAM.E3<-subset(MAM.ERA.3, x > 26 & x < 47 & y > 35 & y < 43)

MAM.N3<-subset(MAM.NCEP.3, x > 26 & x < 47 & y > 35 & y < 43)

JJA.E3<-subset(JJA.ERA.3, x > 26 & x < 47 & y > 35 & y < 43)

JJA.N3<-subset(JJA.NCEP.3, x > 26 & x < 47 & y > 35 & y < 43)

SON.E3<-subset(SON.ERA.3, x > 26 & x < 47 & y > 35 & y < 43)

SON.N3<-subset(SON.NCEP.3, x > 26 & x < 47 & y > 35 & y < 43)
```

```
# # # # # # SELECTING P, C, DP, RD
DJF.Es3<-DJF.E3[,c("p","c","dp","rd")]
DJF.Ns3<-DJF.N3[,c("p","c","dp","rd")]
MAM.Es3<-MAM.E3[,c("p","c","dp","rd")]
MAM.Ns3<-MAM.N3[,c("p","c","dp","rd")]
JJA.Es3<-JJA.E3[,c("p","c","dp","rd")]
JJA.Ns3<-JJA.N3[,c("p","c","dp","rd")]
SON.Es3<-SON.E3[,c("p","c","dp","rd")]
SON.Ns3<-SON.N3[,c("p","c","dp","rd")]
# # # # # # AVERAGING
DJF.Em3<-colMeans(DJF.Es3)
DJF.Nm3<-colMeans(DJF.Ns3)
MAM.Em3<-colMeans(MAM.Es3)
MAM.Nm3<-colMeans(MAM.Ns3)
JJA.Em3<-colMeans(JJA.Es3)
JJA.Nm3<-colMeans(JJA.Ns3)
SON.Em3<-colMeans(SON.Es3)
SON.Nm3<-colMeans(SON.Ns3)
library(ggplot2) library(readxl)
source("/Users/merihbozbura/Documents/THESIS RELATED/TURQUA-POSTER/R/read.R")
exdata=readxlsx("/Users/merihbozbura/Documents/THESIS RELATED/TURQUA-POSTER/R/read.xlsx")
themeupdate(plot.title = elementtext(hjust = 0.5)) # Default position of title(centering the title)
ggplot(exdata,aes(x=exdata$days,y=exdata$valueera,fill=factor(exdata$era)))+ geombar(stat="identity",position="dodge")+ scalefillmanual(name="Seasons", values = c( "# f4abb1", "# f1e1df", "# dbe0d9", "# bacec4"), labels=c("DJF", "MAM", "JJA","SON") )+ scaleycontinuous(breaks=seq(0, 32000, 10000)) + xlab("Lifetime [day]")+ylab("Number of Tracks") + ggtitle("Trajectoy Lifetime - ERA Interim") ggsave("Lifetime-ERA.png")
ggplot(exdata,aes(x=exdata$days,y=exdata$valuencep,fill=factor(exdata$era)))+ geombar(stat="identity",position="dodge")+ scalefillmanual(name="Seasons", values = c( "# f4abb1", "# f1e1df", "# dbe0d9", "# bacec4"), labels=c("DJF", "MAM", "JJA","SON") )+ scaleycontinuous(breaks=seq(0, 32000, 10000)) + xlab("Lifetime [day]")+ylab("Number of Tracks") + ggtitle("Trajectoy Lifetime") ggsave("Lifetime-NCEP.png")
ggplot(exdata,aes(x=exdata$days,y=exdata$pera,fill=factor(exdata$era)))+ geombar(stat="identity",position="dodge")+ scalefillmanual(name="Seasons",
```

values = c("# 307e80", "# 69b18f", "# 95d7a4", "# c4e899"), labels=c("DJF", "MAM", "JJA" ,"SON"))+ xlab("Lifetime [day]")+ylab("Pressure [hPa]") + coordcartesian(ylim = c(1000,1008))+ ggtitle("Central Pressure - ERA Interim") ggsave("p-ERA.png")

ggplot(exdata,aes(x=exdata$days,y=exdata$pncep,fill=factor(exdata$era)))+ geombar(stat="identity",position="dodge")+ scalefillmanual(name="Seasons", values = c("# 307e80", "# 69b18f", "# 95d7a4", "# c4e899"), labels=c("DJF", "MAM", "JJA" ,"SON"))+ xlab("Lifetime [day]")+ylab("Pressure [hPa]") + coordcartesian(ylim = c(1000,1008))+ ggtitle("Central Pressure") ggsave("p-NCEP.png")

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