MODELING THE IMPACT OF CLIMATE VARIABILITY ON ANCHOVY OVERWINTERING MIGRATION IN THE BLACK SEA

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BY

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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ABSTRACT

MODELING THE IMPACT OF CLIMATE VARIABILITY ON ANCHOVY OVERWINTERING MIGRATION IN THE BLACK SEA

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Black Sea anchovy *(Engraulis encrasicolus ponticus)* undertake extensive (~1000km long) overwintering migration in autumn from northern spawning grounds to the overwintering areas located at the south-eastern coasts of the Black Sea. When arriving at the Anatolian coast, they support important fisheries in Turkey. Black Sea anchovy is known to experience stock variability quite frequently including stock collapses, which are believed to be closely linked with environmental conditions. Therefore, it is of importance to understand the mechanisms that set the scene for a successful migration and explore routes feasible for migration. To investigate anchovy overwintering migration, a fish behavior model embedded into a 2D Lagrangian particle tracking model is used. Particles are released into the surface circulation field calculated from AVISO sea level anomaly data. Model simulations are performed during years of very different physical conditions from 2001 to 2003. The results show that while advection by currents influences transport pathways, temperature used as a guide for migration is of more importance for high migration success. Simulations reveal highly variable migration pathways driven by the onset and course of winter cooling processes, cross-shelf transport, and variability in eddy formation and persistence.

Keywords: Black Sea, Lagrangian particle tracking model, anchovy, migration behavior, climate variability

ÖZ

İKLİM DEĞİŞKENLİĞİN KARADENİZ'DEKİ HAMSİNİN KIŞLAMA GÖÇÜ ÜZERİNE ETKİSİNİN MODELLENMESİ

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Karadeniz hamsisi *(Engraulis encrasicolus ponticus)* sonbaharda kuzeydeki yumurtlama alanlarından Karadeniz'in güneydoğu kıyılarındaki kışlama alanlarına doğru geniş çaplı (~1000 km.) bir kışlama göçü gerçekleştirir. Hamsi Anadolu kıyılarına vardığı zaman Türkiye balıkçılığı için önemli bir kaynak teşkil eder. Karadeniz hamsisi, çevresel koşullara bağlı olarak ani stok çökmelerine neden olan dalgalanmaları oldukça sık yaşar. Bu nedenle, başarılı bir göç için gereken mekanizmaların anlaşılması ve elverişli göç yollarının aydınlatılması önem arz etmektedir. Hamsi kışlama göçünü incelemek amacıyla 2D (iki boyutlu) Lagrangian parçacık izleme modeline bütünleşik balık davranış modeli kullanılmıştır. Parçacıklar AVISO deniz yüzey yüksekliği anomalisi veri seti kullanılarak hesaplanan jeostrofik yüzey akıntı sahasına bırakılmıştır. Simülasyonlar oldukça farklı fiziksel koşulların hakim olduğu 2001-2003 yılları arasında gerçekleştirilmiştir. Sonuçlarda adveksiyon taşınımının göç yolları üzerindeki etkili olduğu ortaya çıkarken, sıcaklığın göç davranışına kılavuz olarak dahil edildigi simülasyonların yüksek göç başarısı açısından daha önemli bir yere sahip olduğu görülmektedir. Simülasyonlar sonucunda, kış soğumasının başlama zamanı ve soğumanın süresi ile, kıta sahanlığından taşınım ve girdap oluşumu ve sürekliliğindeki değişkenlik mekanizmaları ile kontrol edilen yüksek derece degişkenlik gösteren göç yolları ortaya çıkarmıştır.

Anahtar kelimeler: Karadeniz, Lagrangian parçacık izleme modeli, hamsi, göç davranışı, iklimsel değişkenlik

to 'Şehmus'

to my parents

and to all my family

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INTRODUCTION

Black Sea anchovy (*Engraulis encrasicolus*) undertake extensive overwintering migration every fall from their spawning/nursery grounds to warmer overwintering areas located at the south-eastern coast of the Black Sea. When arriving at the Anatolian coast, they support an important fishery in Turkey with a catch of an average of 350 ktons per year, making up 60% of Turkish water resources (Bingel and Gucu, 2010). This anchovy fishery constitutes an important income for the regional population and supplies an unrivaled income for Turkey's fisheries economy. Black Sea anchovy has experienced significant stock collapses in the last decades and it has been observed that in some years, particularly when autumn temperatures are warmer, migrating anchovy schools are seen to arrive late at the Anatolian coast or not at all (Gucu, personal communication). It is therefore of importance to understand the mechanisms that set the scene for a successful overwintering migration and explore feasible migration routes. This study investigates the influence of environmental parameters such as temperature and geostrophic currents, their variability from year to year, as well as the influence of migration behavior on the success of anchovy overwintering migration during three years 2001 to 2003.

This first chapter of the thesis provides an introduction to the Black Sea circulation and ecosystem dynamics and provides background information on anchovy life cycle and migration observed in the Black Sea. The chapter closes with a detailed description of the aims of this study.

1.1 Black Sea circulation and ecosystem

The Black Sea is a land-locked basin extending between the latitudes of 41° to 46° N and longitudes of 28° to 41.5° E (Figure 1). It shares boundaries with Europe, Anatolia and the Caucasus. It is connected to the Mediterranean Sea via the straits of Bosphorus and Dardanelles, called the Turkish Straits System (Oguz, 2005). In the north, it is connected to the Sea of Azov through Kerch Strait.

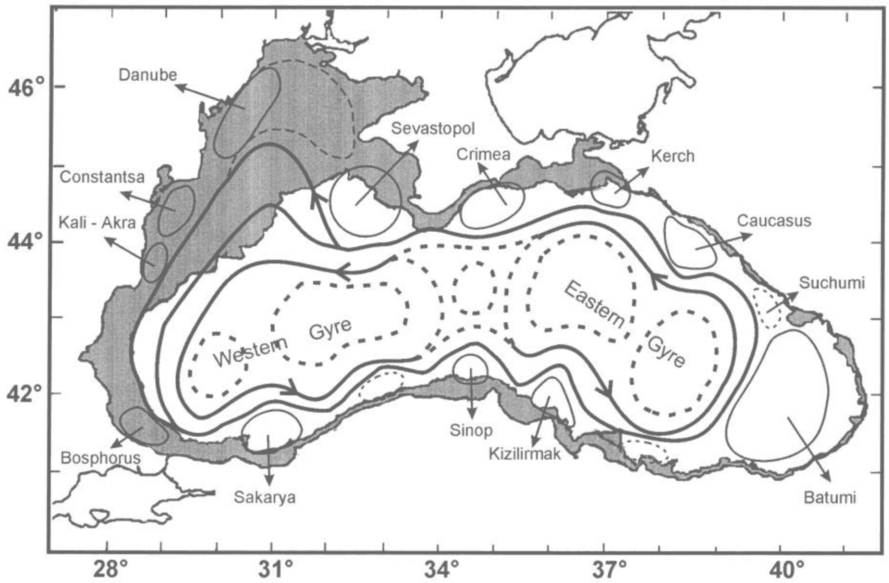

Figure 1 General circulation of the Black Sea (from Oguz et al., 1995).

The basin spreads over 432,000 km² approximately, has total volume of 547,000 km³ and extends down to a maximum depth of 2200 m within the interior basin. In terms of water budget, the Black Sea possesses positive water balance, as influx via rainfall (~300 km³ yr^{-1}) and river discharge (~350 km³ yr^{-1}) is greater than outflux via evaporation (~350 km³ yr^{-1}) () (Özsoy & Ünlüata, 1997; Ünlüata et al., 1989). The difference represents the net outflow from the Bosphorus Strait.

The upper layer circulation system exhibits some major features such as the Rim Current, a cyclonic boundary flow system that is flowing over the steep continental shelf topography, intensifying in winter. Acoustic Doppler Current Profiler (ADCP) based studies measured the speed of the Rim Current as 50-100 cm/s at the surface and 10-20 cm/s in between depths of 150-300 m. (Oguz & Besiktepe, 1999) (Figure 1). In addition, the presence of two cyclonic gyres circling within the peripheral flow and a number of anti-cyclonic eddies located in the zone between the coast and the Rim Current; namely the Bosphorus, Sakarya, Sinop, Kızılırmak, Batumi, Sukhumi, Caucasus, Kerch, Crimea, Sevastopol, Danube, Constantsa and Kali-Akra eddies are documented (Korotaev et al., 2003; Oguz et al., 1998). Moreover, the Rim Current structure is separated into two branches near the southern Cape of Crimea. They unite to form the Rim Current again at the south of Kali-akra coast (Oguz et al., 1998).

The Black Sea is the largest anoxic water body in the world. Within the second half of the last century it has gone through several transitions in physical and biogeochemical characteristics (Figure 2). At the beginning of 1960s it was considered to be a healthy and stable environment sheltering relatively diverse fauna represented by three cetacean species and abundant demersal, piscivorous and small pelagic fish species in a mesotrophic ecosystem state as with primary production levels of 100 to 200 mg C m^2 y^{-1} (Oguz, et al., 2012). During the following two decades, its ecosystem destabilized as a response to to several disturbances which include, (i) increasing anthropogenic nutrient input due to increased fertilizer use in the Danube catchment basin leading to increased primary and secondary production levels, (ii) over-exploitation of marine resources, causing severe reduction in marine mammals, demersal and piscivorous fishes, (iii) introduction of non-native species, and (iv) climate-induced variability (Oguz, 2005a; Oguz, 2005) (Figure 2). The result of these concurrent processes was disastrous and the Black Sea lost many of its commercially valuable marine resources irreversibly (including mammals, large pelagics and demersals) at the end of the 1960s and small pelagics stocks increased sustaining a catch of 500kt (mainly anchovy) during the 1970s to 80s. Then, with the growth of Turkish fishing fleet and technology (A. C. Gucu, 2002), the size of Turkish fishery yield collapsed at the beginning of 1980s to only 150 kt in 1989 (Oguz, 2007). The fishery collapse is synchronous with the outburst of opportunistic gelatinous carnivore, comb jelly *Mnemiopsis leidyi*. In the following years, although the size of Turkish fishery catches is recovered to approximately 300 ± 100 kt, it remained at very low numbers for the rest of the Black Sea riparian countries (Oguz et al., 2012). During this recovery period, *Mnemiopsis* bloom levels were oppressed by the natural predator, *Beroe ovata* (Mayer, 1912), newly introduced to the Black Sea. Since the end of 1990s, the entire Black Sea basin is characterized by moderate levels (200-400 mg C m^{-2} y^{-1}) of primary (Oguz et al., 2012) and secondary production

(McQuatters-Gollop, et al., 2008; Mee, 2006) except for the northwestern shelf and coastal region where the ecological state is still in the process of recuperating and restoring (Oguz & Velikova, 2010).

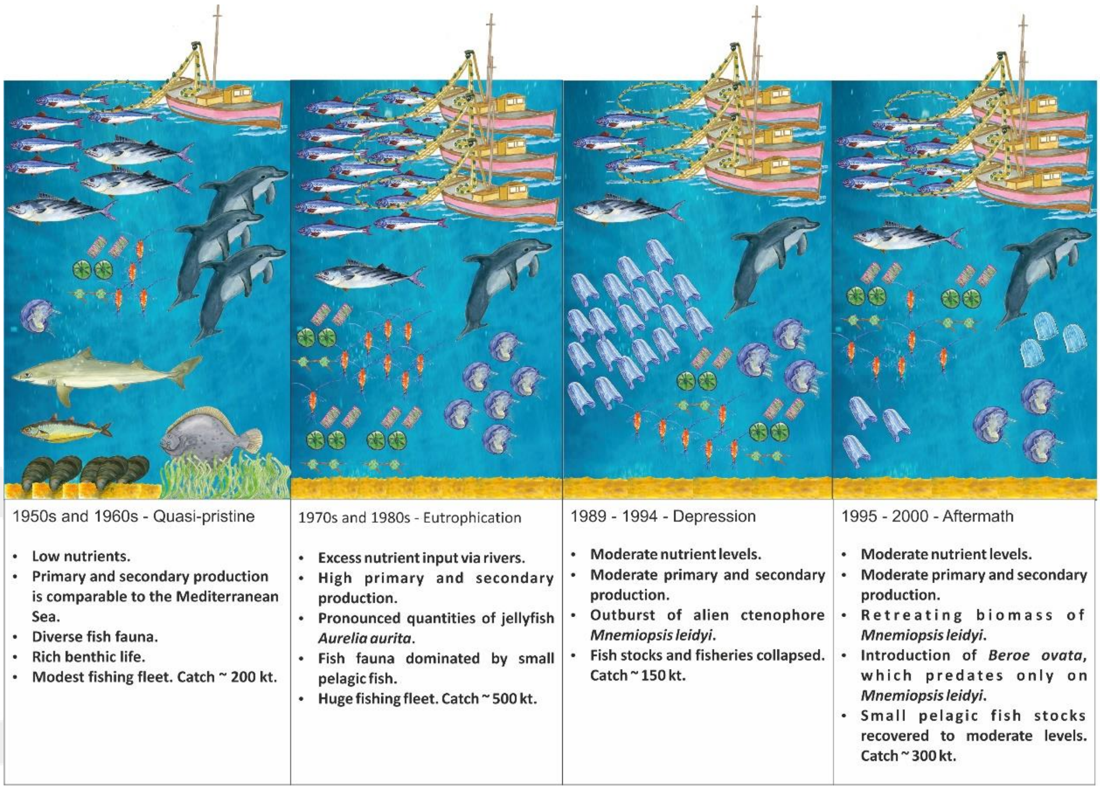

Figure 2 Schematic illustration of the state of the Black Sea over time (adapted from Akoglu, et al., 2014).

1.2 Anchovy in the World Oceans

The family of forage fish *Engraulidae* to which anchovy belongs comprises an important fisheries resource not only in the Black Sea alone, but also widely spread in other seas. Anchovy is a small pelagic clupeoid fish species that is found in all oceans with other species of the same kind, namely sardine, herring, etc. Together they constitute 20-25% of annual catch of the world (Alheit et al., 2012; Alheit, et al., 2009; Hunter and Alheit, 1995). Anchovy species generally predominate in tropical and sub-tropical seas. They form off-shore schools and are sometimes entering river deltas. The eight subspecies of anchovy sustaining high yield capacity in those areas can be listed as follows (Bingel & Gucu, 2010):

Engraulis anchoita (Argentine anchovy)
Engraulis australis (Australian anchovy)
Engraulis capensis (South African anchovy)
Engraulis encrasicolus (The European anchovy residing in Turkish waters)
Engraulis eurystole (Silver anchovy)
Engraulis japonicus (Japanese anchovy)
Engraulis mordax (Californian anchovy)
Engraulis ringens (Peruvian anchovy)

Although Black Sea populations of anchovy rank the lowest among catches of anchovy subspecies in the world seas, its catch amounts to more than 60 percent of Turkish water resources (Bingel and Gucu, 2010).

1.3 Black Sea Populations of Anchovy

In the Black Sea domain, there are two recognized populations of the European anchovy: the Black Sea anchovy (*Engraulis encrasicolus ponticus* Alexandrov, 1927) and the Azov Sea anchovy (*Engraulis encrasicolus maeoticus* Pusanov, 1936) (Aleksandrov, 1927; Mayorova, 1934; Pusanov, 1936, as cited in Chashchin et al., 2015). Although each sub-species exhibits variability in its growth rate, otolith ratio, parasitism frequency, blood type and microsatellite markers (Chashchin, 1996), there is a spatial overlap of the habitats of two races reported by several authors (Marty, 1980 as cited in Chashchin, 1996). Both races in are often exploited during winter in the same areas using the same fishing gear. Moreover, the Black Sea anchovy juveniles are observed to co-exist with the Azov anchovy within the Sea of Azov in summer and within the less saline waters of the northwestern shelf region (Chashchin, 1996).

The Black Sea fisheries has an important role in Turkish population health and economy, both by supplying the increasing animal protein demand of the growing population and by contributing to the gross domestic product via increasing employment rates. In 2013, the exploitation of water resources in the Black Sea corresponded to 62% of the total catch from the Turkish seas, and the employment of 15 thousand fishermen corresponded to 45% of the total employment in marine fisheries (TÜİK, 2013). The 154 ktons of anchovy catch amounts to 58% of the total water resources catch within the Turkish Black Sea EEZ and contributing ~249 million Turkish Liras (TRY) to the national income. Therefore, anchovy fisheries constitutes a very important part in Turkish fisheries.

1.3.1 Black Sea anchovy (*Engraulis encrasicolus ponticus*, Alexandrov)

Anchovy is a planktivorous fish suggesting that they are the second level consumers in the marine food web feeding not only on zooplankton but phytoplankton as well. Therefore, they have a wide range of prey resources which in turn sustain high yield. Species of the Copepoda (genus *Calanus*) and Cladocera subclasses frequently dominate the abundant prey for anchovy. When food availability is low, anchovy switches its diet towards mysids, ichthyoplankton, fish larvae, polychaete larvae and phytoplankton (Whitehead, 1985 as cites in Dulvy, et al., 2016; Bulgakova, 1993 as cited in Tudela & Palomera, 1995). Being visual feeders, their two-way filter- and particulate-feeding ability help to better utilize their wide range of prey (Bulgakova, 1993).

Sprat (*Sprattus sprattus*), Black Sea herring (*Alosa pontica*), sardine (*Sardina pilchardus*) and other organisms such as Ctenophora and Meduzae are sharing the same trophic level with anchovy and are therefore competing for food (Bingel and Gucu, 2010). In this competition, anchovy has an advantage over passive swimmers like Ctenophora and Medusae whereas has a disadvantage compared to the other active swimmer fish. Anchovy tries to cover this drawback with its constant feeding behaviour (Bingel and Gucu, 2010).

Anchovy spawning season starts in mid-May when the water temperatures are around 15 -16°C and lasts until middle or end of August with temperatures around 25-26°C (Lisovenko & Andrianov, 1996). Peak spawning takes place when temperatures exceed 20°C, generally in July (Niermann et al., 1994). The length and weight at first maturity is 55 to 60 mm and 1.2 – 1.5 g for males while it is 60 to 65 mm and 2.1-2.4 g for female individuals (Lisovenko &

Andrianov, 1996). *Engraulis encrasicolus ponticus* is a typical batch spawner and gains first maturity within the first year. Only a small percentage of Black Sea anchovy matures within the first two or three months after hatching and spawns at the end of spawning season (Lisovenko & Andrianov, 1996). Batch spawning takes place through 9 – 12 batches and more (Owen, 1989) or even up to 50 batches (Lisovenko and Andrianov, 1996). Owen, (1989) claims that during the course of summer months an individual anchovy spawns once in every 7.5 and 9 days while Lisovenko and Andrianov (1996) suggests that spawning takes place on every second day. According to Slastenenko (1955/56) at the time of spawning the optimum conditions of water temperatures are around 17-18°C, whereas Lisovenko and Andrianov (1996) states that spawning takes place between 19-24°C range and at 5-10 meter below the surface in areas influenced by riverine and estuarine discharge (Slastenenko, 1955/56; Lisovenko and Andrianov, 1996). Spawning areas are rather brackish with a salinity of 12-18‰ (Lisovenko and Andrianov, 1996). Anchovy spawners lay pelagic and prolate ellipsoidal eggs and eggs generally develop into larvae within the first 24 hours depending on the water temperatures (Slastenenko, 1955/56). Their shape determines that they are sinking slower in the water column than round eggs according to Stoke's Law (Denny, 1993; McNown and Malaika, 1950 as cited in Coombs et al., 2004). When the turbulent environment of the ocean is considered the anchovy eggs are likely to become suspended in the water column while they are known to occupy at the superficial layer of the water column in marine habitats characterized by strong stratification (Motos, 1996; Motos and Coombs, 2000 as cited in Somarakis et al., 2004). In the Black Sea, the eggs are concentrated within the first 20 or 45 meters below the surface above the thermocline whereas the majority is observed within the upper 1 – 3 meter below the surface (Niermann et al., 1994). Anchovy egg mortality is high, hence anchovy overall mortality is estimated as 81.18% with the maximum mortality (96.5%) observed in July (Şahin & Hacimurtazaoğlu, 2013).

Both adults and young-of-the-year anchovies have a distinct diel rhythm of egg release, serial spawning, and constant development of oocytes in the ovaries (Lisovenko & Andrianov, 1996). Average weight and energetic value of one egg is estimated as 0.226 mg and 0.81 calories (Lisovenko & Andrianov, 1996). Total number of eggs deposited by one average female within the spawning season is given as 138,203 (in 1988) and 231,184 (1990) (Lisovenko & Andrianov, 1996). Moreover, in 1990, total biomass of the spawners is estimated as 48,000 tons and their population is 5.7 billion fish 2.9 billion of which is females (average weight of females and males is 8.85 g and 7.9; sex ratio 1:1) (Lisovenko & Andrianov, 1996).

Fecundity values of individual anchovy are suggested to be 42,000 (Gucu, et al., 2016; Owen, 1989) and may vary by one order of magnitude up to 200,000 (Lisovenko and Andrianov, 1996) eggs per one female in spawning season in later studies. This means that Black Sea anchovy has extraordinarily high reproduction ability. Such a potential cannot be secured only by the fat reserves built up in the female's body prior to spawning season as in the case of boreal fish species (Lisovenko & Andrianov, 1996). Rather, the necessary energy is compensated by the active feeding behaviour during the entire spawning season (Lisovenko & Andrianov, 1996). The energetic costs of basal metabolism, somatic growth and active reproduction are covered by this extraordinary feeding capacity (Lisovenko & Andrianov, 1996). There is a strong direct relationship between the batch fecundity and spawning frequency with the ambient temperatures (Lisovenko & Andrianov, 1996).

Although anchovy is considered to be a migratory fish, anchovies do not totally leave the Anatolian coast waters in spring (Artuz, 1976). Anchovy is present in Turkish waters all around the year and intense spawning takes place close to the coast when optimum conditions hold for them (Bingel and Gucu, 2010).

The immense reproduction ability, short life span and rapid growth of age-0 class individuals within a year bring about high frequency natural annual stock and biomass fluctuations (Lisovenko & Andrianov, 1996). In spring, Black Sea anchovy abundance and biomass drop to a minimum. In summer and fall, abundance and biomass increases rapidly as a result of reproduction and somatic growth of the YoY in particular (Lisovenko & Andrianov, 1996). Maximum in abundance and biomass is reached before winter in November-

December. In winter, however, drastic reduce of abundance and biomass is seen (Lisovenko & Andrianov, 1996).

1.3.2 Azov Sea Anchovy (*Engraulis encrasicolus maeticus*, Pusanov)

During the period between May and August, Azov anchovy occupy the Azov Sea basin for foraging and spawning. With the approach of cold temperatures in September and October, Azov anchovy migrate to the Black Sea through Kerch Strait and may settle at in areas located along the coastal region of northern Caucasus and southern Crimea (Chashchin, 1996 and references there in, Bingel and Gucu 2010, Öztürk, et al., 2011). Furthermore, schools can migrate further southwards towards the Anatolian coast (Bingel and Gucu 2010). In spring, from mid-April to the end of May, Azov anchovy undertakes a return migration to the nursery grounds at the Azov Sea (Chashchin 1996 and references there in). In some years the Azov anchovy may dominate and hence cross-fertilization (hybridization) rates increase between the two sub-populations. In this case the abundant Azov anchovy and especially young-of-the-year class of the Azov population do not necessarily return to the Sea of Azov after winter, but rather stay in the northwestern part of the Black Sea for foraging and spawning. The hybrids are often not very successful in producing healthy offspring that can survive in relatively more saline waters of the Black Sea (Chashchin et al., 2015).

The northeastern Black Sea is connected to the northern shallow Sea of Azov through Kerch Strait. The water exchange between those two seas is dominated by the prevailing winds and river outflow. The excess discharge by Don and Kuban rivers result in relatively brackish conditions in the Sea of Azov characterized by salinity vales between 9 and 15‰ and high primary production levels. The high plankton production within the Black Sea shelf and the Sea of Azov sustains favorable prey conditions for planktivorous fish species (i.e., anchovy), and hence the anchovy populations in the Black Sea and the Sea of Azov exceed those in the Mediterranean and in the eastern Atlantic (western Europe) regions. The annual anchovy catch in the Black Sea and the Sea of Azov varied within the range of 90 – 600 ktons with 315 kton average within the last three decades (Chashchin et al., 2015). Although the intensive catch of anchovy takes place at the southern (Anatolian) coast of the Black Sea when they aggregate to form dense overwintering schools, the northern basin controls the recruitment strength and hence the stock size of migrating anchovy (Chashchin et al., 2015).

1.3.3 Comparative Analysis of the Two Populations

Sub-population differentiation studies have been performed with the use of morphological characteristics (i.e., growth parameters, otolith shape, body length and proportions) (Skazkina, 1965; Gubanov & Limansky, 1968; Shevchenko, 1980; Chashchin 1985 as cited in Chashchin et al., 2015) and genetics. The genetic methods include blood type analysis (Altukhov, 1974; Kalnin et al, 1984, 1985 as cited in Chashchin et al., 2015) and muscle protein divergence (Ivanova & Dobrovolov, 2006). Moreover, the occurrence rate of parasitic nematode (*Conracaecum aduncum*) larvae in the body cavities of Azov and Black Sea anchovies has an important role in differentiation of both subspecies. The anchovy that forage in the Black Sea are more susceptible to nematode infestation in their body cavities as this parasite only exists in Black Sea waters (Terekhov, 1979; Chashchin, 1981 as cited in Chashchin et al., 2015). Moreover, the two races are differentiated by their metabolism. The Azov population accumulate more fat than Black Sea population in the visceral cavity and in muscles in summer when they feed on zooplankton in the Sea of Azov, in a basin that is richer in fodder zooplankton (Shulman, 1972 as cited in Chashchin et al., 2015). Accordingly, the Azov race is able to leave the Sea of Azov earlier, when the cold temperatures onset in October (Chashchin et al., 2015) than the Black Sea population. However, the opportunity of prolonged foraging season within a relatively warmer environment (with respect to the Sea of Azov environment) in the Black Sea results in an increase in consumption for the somatic growth. Consequently, in the Black Sea race, the somatic growth rate and body length is always higher than the Azov anchovy whereas body fat percentage is always lower than the Azov population (Chashchin, 1995, 1996). The Black Sea anchovy can reach a maximum length of 18-20 cm (Slastenenko, 1955/56; Fischer, 1973) as Azov anchovy can reach up to 15 cm length (Slastenenko, 1955/56).

Moreover, another differentiation method for both subspecies and a natural selection that their hybrid generations face with is the shape of the eggs (Chashchin, 1995, 1996 as cited in Chashchin et al., 2015). The eggs of the Azov anchovy are rounder so that they have higher buoyancy and hence more adapted to the Sea of Azov basin that possess less dense water. On the other hand, the eggs of Black Sea anchovy are more elongated and therefore more adapted to denser Black Sea water characteristics. The differences in egg form introduces heavy natural selection over both populations. Therefore, the hybrid has poor chances of survival when it cannot produce the egg shape necessary to adjust buoyancy and secure survival when it enters the more saline Black Sea water (Chashchin et al., 2015).

Furthermore, the Azov anchovy reaches first maturity at age 2+ whereas the Black Sea anchovy is able to spawn as yearlings. However, within only 2-3 months a negligible portion (<3%) of the Black Sea anchovy population eggs develop and gain maturity and becomes ready to breed at the end of the spawning season (Lisovenko & Andrianov, 1996).

1.4 Fish Migration

Mobile organisms often have the ability to move towards most advantageous habitat conditions or geographic region and fish are no exception (Jonsson & Jonsson, 2011). Fish tend to select their habitat based on evaluation of benefits and costs when selecting a particular habitat (Jonsson & Jonsson, 2011; Werner et al., 1993). The benefit of migration activity might be the access to better food resources (Gross et al. 1988), or prevention of unfavorable physical conditions (Jonsson & Jonsson, 2011) and predation pressure (Katinic, et al., 2015). Fish are also expected to assess the risks of migration as migration is a labor-intensive activity which demands a lot of energy and hence introduces mortality (Jonsson & Jonsson, 2011). Recently, there is an increasing trend towards appreciation of movement of individuals using approaches relating species' geographical distributions (Steinberg and Kareiva, 1997). Movement is one of the essential population phenomena which remains rather unresolved (Patterson, et al., 2008).

Fish may change their position via passively drifting in oceanic currents, actively swimming themselves or by using both (Jonsson & Jonsson, 2011). The role of physical environment should not be overlooked when considering fish migration. Currents supply certain routes for migration or cues for migrating fish species (Arnold, 1981). According to Murawski (1993), migration and phenology are among the first biological phenomena susceptible to alterations in the currents, ambient temperature and food.

Migration activity remains an intricate and compelling subject which covers a wide range of animals from birds to mammals (Dingle, 1980). Apart from interaction with their biota (Hussko et al., 1996 as cited in Goodwin et al., 2006), the species interactions with their physical environment has a significant control over their distribution patterns (Pientka and Parrish, 2002). According to Ramenofsky and Wingfield (2007) the effect of environmental conditions on species migration patterns can be classified into three sections: (i) anticipated inter-seasonal alterations in the environmental conditions (i.e., temperature, radiation) that is closely linked to resource availability, (ii) unanticipated alterations caused by disturbance processes (i.e., climate-induced, human-induced activities, predator-prey interactions), and (iii) intercommunal relations that are associated with life-history traits. In migratory fish, attention is mostly concentrated on anticipated movement between nursery and on-nursery grounds (Lucas & Baras, 2000; Northcote 1984). Realizing migration comprises evaluation of both behavioral (signal that determines the fish to migrate) and physiological (condition to follow the signal) aspects (Cooke, 2008; Bat et al., 2007; Hinch et al., 2006).

Estimation of the available species in a system requires an understanding of their geographical distribution variety (Hart et al., 2002). Studying movement of populations can provide valuable insights in fisheries science (Goodwin, et al., 2006). Movement can affect fish populations through changes in population density, modifying interspecific interactions or through genetic reorganizations (Turchin & Omland, 1999). In fisheries assessment and management, the patterns of fish movement can be used explain the stock fluctuations (Pelletier et al., 1994). The way that marine organisms disperse depends on the species, species behaviour and currents (Marinone, et al., 2008). Therefore, simulation of movement of individual particles in a dynamic environment is an important tool for investigating ecological processes in marine environment (Hare, et al., 1999; Heath et al., 1998; Miller et al. 1998).

Today's sustainable fisheries management strategies should be relying not only on ecosystem-based management, but also on the potential effect of physical environment on such systems (Wang, et al, 2013). It is known that the environmental conditions that fish perceive can have an effect in altering fish population dynamics through modification of lower trophic level dynamics (Guraslan, et al., 2014). And such alterations might eventually change fish migration pathways (Yuheng et al., 2013).

Many species of fish perform long distance migrations to reach their spawning, feeding and/or overwintering habitats, i.e., herring at the west coast of Norway (Huse, et al.,, 2010; McQuinn, 1997), capelin in the Barent Sea (Huse & Ellingsen, 2008), sardine stock in the Pacific (Zwolinski et al., 2012; Zwolinski, et al., 2011), northeast Atlantic mackerel (Iversen, 2002), European eel (Tesch, 2003), blue whiting in the Norwegian Sea (Utne, et al., 2012), whale sharks in the western Pacific (Anderson & Ahmed, 1993).

Temperature is an important stimulus on the migration and distribution of fish as fish are very sensitive to this stimulus ((Humston, Ault, Lutcavage, & Donald, 2000; Sims, Wearmouth, Genner, Southward, & Hawkins, 2004) (Sims et al., 2004) Humston et al., 2000, Sims et al., 2004, Olafsdottir and Rose, 2013). Although fish tend to acclimate in non-optimal temperature environment, they prefer specific temperatures within gradients, i.e., the marine greenfish *Girella nigricans* (Doudoroff, 1938), speckled trout, *Salvelinus fontinalis* (Sullivan, 1949). Moreover, the migratory thermophilic fish, *Tilapia mossambica* (Peters), has been shown to select higher temperatures following extended periods in the temperature gradient (Badenhuizen, 1967).

1.5 Black Sea Anchovy Migration

Anchovy migration in the Black Sea is not well understood and contrasting theories on overwintering migration exist. Earliest studies on Black Sea anchovy dates back to the 1910's and suggest that from their spawning habitats in the Marmara Sea, anchovy starts wintering migration to Anatolian coast 20 days after St. Dimitrios Day, on 28 November, and migration continues until March (Deveciyan, 1926). However, the later studies all agree on location of spawning grounds in the Black Sea only (Einarson and Gurturk, 1960 as cited in Gucu et al., 2016; Ivanov & Beverton, 1985; Niermann et al., 1994; Chashchin, 1995). Among the recent theories, one suggests that Black Sea anchovy spawning and nursery grounds are located mainly in the northern part of the Black Sea (Northwestern Shelf, in particular) and anchovy are exhibiting long-distance overwintering migration from their nursery grounds on the northwestern shelf to the southeastern coast of the Black Sea by either beginning of October (Ivanov & Beverton, 1985; Lisovenko & Andrianov, 1996, Shulman, 2002) or by mid-November (Chashchin, 1995) (Figure 3). In addition, anchovy distributed within the eastern basin is suggested to overwinter at the coast of Georgia and sometimes at the Turkish coast (Chashchin, 1996 and the references therein).

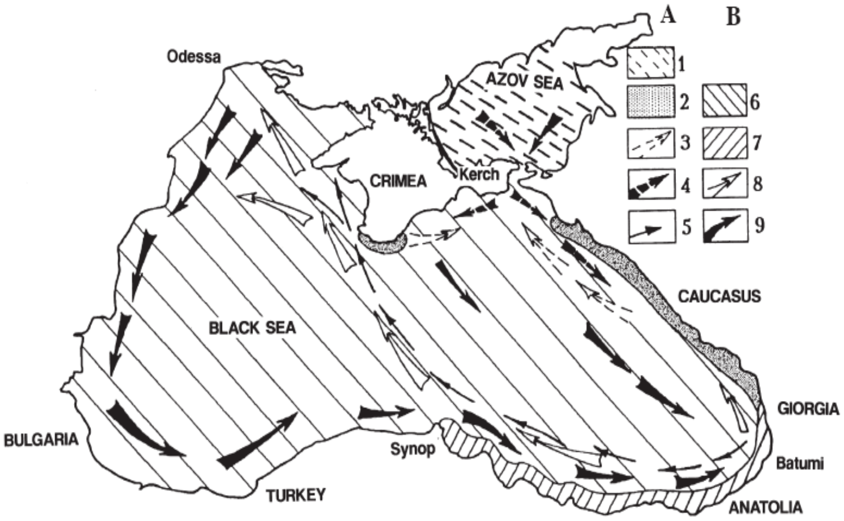

Figure 3 The general scheme of Azov and Black Sea anchovy spawning and foraging region (1&6); wintering region (2&7); spring migration (3&8); autumnal migration (4 & 9); periodic migrations of mixed sub-populations (5) (from Chashchin, 1995).

However, in multiple the studies covering the entire Black Sea (Einarson and Gurturk, 1960) in the 1950s and the southern Black Sea in the 90s (Niermann et al., 1994(Figure 4) show that high egg and larvae abundance is found also within the Turkish Exclusive Economic Zone, which suggests that local anchovy of the southern Black Sea migrate to this overwintering ground which has been supported by later studies (Kideys et al., 2000). Recent findings by Gucu et al. (2016) clearly showed very high summer egg distribution off the Anatolian coast, an order of magnitude higher than any other study before, and thus confirmed there is a non-migrating population inhabiting in Turkish EEZ all year round.

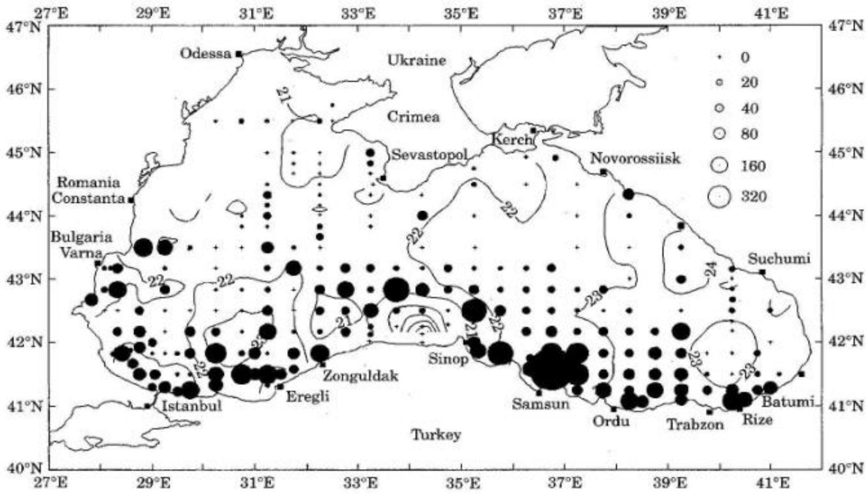

Figure 4 Distribution of eggs & larvae on July 1992 (from Niermann et al.,1994).

With the approach of cold temperatures, adult and juveniles are observed to aggregate to form dense schools and undertake a wintering migration towards warmer waters located the southern Black Sea, at the Anatolian coast, although different migration routes have been suggested in the literature (Chashchin, 1996; Ivanov and Beverton, 1985; Shulmann, 2002). It is known that anchovy migration is at least partially driven by ambient temperature (Chashchin & Akselev, 1990; Panov & Chashchin, 1990; Panov & Spiridonova, 1998; Berdnikov et al., 1999; Shulman, 2002; Shulman et al., 2008). The upper temperature threshold for Black Sea anchovy to start gathering schools and migration given by different authors is 10.5-13.5 °C for juveniles and 11.5-15.0 °C for adults (Shulman et al., 2008), at least 12 °C (Chashchin & Akselev, 1990) and 14 °C (Panov & Spiridonova, 1998), or between 12-14 °C (Panov & Chashchin, 1990). The internal stimuli driving migration is thought to be the body fat content (Shulman, 2002).

Bingel and Gucu (2010) suggest that when there is a slow decrease of temperatures the winter migration follows the coast and when there is a significant drop in temperatures anchovy migrate across the tip of Crimean Peninsula towards Sinop region. Likewise, Azov anchovy (*Engraulis encrasicolus maeticus*) feeds in the Sea of Azov and migrates following

Crimean coast and pass across the midway between Western and Eastern Gyres approaching Anatolian coast or following Caucasian coast they migrate to the south to Suchumi region or further down to Anatolian coast (Chashchin, 1990).

1.6 Modeling as tool to understand migration

The effect of climate change on fish migration is hard to resolve because of the simultaneous changes taking place at both physical and biological levels. However, multi-decadal climate fluctuations are not only seen to damage marine resources via triggering regime shifts but also leading to serious economic consequences (Steele, 1998). Models are very useful tools for understanding and simulating fish behavior under changing environmental conditions (Goodwin et al., 2006). Different modeling studies have reported close relationships of small pelagics abundance and distribution patterns and sea surface temperature distributions, i.e., in herring in the Barents Sea (Gjøsæter, 1998; Gjøsæter et al., 1998; Huse et al., 2010), capelin in the Barent Sea (Dommasnes and Røttingen 1985; Huse & Ellingsen, 2008, Ozhigin and Luka, 1985;), sardine at the Pasific (west) coast of USA and Canada and the seas around Japan (Tameishi, 1996; Zwolinski et al., 2012; Zwolinski et al., 2011) and mackerel in the Norwegian Sea (Iversen, 2002).

The details of Japanese anchovy's spawning migration from East China Sea towards Taiwan has been explored with a model that couples a hydrodynamics model with anchovy migration and 'decision making' model (Tu et al., 2012). To explain the relationship between anchovy distribution plus stock abundance and the climatic/physical fluctuations caused by ENSO (El-Nino Southern Oscillation) ocean-atmosphere interactions in southern US, which leads to frequent stock collapses, Peruvian anchovy population dynamics were successfully explored by (Xu, et al., 2013).

Although the anchovy stock distribution and behavior in relation to physical environment (currents, SST, etc.) is currently being explored with models in the world seas, so far there is no reported study among the Black Sea literature. The start and arrival location during migration period, the timing and duration of migration, the internal and external stimuli affecting migration are already partially known. However, there is no complementary view focusing on the role that the Black Sea circulation field and environmental factors play on the fate of anchovy arrival at the Anatolian coast. At this point, Lagrangian Particle Tracking models are modeling tools that offer the opportunity to work at various time and space scales and implementation of behavioral aspects.

In an earlier study by Fach, (2014), the dispersal and connectivity of virtual anchovy eggs and larvae placed at different regions within the Black Sea were investigated with means of a larval individual-based model embedded within a Lagrangian Particle Tracking model. The results revealed that the larval dispersal patterns are indeed strongly linked with the mesoscale variability patterns. However, this larval model is not resolving adult anchovy migration behavior.

1.7 Aims of This Study

Within the scope of present study adult anchovy behavior and the processes of decision-making are incorporated into an existing Lagrangian Model to investigate possible anchovy overwintering migration routes from different nursery grounds to the overwintering grounds located along the south-eastern coast of the Black Sea. The aim of the study is to explore the influence of variability in environmental conditions of the Black Sea, focusing specifically on sea surface temperature and geostrophic current variability, influences the migration pathways and migration success of anchovy in addition to such decision-making processes in three very divergent years (2001-2003). The goal of this research is to understand the different factors influencing successful anchovy migration as well as determine from which regions in the Black Sea anchovy can successfully migrate.

The specific research questions to be answered are as follows:

1) What are the possible overwintering migration pathways for anchovy originating on the northwestern shelf, and do they change with different environmental conditions (currents and temperature) in different years?
2) Do mesoscale eddies, frontal processes and unstable filaments have an effect on this migration success? How do they affect migration?
3) What is the effect of behavior in the form of swimming direction and following the maximum temperature on the success of overwintering migration?
4) Does intra-annual (seasonal) environmental variability in temperature and currents have an effect on the migration pathways and if it does, to what extend?
5) Where are the nursing areas located considering the overwintering areas of anchovy? Do they change between the colder and warmer year?

Following this general Introduction to the thesis, the methods detailing the model as well as the satellite data used in this study are described in detail in the second chapter. Following this, a detailed analysis of the weekly mean environmental conditions (SST, current, dynamic sea level maps) in the Black Sea during the months relevant to anchovy migration (September – December) during 2001- 2003 are given in the third chapter. The contribution of each respective year in the overwintering migration is presented in this chapter as a reference for the following chapters 4-7 in which the research questions posed above are answered.

In the fourth chapter the inter-annual variability of overwintering migration pathways and migration success of anchovy under different environmental conditions (currents and temperature) as well as anchovy behavior is explored, assuming the nursery region of anchovy starting overwintering migration is the northwestern shelf area. In addition, the contribution of mesoscale processes (anticyclonic eddies, fronts and formation of jet structures) to the success of migration is elucidated. The first three research questions are answered for assuming the northwestern shelf as the only source area for anchovy.

In the fifth chapter the effect of inter-annual variability in environmental conditions (currents and temperature) as well as anchovy behavior on overwintering migration pathways and migration success of anchovy for anchovy originating in the rest of the Black Sea is examined. The contribution of mesoscale features and temperature changes is evaluated and the first three research questions are answered for anchovy in the entire Black Sea, excluding the northwestern shelf.

The influence of seasonal variability in currents and temperature on the migration pathways and migration success from the different origin regions in the year of highest observed mesoscale variability (2003) and highest migration success is explored in chapter 6 answering the fourth research question. The last research question about source regions of those anchovy found in the overwintering area is answered in chapter 7 by backtracking drifters in time. The thesis then closes with final conclusions in chapter 8.

Chapter 2
MATERIAL AND METHODS

In this study the surface geostrophic currents of the Black Sea are calculated from satellite data of Sea Level Anomaly and the mean topography of the Sea. Using these geostrophic currents an anchovy transport model is employed to simulate Black Sea anchovy advection across the Black Sea including swimming behavior such as the seasonal overwintering migration. The model tracks the trajectories of anchovy adults as they migrate from possible spawning grounds to known overwintering grounds located at the southeastern coast of the Black Sea. Anchovy biological processes (i.e., growth, reproduction, mortality) are neglected in this model as they were studied extensively in previous modeling studies (Güraslan et al., 2014; Oguz, et al, 2008). Instead, the effect of year-to-year and seasonal variability in surface currents and swimming behavior on migratory success and migration paths is tested in the simulations. This tracking of anchovy migration pathways based on surface currents is a valid assumption, because anchovy is known to occupy warm, upper mixed layer waters and avoid cold temperatures of the Cold Intermediate Layer below (Niermann et al., 1994; Kideys et al. 2000; Satilmis et al., 2003).

To test different environmental conditions in consecutive years, the years 2001 to 2003 were chosen after the analysis of satellite data of two decades, 1990s and 2000s, showed that 2001 is an exceptionally warm year with strong stratification, mainly because of reduced wind stress in the winter of 2000-2001 (McQuatters-Gollop et al., 2008, Buongiorno Nardelli et al., 2010). The year 2002 is average in terms of temperature distribution and 2003 is remarkably cold when compared to the mean conditions, with significantly higher wind stress (McQuatters-Gollop et al., 2008). Based on this analysis and to be able to compare results with the previous study of anchovy larval dispersal (Fach,

2014) the years 2001 to 2003 are chosen for this study to be able to investigate the upper and lower extremes of environmental variability in the Black Sea, respectively.

2.1 Satellite Data

Black Sea surface circulation fields are calculated using the AVISO+ (*Archiving, Validation and Interpretation of Satellite Oceanographic data)* Sea Level Anomalies (SLA) & geostrophic velocity anomalies regional product for the Black Sea. They are level 4 delayed time (DT) daily multi-mission sea surface heights anomalies data on a regular 1/8° x 1/8° grid created by a multi-satellite altimetric ground segment called SSALTO/DUACS (*Segment Sol ALTimétrie et Orbitographie)* system which is operating under Centre National d'Etudes Spatiales (CNES) and made available for use via AVISO+ catalogue http://www.aviso.altimetry.fr/en/data/products/sea-surface-height-products/regional/msla-black-sea.html. This daily AVISO data is then interpolated spatially onto a 1/16° x 1/10° (7 km x 8 km) grid and interpolated temporally to daily sea level anomaly fields. The mean sea surface height provided by Korotaev et al. (2003) is then added to these daily AVISO fields to compute the absolute dynamic topography (ADT) of the Black Sea and geostrophic surface currents are computed from these fields (Figure 5). Velocities calculated to be greater than 0.5 cm/s were assigned to 0.5 cm/s in order to reduce erroneous satellite data at the boundaries. However, it should be noted that this process smoothes out offshore jets that are shown to extend 100 km from the shelf break and reach velocities of about 70 cm/s (Ivanov et al., 1985).

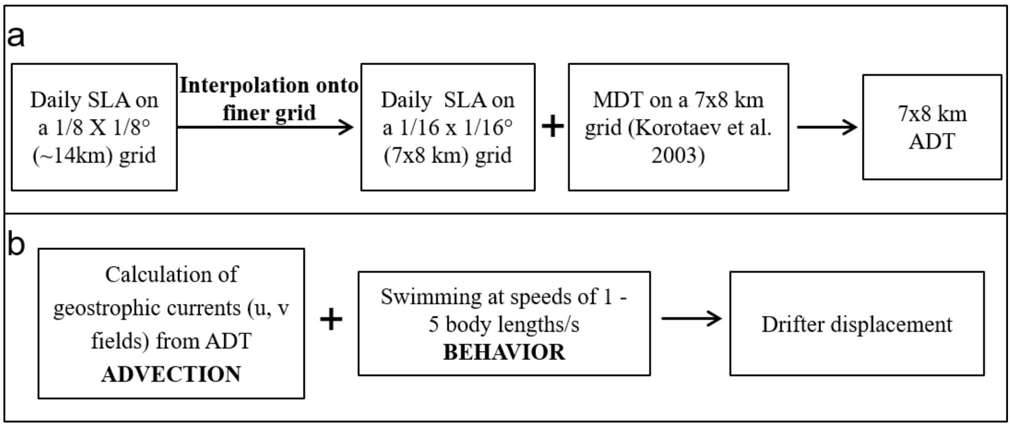

Figure 5 Schematic diagram of data processing and anchovy displacement calculation performed this study: A) Daily Sea Level Anomaly (SLA) fields were interpolated spatially to a 7x8km grid. The mean dynamic topography (MDT) compiled by Korotaev et al. (2003) was added to the SLA fields to obtain Absolute Dynamic Topography (ADT) fields from which geostrophic currents were computed. B) Anchovy swimming behavior added to current advection give the net drifter displacement.

As temperature is known to influence anchovy migration (Chashchin, 1995) temperature data obtained from Gruppo di Oceanografia da Satellite (GOS) is compiled and used in the model. It is the daily temperature product for the Black Sea created using optimal interpolating Advanced Very High Resolution Radiometer (AVHRR) onto a $1/16^0$ x $1/16^0$ grid (http://gosweb.artov.isac.cnr.it/). This data is then interpolated to get $1/16^0$ x $1/10^0$ (7 x 8 km) grid resolution as well to match the AVISO data.

2.2 Lagrangian particle tracking model

In fluid dynamics, Eulerian and Lagrangian specification of the flow are the two approaches that are used to describe fluid motion. Most frequently the Lagrangian method is employed, that is the method which studies a velocity field from the viewpoint of particles or tracers transported by it (the Eularian approach, instead looks at the properties of the velocity field from a fixed position in space). In the Lagrangian approach individual elements (particles or parcels of water) can be followed through continuous space and time and hence, this method is commonly used in models of contamination dispersion (Brickman and Smith, 2002; Hunter et al., 1993), in sediment transport models (Mead and Rodger, 1991; Soulsby et al., 2007), in spill monitoring models

(North et al., 2015), or in individual based models of different species such as anchovy (e.g. Xu et al. 2013, Fach, 2014).

The choice of time integration scheme of the model is important in terms of accuracy, skill assessment and CPU necessities. The common schemes in-use are (i) the forward Eulerian method, (ii) the Runge-Kutta (RK) method and (iii) the advanced Adams-Bashfold-Moulton (ABM) method. Moreover, the choice of time step is critical to fulfill accuracy and efficiency demands (Darmofal et al., 1996, Guizien, Brochier, et al., 2006). In this study a single drifter in the Lagrangian Particle Tracking algorithm is following the Eularian time integration and solves the following Equation 1;

$$dX/dt = V(X,t) \qquad \text{Equation 1}$$

where, the particle location is denoted by *X* at a certain time *t* and the velocity at location *X* is represented by *V*.

The novelty compared to the previous particle tracking study of Black Sea anchovy by Fach (2014) is that in this study not only advection of anchovy is considered, but also the swimming behavior of anchovy, such as migration, is included. This is achieved by extending Equation 1 with behavioral movement term as follows (Equation 2):

$$dX/dt = V_a(X,t) + V_b(X,t) \qquad \text{Equation 2}$$

where, now displacement by advection (V_a) and behavioral swimming (V_b) both influence the velocity of a particle at location *X* and time *t*. When total velocity (*V*) acting on the particle is the sum of both behavioral and advective velocities, the integration of Equation 2 gives

$$X(t^{n+1})=X(t^n)+ \int^{tn} V\ (X,t)dt \qquad \text{Equation 3}$$

Here the time step (*dt*) is equal to t^{n+1}-t^n where n is the index for time and is chosen to be 1 (one) minute in this study. Forward Eulerian method is used to integrate Equation 2 (Guizien et al., 2006; Lett, et al., 2007; Parada, et al., 2003) and applied as

$$X^{n+1}=X^n+V(X^n, t^n)dt \qquad \text{Equation 4}$$

One major benefit of using this method is that it requires only the position at the current time step (X^n) and one velocity field at the current time step $V(X, t^n)$ to estimate and the new position X^{n+1} of the drifter. Another advantage of this scheme is due to lower CPU requirements compared to fourth order RK scheme.

The main disadvantage of choosing this first order differencing scheme is the low accuracy which may eventually lead to divergence from real drifter trajectories (Bennett et al., 1987). To counteract such errors, the time step must be chosen very small. Here the choice of a 60 second time step is small enough to ensure accuracy comparable to a second-order accurate scheme (Fach, 2014).

It should be noted at this point that sub-grid scale dispersion processes, which are the processes that happen on the scale of less than the 7x8 km grid resolution of this model, cannot be resolved by the velocity fields used here. They are however of importance and do influence particle trajectories, which is a common problem Lagrangian models face. Hence, they are often included in particle tracking algorithms by superimposing a random walk term for each particle and time step (Cowen, et al., 2006; Xue et al., 2013). This is omitted purposefully in this study because the satellite-based estimate of surface circulation is already a rough approximation of the actual flow field and accounts only accounts for the geostrophic part of the flow. Artificially adding dispersion will to this will not enhance simulation results.

2.3 Parameterization of anchovy behavior

When using Individual Based Modeling approach, fish populations can be represented as 'super-individuals' (Scheffer, et al., 1995). Each super-individual represents a group of many identical individuals, in our case is referred to as adult anchovies (from here on they will be referred as 'drifters' simply). In this study the focus is on the modeling of the overwintering migration towards the overwintering grounds located along the Anatolian coast (Chashchin, 1995, Ivanov and Beverton, 1985), hence all drifters that reach narrow shelf region at the southern Black Sea (≤ 1500 m.) towards the east of the 35^0E longitude are considered as drifters achieving a successful migration (Figure 6).

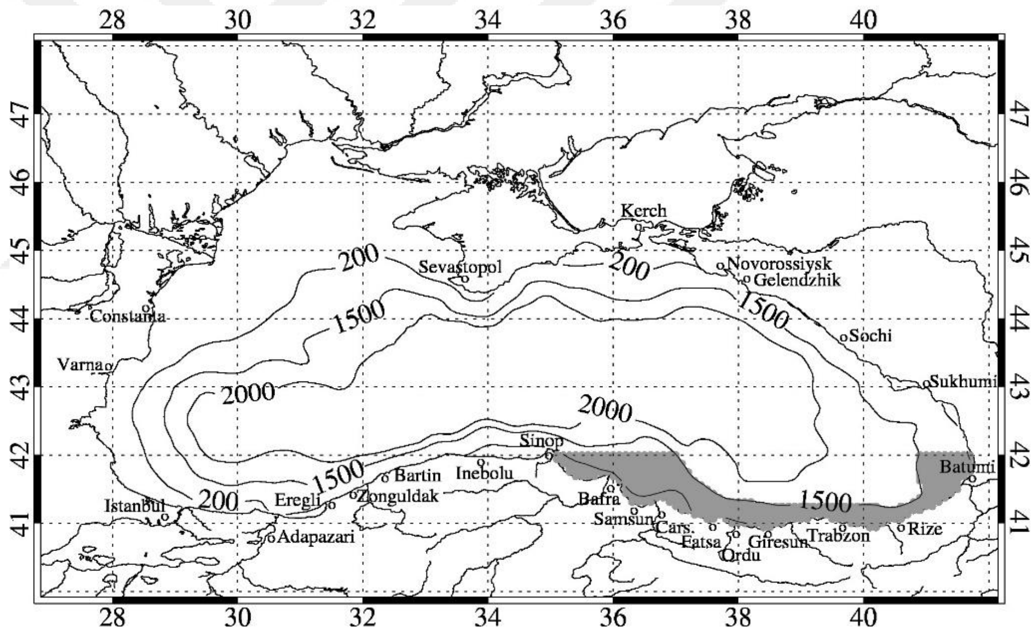

Figure 6 Topographical map of the Black Sea. The grey area at the southeastern part of the basin represents the overwintering area (< 1500 m.).

Drifters are released in the entire Black Sea at 5 different times during autumn (September 1 & 15; October 1 & 15 & 30) when anchovy migration is likely to start (Chashchin, 1995) of the representative years 2001-2003 and tracked over two months. Initially drifters are tracked using only advection of the oceanic currents. To include swimming behavior, it is then assumed that anchovy swim towards the overwintering grounds with directed movement of

1 body lengths/sec (bl/s) towards SE, ESE, SSE direction in combination with the advection of ocean currents. This directed movement is chosen to lead drifters towards the southeast region of the Black Sea basin (Table 1).

However, this approach may not be very realistic, given that anchovy have been observed to be able to swim much faster for long periods of time. Peruvian anchovy anchovy is known to sustain high swimming speeds up to 5 bl/s over extended periods of time (Peraltilla & Bertrand, 2014). Similar swimming speeds have been observed in Black Sea anchovy as well (Gucu, personal communication). Therefore, simulations with 5bl/s swimming speeds are undertaken in this study (Table 1). In addition, it has been shown that changes in temperature trigger Black Sea anchovy migration and anchovy are likely following temperature to move to the warmer overwintering grounds (Chashchin, 1995). Hence, as a further set of simulations that includes movement following temperature gradients with 1 and 5 body-lengths/second swimming speed is added on top of advection is performed (Table 1).

Table 1: List of model simulations.

Interannual variability - start October 30 from Northwestern Shelf	**Chapter 4**
Advection only	Figure 21
Directed movement towards SE and ESE direction with 1 bl/s	Figure 22, Table 4
Directed movement towards SE and ESE direction with 3 bl/s	Figure 23, Table 5
Temperature following with 1 ad 5 bl/s	Figure 24, Table 6
Interannual variability - start October 30 from entire Black Sea basin	**Chapter 5**
Advection only	Figure 28, Table 7
Directed movement towards SE, ESE, SSE, S direction with 1 bl/s	Table 8
Directed movement towards SE, ESE, SSE, S direction with 3 bl/s	Table 9
Temperature following with 1 and 5 bl/s	Figure 29, Table 10
Seasonal variability - start September 15, 30 and October 15 in 2003	**Chapter 6**
Advection only / temperature following with 5 bl/s: NWS area	Figure 30, Table 11
Advection only / temperature following with 5 bl/s: Kerch Strait area	Figure 31, Table 12
Advection only / temperature following with 5 bl/s: northern basin	Table 13
Advection only / temperature following with 5 bl/s: central Anatolia	Table 14
Interannual variability - backtracking from overwintering area	**Chapter 7**
Advection only / temperature following with 5 bl/s: start December 30 (62 days)	Figure 32
Advection only / temperature following with 5 bl/s: start November 30 (31 days)	Figure 33

To incorporate movement of anchovy following temperature gradients this study follows the parameterization of Xu et al. (2013). Daily distance an individual could swim is then calculated by multiplying the swimming speed (bl/sec) with the number of seconds (86400) in a day. Then the temperature in all directions surrounding the drifter location is checked for the warmest temperature within a radius of distance that anchovy can swim. Because temperature changes only daily in these satellite derived 2-D fields, this is a valid simplification instead of checking temperature at each time step (1hr). Second, the drifter keeps swimming towards that direction at the given speed at each time step during that day although its position keeps being readjusted by advection. Keeping the direction of the drifter throughout the day is reasonable given again the fact that in this study current velocities are derived from daily velocity fields. The resultant displacement of the drifter is obtained by adding the behavioral movement vector to that of advective velocities starting from the drifter’s initial position (Figure 7). The choice of picking the same initial position for both behavioral movement and advection is a reasonable assumption supported by an earlier sensitivity study done by Xu et al (2013).

As detailed above in Equation 2, movement in the model is established by adding behavioral component (swimming) (V_b) on top of passive movement through advection (V_a). At each time-step behavioral movement is added on top of geostrophic velocities and as the drifter moves, its position is updated in continuous terms, as space and time (Figure 7). Swimming speeds are calculated by multiplying the mean length of anchovy in the super individuals by the number of body lengths individuals are assumed to be able to swim within a second (bl/s). As mean length of individual adult anchovy 10 cm is assumed in this study.

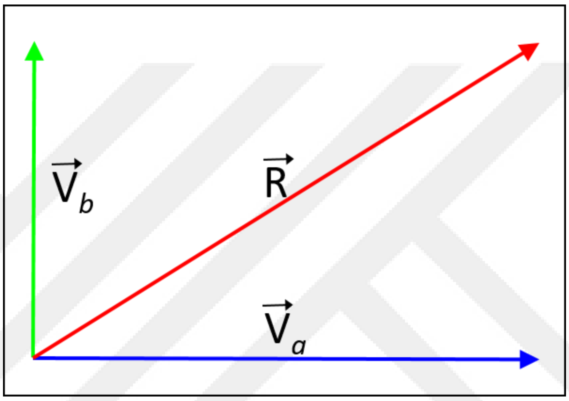

Figure 7 Schematic representing the calculation of the movement in the model.

2.4 Statistical Reliability Study

To assure the choice of number of drifters tracked from different areas of the Black Sea in each simulation is sufficient and not biasing the results of the modeling study a statistical reliability study is performed. Results obtained with tracking 1026 drifters released from the northwestern shelf are compared with a simulation that released 7888 drifters from the same region with 1 bl/s swimming speed on October 30 of 2001, 2002 and 2003. Results of this analysis are documented in (Table 2), showing that the % difference between the simulation results with 7888 versus 1026 drifters is calculated to be low (0.1, 5.2 and 0.0% towards SE and 0.1, 3.0 and 9.8% towards ESE in 2001, 2002 and 2003, respectively). It is found that the results between both simulations do not differ significantly and the percentages of drifters reaching the overwintering area are very similar and the observed maximum difference (of 9.8%) is within the acceptable ranges. To visiualize this minor difference between simulations, the spatial distribution of source areas for successful drifters migrating 2, 4, 6 and 8 weeks in 2001, 2002 and 2003 using 7888 (Figure 8a,b,c) and 1026 (Figure 8d,e,f) drifters are provided in Figure 8. It is seen that there is a significant spatial overlap between the areas the successful drifters originate from. Hence, tracking smaller number of drifters is a reasonable choice in reducing CPU requirements and run time.

Table 2 Statistical reliability analysis results for the employing 7888 and 1026 drifters that are started in mid-October from North-western shelf and swim with 1 bl/s along SE and ESE direction in years 2001, 2002 and 2003.

Simulation	Drifters	Start date	Year	Speed	Direction	2 weeks	4 weeks	6 weeks	8 weeks	Total arrival	Success %	Figure #
Directed swimming	7888	OCT 30	2001	1 bl/s	SE	0	119	925	1451	2495	31,6	8a
"	7888	OCT 30	2002	1 bl/s	SE	0	42	254	2113	2409	30,5	8b
"	7888	OCT 30	2003	1 bl/s	SE	0	266	126	613	1005	12,7	8c
"	7888	OCT 30	2001	1 bl/s	ESE	0	0	415	2039	2454	31,1	not shown
"	7888	OCT 30	2002	1 bl/s	ESE	0	0	679	3356	4035	51,2	not shown
"	7888	OCT 30	2003	1 bl/s	ESE	0	0	132	792	924	11,7	not shown
"	1026	OCT 30	2001	1 bl/s	SE	0	9	25	291	325	31,7	8d
"	1026	OCT 30	2002	1 bl/s	SE	0	5	19	236	260	25,3	8e
"	1026	OCT 30	2003	1 bl/s	SE	0	0	10	120	130	12,7	8f
"	1026	OCT 30	2001	1 bl/s	ESE	0	0	8	310	318	31	not shown
"	1026	OCT 30	2002	1 bl/s	ESE	0	0	9	486	495	48,2	not shown
"	1026	OCT 30	2003	1 bl/s	ESE	120	0	0	0	120	11,7	not shown

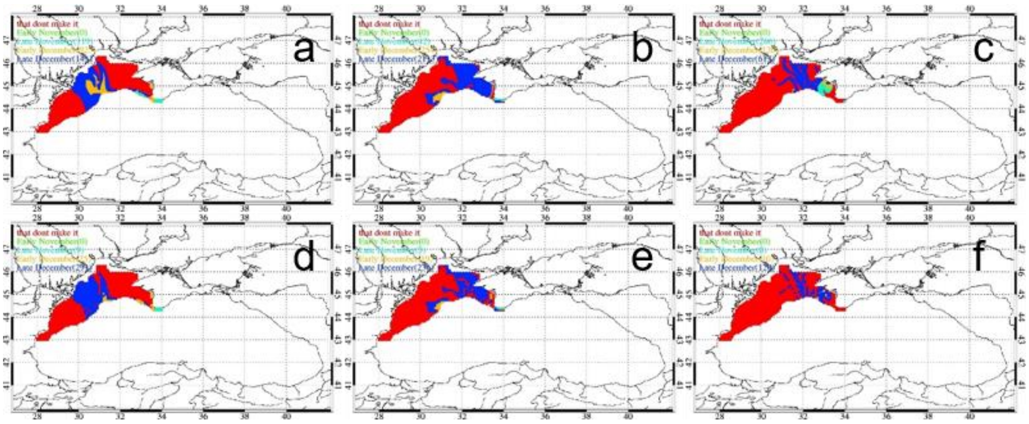

Figure 8 Release points of the 7888 (a, b, c) versus 1026 virtual drifters (c, d, e) launched on October 30 2001 (a, d), 2002 (b, e) and 2003 (c, f), respectively. Drifters are simulated to swim towards SE with 1 bl/s and the release points of those reaching the overwintering area in 2, 4, 6 and 8 weeks are color-coded as green, cyan, yellow and dark blue, respectively. The ones that do not are marked as red.

2.5 Altimeter Data Uncertainty

Data of sea surface height obtained by satellite altimeter are associated with errors. Errors in the estimation of mean sea level occur due to different factors, of which the main contributors are listed as orbit determination (+/-0.15 mm/year), the wet troposphere (+/-0.30 mm/year), corrections from weather data fields (+/-0.10 mm/year), altimetry parameters itself (+/-0.10 mm/year) and SSH bias (+/-0.25 mm/year), and amount to a total error of +/-0.6 mm/year with a confidence interval of 90% (Ablain, et al., 2009).

Because of a lack of accuracy on the knowledge of the geoid (10 cm at scales greater than 1000 km), the sea level anomaly is calculated precisely with respect to a predetermined mean (Le Traon & Gauzelin, 1997). Errors are caused by the worsening uncertainty in geoid height at scales less than 1000 km and the forced oscillation of the sea surface in the marginal seas in estimating the dynamical sea level. In the case of the Black Sea however tidal and wet troposphere refraction corrections can be disregarded (Koblinski et al., 1999, Korotaev, et al., 2001).

However, in the Black Sea the effect of water exchange through the boundaries of the basin, and steric oscillations of the sea level are of importance. For the Black Sea previous studies have estimated the root mean square accuracy of altimeter data to be between 3 to 5 cm (Koblinski et al., 1999b), which was further evaluated through validation against Black Sea hdrography data by Korotaev et al. (2001) and found to be 3 cm. Hereby the highest root mean square values are observed along the Rim Current (3 cm) characterized by low mesoscale variability and the regions of increased variability (i.e., the Northwestern shelf) (Blatov et al., 1984 as cited in Korotaev et al., 2001). The latter is attributed to the high-frequency oscillations (western phase propagations) in the region (Korotaev et al., 2001).

Chapter 3

ANALYSIS OF TEMPERATURE AND GEOSTROPHIC CURRENT VARIABILITY IN THE BLACK SEA

In this chapter, an extensive analysis of temperature and surface geostrophic current variability available from satellite data during autumn and winter of the years 2001-2003 is presented to elucidate the influence of different circulation features and temperature distribution on anchovy overwintering migration. As detailed above in chapter 2, choosing the years 2001 to 2003 makes it possible to evaluate the extent of environmental variability on both seasonal and inter-annual migration patterns. To do so the weekly sea surface temperature, geostrophic currents and ADT data from September to December of the years 2001 and 2003 are analyzed in detail.

3.1 Results

Figures 9 through 20 show weekly mean SST, geostrophic currents and absolute dynamic topography (ADT, which will be referred to as, '*sea surface heights (SSH)*' from hereon) variability fields over the Black Sea basin in four particular months (September, October, November, December) during years 2001, 2002 and 2003. The environmental variability in the months September to December are of importance because his is the time window during which anchovy migration is likely to happen (Ivanov and Beverton, 1985; Chashchin and Akselev, 1990; Chashchin, 1996; Lisovenko and Andrianov, 1996; Panov and Spiridonova, 1998; Shulman et al., 2008).

Table 3 Monthly mean SST (°C) values over the Black Sea basin during September, October, November and December of 2001, 2002 and 2003.

Year	September	October	November	December
2001	23,7 ± 0,81	19,9 ± 0,94	14,4 ± 1,00	10,0 ± 0,99
2002	23,2 ± 0,99	19,8 ± 1,37	15,3 ± 1,18	11,3 ± 1,12
2003	22,6 ± 0.72	18,6 ± 0.95	13,5 ± 0.89	10,7 ± 0.91

In 2001, the estimated monthly basin averaged SST value in September is 23.7±0.81°C (Table 3). Cooling progresses and by October the mean temperature decreased by almost 4°C, and drops again by more than 5°C between October and November, further decreasing to 10°C by December. Spatially speaking the initial cooling starts within the northwestern shelf area during the last week of September (Figure 9) and it intensifies during the following month (Figure 10). By November, the cold SST signal is seen to expand all over the basin excluding the Batumi Gyre area and southern coastal areas (Figure 11). The cooling results in a northwest-southeast (will be referred to as 'NW – SE' from hereon) gradient over the basin. The formation of Sevastopol eddy in the third week of September helps continuous transport of warmer waters into the colder NWS region during nine weeks from the first week of October (Figure 10) to the second week of December (Figure 12). The Sevastopol eddy propagates westward along the shelf break and attaches itself to the shelf break front in November. Representative of the summer characteristics, the interior basin has a composite structure in the first week of September that results in relatively strong peripheral flow. However, this composite interior cell structure subjects to disintegration during autumn with increasing basin wide mesoscale variability. One of the most dominant mesoscale features of the basin together with the Sevastopol eddy is the Batumi eddy. However, the Batumi eddy is seen to turn into a mushroom shaped structure and therefore losing intensity by the second week of September. Thus, it never attains its full intensity until the end of 2001. Kerch, Caucasus, Suchumi, Sinop, Bosphorus and Constansa eddies are the active structures during September, Crimea, Sevastopol, Caucasus and Suchumi eddies are the dominant features in October and November. In December, with the establishment of a strong contrast between the coastal region and the inner basin, the Rim Current recovers and the system switches to a strong winter mode. In 2001, the system is subject to prolonged cooling and high mesoscale variability causing the occurrence of a number of coastal eddies.

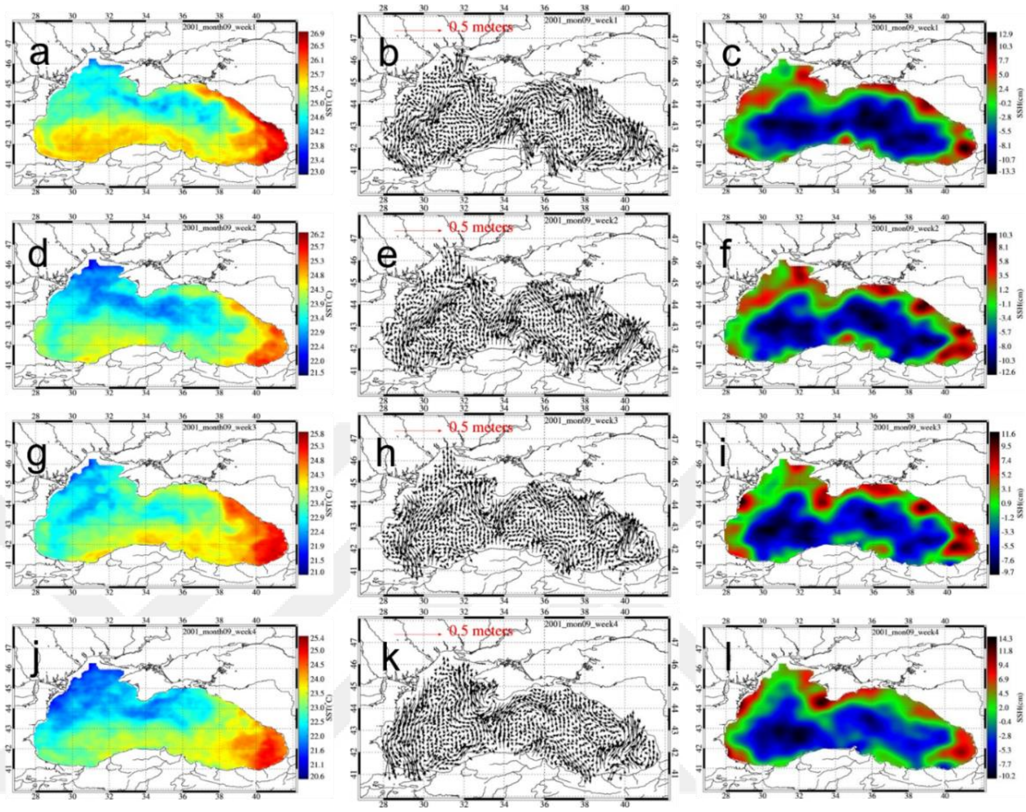

Figure 9 Mean SST, geostrophic currents and SSH fields (columns) for the 1st, 2nd, 3rd and 4th week (rows) of September 2001.

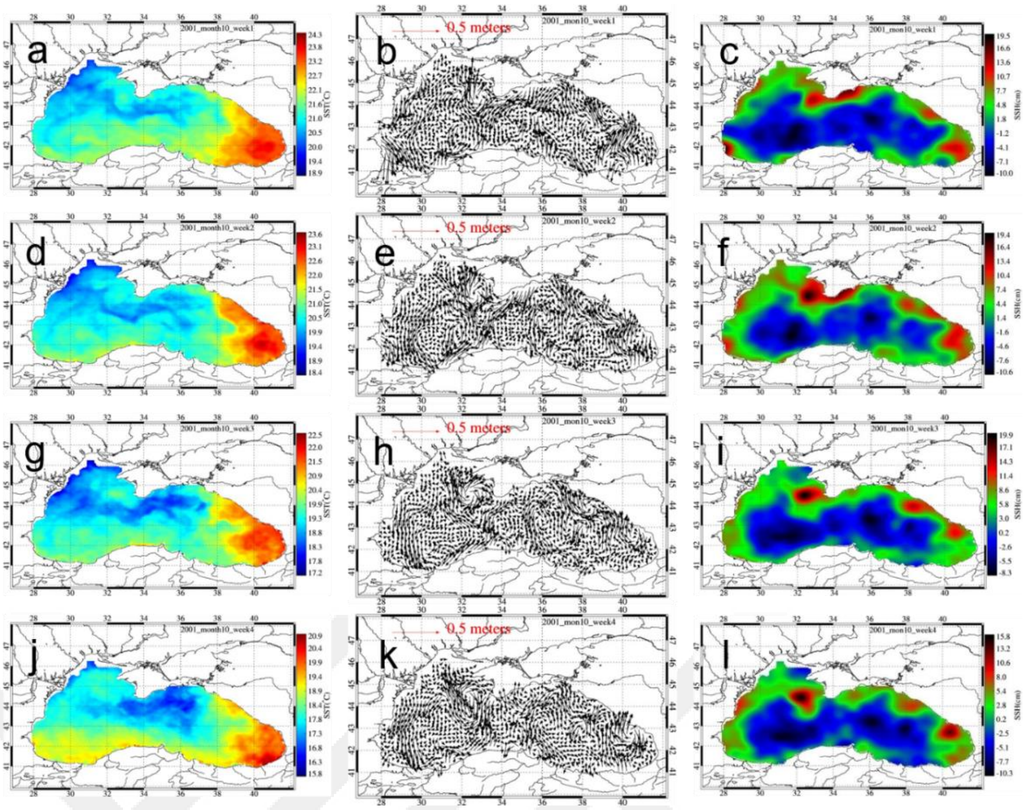

Figure 10 Mean SST, geostrophic currents and SSH fields (columns) for the 1st, 2nd, 3rd and 4th week (rows) of October 2001.

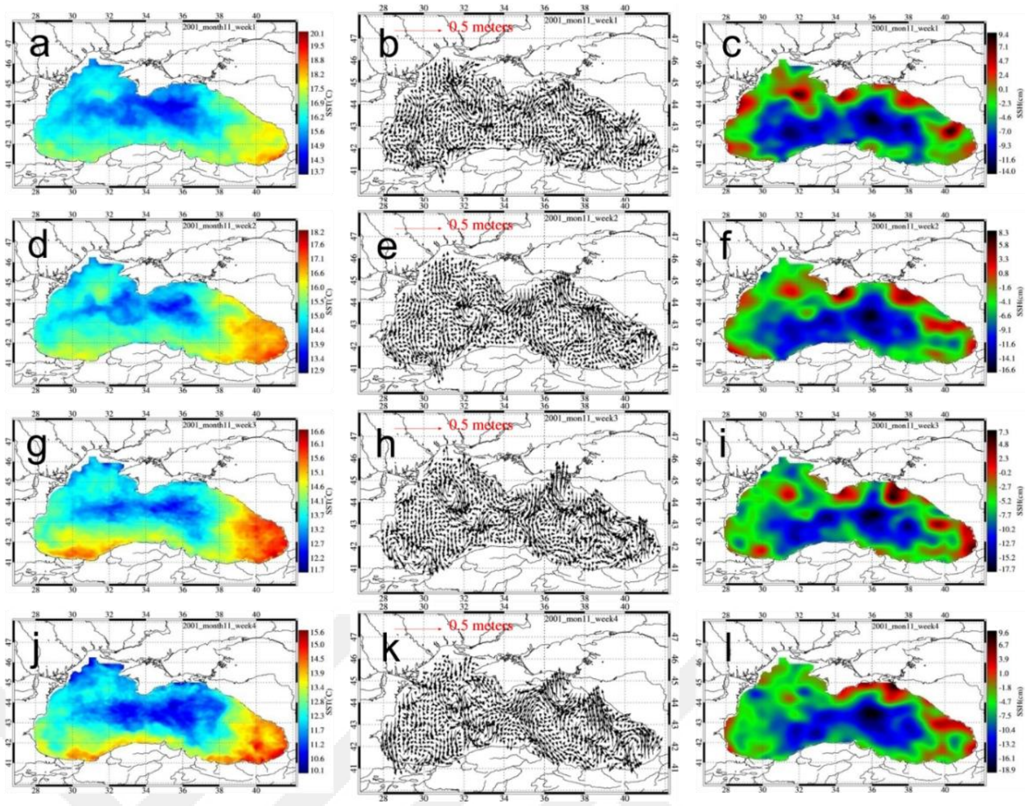

Figure 11 Mean SST, geostrophic currents and SSH fields (columns) for the 1st, 2nd, 3rd and 4th week (rows) of November 2001.

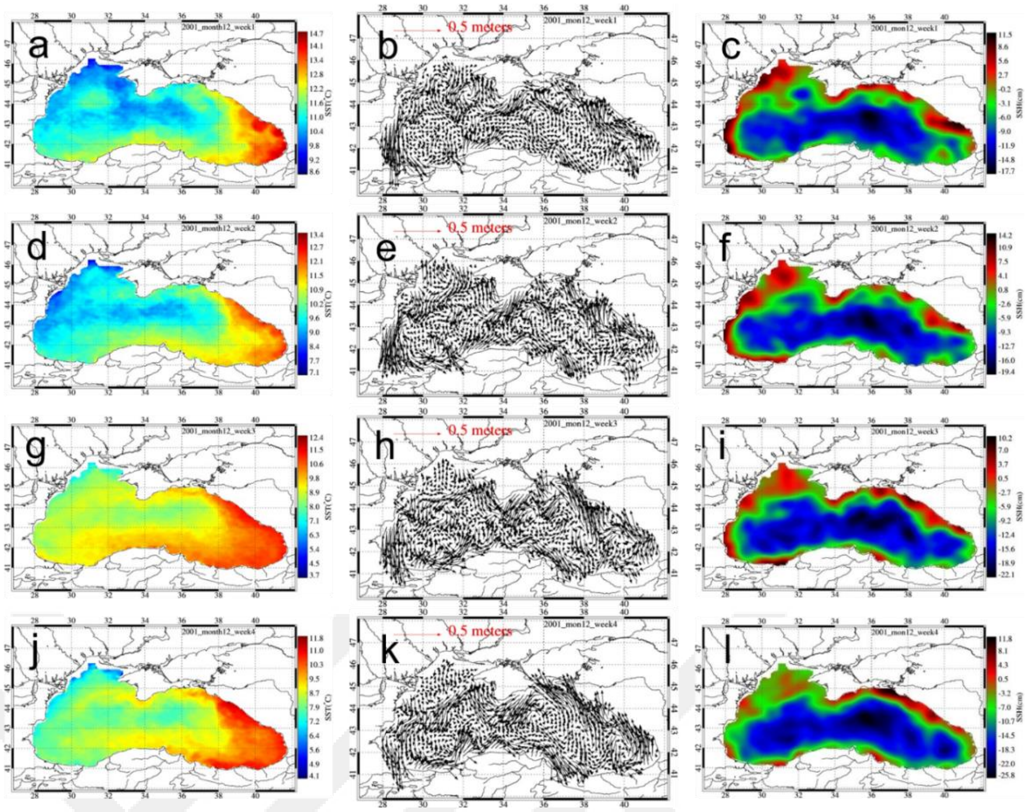

Figure 12 Mean SST, geostrophic currents and SSH fields (columns) for the 1st, 2nd, 3rd and 4th week (rows) of December 2001.

The monthly mean SST value of September 2002 is similar to 2001 with 23.2±0.99 (Table 3). By October the mean temperature decreased by 3.5°C, further decreasing by 4.5°C between October and November and finally arriving at 11.3±1.12°C in December, which means that the Black Sea is on average 1°C warmer in November and December of 2002 compared to 2001. However, the mean temperatures across the entire Black Sea cannot show the difference how cooling spreads across the Black Sea. In 2002 cooling starts in the third week of September (Figure 13) at the west coast of the Black Sea and the very cold SST is seen to enter into the eastern inner basin during the following weeks. In the first three weeks of October (Figure 14), the very cold temperature signal is seen to cover all over the western basin that resulted in better lateral mixing and therefore a stronger west – east (will be referred to as 'W – E' from hereon) SST gradient. In the second week of November (Figure 15) very cold SST coverage is observed in the western basin. A similar and a more wide-spread cold SST domination event is also observed during the first week of September that in turn resulted in a stronger Rim Current flow structure. In 2002, the autumn months which are generally characterized by increased variability, display the lowest variability structure among all years. The most unorganized time frame of this relatively stable period corresponds to the last two weeks of October. The most prominent feature of this stable flow system is the Batumi eddy that persists from the beginning of September to the end of December (Figure 16).

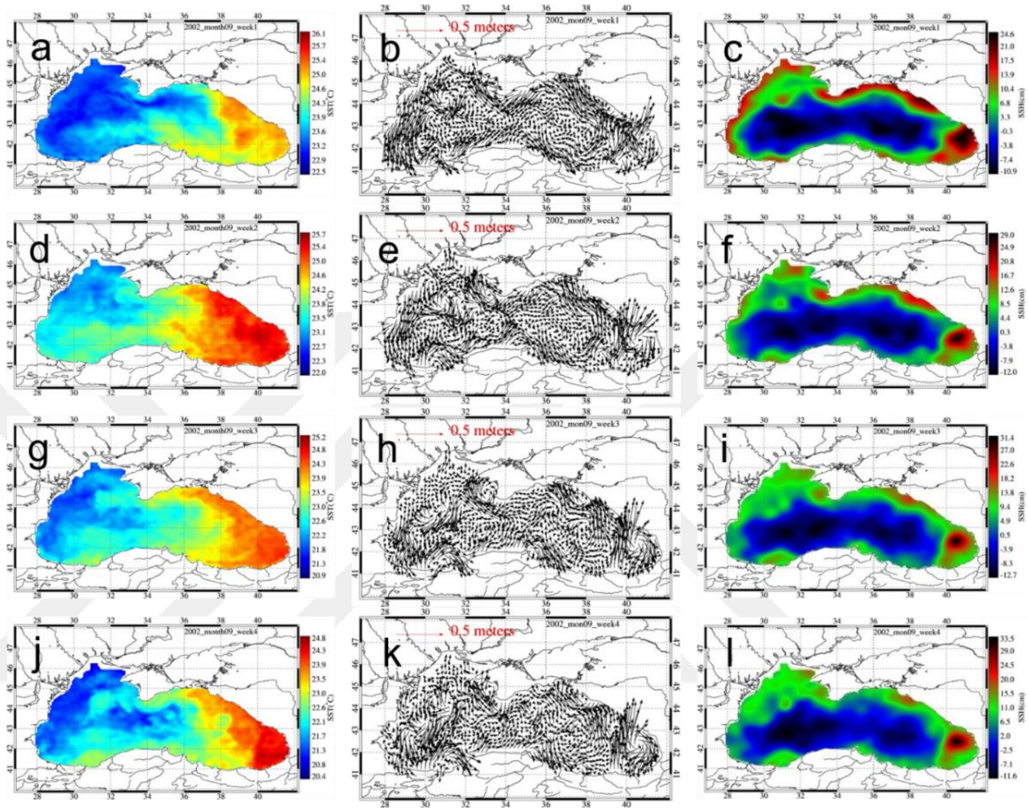

Figure 13 Mean SST, geostrophic currents and SSH fields (columns) for the 1st, 2nd, 3rd and 4th week (rows) of September 2002.

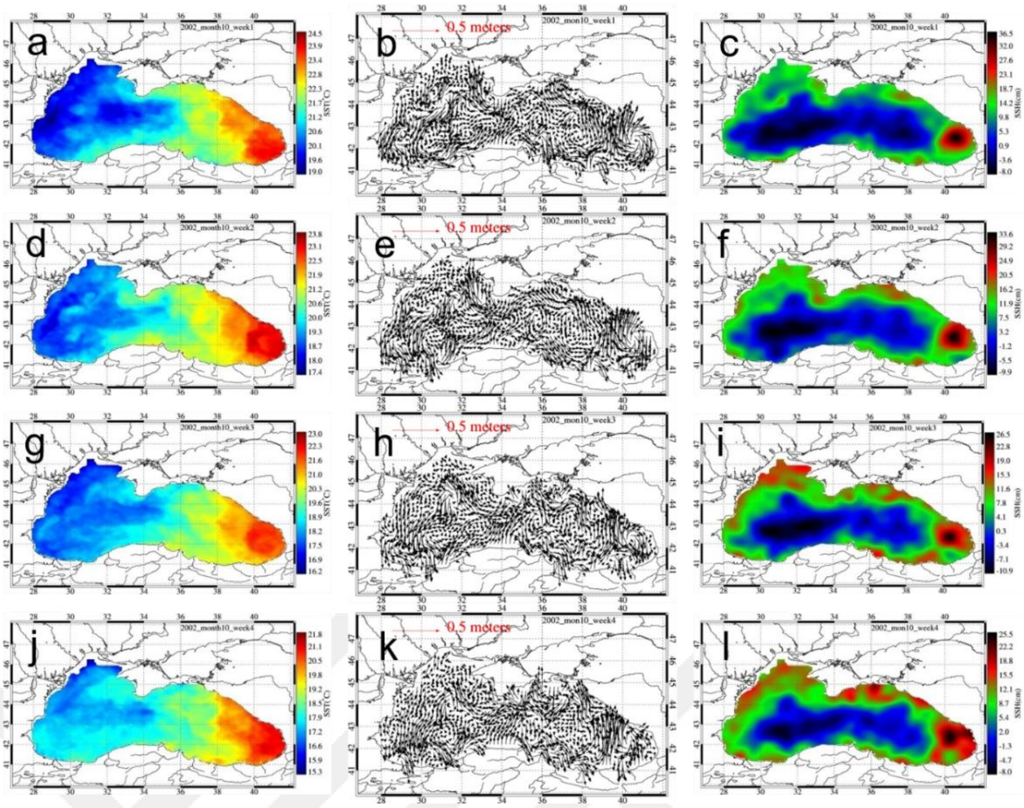

Figure 14 Mean SST, geostrophic currents and SSH fields (columns) for the 1st, 2nd, 3rd and 4th week (rows) of October 2002.

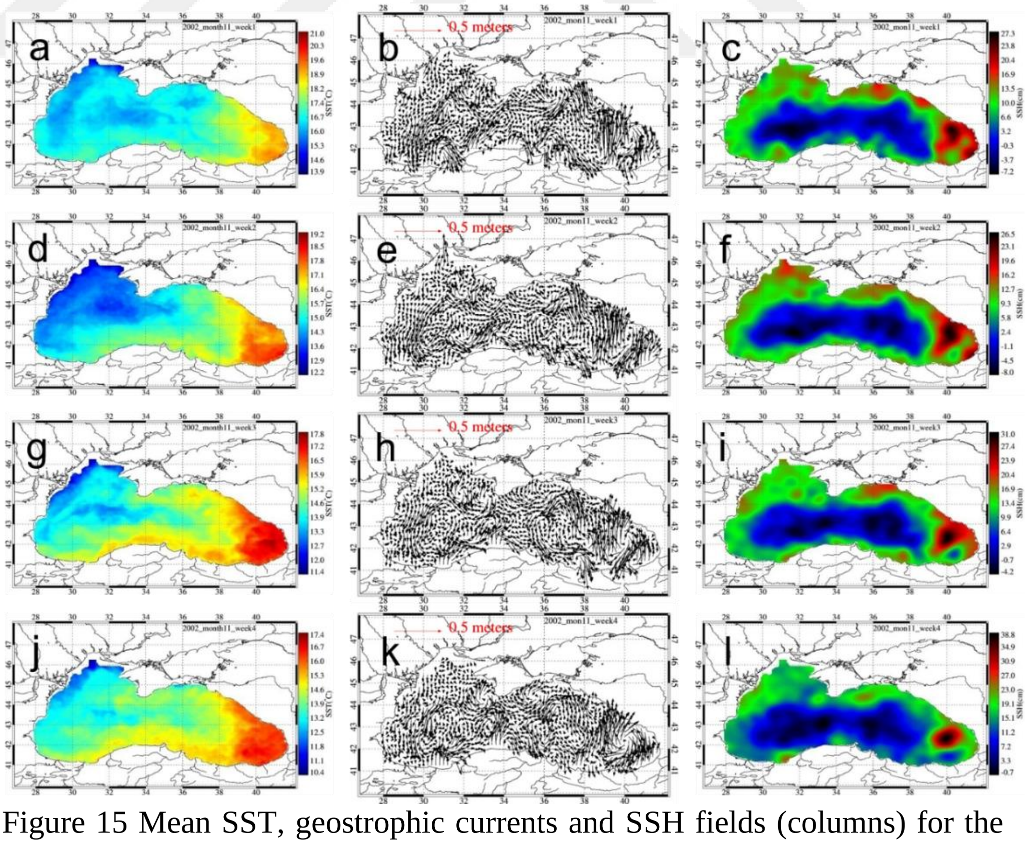

Figure 15 Mean SST, geostrophic currents and SSH fields (columns) for the 1st, 2nd, 3rd and 4th week (rows) of November 2002.

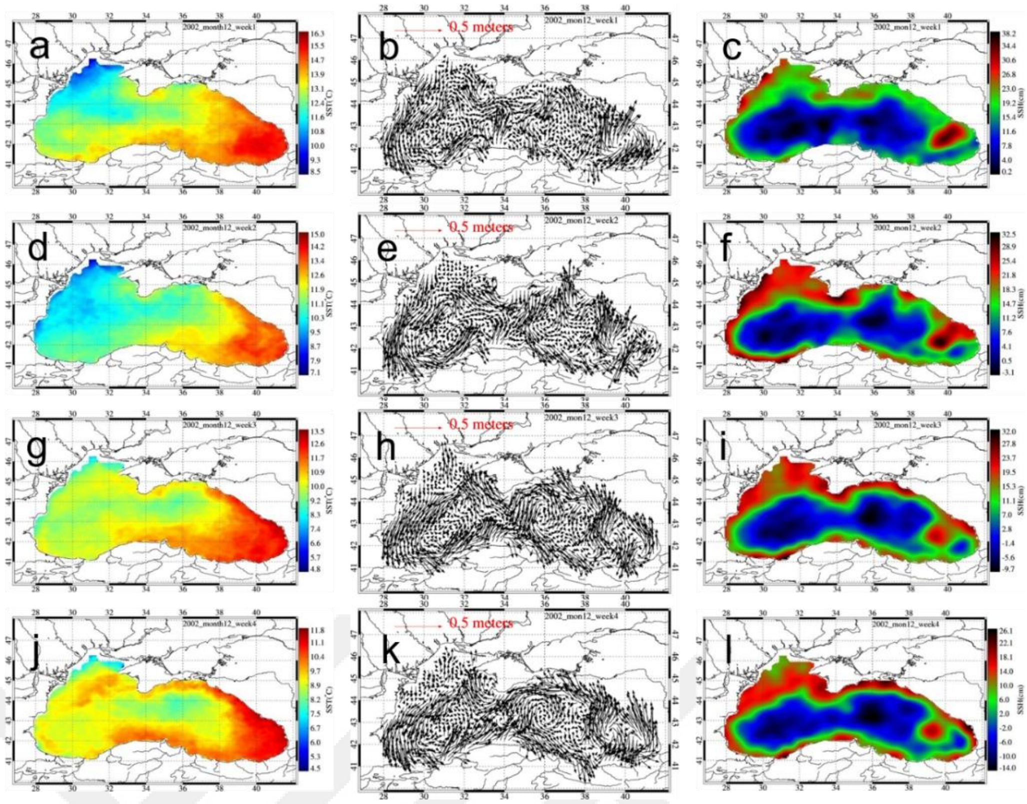

Figure 16 Weekly mean SST, geostrophic currents and SSH fields (columns) for the 1st, 2nd, 3rd and 4th week (rows) of December 2002.

In September 2003 the calculated monthly basin averaged SST is 22.6±0.72°C, which is 0.5°C lower than in 2001 and 2002. A 4°C drop in temperature is observed from September to October and a more than 5°C temperature drop is observed in the overall mean SST from October to November, leading to mean SST values that are ~1°C colder in October and November 2003 than in previous years. The mean basin-wide SST in December is 10.7°C. While in September of 2001 and 2002, the peripheral flow system is more stable to the stronger interior cell remnant of the summer structure, in September 2003, exceptionally high variability conditions are observed over the entire basin (Figure 17). These conditions are characterized with the absence of the Rim Current and the presence of stronger anticyclonic eddies within the entire basin. The main features of this unusual system are then the strong Bosphorus, Crimea, Caucasus, Batumi, Sevastopol eddies and the anticyclones at the southern part of the Crimea eddy and western part of the Sevastopol eddy. Although still very high, the slight decrease in variability leads to the formation of an unorganised boundary flow (Rim Current) structure at the western, eastern and northern coasts of the basin in October (Figure 18). In October, the shift in Sevastopol eddy towards the shelf break region while attaching itself to the shelf break front is observed at the NWS area. The Crimea eddy and the small anticyclone at the southern part of Crimea eddy still persist in this period. Moreover, the intrusion of Caucasus eddy southwestward into the eastern inner basin via becoming a filament-like structure is observed in this period. This structure further connects with the eddy at the southern part of Crimea eddy at the southwest and with the Batumi – Suchumi filament-like structure along the eastern coast within the second week of October. This connection enables the formation of strong jets around the eastern gyre. In the third week of October, strong cooling is seen to take place at the northern half of the western basin (including the NWS area) and extending towards the northern parts of the eastern basin. The cooling resulted in a NW – SE SST gradient within the basin that is more significant during November (Figure 19). The approach of cooling result in stronger currents that eventually create a strong SSH gradient across the coastal and open sea regions and leads ot the formation of strong boundary flow (Rim Current) encircling the basin starting from the second week of November. Although, the establishment of a better structured Rim Current acts to smooth out the activity of strong eddies (Sevastopol, Batumi, Crimea Eddies) within the basin and hence the system enters the winter mode earlier, the eddy at the southern part of Crimea eddy is seen to establish a connection between the Anatolian coast (Kizilirmak region) and the Crimea region and therefore remain as a natural barrier between the western and the eastern basin. In 2003 November, the flow system reaches its highest intensity and maintains a continuous flow all over the basin for four weeks starting from the second week of November. However, this high variability system loses its intensity by the second week of December and the Rim Current becomes weaker (Figure 20). The mesoscale variability in the system is increased compared to the November period of 2003 and with respect to the low mesoscale variability systems during December of 2001 and 2002.

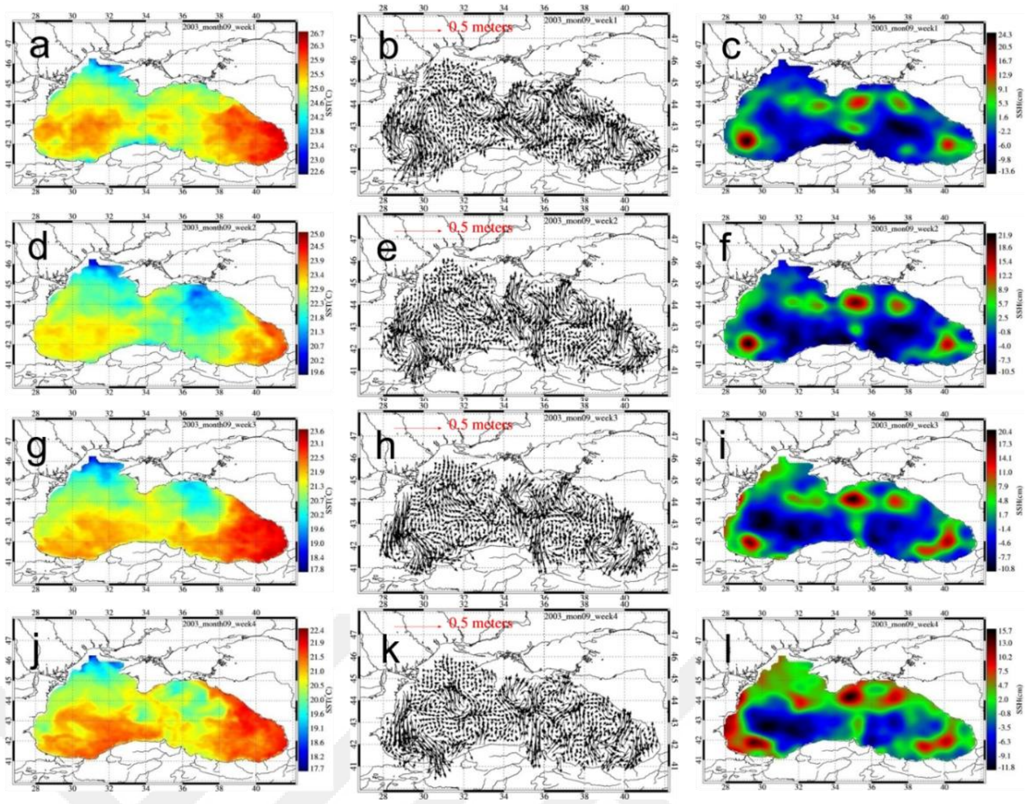

Figure 17 Mean SST, geostrophic currents and SSH fields (columns) for the 1st, 2nd, 3rd and 4th week (rows) of September 2003.

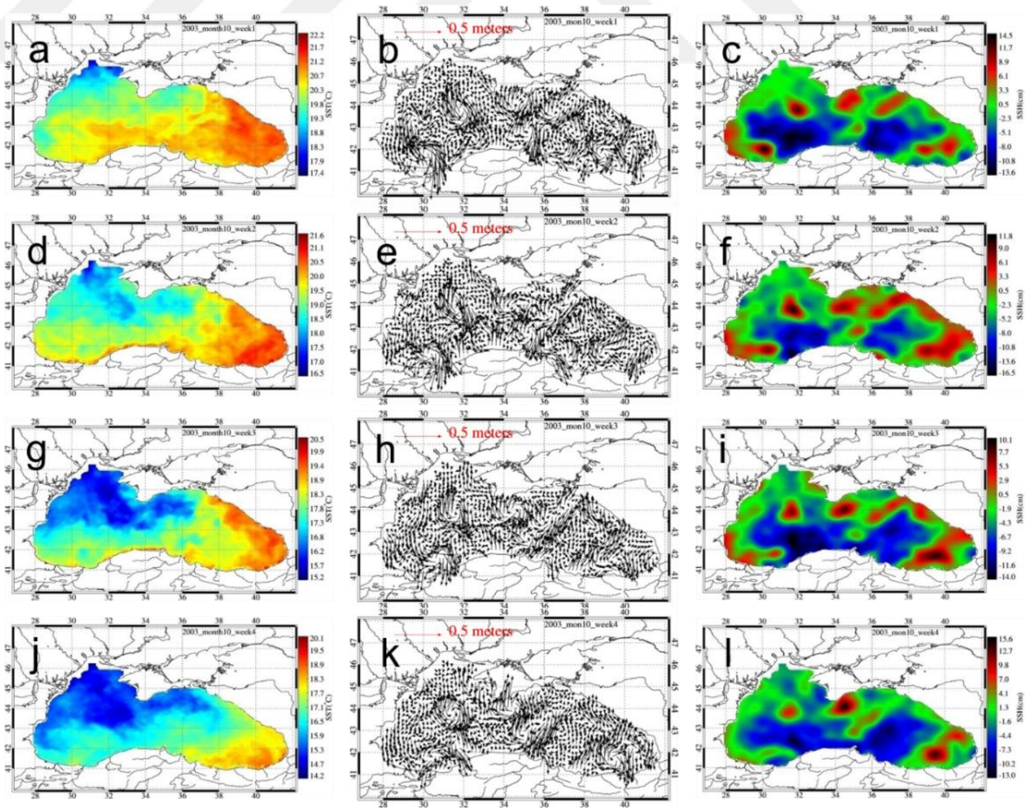

Figure 18 Mean SST, geostrophic currents and SSH fields (columns) for the 1st, 2nd, 3rd and 4th week (rows) of October 2003.

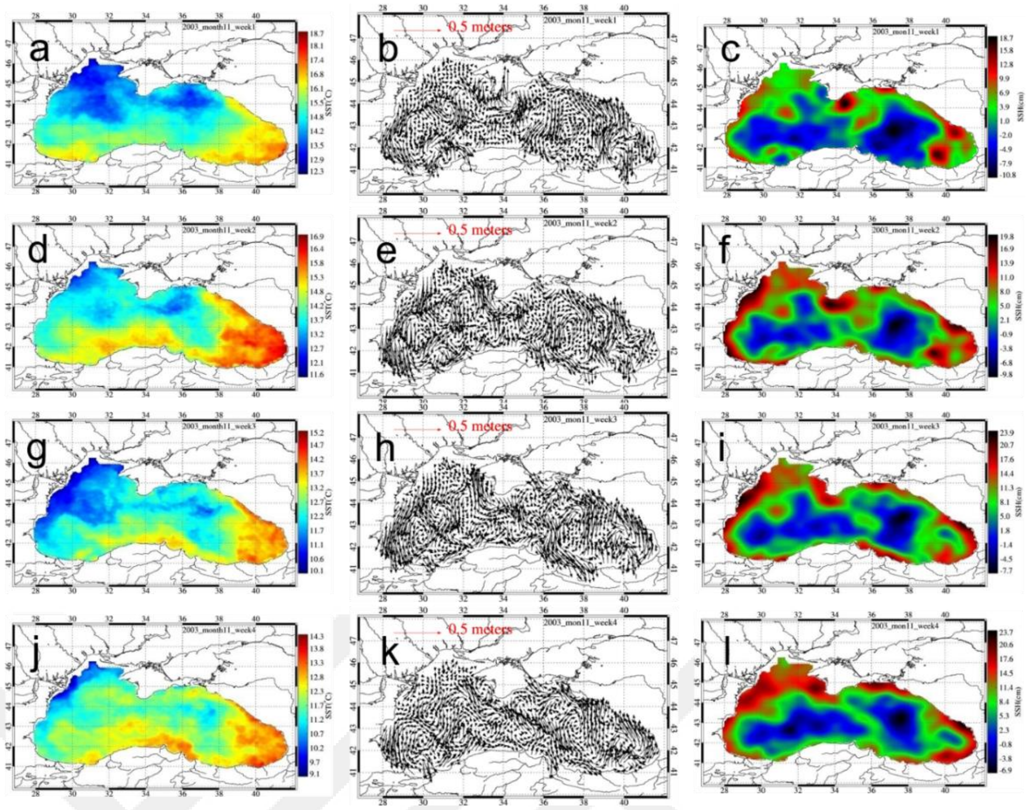

Figure 19 Mean SST, geostrophic currents and SSH fields (columns) for the 1st, 2nd, 3rd and 4th week of November 2003.

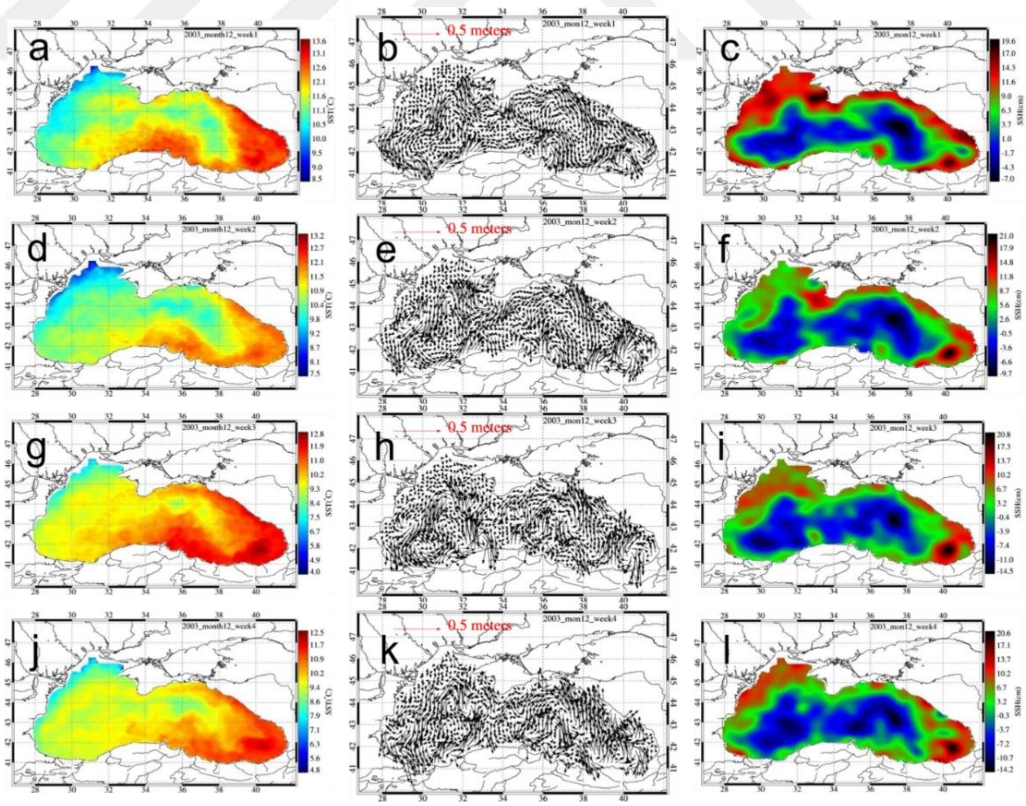

Figure 20 Mean SST, geostrophic currents and SSH fields (columns) for the 1st, 2nd, 3rd and 4th week (rows) of December 2003.

3.2 Discussion

3.2.1 Temperature variability

The mean SST value analysis over the entire basin indicate distinct differences in the cooling process among the years of interest, in terms of timing (of the specific years) and rates (across the weeks) that has implications for the migration of anchovy in the Black Sea. The year 2001 has the highest September (23,7±0,81°C), October (19,9±0,94°C) mean SST values with respect to years 2002 and 2003 whereas the December of 2001 (10,0±0,99°C) is the coldest among the Decembers. Each year a sharp drop in monthly mean SST occurs between October – November which amounts to 5.5°C, 4.5°C and 5.1°C in the years of 2001, 2002 and 2003, respectively. The external trigger for anchovy to start migration is the cooling (i.e., sudden drop of temperature). So according to the analysis above it is likely that anchovy started migrating later in 2001 than 2002 and 2003. Earliest migration may have started in the cold year 2003. However, not only the onset of cooling but the cooling patterns (the direction of temperature gradient) may also have an effect on the fate of migration of this species. It is assumed that anchovy follow a temperature gradient towards warmer regions and in the 2001 and 2003 migration season, the cooling propagated along NW – SE direction, as the strong cooling phase occurred in November and October, respectively. However, in case of 2002, the SST gradient is along W – E direction and strong cooling takes place in October. These effect of these different spatial patterns on migration success will be elucidated in detail in chapters 4 and 5.

The overall analysis results show that the NW shelf region is significantly colder than the rest of the basin. However, when the Sevastopol eddy forms attaching itself to the shelf-break front at the NWS region and the activity of Rim Current increases in this region, significant exchange (of water mass and biota) between the shelf and the open sea occurs (Oguz et al., 1992; Shapiro, et al., 2010). When this happens the NWS area becomes considerably warmer (Capet, et al., 2012). The satellite data analyses performed in this study support this hypothesis. For instance, during October, November and December (first two weeks) of 2001, the formation of a strong Sevastopol eddy at the western coast of Crimea and then shifting towards the shelf break with the presence of an uninterrupted (continuous) active Rim Current in this region result in significant warming at the shelf through cross shelf transport mechanism. Moreover, in September 2002, the formation of Sevastopol eddy at the western part of Crimea and its connection with an eddy at the shelf-break area results in transport of warmer waters into the NWS. On the other hand, in October 2003 the presence of strong Sevastopol eddy at the shelf break region is not applicable for establishment of cross-shelf transport mechanism alone unless the active Rim Current presents at the shelf-break zone.

The inter-annual and seasonal variability in the SST is largely due to the weather systems operating over the Black Sea region. However, weather system dominating the basin is not uniform as there are various systems, i.e., Siberian anticyclone is responsible for more severe climate conditions over the northern and northeastern parts of the basin (Shapiro et al., 2010) and the milder Mediterranean weather system dominating at the southern parts of the basin (Sukhovey, 1986).

The general atmospheric patterns are characterized by the dominance of Azores and Siberian high versus Asian low-pressure systems (Arkhipkin, et al., 2014). With the onset of winter cooling in late October and November, the eastward moving cyclonic formations are frequently visiting the area (Özsoy & Ünlüata, 1997). The Carpathian Mountains, Transylvanian Alps and Balkan Mountains act as a natural barrier for the entrance of air masses from the west whereas the low level Marmara Sea allows air passage (Ozsoy and Unluata, 1997). The North Anatolian mountains in the south and Caucasian mountains in the east block the air flow (Brody and Nestor, 1980) rendering the Black Sea accessible to cold air masses from north through the flat-lying Crimea especially during times when there is prolonged anti-cyclone domination over the Balkans (Ozsoy and Unluata, 1997). Prevailnace of northerly winds are observed in the western basin and as the travel eastward cyclonically they become northwesterlies (Oguz et al., 1996). The wind patterns remain variable during winter (Ozsoy and Unluata, 1997). The NWS area is often subject to gales in winter as they bring cold and dry northerly winds (Ozsoy and Unluata, 1997).

These regional athmospheric conditions such as wind stress, evaporation, precipitation and pressure, have been shown to be influenced by the North Atlantic Oscillation (NAO) (Oguz et al., 2006). In the Black Sea a positive NAO index means cold and dry winters, and a negative NAO results in milder and wetter winters (Oguz et al., 2006). That is because the positive mode of NAO index is accompained by a sharp atmospheric pressure gradient between the Azores high pressure system and the Icelandic low, resulting in cold and dry air masses introduced to south Europe and the Black Sea via prevailig strong northwesterlies (Hurrell et al., 2003). On such occasions, the Black Sea region is influenced by the Azore high pressure center that is associated with elevated air pressure measurements at the surface (Oguz et al., 2006). The negative NAO index is linked with reduced atmospheric preesure gradients at the surface between the pressure centers of Azores high and Iceland low (Oguz et al., 2006) and characterized by milder winters and increased air temperatures. In such conditions, southwesterlies influencing the Black Sea introduces wetter winters (Oguz et al., 2006). The general wind regime over the Black Sea is characterized by two main patterns, southern-western (SW) and northern-eastern (NE) wind (Titov, 2003; Kazmin and Zatsepin, 2007). Moreover, Kazmin et al. (2010) states that in the Black Sea the positive phase of NAO results in weakening of the southern wind and the negative phase is associated with the strengthening of the southern wind. Moreover, it is suggested that in the Black Sea the elevation/drop in long-term winter mean surface air temperature (SAT) is correlated with intensification/weakening of the southern wind (Kazmin et al., 2010).

The second strongest influence on the regional atmospheric patterns of the Black Sea is the winter mean East Atlantic – West Russia (EAWR) index (Molinero et al., 2005). Its positive mode is linked to the combined effect of an increased anticyclonic center over the North Sea, and an increased cyclonic anomaly center over the Caspian Sea (Oguz et al., 2006). In such case, the Black Sea region is subjected to cold and dry air masses from the northeast-to-northwest sector. The negative mode is charaterized by the cyclonic anomaly center over the North Sea and the anticyclonic activity over the Caspian Sea region and the Black Sea region is affected by warmer and wetter winter conditions under the influence of increased southwesterlies-to-southeasterlies (Oguz et al., 2006).

3.2.2 Seasonal and Interannual Variations of the Black Sea Circulation

The Black Sea general circulation system has some distinct features during the course of a year. Although inter-annual variations may exist, at its most intense phase, in winter (January to March), it is characterized by well-defined strong cyclonic twin-gyre system around the periphery with anticyclonic eddies of the same strength appearing between the Rim Current and the coast (Korotaev et al., 2003, Oguz et al., 1994, Oguz et al., 1993). As the spring season approaches, the two-cell structure alters into single-cell form with weaker currents at the periphery, during April, May and June months (Korotaev et al., 2003).

During the summer months of July, August and September, the single-cell cyclonic structure breaks down to multiple cyclonic eddies (Korotaev et al., 2003). During the Autumn months (October, November, mid-December), the intensity of the summer circulation structure is subject to further weakening and the interior basin cyclonic circulation patterns disintegrate into smaller-size eddies (Korotaev et al., 2003) as the basin wide mesoscale variability reaches its highest level.

In this study the weekly mean SSH and flow field analyses of September 2001 and 2003 (Figure 17) revealed the presence of a number of smaller cyclones within the interior basin accompanied by a weaker interior basin structure. In 2003 September the Rim Current disappeared during the first three weeks of September whereas in September 2002, a more intense Rim Current summer structure existed compared to those observed during 2001 and 2003. Such contrasting summer flow dynamics are also observed by Korotaev et al. (2003) during the summer structure of higher mesoscale variability years (of 1993, 1994 and 1997) and lower variability years (of 1995 and 1996). The basinwide mesoscale variability increases further during autumn period and attains maximum level in November (Korotaev et al., 2003). Same situation applies to the flow structure in 2001 and 2002 as variability increases and strength of the peripheral circulation decreases from October to November. On the other hand, opposite situation happened in 2003 during October and November and the flow converted from being very turbulent, eddy dominated towards more stable and organized with respect to October 2003 (Figure 20). This situation indicates for a decrease in mesoscale variability over the basin from October to November 2003 which is expected to have important implications for the anchovy overwintering migration.

Over the course of the month December in 2001 and 2002 the system converts from a disorganized mode towards a more organized one. However, the Rim Current is not yet strong enough (discontinuous at the southern coast) to overcome the eddy activity at the shelf-break and the meanders at the northern coast in the first two weeks of 2001 and 2002 but in the second part of December the Rim Current strengthens at the southern coast and enters into its well-structured winter phase.

Furthermore, the geostrophic current speeds in the present study along the axis of the Rim Current are calculated in the range between 0.2 – 0.3, 0.25 – 0.35 and 0.2 – 0.25 cm/s when the system shows winter characteristics in December of 2001, 2002 and 2003, respectively. These values are similar to previous study results that state that the geostrophic currents attain speeds of 0.2 to 0.3 cm/s on the periphery of the Rim Current (Oguz et al., 1994; Oguz et al., 1995). However, Acoustic Doppler Current Profiler (ADCP) measurements suggest a more intense Rim Current with speeds exceeding 50 cm/s at the surface layer (Oguz et al., 1995) which indicates that estimation of surface currents from satellite underestimates the actually currents.

To summarize, analysis of 2001 - 2003 in the Black Sea indicated a higher mesoscale variability during 2001 and 2003. In 2002 the Black Sea circulation is more stable. Such low variability and high stability is stated of being accompanied by the intensity of the interior basin cyclones that join to form larger cells (Korotaev et al., 2003). Korotaev et al. (2003) has observed cases of high variability in November associated great disorganization with weakest Rim Current intensities in 1993, 1994 and 1998 similar to our findings in 2001 and 2003. Moreover, in their analyses the Batumi eddy is seen to weaken similar that is in line with weakening observed in the Batumi eddy in 2001 and 2003 of the present study.

3.2.3 Mesoscale Features of importance for anchovy migration

The Batumi anticyclone is observed together with two neighboring eddies; a northern (Sukhumi) and a quasi-persistent south-western (Trabzon) eddy during 2001 and flow in the region is subject to strong variability. In 2003 this eddy is very weak, strengthening only in November and December. However, within the more structured flow system of 2002, the Batumi Eddy persists with a relatively high intensity from the beginning of September to the end of December. Therefore, the Batumi eddy is likely to be a strong retention area for migrating anchovy at slow velocities.

The Rim Current has a tendency to follow constant topography contours and flows closer to the coast in the south where it generates small amplitude meanders and sometimes coastal anticyclonic eddies (Korotaev et al., 2003). Along the Anatolian coast the Bosphorus and Batumi eddies have a quasi-persistent nature and appear close to the southwestern and southeastern edge of the Black Sea in most of the observations, respectively. They are seen to vary in position and strength in the years 2001-2003 and only very rarely disappear completely during the September-December timeframe, hence they are of importance for anchovy transport in those regions. Further along the coast the Sakarya, Sinop and Kızılırmak eddies are considered as “semi-persistent” as they do not appear as frequently as “quasi-persistent” Batumi and Bosphorus eddies (Korotaev, et al., 2003). The once or twice a year appearance of these eddies are mostly due to development of meanders in the Rim Current system, thus these eddies tend to shift in counter-clockwise direction (Korotaev et al., 2003). In the first two weeks of September 2001 (Figure 9b,c,e,f), all three of these eddies are present and also in 2002 they are observed. Over the course of time they are observed to shift towards the east and/or disappear. In September 2003 mesoscale features along the Anatolian coast are rare, excluding the quasi-persistent Bosphorus and Batumi eddies. Only at the end of September the three eddies are seen to form and meander along the coast. Though semi-persistent, these features can be quite important for the migration of anchovy, as they tend to help deliver anchovy to the overwintering region just east of them.

The Rim Current structure follows a further offshore path along the Caucasian region defined between the Batumi region at the southeast and Kerch Strait region at the northwest extent, thus creating greater magnitude meanders and larger form anticyclones at the coastal side (Korotaev et al., 2003). The Caucasian eddy forms as the Rim Current intrudes further into the interior part of Eastern Gyre (Korotaev et al., 2003). Moreover, the Kerch and Caucasus anticyclones have rather dynamically interacting features than being completely independent (Korotaev et al., 2003). Both these anticyclones are observed in the satellite data analysis and display strong variability between years. Of special interest for anchovy migration however is a feature that was observed in October 2003 (Figure 18), when the Caucasus eddy becomes elongated and together with the Rim Current forms a large offshore protrusion toward the interior of the eastern cyclonic gyre as has previously been suggested by Korotaev et al. (2003). This interior basin intrusion causes formation of a NE-SW jet cross-cutting the entire Eastern Basin for three weeks that weakens in the first week of November 2003 (Figure 19) and dissipates. This jet-like feature can facilitate fast transport of anchovy from the northeastern Black Sea towards the southwest.

There are two quasi-persistent anticyclones at the eastern and western coastal region of the Crimean Peninsula, the Crimea and Sevastopol eddies, respectively (Korotaev et al., 2003). While the Crimea eddy is generally confined to the southern tip of Crimea region, the position of the Sevastopol eddy depends on the position of the local structure of the Rim Current (Korotaev et al., 2003). The Sevastopol eddy either forms at the southwest part of Crimea within the strong offshore meander of the Rim Current as controlled by the strong topographic slope, or, divides into two northward branches at the western side of the Crimea and the Sevastopol eddy then forms at the coastal side of the northward branch (Korotaev et al., 2003).

In addition to these eddies, another small eddy on the western side of Sevastopol eddy was observed to be a persisting feature during September 2003. It merged with the Sevastapol eddy at the southwest side of the tip of Crimea in the third week of September, became larger and stronger and was situated on the shelf-break frontal jet remaining there for 8 weeks until the last week of November. This eddy is called 'the shelf-break front eddy' by Shapiro et al. (2010) and is likely of importance for transport of anchovy from the Crimea region towards the interior of the Black Sea.

The regional circulation pattern within the northwestern shelf is driven mainly by Rim Current intrusions and discharge by the Europe's major rivers, Danube, Dniepr and Dniestr. The riverine discharge by Danube is amounting to approximately 400% of the sum of the Dniepr and Dniestr rivers (Korotaev et al., 2003). Therefore, the characteristic flow structure follows a southward pattern during high discharge periods within the inner shelf region (Korotaev et al., 2003). However, the inner shelf basin is dominated by small coastal anticyclonic eddies of Danube eddy at the northern part of the NWS region, Kali-Akra at the narrow band at the southwestern part and Constansa eddy at the northern side of Kali-Akra eddy during low-discharge seasons, whereas during high-discharge seasons these eddies remain embedded within the regional flow system (Korotaev et al., 2003).

The buoyancy-driven current at the shelf and the Rim Current along the steep topographic slope together are suggested to be responsible for the formation of the strongest current in the basin (reaching 0.3 cm/s at the surface layer), a.k.a 'the shelf-break front' (Oguz et al., 1992, Oguz et al., 1994). During the time frame of the present study, the shelf break front is shown to reach its maximum speed (of 0.3 – 0.4 cm/s) during the September and October of 2002. Although the frontal structure at the shelf is one of the most persistent features of the thermohaline system, in the exceptional case of 2003 during September and October the shelf-break front is missing over the shelf region corresponding to the period of approximately zero wind stress anomaly calculated by

McQuatters-Gollop et al. (2008). At the time when the system switches to the winter mode in December of 2001 and 2002 and in November 2003, the speed of the shelf break front is then 0.15, 0.2 and 0.1 cm/s. However, the highest speed of the front is observed as 0.25 – 0.3 cm/s during the intense December of 2003, revealing a large potential for transport of anchovy in the area.

3.3 Conclusions

In the Black Sea the riverine discharge plus the high salinity Mediterranean under flow through the Bosphorus Strait together creates a strong density stratification and therefore renders upper 150 m of the water column more active and responsive to changes in the environmental conditions (Capet et al., 2012). The satellite data observations examined in this study confirm the spatially and temporally modified meanders at the periphery and the mesoscale eddies suggested in earlier studies (Oguz et al., 1992, Oguz et al., 1995, Korotaev et al., 2003). The geostrophic currents at the periphery of the Sevastopol, Crimea and Caucasus eddies at the north are stronger compared to the flow of the smaller and weaker eddies at the Anatolian coast (Oguz et al., 1994). This can be explained by the operating Siberian anticyclonic atmospheric forcing that is responsible for severity of the climate over the northern and northeastern parts of the basin (Shapiro et al., 2010a). On the other hand, the southern and southwestern parts of the basin is influences by the Mediterranean weather system that is characterized by milder climatic conditions in this area (Sukhovey, 1986).

The present study makes use of 12 months of AVISO sea surface heights anomaly data to evaluate the mesoscale, intra- & inter-annual variability in the surface circulation in the Black Sea with the help of AVHRR SST distribution during the same period. It should be kept in mind that the satellite sensors are associated with a certain degree of error when estimating sea surface level. The root mean square error for the Black Sea has been determined to be 3 cm (Korotaev et al., 2001). In addition, geostrophic currents do not represent any of the currents associated with turbulence. Therefore, the currents calculated from satellite data in this study is most likely underestimating the actual flow fields.

The flow dynamics in September represent the summer season dynamics and it is characterized by the presence of many small-scale cyclonic features within the interior basin as suggested by Korotaev et al. (2003). In the present study, during 2001 and 2003, September is a weaker and smaller eddy dominated system than the more composite and intense system of 2002. Therefore, in the case of September of 2001 and 2003, the Rim Current flow system around the interior cell is subjected to a more noticeable mesoscale variability. Correspondingly, during the summer season, the weak Batumi eddy is seen to coexist with Suchumi eddy during September of 2001 and exists alone in September of 2003, while a strong Batumi eddy is observed during September of 2002 in the presence of stronger flow structure within the interior cyclonic cell. The summer structure of the interior basin is then destabilized during the autumn months (October, November, and mid-December) and the flow is divided into smaller and weaker eddies. In this period the flow is least organized and most turbulent structure contrasting the well-organized winter case (Korotaev et al., 2003). The Rim Current weakens simultaneously with the weakening of the interior basin flow dynamics being subject to high level of lateral variability (Korotaev et al., 2003). The flow field in 2003 is exceptional, as there is a high degree of turbulence induced disorganization in the first three weeks of September that continues slightly reduced until November. However, from the second week of November until the second week of December the system enters into a more organized state, with a weak, meandering peripheral flow establishing. Therefore, the flow does not enter the well-organized circulation structure associated with winter that is usually observed in December.

The altimeter data analysis indicates a strong seasonal and year-to-year variability in the basin-scale peripheral circulation system. These findings are in agreement with findings of earlier studies that suggest that after each November-December the basin wide turbulent structure is promptly changing into a more intense and organized system (Korotaev et al., 2003). It is seen that the conversion from high variability to low variability state takes place by the third and second weeks of December 2001 and 2002, respectively, whereas in 2003 the transition to winter mode does not occur by the end of December. Moreover, Korotaev et al. (2003) suggested that each winter is characterized by a well-defined two gyre system without any significant lateral variability. This suggestion agrees well with the observed winter flow structure during December of 2001 and 2002, however not in 2003 during the winter state when instead a strong eddy extending between the northern (southeast Crimea) and southern (Samsun) coasts is observed.

Chapter 4

MODELING THE IMPACT OF INTER–ANNUAL ENVIRONMENTAL VARIABILITY ON ANCHOVY OVERWINTERING MIGRATION FROM THE NORTH-WESTERN SHELF REGION

In this chapter, the migration success of Black Sea anchovy originating from spawning and nursery grounds on the northwestern shelf (NWS) is tested using a total of 1026 virtual drifters located at the NWS area (< 200 m). The drifters are released at the end (30^{th}) of October in the years of 2001, 2002 and 2003 and are tracked over two months (eight weeks). Anchovy starts migration with cooling that takes place in autumn between October and November (Ivanov & Beverton, 1985; Lisovenko & Andrianov, 1996; Chashchin, 1995). Considering the period between October and November is the time of highest mesoscale variability in the Black Sea (Korotaev et al., 2003) as it also corresponds to autumn cooling, the choice of October 30^{th} as the start time of migration is a valid assumption for the experiment design. Moreover, arrival of anchovy schools to the south-eastern overwintering area is subject to significant year-to-year variability. Therefore, different types of migration behavior and their influence on migration success is explored via three different sets of simulations in which particle displacement is due to a) horizontal advection by the oceanic currents, b) directed movement with 1 and 3 body lengths/second (bl/s) towards SE and ESE direction in combination with the advection by surface currents, and c) movement following the highest temperature with 1 and 5 bl/s together with advection.

The choice of directed movement towards a certain direction is representing a more theoretical approach to explore which type of behavior may be most beneficial for anchovy adults. The most realistic simulation of migration is that of adult fish following temperature gradients toward warm temperature with swimming speeds up to 5 bl/s.

4.1 Results

When virtual drifters representing adult anchovy are released in the surface geostrophic circulation fields calculated from satellite data and are advected by the currents thoughout the basin without any behavior of their own, the results of the simulations show that the transport of anchovy from NWS to the overwintering grounds located at the southeastern basin is not possible given the variability by currents alone and hence migration fails in years 2001-2003 (Figure 21).

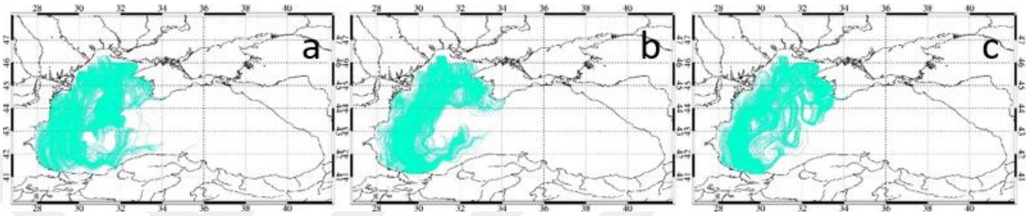

Figure 21 The paths of 1026 drifters starting at the end of October and being advected by currents only in years of a) 2001, b) 2002, and c) 2003. The paths of drifters reaching the overwintering area in 2 months are marked in blue, the ones that do not reach are marked in green.

In the first simulation including directed movement of the virtual anchovy towards SE direction with 1 bl/s successful drifters tend to go through the Western Gyre in case of 2001(Figure 22a, blue lines) and 2002 (Figure 22b, blue lines). The successful drifters are seen to originate both from the Danube inner and outer shelf region in 2001(Figure 22g) and only from the outher shelf in 2002 (Figure 22h). Moreover, in 2002 and in 2003 (Figure 22c), drifters tend to in through the midway between Western and Eastern Gyres. In this case, the successful drifters are those that start from the western part of Crimea (Sevastopol region) (Figure 22h,i).

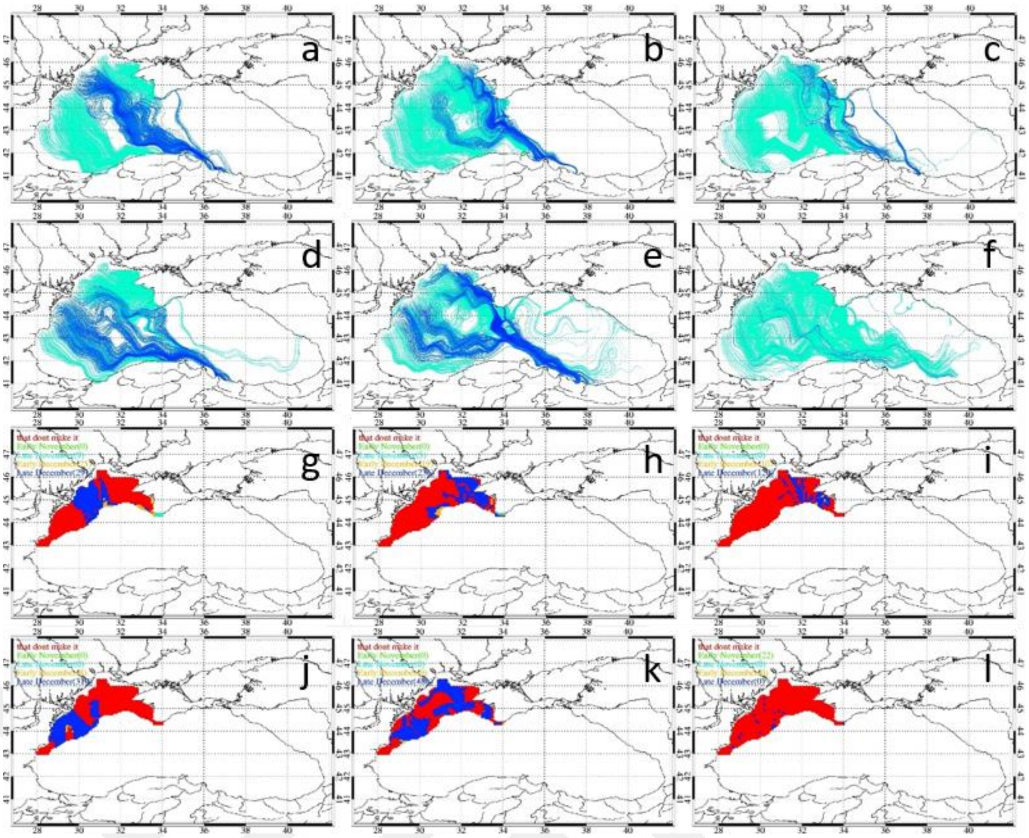

Figure 22 The paths (a-f) and start points (g-l) of 1026 drifters starting at the end of October swimming actively at 1 bl/s along SE (a-c,g-i) and ESE (d-f,j-l) directions towards overwintering area in years 2001, 2002 and 2003 (left, middle, and right column). The paths of drifters reaching the overwintering area in two months are marked as blue, the ones that do not reach are in green. The start points of drifters that complete a successful migration in two, four, six and eight weeks are color-coded as green, cyan, yellow and dark blue, respectively.The start points of the drifters that do not reach the overwintering grounds are denoted as red.

When simulating swimming behavior towards ESE direction with 1 bl/s speed, successful drifters are using multiple pathways in 2001(Figure 22d) and in 2002 (Figure 22e). These pathways are across the Western Gyre and following first the western and then southern edge of the Western Gyre via following the Rim Current in 2001. In 2002 the majority of the drifters are seen to follow the directed transport pathway between Crimea and southern coast in between the two gyres as well as a path along the western and then southern periphery of the Western Gyre. The source areas of drifters completing successful in are either down stream part of Danube region (in 2001 and 2002) and upstream part of Danube region at the northern part of NWS (in 2002) (Figure 21j,k). Although, in 2003 (Figure 22i,l) few number of the drifters are able to reach the overwintering area, they are shown to use all three pathways suggested above.

Table 4 Migration success of drifters released from the northwestern shelf area and swimming towards SE and ESE direction with 1 bl/s swimming speed.

Simulation	Drifters	Start date	Year	Speed	Direction	2 weeks	4 weeks	6 weeks	8 weeks	Total arrival	Success %	Figure #
Directed swimming	1026	OCT 30	2001	1 bl/s	SE	0	9	25	291	325	31,7	22a,g
"	1026	OCT 30	2002	1 bl/s	SE	0	5	19	236	260	25,3	22b,h
"	1026	OCT 30	2003	1 bl/s	SE	0	0	10	120	130	12,7	22c,i
"	1026	OCT 30	2001	1 bl/s	ESE	0	0	8	310	318	31,0	22d,j
"	1026	OCT 30	2002	1 bl/s	ESE	0	0	9	486	495	48,2	22e,k
"	1026	OCT 30	2003	1 bl/s	ESE	120	0	0	0	120	11,7	22f,l

When simulating swimming towards SE direction at 1 bl/s the total number of drifters (of 1026) completing successful migration is highest in 2001 with 325 drifters (31.7%). In 2002 less drifter (260, 25.3%) and in 2003 the least amount of drifters (130, 12.7%) arrive in the overwintering area (Figure 22). When simulating swimming towards ESE direction, the total numbers reaching the target area in time are similar to the SE simulation in years 2001 and 2003, but almost double those of the SE in 2002. Simulation results show that the choice of SE and ESE direction reveal no difference in terms of migration success in years of high mesoscale variability (in 2001 and 2003). However, in low mesoscale variability year, 2002, the application of ESE swimming direction over SE almost doubles the migration success with 495 drifters completing successful migration in six and eight weeks as they are able to better utilize the strong Rim Current with this migration strategy.

When simulating active swimming speed equal to and higher than 3 bl/s towards either SE or ESE, the drifters are able to override the currents irrespective of the choice of SE or ESE direction in 2001, 2002 and 2003 (Figure 23). Accordingly, the migration time shortens with respect to choice of 1 bl/s swimming speed and as drifters go straight from northwestern part of the basin to the southeastern part the migration success increases, except in case of choice of ESE direction in 2001(Figure 23). When simulating swimming towards SE direction roughly 40% of the drifters from the Northwestern shelf reach the overwintering area in each year (42.1%, 38.3%, and 44.2% in 2001, 2002 and 2003)(Table 5). However, when simulating swimming towards ESE direction the percentage of successful drifters reaching the overwintering area in 2001 is 28.7%, but ~ 60 % of them reaching in 2002 and 2003(Table 5). It should be noted that when swimming towards SE the successful drifters start from the northern Northwestern shelf area, near the Dniepr and Dniester inflow, while in the ESE simulation successful drifters start further South off the Danube infow (Figure 23).

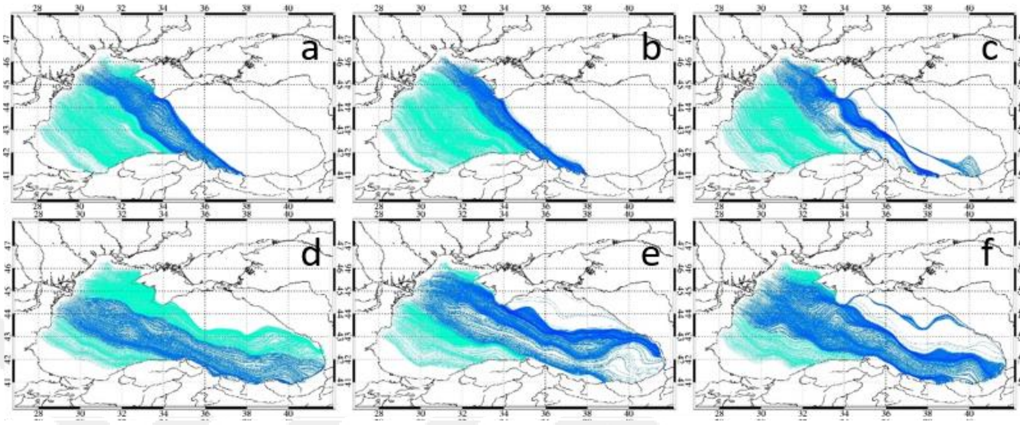

Figure 23 The paths of 1026 drifters starting at the end of October swimming actively at 3 bl/s along SE (a-c) and ESE (d-f) directions towards overwintering area in years 2001 (a,d), 2002 (b,e) and 2003 (c,f), respectively. The paths of drifters reaching the overwintering area in two months are marked as blue, the ones that do not reach are in green.

Table 5 Migration success of drifters released from the northwestern shelf area and swimming towards SE and ESE direction with 3 bl/s swimming speed.

Simulation	Drifters	Start date	Year	Speed	Direction	2 weeks	4 weeks	6 weeks	8 weeks	Total arrival	Success %	Figure #
Directed swimming	1026	OCT 30	2001	3 bl/s	SE	10	422	0	0	432	42,1	23a
"	1026	OCT 30	2002	3 bl/s	SE	0	215	0	178	393	38,3	23b
"	1026	OCT 30	2003	3 bl/s	SE	0	171	260	22	453	44,2	23c
"	1026	OCT 30	2001	3 bl/s	ESE	0	92	202	0	294	28,7	23d
"	1026	OCT 30	2002	3 bl/s	ESE	0	148	450	2	600	58,5	23e
"	1026	OCT 30	2003	3 bl/s	ESE	0	166	460	5	631	61,5	23f

To then simulate migration behavior more realistically, following above theoretical approach are simulations in which drifters are allowed to follow the temperature gradient during migration with a migration speed of 1 bl/s. Simulation results show that in warm year 2001 (Figure 24a,g) and moderate year 2002 (Figure 24b,h) only 12(1.2%) and 3(0.3%) of the 1026 drifters successfully arrive at the overwintering area in eight weeks (Table 6). However, in the relatively cold year 2003, none of the drifters complete successful migration (Figure 24c,i). This may be because in November of 2001, the Sevastopol eddy at the shelf-break zone, the small anticyclone at the southeastern part of Sevastopol eddy and the Constantsa eddy at the southern part of the NWS are major retention areas as they are characterized by warmer SST values than the surrounding regions attrackting migration towards it (see Chapter 3). The rest of the drifters that fail to migrate are oriented along the western coastal and offshore areas and they arrive at the warmer coastal regions of the western Anatolia after two-month migration. The 1.2% successful drifters in 2001 are originating from the southwest part of the tip of Crimean Peninsula (Figure 24g). During the course of November these drifters are subject to prolonged cooling that extend between northern parts of the western and eastern basin. Therefore, persisting cold zonal temperatures during November force the drifters move towards warmer southern basin (Figure 24a). On reaching the southern basin at the end of November, they start following an eastward path towards the overwintering area following the warm front on the Rim Current. Finally, they arrive to Samsun-Carsamba region between 36.5 and 37.0°E longitude.

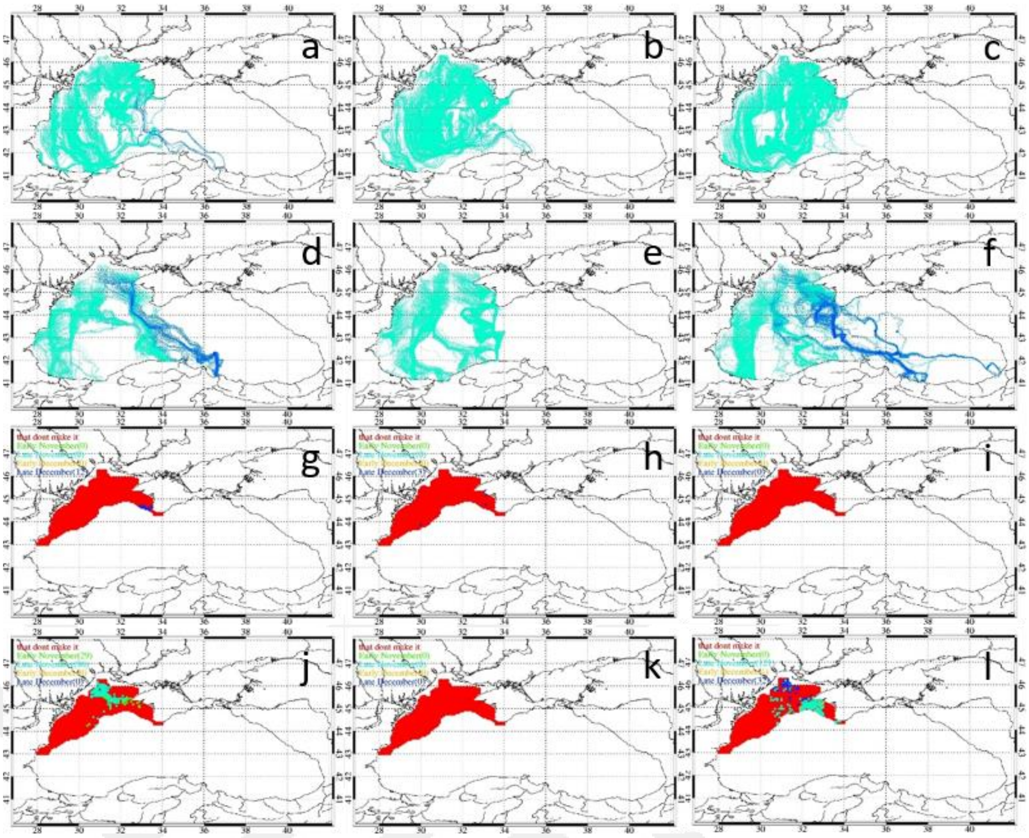

Figure 24 The paths (a-f) and start points (g-l) of 1026 drifters starting at the end of October swimming actively at 1 bl/s (a-c, g-i) and 5 bl/s (d-f, j-l) along direction of the highest temperature in addition to advection in 2001, 2002 and 2003 (left, middle, and right column). The paths of drifters reaching the overwintering area in two months are marked as blue, the ones that do not reach are green. The start points of drifters that complete a successful migration in two, four, six and eight weeks are color-coded as green, cyan, yellow and dark blue, respectively. The start points of the drifters that do not reach the overwintering grounds are denoted as red.

Table 6 Migration success of drifters released from the northwestern shelf area following temperature gradients with 1 and 5 bl/s swimming speeds.

Simulation	Drifters	Start date	Year	Speed	2 weeks	4 weeks	6 weeks	8 weeks	Total arrival	Success %	Figure #
Temperature following	1026	OCT 30	2001	1 bl/s	0	0	0	12	12	1,2	24a,g
"	1026	OCT 30	2002	1 bl/s	0	0	0	3	3	0,3	24b,h
"	1026	OCT 30	2003	1 bl/s	0	0	0	0	0	0,0	24c,i
"	1026	OCT 30	2001	5 bl/s	29	96	0	0	125	12,2	24d,j
"	1026	OCT 30	2002	5 bl/s	0	0	0	0	0	0,0	24e,k
"	1026	OCT 30	2003	5 bl/s	0	121	4	32	157	15,3	24f,l

In 2002 the majority of the drifters are seen to follow a southward path along the western side of the Western Gyre as very cold temperatures are observed to cover the northern part of the western basin in the second week of November (see Chapter 3). Then as the intensity of the circulation increases in December almost all drifters become trapped within the Western Gyre as 1bl/s (10cm/s) swimming speed is not sufficient to overcome the strong current velocities in this period. The successful pathways that the successful three drifters use are the one following the Western Gyre and the direct pathway through the midway between the Western and Eastern Gyres.

With application of 1 bl/s swimming speed none of the drifters complete a successful migration in 2003 in the presence high variability conditions within the western basin as evident by the number of small cyclones prevailing within the western inner basin. Although in this period the increased sea level gradients between the coastal zone and the open sea result in formation of Rim Current as in the case of winter, it is not yet strong enough to suppress the high variability associated formations and meanders until the last week of November. Much of the drifters retained within the Western Gyre during migration, or in the Sevastopol region that is characterized by warm temperatures in November 2003.

Because it may be an unrealistsic assumption that anchovy only move at 1 bl/s during overwintering migration further simulations were done assuming a migration speed of 5 bl/s as observed in Peruvian anchovy (Peraltilla & Bertrand, 2014), as well as Black Sea anchovy (Gucu, pers. com.). Simulation results show that drifter in the warm year 2001 move at an almost diagonal path across from source areas at the northern part of the northwestern shelf to final destinations near Sinop (35.0°E longitudes) and Samsun (36.5°E longitudes) in the overwintering area (Figure 24d). A total of 125 drifters (among 1026) complete successful migration in this period (Figure 24). Among those, 96 drifters from the northern part of NWS reach the overwintering area in four weeks. Successful drifters moved towards the northern edge of Sevastopol anticyclone and later to the small anticyclone at the southeastern part of Sevastopol anticyclone. Drifters approach to the southern basin within the first two weeks of November following the south-eastward front formed at approximately 15 nm offshore of Sinop region, some following the warm signal eastward along the southern coast and stop at the Samsun region. Many drifters from the northwestern shelf still fail migration in this simulation, because of persistently cold temperatures in the interior basin which guids drifters to following the warmer western coast of the Black Sea and reach only until the Istanbul and Sakarya region.

In 2002, none of the drifters are seen reach the overwintering area even with application swimming speed as high as 5 bl/s (Figure 24e, Table 6). During the second week of November 2002, very cold temperatures (19.0 – 21.0°C) are observed to all over the Western Basin, leaving a slightly warmer region at the Anatolian coast. Hence, the drifters originating from the Daube and Constantsa area are seen to follow the relatively strong Rim Current at the western part of the basin and stop at the west coast of Anatolia (between Bosphorus and Eregli region). Other drifters are seen to reach only the Zonguldak-Inebolu region. In this year, the stronger flow around the larger and more intense cyclonic cells within the interior parts of the Western Gyre is the main control on the pathways at the west part of the basin. However, regional temperature distribution is the main factor in regulating the orientation of the migration pathways that fail to transport the drifters to the overwintering areas.

In 2003 the movement towards highest temperatures with 5 bl/s swimming speed reveals the highest success rate among all three years and a total of 15.3% drifters successfully reach the overwintering area. Among the drifters, most reach the overwintering area in four weeks (Table 6). The drifters originating from the areas located at the outer shelf between the 31.8 and 33.3°E longitudes at the western side of Sevastopol region are seen to reach to target areas in four weeks (Figure 24f). Those drifters initially move south towards along the edge of the cyclonic formation at the Sevastopol coast that is active in the first week of November and reach warmer central basin. In the second week, these drifters follow the front that extends northwards from the edge of the warm Sinop anticyclone carrying warmer waters northward into the central inner basin. Once they approach the front at the north part of the Sinop eddy, drifters follow the warm waters of the Rim Current and move along with it eastward. They finally complete a successful migration arriving at the Carsamba (Samsun) and Fatsa (Ordu) coast. Some of the drifters approaching the tip of Crimea are observed to move southeastward following the pathway between the anticyclone within the inner basin and the Eastern Gyre. These drifters follow an eastward path along the 42°N latitude line and approach to the warmest regions of the basin located at the southeastern edge of the Black Sea (a.k.a. ‘the Batumi Region’) in four weeks. In this time period, the drifters from the northernmost parts of the NWS are seen to be able to access to the overwintering area in eight weeks. They follow the southern edge of the Sevastopol eddy at the shelf break and within the Western Gyre they follow a path that goes through the thermal fronts around the cyclones of the interior basin. Finally, once that reach the warmer Rim Current jet at the periphery, they follow an eastward path along this basin wide flow system and approach the Samsun – Ordu region at the overwintering area.

The intense cyclonic activity within the western basin, the increased Danube fresh water discharge flow and the Western Gyre are the features that causes retention of the drifters, leading them towards the nearest warmer regions at the Bulgaria, Bosphorus and Zonguldak – Inebolu coasts.

4.2 Discussion

The simulation results presented here aim to elucidate the influence of surface circulation and temperature together with application of simple behavior on the overwintering migration success of anchovy in the Black Sea during the period between 2001 and 2003.

During the November – December time period in 2001, 2002 and 2003 overwintering migration of anchovy towards southeastern overwintering areas is not possible given the dispersal by geostrophic currents alone. However, application of directed swimming (along SE and ESE direction) with hypothetical swimming speeds of 1-3 bl/s yields a sound migration success when added on top of advection at each time step. Variability in migration patterns in different years is due to variability in circulation. Migration is partly sensitive to currents given 1-2.5 bl/s swimming speed. The currents are overridden at speeds greater than 2.5 bl/s. The transport times are on average 8 weeks.

Three different pathways are identified for anchovy overwintering migration from simulations using directed swimming along SE and ESE directions at 1 bl/s (Figure 25). They can be summarized conceptually as (1) direct transport from Crimea midway between Western and Eastern Gyres, (2) crossing the Western Gyre, and (3) following the western and then southern periphery of the Western Gyre and reaching overwintering grounds following the Rim Current. Anchovy originating from the regions close to the Danube plume, prefer transport pathway (1), Constanta region prefer transport pathway (2), Kali-Akra region prefer transport pathway (3).

These conceptual transport pathways are comparable with some of the major transport patterns previously suggested by Ivanov and Beverton (1985) (Figure 26), who also show one overwintering pathway that follows the Bulgarian coast as well as suggest that some migration takes place midway between the Western and Eastern Gyres. However, the simulated pathways intentify one additional pathway that passes through the western gyre. Chashchin (1995) also included the presence of the pathway that follows the Bulgarian coast in order to reach to the southeastern overwintering grounds (Figure 3) which is in agreement with the findings of the directed movement simulations (Figure 25) of the present chapter. However, the pathway that exists between the Western and Eastern Gyres and follows a southwards path as stated by Ivanov and Beverton (1985) is presented as a spawning migration (return migration) pathway that follows SE-NW route in Chashchin's (1995) study.

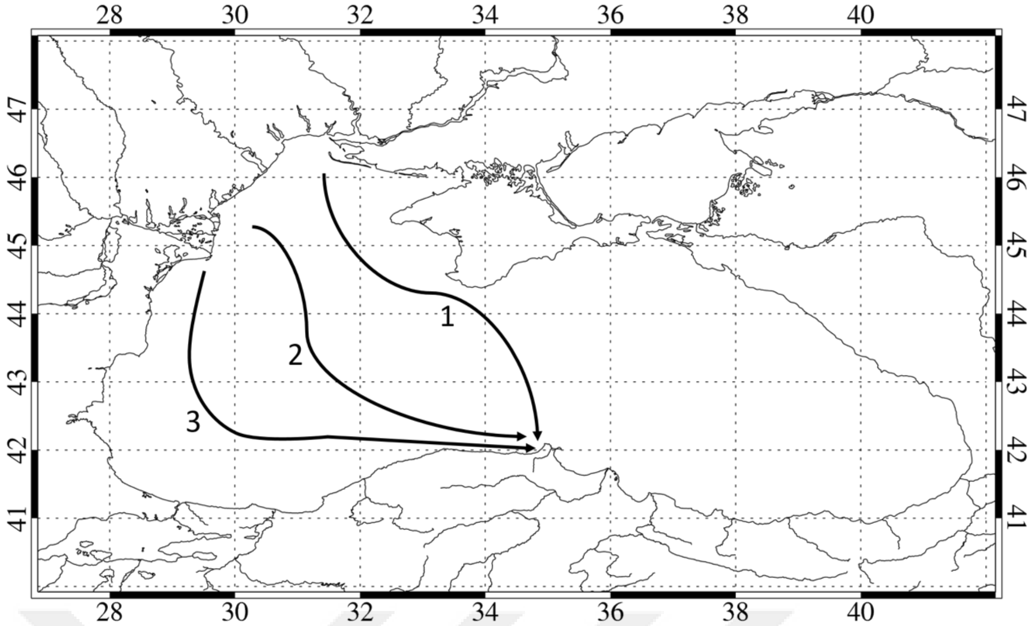

Figure 25 Conceptual figure showing the summary of migration pathways for directed movement simulations (towards SE and ESE at 1bl/s).

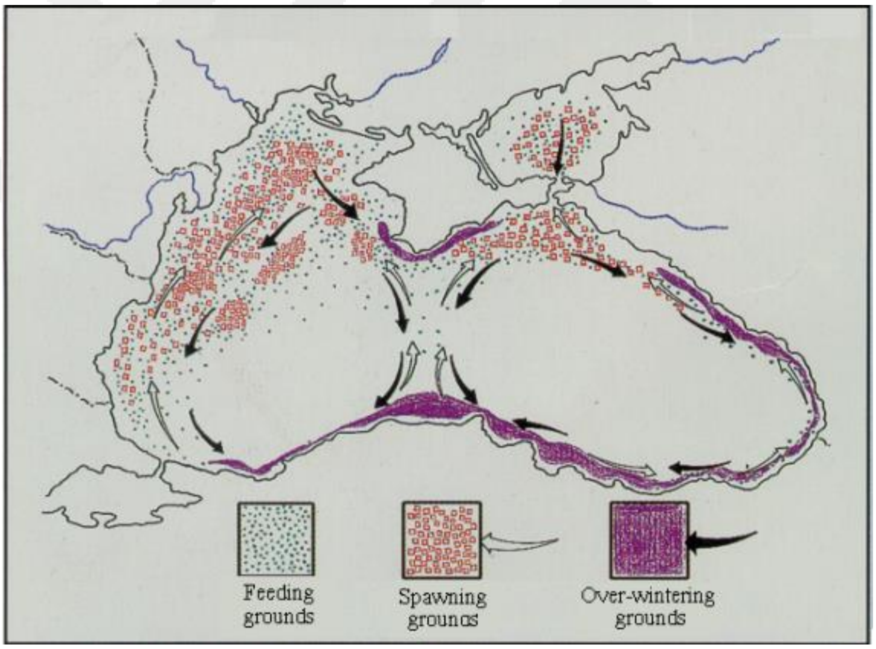

Figure 26 The anchovy migration pathways (from Ivanov and Beverton, 1985).

As detailed above, migration of anchovy directed towards a certain direction may be rather simplistic as anchovy are known to prefer warm temperatures and move towards warmer regions. Hence simulations of drifters following temperature gradients were undertaken that showed that at only 1bl/s swimming speed this migration behavior yields very low (up to ~1%) success rate for anchovy originating on the northwestern shelf. The very few successful drifters in 2001 and in 2002 originated from the tip of the Crimea (in 2001), as well as from outer shelf part of Constantsa and from Sevastopol regions (in 2002) following a direct transport pathway in between the Western and Eastern Gyres. However, applying the more realistic swimming speed of of 5bl/s swimming resulted in a more complicated migration patterns than those suggested in the directed swimming simulations (Figure 27). Simulations of drifter transport following temperature gradients suggests three different pathways (1) from Crimea midway between Western and Eastern Gyres (in 2001 and 2003) and (2) through the Western Gyre (in 2003, fails in 2001). An additional pathway is identified within the eastern basin in which the drifters are first (3) transported by the Crimea eddy, then reach the southern part of the eastern basin via going across the Eastern Gyre (in 2003). Variations of these paths can appear due to the variability in gyres and eddies from year to year (Figure 27, dashed lines).

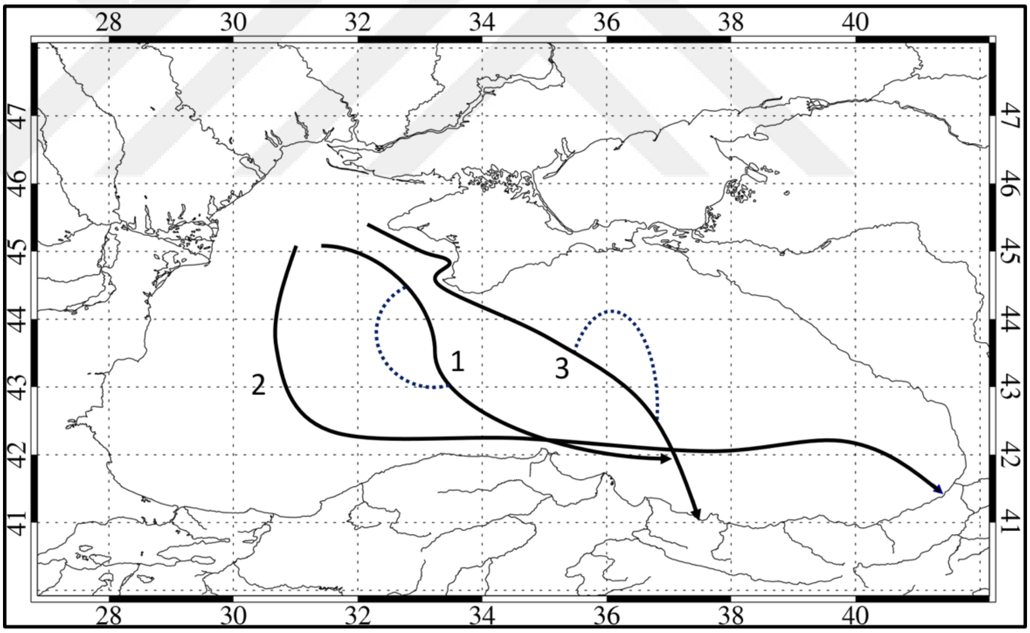

Figure 27 Conceptual figure showing the summary of migration pathways for temperature following simulation with 5bl/s.

Following temperature gradients, in warmer year (2001), drifters reach target area within 4 weeks, whereas in colder year (2003), it takes them 4 – 8 weeks to complete successful migration. Eddies that help migration in 2003 are the Sevastopol eddy, Crimea eddy, Sinop eddy, Kizilirmak eddy, Batumi eddy, Crimea and the anticyclonic eddy at the southeastern part of the Crimea eddy, whereas in 2001, Sevastopol eddy, the small anticyclone at the southeastern side of Sevastopol eddy, Sinop and Kizilirmak eddies help efficient transport to overwintering area. However, the presence of these eddies is not conducive to migration success when simulating advection by currents alone. Adding to that, the presence of Sevastopol eddy at the shelf break in 2001 and 2003 help transport of drifters to the overwintering area via increased thermal gradients in this frontal region. In 2003 due to increased basin wide variability, the occurrence of unstable jets and filaments increased from the warmer southern coastal regions towards the northern ones increasing chances of successful migration via providing warm short cuts.

The spatial distribution of SST and duration of cooling have significant effect on the orientation of migration pathways in temperature following simulation (with 5 bl/s). For instance, although in 2001 and in 2003, the SST gradient follows a NW-SE pattern that help successful migration to the overwintering area, in 2002 the W-E SST gradient result in fail of migration. Another important factor that needs to be mentioned is that during the short cooling period that takes place in the second week of November 2002, the very cold temperatures approaching from west are prevailing almost all over the Western basin (except the limited area of relatively warmer SST at the west coast of Anatolia). This incident ultimately played an important role in decreasing the opportunity to find warm areas and fail the migration.

With the application of realisticaly swimming speeds for adult anchovy, the pathways are seen to orient along thermal fronts around the eddies due to the physical environment alone. Numerous studies however have indicated an increase in biological activity at the frontal regions, which may be of additional benefit for migrating anchovy. The accumulation of organism along such fronts is known as the edge-effect. The fronts are the areas where lateral and vertical exchanges takes place and hence allow for increased gradients of properties (density, salinity or nutrients) in water and facilitate convergence at the surface and therefore increased primary and secondary production is observed in these habitats (Olson and Backus, 1985). Oceanic fronts play an important role for the oceanic life through enhanced productivity that fuels species diversity in fishes, birds, squids and marine benthos (Acha et al., 2004). Most fish have been found to accumulate at fronts (Roberts 1980; Kleckner and McCleave, 1988; Castillo et al., 1996; Reese et al., 2011). Fish accumulations along fronts are driven by two factors, increased prey availability and optimum temperature conditions at the front (Owen, 1981; Largier, 1993). Although plankton aggregations are strongly influenced by the physics of the ocean, larger fish have strong selectivity towards the areas of physical gradients as they have the capacity to select the favorable habitats (Brandt, 1993). Still,

Except for the direct transport pathway between the eastern and western gyre, the identified pathways by the temperature following simulations are seen to change on a yearly basis and are more complex than the migration routes suggested earlier by Ivanov and Beverton (1985) (Figure 26) and Chashchin (1995) (Figure 3). It is important to note the pathway following the Bulgarian coast is not apparent in the temperature folloing simulation (5bl/s) which is in contrast to Chashchin et al. (2015) who state that the most important autum migration route is the one following the western coast of the Black Sea. However, other studies report that the fishery in Bulgaria (and Romania) on was available only until the anchovy collapse observed during 1989/90 all over the Black Sea (STECF, 2013; Gucu et al., 2016). While the Turkish anchovy has recovered back to the pre-collapse stock levels, so far there is no reported recovery signs for the Bulgarian/Romanian anchovy fishery which indicates that most likely anchovy are not migrating along that route anymore (Gucu et al., 2016). The results of study show that due to the environmental conditions in terms of temperature and surface circulation alone, anchovy that are assume to follow temperature gradients at 5 bl/s are not likely to along the Bulgarian-Romanian coasts at all, supporting Gucu et al. (2015) and providing a possible explanation for why the route is not used anymore. It can be concluded that the Bulgarian/Romanian pathway (Ivanov and Beverton, 1985; Chashchin, 1995) is no longer available to virtual drifters due to the environmental connditions of the Black Sea during the time of this modeling study (2001-2003). It may even be possible that a shift in currents and cooling events has caused the collaps of this fisheries because anchovy reach overwintering regions easier via open ocean pathways.

Most importantly, the simulations reported in this chapter support the conclusion that really it is rather difficult for anchovy located on the northwestern shelf to manage to migrate to the western Anatolian coast for overwintering in two months. The highest migration success in the directed movement along ESE direction simulation was found to be 48% at 1 bdl/s. Although the application of 3 bl/s swimming speed reveals high drifter success in the majority of the directed swimming simulations that the variability of currents is overridden in case of choice of 3 bl/s swimming speed. Since anchovy schools have not been shown to travel in such a many, it is safe to assume that the results of this theoretical experiment are not very reliable. It is important to note though that drifters in the most realistic simulation of all (temperature following, 5bl/s) could only show a migration success of 12-15% in years 2001 and 2003, migration failing completely in 2003. It is concluded therefore, that the anchovy found to arrive at the overwintering area are not originating from the northwestern shelf as suggested in previous studies (Ivanov and Beverton, 1985; Chashchin, 1995; Shulman, 2002), but that up to 90% of them are originating from elsewhere in the Black Sea. In the following chapter these alternative source areas will be examined.

The ongoing warming trend in the oceanic environment will inevitably impact species distribution and migratory pathways that are dependent on temperature as an external stimuli. For Black Sea anchovy this mean that migration may start later in the year due to warmer temperatures in autums, or even no migration at all when temperatures are warm enough for anchovy to stay in their nursing areas. However, the response of fish population dynamics to continue warming is rather complex and non-linear, as anchovy metabolism, as well as spawning and recruitment success is temperature dependent (Guraslan et al., 2014). It should be noted that each fish species has a different optimal temperature and as climate warms a shift in species distribution in the world oceans is expected and has already been observed for some fish (Genner et al., 2004; Perry et al., 2005; Dulvy et al., 2008; Nye et al., 2009; Simpson et al., 2011; Sunday et al., 2015; Punzon et al., 2016). In the Black Sea, thermopylic species like anchovy will benefit from warming and may possibly respond to increased temperatures with increased fecundity rates.

For anchovy migration in the Black Sea however, it may be expected that anchovy behave differently in a warming ocean as this species prefer to move towards warmer areas of the basin once sensing a strong temperature drop below a threshold of 13.5 – 17.0°C (Shulman,2002 ;Chashchin, 1996). If cooling does not decrease temperature this low anchovy may prefer not to migrate and may stay in the source areas instead. In such cases the school formation ceases and hence anchovy remain dispersed and not an easy target for industrial fisheries. Part of the anchovy stocks in the Black Sea has already been shown to be non-migrating in some years (Gucu et al., 2016, STECF, 2013). However, the local population of anchovy that resides in the overwintering zone (Gucu et al., 2016) might not be affected by the warming as they are acclimatized in this region and they do not perform migration. However, this stock of anchovy may not enough to sustain a regular high catch amounting to 350 kton annually.

4.3 Conclusions

In this chapter of the thesis questions 1-3 were answered for anchovy originating on the northwestern shelf. It can be concluded that overwintering migration pathways are strongly influenced by the prevailing currents and cooling events of each specific year (research question 1). While three main migration pathways were identified, these pathways are subject to interannual variability that cause deviations from the main pathways. Further it was found that mesoscale eddies and frontal processes are vital in facilitating successful migration, especially the shelf-break from at Crimea and eddies forming at the Anatolian coast. These system enable the transport of anchovy acoss the Black Sea between the two basins and that are subject to interannual variability (research question 2). Finally, answering research question 3, the effect of including temperature gradient following simulations at 5 bl/s provided the most realistic modeling results showing that migration routes previously thought of importance along the Bulgarian-Romanian coast are not feasible in the years studied here because of the prevailing curents and the nature of cooling in these specific years. Simulations suggest other, open ocean transport pathways of importance. Simulations further suggest that only 12-15% of the anchovy located on the entire northwestern shelf can actually successfully migrate to the eastern Anatolian coast for overwintering some years, while migration is failing completely in other years. This indicates that anchovy migration successfully to the overwintering grounds are most likely originating elsewhere in the Black Sea and not from the northwestern shelf.

Chapter 5

MODELING THE IMPACT OF INTER–ANNUAL ENVIRONMENTAL VARIABILITY ON ANCHOVY OVERWINTERING MIGRATION FROM DIFFERENT REGIONS OF THE REMAINING BLACK SEA

In this chapter the migration success of anchovy in the Black Sea originating from all the entire Black Sea basin is tested. To do this, a total of 7175 drifters are released from the start points covering the entire Black Sea basin on October 30th in the years 2001 to 2003 and particles are tracked over two months. Three sets of simulations are conducted in parallel to the simulations in chapter 4, in which particles resembling adult anchovy move due to (a) advection by surface currents (passive movement), (b) directed swimming with 1 and 3 bl/s towards SE, ESE, SSE and S direction together with advection (active movement), and (c) swimming with 1 and 5 bl/s towards the direction of the highest temperature together with advection (active movement). In Chapter 4 the choice of directed movement along SE and ESE directions is valid in simulating the migration of drifters representing the Black Sea anchovy from the NWS area towards the southeastern coast of the Black Sea. However, in this chapter the release of drifters from all over the Black Sea basin aims at investigating not only the migration of Black Sea anchovy but also the Azov Sea anchovy. Therefore, in this chapter two additional directions (SSE, S) are included in the directed movement simulations. Hereby the choice of directed movement towards a certain direction is a theoretical study of which type of behavior may be most beneficial for adult anchovy. However, the most realistic simulation of migration is that of anchovy following temperature gradients toward warm temperature with swimming speeds up to 5 bl/s.

5.1 Results

When the drifters are released with a circulation field only, without application of any active swimming behavior, it takes between 4 to 8 weeks for successful drifters to complete a migration from different regions of the Black Sea, specifically from the mouth of Kerch Strait, along a longitudinal transect between the Azov Sea and the Anatolian coast, the central coast of Anatolia (in the warm year) and the Batumi region (in the cold year) (Figure 28). Successful migration varies significantly between years, with most drifters (18.8%) arriving in 2001, 15% in 2003 and only 6.6% in 2002 after different migration times (Table 7), showing that in 2001 the overwintering area was a region of strong currents and dispersal which reduces retention in this area.

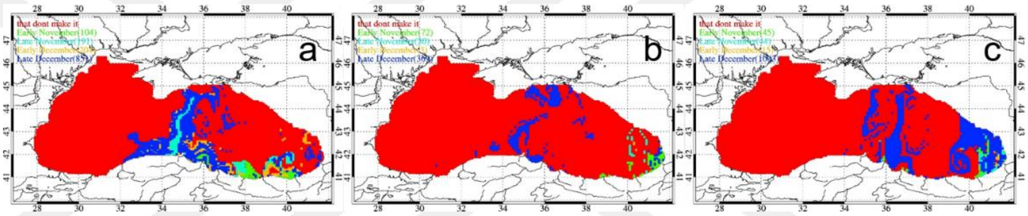

Figure 28 Start points of 7175 drifters starting at the end of October drifting passively with the advection by currents in years 2001 (a), 2002 (b) and 2003 (c). The start points of the drifters that successfully reach to overwintering area in 2, 4, 6 and 8 weeks are color-coded as green, cyan, yellow and blue, respectively. The ones that do not are denoted as red.

Table 7 Migration success of drifters released from the entire Black Sea domain drifting with the advection by currents.

Drifters	Start date	Year	Speed	2 weeks	4 weeks	6 weeks	8 weeks	Total arrival	Success %	Figure #
7175	30 OCT	2001	0	104	191	204	851	1350	18,8	28a
7175	30 OCT	2002	0	72	30	3	369	474	6,6	28b
7175	30 OCT	2003	0	45	44	15	1005	1107	15,4	28c

In the directed movement simulations when drifters are released on October 30^{th} and swim with 1 bl/s towards SE more drifter reach the overwintering areas than with advection alone. In 2001 a total of %44 complete migration in 2001, 10% less in 2002 and 50% in 2003 (Table 8), leaving again 2002 as the least successful year. Similar numbers of successful drifters are obtained from simulations swimming towards ESE direction, with 35.7%, 46.6% and 54.4%

in 2001-2003, respectively (Table 8). Simulations show that in 2003 the source areas for successful drifters were predominantly located in the eastern basin, whereas in 2001, the majority of the successful drifters are seen to originate from the western basin. Moreover, in 2003, due to increased circulation variability the migration of drifters originating from the Western basin (except Batumi area and offshore regions of central Anatolia) takes a longer time (8 weeks) when compared with the previous two years.

Table 8 Migration success of drifters released from the entire Black Sea domain swimming towards SE, ESE, SSE and S direction with 1 bl/s swimming speed.

Simulation	Drifters	Start date	Year	Speed	Direction	2 weeks	4 weeks	6 weeks	8 weeks	Total arrival	Success %
Directed swimming	7175	OCT 30	2001	1 bl/sec	SE	919	1237	355	644	3155	44,0
"	7175	OCT 30	2002	1 bl/sec	SE	710	372	659	633	2374	33,1
"	7175	OCT 30	2003	1 bl/sec	SE	764	787	356	1677	3584	50,0
"	7175	OCT 30	2001	1 bl/sec	ESE	476	497	708	883	2564	35,7
"	7175	OCT 30	2002	1 bl/sec	ESE	551	902	800	1091	3344	46,6
"	7175	OCT 30	2003	1 bl/sec	ESE	765	901	321	1918	3905	54,4
"	7175	OCT 30	2001	1 bl/sec	SSE	1161	841	231	669	2902	40,4
"	7175	OCT 30	2002	1 bl/sec	SSE	786	540	225	854	2405	33,5
"	7175	OCT 30	2003	1 bl/sec	SSE	875	405	738	931	2949	41,1
"	7175	OCT 30	2001	1 bl/sec	S	1186	826	423	410	2845	39,7
"	7175	OCT 30	2002	1 bl/sec	S	758	548	324	524	2154	30,0
"	7175	OCT 30	2003	1 bl/sec	S	1037	346	347	463	2193	30,6

When swimming speed is increased up to 3 bl/s, drifters overcome current speeds in the area and move directly towards the chosen direction. That means a higher migration success in all three years for the SE and ESE direction simulations. Success rate is between 60.8 and 64.4% for the SE directed swimming and slightly higher for the ESE direction (~74%), except for the warm year 2001, where the success rate was much lower (45%) (Table 9). This matches the simulations from the northwestern shelf (see Chapter 4), where migration success was also significantly lower in 2001 when employing this migration strategy.

The spatial distribution of the source areas in simulations with swimming towards SE (with 3 bl/s) reveal that in all years drifters from the entire eastern basin reach the overwintering area, as well as some from the northern northwestern shelf region and the band connecting both areas (not shown). However, in the ESE simulation drifters from the eastern basin and regions of the southern to mid-northwestern shelf complete migration successfully. The year 2001 with significant lower success rate is exceptional in that only drifters from the southern northwestern sheld, as well as the southern eastern basin migrate successfully, hence the reduced numbers.

Table 9 Migration success of drifters released from the entire Black Sea domain swimming towards SE, ESE, SSE and S direction with 3 bl/s swimming speed.

Simulation	Drifters	Start date	Year	Speed	Direction	2 weeks	4 weeks	6 weeks	8 weeks	Total arrival	Success %
Directed swimming	7175	OCT 30	2001	3 bl/sec	SE	2939	1551	27	0	4517	63,0
"	7175	OCT 30	2002	3 bl/sec	SE	2384	1380	33	563	4360	60,8
"	7175	OCT 30	2003	3 bl/sec	SE	2724	1176	353	295	4548	63,4
"	7175	OCT 30	2001	3 bl/sec	ESE	1407	1421	432	0	3260	45,4
"	7175	OCT 30	2002	3 bl/sec	ESE	2508	1866	781	109	5264	73,4
"	7175	OCT 30	2003	3 bl/sec	ESE	2390	1928	1001	8	5327	74,2
"	7175	OCT 30	2001	3 bl/sec	SSE	2873	649	78	5	3705	51,6
"	7175	OCT 30	2002	3 bl/sec	SSE	2261	919	187	122	3489	48,6
"	7175	OCT 30	2003	3 bl/sec	SSE	2671	556	134	147	3508	48,9
"	7175	OCT 30	2001	3 bl/sec	S	2889	38	98	0	3325	46,3
"	7175	OCT 30	2002	3 bl/sec	S	2157	579	160	18	2914	40,6
"	7175	OCT 30	2003	3 bl/sec	S	2473	443	90	7	3013	42,0

When increasing the swimming speed to 3bl/s while swimming towards SSE the migration success is between ~49-52%, while it is slightly lower for swimming towards S with ~41-46% (Table 9). Migration takes 2 weeks in both simulations for majority of the drifters within the Eastern basin while the drifters from the Azov Sea exit region and Caucasian region are obsrved to approach the desired areas in 4 to 8 weeks time. Only a small percentage of drifters are shown to complete migration from the western coast of Crimea swimming towards SSE direction in years 2001 and 2003 (not shown). Those drifters complete a successful migration in 4 weeks.

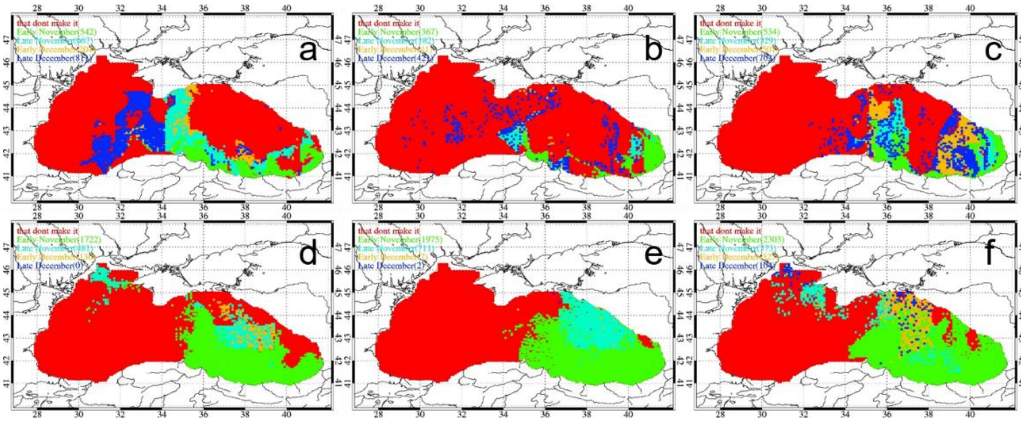

Figure 29 Simulations showing start points of 7176 drifters starting at the end of October swimming actively at 1(a,b,c) and 5(d,e,f) body-lengths/second towards the direction of the highest temperature in addition to advection by currents in 2001, 2002 and 2003, respectively. The start points of the drifters that successfully reach to overwintering area in 2, 4, 6 and 8 weeks are color-coded as green, cyan, yellow and blue, respectively. The ones that do not are denoted as red.

When moving on to the more realistic simulations of assuming anchovy is following temperature gradients at 1bl/s (Figure 29), it is seen that migration success is around 30% in the years 2001 and 2003 (Table 10), but only half of that (14%) in 2002. Most drifters reach the overwintering area in short migration times, as low as 2 weeks (Table 10). When looking at the spatial structure of successful drifter release points it is seen that in the warm year (2001), a natural boundary (along 34°E longitude) is drawn between the western and eastern basins representing the natural barrier between the two (Figure 29). The drifters at the eastern part of this barrier (within the Eastern basin) are shown to complete migration in 4 weeks whereas those at the western part of the barrier (in the Western basin) complete migration in 8 weeks. In a higher percentage of drifters are seen to originate from the Eastern basin with the majority originating from the Batumi region and western part of the eastern basin. In both 2001 and 2003, the overwintering area is also asource region for a high number of drifters. In 2002, on the other hand, the source areas are seen to retreat towards the coast of Georgia and to the coast between Sinop and Samsun (of the overwintering area). In this case the origin areas reveal a more dispersed pattern.

Table 10 Migration success of drifters released from the entire Black Sea domain following temperature gradients with 1 and 5 bl/s swimming speeds.

Simulation	Drifters	Start date	Year	Speed	2 weeks	4 weeks	6 weeks	8 weeks	Total arrival	Success %	Figure #
Temperature following	7175	30 OCT	2001	1bl/s	542	667	204	811	2224	31,0	25a
"	7175	30 OCT	2002	1bl/s	367	182	41	421	1011	14,1	25b
"	7175	30 OCT	2003	1bl/s	534	329	501	703	2067	28,8	25c
"	7175	30 OCT	2001	5bl/s	1722	481	136	0	2339	32,6	25d
"	7175	30 OCT	2002	5bl/s	1975	711	7	2	2695	37,6	25e
"	7175	30 OCT	2003	5bl/s	2303	373	327	104	3107	43,3	25f

When a more realistic 5bl/s is applied as the swimming speed of drifters (Figure 29,d-f), the drifter success is increased significantly (32.6-43%) and the migration duration is decreased. Moreover, only in case of selection of 5 bl/s speed, drifters originating from northwestern shelf region can arrive at the overwintering area. The eastern basin is the dominating source area in all simulations using 5 bl/s. In particular, the southern part of the eastern basin is seen to transport drifters in 2 weeks in all years. If successful, the drifters from the northern half of the eastern basin are seen to complete migration in 4 or 6 weeks in 2001 and 2002 simulations. However, in 2003, the majority of the drifters at the northern half of the eastern basin are able to complete migration in 2 weeks. Only in 2001 and 2003 drifters from the northwestern shelf are shown to migrate in 4 weeks and in 8 or 4 weeks, respectively. In 2001, the region at the northern part of 45°N latitude is the source area for drifters migrating in 4 weeks. Whereas, in 2003, regions at the northern and southern part of the 45°N latitude are the source areas of drifters migrating to the overwintering area in 8 and 4 weeks, respectively.

5.2 Discussion

The present chapter explores the possible source areas from where the anchovy migrate successfully to the overwintering areas, as it was shown in the previous chapter (Chapter 4) that up to 90% of anchovy may originate from outside the northwestern shelf. These simulations include a special focus on Azov anchovy that may be found migrating through the Black Sea after exiting Azov Sea from Kerch Strait. Simulations therefore started drifters from the entire Black Sea.

The advection only simulation results in the lowest migration success values for each year among all the simulations performed in this chapter. In the year of moderate mesoscale variability, 2001, the geostrophic current speeds both along the axis of the Rim Current and along the western edge of the Eastern Gyre are observed to vary between 0.15 – 0.2 m/s and more drifters from the central Anatolia coastal region and from the western periphery of the Eastern Gyre can complete migration in four or eight weeks in addition to drifters originating in the overwintering area itself. In the year of lowest mesoscale variability, 2002, lowest number of drifters arrive at the overwintering area due to increased lateral transport. The western periphery of the Eastern Gyre and the coast of Batumi are the main source areas in this period. During the year of highest level mesoscale variability, 2003, the presence of unstable jet formations and weakening in the Batumi eddy that is associated with high variability results in considerable retention and hence migration success. In addition, the high intensity of the Batumi eddy in 2002 period results in less migration success for drifters originating from this region.

The application of temperature following movement increases migration success significantly in providing more efficient transport to the overwintering areas. The choice of 1 bl/s swimming speed result in the highest and lowest migration success in the years of moderately high and low mesoscale variability, 2001 and 2002, respectively, which is similar to observed migration success order given in the ‘advection only’ simulation. Compared to the advection only simulation results, the transport duration in 2001 is decreased from 8 weeks to 4 weeks. Moreover, the start points of the successful drifters show that there is a sharp difference for the drifters that successfully complete migration from the eastern part of western basin and western part of the eastern basin, as the transport duration for the ones from the western basin is eight weeks whereas from the eastern basin it takes four weeks to arrive. This situation can be explained by the dynamics of the two basins with the western basin is subject to higher variability while the cyclonic cells within the eastern interior basin are much larger than their western counter-part which indicates lower variability and hence stronger peripheral flow structure. In 2002 the simulation reveals more scattered patterns than those observed in 2001 and

2003 due to the well-defined basin wide flow structure. Fewer number of drifters are seen to complete a successful migration from the western inner basin and fewer drifters are able to complete a migration originating from the western axis of Eastern Gyre. However, the number of drifters originate from the Batumi region are close to those observed in 2001 and less than those observed in 2003. In 2003, the drifters originating from the western basin further decrease. The majority of the drifters originate from the Batumi Gyre region and from the region at the western part of the strong and single-cell Eastern Gyre in this period.

With the application of a realistic swimming speed of 5 bl/s, the source regions of successfully migrating drifters are seen to shift towards the eastern basin in all simulated years. The highest number of drifter success is observed in the year of highest observed variability, 2003, followed by 2002 and 2001. In addition, drifters originating off Kerch Strait, which can be assume to be representing Azov anchovy are shown to follow two major pathways (not shown). One that follows goes offshore at eastern Crimea and following the Eastern Gyre reaching the region between Sinop and Samsun, and another path that moves parallel to the east coast againts the Rim Current (that carries warm waters of the south towards north). However, depending on the proximity of the Rim Current to the east coast, in the warm year (2001) the pathway is shifted offshore whereas in the cold year (2003) the path runs close to the shore and reaches Georgia coast. These findings are agreeing with observations of Chashchin et al. (2015) that state that in cold years the anchovy aggregations are seen to approach to the Caucasia coast. Moreover, at times when Azov anchovy has a significantly high stock (i.e., in 2010-2012), some part of the stock is reported along the eastern coast of Crimea (Chashchin et al., 2015), that agrees with the presence of the pathway following the eastern coast of Crimea in this study.

The higher migration success of drifters originating from the entire Black Sea (32.6 - 43.3%) compared to the very low success rate from the northwestern shelf (see Chapter 4) that translates to only 0-2.1% of all drifters in the entire Black Sea strongly suggest the presence of alternative spawning areas within the Black Sea domain. These areas are concentrated within the eastern basin in each of the simulated years and the majority of the drifters complete migration in 2 weeks. In 2001, the source areas are located within the open sea regions of the eastern basin. The warmer coastal anticyclonic eddies are retention areas for drifters at the beginning of November when the areas of very high temperatures are retreated to the narrow area at the southeastern edge of the Black Sea. In 2002, drifters at the southern and northern parts of the eastern basin are seen to migrate in 2 and 4 weeks. The W-E SST gradient becomes stronger during November 2002, hence contributing to successful migration of drifters from Eastern basin towards this region. Moreover, the observed low mesoscale variability, in particular disappearing coastal anticyclones, and stronger currents in this period establish a relatively better flow system in November of 2002 that causes strong SST gradient in the Batumi region. At the beginning of November 2003 the intense cooling that started in the second part of October results in withdrawal of the highest temperature regions towards the narrow coastal area in the Batumi region. But in the second part of November the region of high SST again extends futher westwards (along 38°E longitude) into the eastern inner basin, enabling successful migration of the majority of the drifters in only two weeks. However, the northwards extension of the warm SST signal in this period delays drifters located on the coastal anticyclones and filaments at the Sochi and Caucasus regions. In this year Kerch Strait region is a source region for drifters completing successful migration in 4, 6 and 8 weeks.

Although the many studies suggests that the northwestern shelf area is the main spawning, as well as nursery ground for anchovy in the Black Sea (Danilevski, 1964; Ivanov and Beverton, 1985; Chashchin, 1995; Lisovenko & Andrianov, 1996) one study covering the entire Black Sea in the 1950s argues that anchovy rather spawn all over the entire basin (Einarson and Gurturk, 1960). This has been supported with further studies within the Turkish EEZ in 1990s (Niermann et al., 1994; Kideys et al., 2000) and 2010s (Gucu et al., 2016). The findings achieved with modeling in this study support the latter studies and propose that anchovy overwintering at the eastern Anatlian coast originate mainly from the eastern Black Sea.

5.3 Conclusions

In this chapter of the thesis questions 1-3 were answered for anchovy originating in the entire Black Sea, complementing the results detailed in Chapter 4. The main result of this chapter is the identification of the entire eastern basin of the Black Sea as the main source region for anchovy successfully migrating to overwintering area along the eastern Anatolian coast. This study showed that, answering research question 1, the overwintering success is influenced by the prevailing currents and cooling events of each specific year, however not as much as in the case of migration from the northwestern shelf. The central and southern part of the eastern basin always supply anchovy to the overwintering area, no matter how strong the variability. However, those regions located at the northern part of the eastern basin, that may also be the regions where mainly Azov anchovy are found, are strongly influenced by interannual variability. For these Azov anchovy two main migration pathways, across the Black Sea from Crimea to Samsun area and migration along the eastern coast of the Black Sea swimming against the Rim Current have been identified.

Further, it was found that also in these simulations mesoscale eddies and frontal processes, which are subject to interannual variability, are seen to facilitating successful migration (research question 2). Finally, as in chapter 4, the effect of including temperature gradient following simulations at 5 bl/s provided the most realistic modeling results confirming migration routes, even against the Rim Current along the eastern Black Sea coast, that have been suggested in earlier studies (research question 3).

Chapter 6

EXPLORING ANCHOVY MIGRATION BEHAVIOR AND SPATIAL–TEMPORAL DISTRIBUTION IN THE BLACK SEA CONSIDERING INTRA–ANNUAL ENVIRONMENTAL VARIABILITY

In the previous chapters, the variability in anchovy overwintering migration behavior in response to inter-annual environmental variability in years 2001-2003 was investigated. In those simulations the virtual drifters representing anchovy are started on a fixed date, October 30th, and then tracked for two months. However, anchovy most likely start overwintering migration depending on temperature (Chashchin & Akselev, 1990; Panov & Chashchin, 1990; Panov & Spiridonova, 1998; Berdnikov et al., 1999; Shulman, 2002; Shulman et al., 2008) and body fat content (Vorobyev, 1945 as cited in Shulman, 2002) and may start migration much earlier than the end of October, as early as mid September (pers. comm. Gucu). In addition, the Black Sea mesoscale dynamics are subjected to not only a high degree of inter-annual variability but also seasonal change of the circulation is evident by the calculation geostrophic flow from sea surface height maps (see Chapter 3). In those maps, it is seen that an individual eddy may change location from one week to the other while in some cases it persists for weeks. Therefore, in this chapter the contribution of intra-annual (seasonal) variability in migration success is explored through releasing drifters at three different times, September 15 and 30 and October 15 2003, the cold year characterized by high variability, from different regions within the Black Sea domain, i.e., (i) the northwestern shelf, (ii) shelf at the Kerch Strait region, (iii) the northern Black Sea, (iv) the western and (v) central part of the Anatolian coastal regions. The choice of the year 2003 was made considering that during this year the most realistic simulation of drifters following temperature at 5 bl/s resulted in the highest number of drifter success and the pathways showed a diverse pattern that encompassed a larger geographical area from where drifters can reach the overwintering area compared to the results of the other simulated years (see Chapter 4 and 5). Only the advection only and temperature gradient following simulations are used in this chapter in an effort to focus on the most realistic simulations only.

6.1 Results

Similar to the results of previous chapters 3 and 4, an analysis of different starting times show that drifters from northwestern shelf can not reach to overwintering area in the only advection simulation even when started in the middle- and at the end of September and mid-October in 2003 (Figure 30a-c,Table 11). The dominating mesoscale features that retain the passive drifters released on September 15 simulation are the Sevastopol eddy at the shelf break at the north western basin, Kali-Akra and Bosphorus eddies at the south western basin. When started on September 30th, the passive drifters that fail to migrate are seen to become trapped within the Sevastopol eddy at the shelf break (anticyclone) and the Bosphorus anticyclone. Drifters released on October 15 are likely to be influenced by the weakening Sevastopol eddy, Bosphorus eddy, and the cyclone/anticyclone structures at the Sevastopol coast and by the cyclonic cells within the western interior basin.

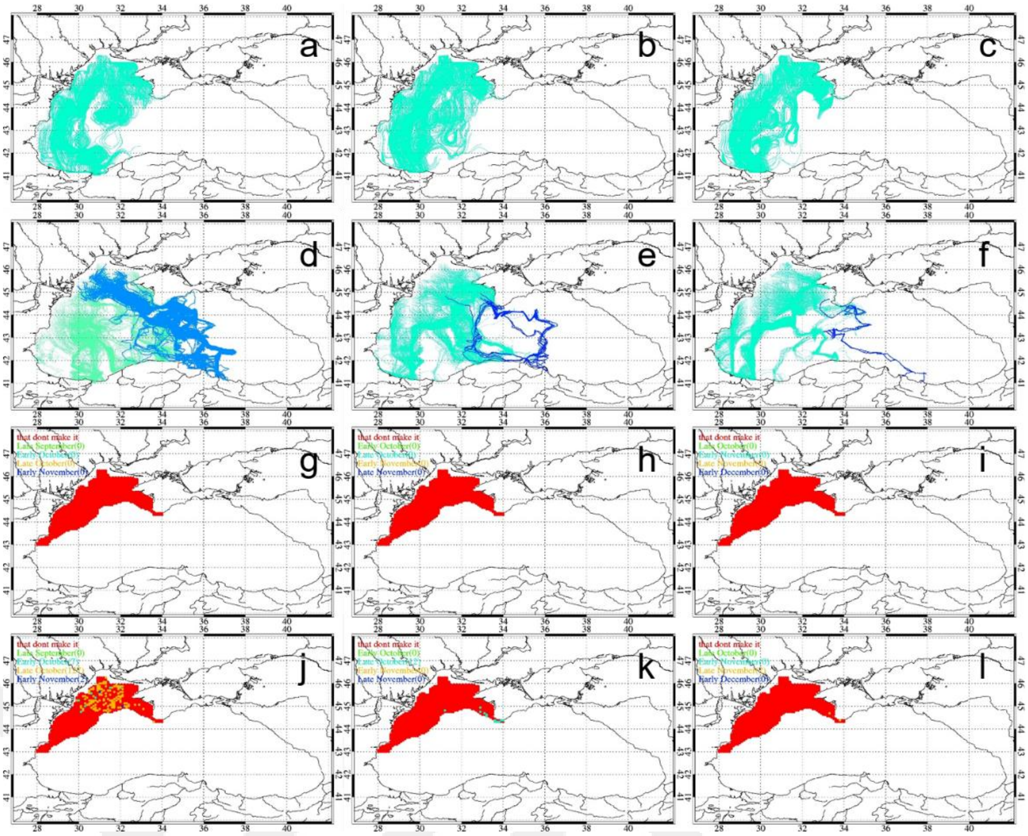

Figure 30 The paths (a-f) and start points (g-l) of 1026 drifters starting on the northwestern shelf on September 15th, 30th and October 15th in 2003 (left, middle, and right column) in the advection only simulation (a-c,g-i) and in temperature following simulation (d-f,j-l). The paths of drifters reaching the overwintering area in two months are marked as blue, the ones that do not reach are in green. The start points of drifters that complete a successful migration in two, four, six and eight weeks are color-coded as green, cyan, yellow and dark blue, respectively. The start points of the drifters that do not reach the overwintering grounds are denoted as red.

Table 11 Migration success of 1026 drifters released from the northwestern shelf on September 15th, 30th and October 30th 2003 in the advection only and the temperature following (with 5 bl/s) simulations.

Simulation	Drifters	Start area	Start date	Year	Speed	2 weeks	4 weeks	6 weeks	8 weeks	Total arrival	Success %	Figure #
Advection	1026	NWS	SEPT 15	2003	0	0	0	0	0	0	0	26a,d
"	1026	NWS	SEPT 30	2003	0	0	0	0	0	0	0	26b,e
"	1026	NWS	OCT 30	2003	0	0	0	0	0	0	0	26c,f
Temperature following	1026	NWS	SEPT 15	2003	5 bl/s	0	7	127	2	136	13,3	26g,j
"	1026	NWS	SEPT 30	2003	5 bl/s	0	12	0	0	12	1,2	26h,k
"	1026	NWS	OCT 30	2003	5 bl/s	0	0	2	0	2	0,2	26i,l

The temperature following simulations show a migration success of 13.3% for drifters starting on mid-September (Figure 30a-c,g-i,Table 11) which is close to the 15% success rate of the reference simulation (start on October 30). Successful drifters move towards the warmer Crimean Peninsula region and approach the warmer southern regions in October by following the warm connection between the southern edge of Crimea eddy and the small anticyclone at the south. At the end of September warm temperatures are seen to reach all the way towards southeastern coast of Crimea while cool SST approach in October from the northwest and the high SST are seen to retreat towards the south. Warm water areas at the southeastern basin then start to retreat towards the eastern coastal areas at the end of October. Therefore, it is of advantage to approach the warmer southern basin prior to the settling of cold SST and arriving at the SST hotspots as the cooling sets in.

However, the drifters that start migration at the end of September (Figure 30e,k) or mid-October (Figure 30f,l) reveal a very low migration success (Table 12). This is mainly due to the intense cooling at the end of October that produces a strong west-east gradient in temperature. Virtual drifters released at the end of September and in mid-October therefore do not move towards Crimea and move south from there, but head towards the warmer SST regions at the southeastern part of the western basin as it is the only warm area accessible within the western basin. At the same time the warm temperatures at the southern coast retreat more towards the Anatolian coastline and drifters arrive either at the central (Bartin – Inebolu) or western (Istanbul) coast of Anatolia hence outside the overwintering area. Only very few drifters make from the tip of Crimean Peninsula.

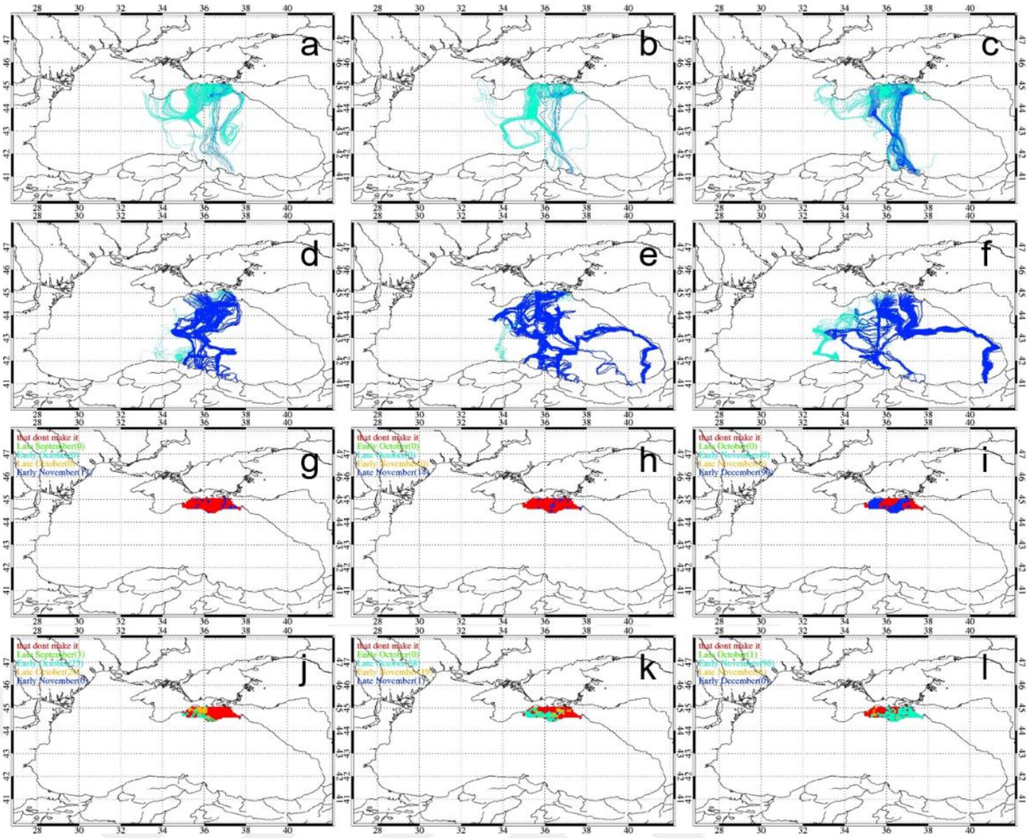

Figure 31 The paths (a-f) and start points (g-l) of 179 drifters released from Kerch Strait starting on September 15th, 30th and October 15th in 2003 in the advection only simulation (a-c, g-i) and in temperature following simulation (d-f, j-l). The paths of drifters reaching the overwintering area within 2 months are marked as blue, the ones that do not reach are in green. The start points of drifters that complete a successful migration in 2, 4, 6 and 8 weeks are color-coded as green, cyan, yellow and dark blue, respectively. The start points of the drifters that do not reach the overwintering grounds are denoted as red.

Table 12 Migration success of 179 drifters released at the Kerch Strait region on September 15th, 30th and October 30th 2003 in the advection only and the temperature following (with 5 bl/s) simulations.

Simulation	Drifters	Start area	Start date	Year	Speed	2 weeks	4 weeks	6 weeks	8 weeks	Total arrival	Success %	Figure #
Advection	179	Kerch	SEPT 15	2003	0	0	0	0	17	17	9,5	27a,d
"	179	Kerch	SEPT 30	2003	0	0	0	0	14	14	7,8	27b,e
"	179	Kerch	OCT 30	2003	0	0	0	0	90	90	50,3	27c,f
Temperature following	179	Kerch	SEPT 15	2003	5 bl/s	3	25	24	0	52	29,1	27g,j
"	179	Kerch	SEPT 30	2003	5 bl/s	0	58	19	1	78	43,6	27h,k
"	179	Kerch	OCT 30	2003	5 bl/s	1	96	6	0	103	57,5	27i,l

When the drifters are released from the Kerch region with only advection by the currents, the successful drifters are seen to follow a direct southwards path and complete migration in 8 weeks time (Figure 31a-c,g-i,Table 12). Migration success is 7.8-9.5% for drifters leaving in mid/end of September, however, drifters leaving in mid-October have a five times higher success rate with 50% of all drifters reaching the overwintering area. The inclusion of temperature following reveals significantly increased migration success for 2001 (29%) and 2002 (44%), and only a slight increase in drifter success in 2003 (57.5%). Pathways of successful drifters are very variable and modified due to the variability of SST distribution and the duration of migration is decreased to 6 and 4 weeks (Figure 31,d-f,i-l). Most migration success is found to be in the simulation starting mid-October with more than half (57.5%) of the drifters completing migration in the overwintering area. That is 35.2% less than the reference simulation (92.7%). The reason for this comparatively low success rate is again the intense cooling period starting at that time, which lets the high SST regions at the southern basin withdraw towards the Anatolian coastline the high SST regions at the eastern part of the Black Sea retreat further. Successful drifter in that time either turn eastward towards Sochi coast and when reaching the coast, they follow a southward route to the overwintering area or alternatively use to the direct southwards route. Migration success at earlier times is low because these drifters try to follow a southwards path during the migration because the high temperatures at the southern coastal region are accessible via warm mid basin filaments and eddies. The cooling event leads some drifters on a southeastwards path or first an eastward and then southwards path depending on their location (closeness to the area of maximum temperature) and the direction of the SST gradient.

Table 13 Migration success of 430 drifters released from the northern part of the eastern basin on September 15th, 30th and October 30th 2003 in the advection only and the temperature following (with 5 bl/s) simulations.

Simulation	Drifters	Start area	Start date	Year	Speed	2 weeks	4 weeks	6 weeks	8 weeks	Total arrival	Success %
Advection	430	North	SEPT 15	2003	0	0	3	9	29	41	9,5
"	430	North	SEPT 30	2003	0	0	1	0	19	20	4,7
"	430	North	OCT 30	2003	0	0	0	0	151	151	35,1
Temperature following	430	North	SEPT 15	2003	5 bl/s	30	165	30	1	226	52,6
"	430	North	SEPT 30	2003	5 bl/s	22	266	24	2	314	73,0
"	430	North	OCT 30	2003	5 bl/s	50	193	5	2	250	58,1

When the drifters are launched from the northern offshore region, the observed paths and migration patterns are similar to those observed in the Kerch Strait simulation (Table 13). The only advection results reveal a three times higher drifter success for those released on mid-October compared to low successrates (4.7 – 9.5%) for September migration. Most drifters need 8 weeks (Table 13) to complete migration. The inclusion of temperature following movement causes a decrease in migration duration by 4 weeks and five to eight-fold increase in migration success for migration starting in mid and end September, respectively. Also in these simulations the general pathways and migration duration is very similar to those observed for Kerch Strait temperature following simulations. Covering a larger area at the south and at the west, the general pattern of the drifters in the temperature following simlations are very similar. Success rate is over 50% for all simulations, up to 73% in the end of September release. Moreover additional southeastern pathways appear to direct drifters towards Fatsa, Trabzon, and Rize region of the overwintering area in September 15 simulations and Giresun, Rize and Batumi regions in October 15 simulations.

Releasing drifters from the coastal and open sea area of the western Anatolia region in advection only simulation revealed that no drifters can reach the overwintering area no matter which time in September or October they are released (not shown). This region is a high retention area and the mesoscale features that retain the drifters in this region are the Bosphorus eddy, the small cyclonic cell of the western interior basin that approaches very close to the coast during the from September 15 to November 7. Even in the temperature following simulations all virtual drifters are retained in the area at all release times, to the presence of strong west-east SST gradients in this region in 2003.

When virtual drifters are released from the central Anatolia region with only advection by the currents, those drifters located initially at the eastern part of the source area (>35°E longitude) are able to arrive at the overwintering area in 2, 4, 6 or 8 weeks time (Table 14). Migration success rates are relatively high for all earlier release times with values between 12.6 and 24.8%. Lowest migration success is noted in the simulation starting at the end of September.

In these simulation it is found that the drifters actually move towards northfirst and then turn around towards the overwintering area. In the temperature following simulation, the inclusion of swimming behavior is seen to increase migration success and duration dramatically for migration starting in mid-September and end of October increasing migration success to ~50%, while doubling the success rate for the end of September simulation.

Table 14 Migration success of 770 drifters released from the central Anatolia region on September 15th, 30th and October 30th 2003 in the advection only and the temperature following (with 5 bl/s) simulation.

Simulation	Drifters	Start area	Start date	Year	Speed	2 weeks	4 weeks	6 weeks	8 weeks	Total arrival	Success %
Advection	770	Central anatolia	SEPT 15	2003	0	67	4	6	114	191	24,8
"	770	Central anatolia	SEPT 30	2003	0	31	1	0	65	97	12,6
"	770	Central anatolia	OCT 30	2003	0	53	0	2	114	169	21,9
Temperature following	770	Central anatolia	SEPT 15	2003	5 bl/s	401	6	2	0	409	53,1
"	770	Central anatolia	SEPT 30	2003	5 bl/s	151	5	0	0	156	20,3
"	770	Central anatolia	OCT 30	2003	5 bl/s	366	3	0	0	369	47,9

6.2 Discussion

The aim of this chapter was to elucidate the impact of intra-annual (seasonal) variability of environmental conditions on the migration success of anchovy that may leave at earlier times in the year than the reference simulation starting at the end of October. Drifter simulations starting in mid- and end-September, as well as mid-October 2003 showed there is considerable variability in the migration success with different starting times depending on which regions virtual drifter started.

Simulations analyzed in this chapter emphasize again that the warm water carrying coastal eddies and both mid-basin and peripheral jets are seen to strongly influence the migration pathways of anchovy from the northwestern shelf area to the overwintering grounds in the year 2003. The extent of these influences varies between migration starting times but the main influence in this particular year is the strong cooling process in the second half of October. The cold moves in from the northwest in the second week of October and very cold SST persists over the entire northern part of the western basin in the third week of October and very cold SST enters the southern basin along Romanian and Bulgarian coast and intruding towards the Inebolu offshore region in the last week of October. The cold signal enters the eastern basin in the third week of October and moves along the Crimea and Kerch regions towards the Caucasus offshore. It causes a southward retreat of the high SST values and by the last week of October warm spots along the Anatolian coast diminish and retreat towards the coast of Batumi - Trabzon region. This SST distribution pattern is shown to have a strong influence in the migration success and migration pathways of anchovy originating on the northwestern shelf and those originating off Kerch Strait in the northern part of the eastern basin. During the discussion here they will be assumed to be Black Sea and Azov anchovy.

The main difference between the different onset of migration simulations for anchovy from the northwestern shelf is that only when starting well before the cold spell in mid-September do drifters actually migrate successfully to the overwintering area, moving from the tip of Crimea Peninsula along warm water fronts around the Crimea connectied with an inner basin eddy, and they access into the warmer southern basin in 3 weeks before the cold spell sets in. The strong retreat of very warm SST towards the southeast edge of the basin following cold dominance results in landing of the drifters at the hot spots between the Sinop – Fatsa coasts of the overwintering area. They are not able to reach the warmest region near the Turkish – Georgian border due to the absence of the Rim Current in this period. The Rim Current is established in the second week of November, hence in Chapter 4 it is shown that the drifters released at the end of October (30th) and successfully access into the central southern basin follow the strong eastward flow to reach to the warmest southeast region of the entire basin. The Rim Current is actively running by that time and help transport of the drifters that come from the northwestern edge of the basin to the southeastern one effectively.

In the case of drifter release takes place on September 30 and October 15, the migrating drifters encounter persisting cold SSTs that cover a very large area. In such conditons, as the chances of cold avoidance becomes limited, the possibility of successful migration reduces significantly. In this cases the majority of the drifters follow straight southwards route and stop at the Bosphorus region, go across the Western Gyre and stop at the central Anatolia coastor they follow the eastern coast and approach Bulgarian – Turkish coast and therefore fail to migrate to the southeastern overwintering grounds.

When drifters are released from the shelf region in front of the Kerch Strait exit assuming they may represent Azov anchovy, the highest migration success is observed in drifters starting migration in mid-October. The drifters started on September 30 and October 15 of 2003 are seen to use multiple and complex pathways whereas those that start as early as September 15 is seen to use only single pathway. They are observed to move southwards to the eastern inner basin going through and around the Crimea eddy that carries warm waters northwards around its western periphery through interaction with a southern anticyclone. Untill the second week of October the warm temperature are extending from Anatolian coast to the inner basin along the southern coast. Therefore, after reaching the eastern inner basin the drifters that complete migration in four weeks move towards the closest warm regions that lay over the western coasts (between Sinop and Samsun) of the overwintering area. The southern coast is more accessible for drifters than the east coast. In this period there is no strong SST gradient to drive drifters eastward and hence they follow the westward front at the northern part of the newly established Eastern Gyre rather than following the east coast towards the Caucasus or Batumi region.

When migration starts on September 30th, the majority of the drifters a shown to complete a successful migration in four weeks and originate from the southwestern part of the shelf region at the exit of Kerch Strait. These drifters initially accumulate at the Crimea eddy region and then drifters approach southwards to the inner basin. With the onset of very cold temperatures apporaching from the northwest part of the basin, the retreat of warm SSts to the coast of Rize and Batumi is seen and some of the drifters follow this gradient moving eastward towards the southern coast of Caucasus (Sochi – Sukhumi) region. The drifters follow this path continue southwards from Sukhumi to Rize coast (by-passing the Batumi coast) and reach to eastern

Anatolia region of the overwintering area. The other two pathways identified in the seasonal analysis include the southward pathway towards the Sinop – Fatsa region and southeastward pathway towards the Trabzon – Rize region. While the former pathway goes around the inner basin anticyclone at the south part of Crimea eddy and follow the front at the edge of Sinop eddy, the latter path goes across the Eastern Gyre through the small cyclones of the interior basin.

When the drifters are started on October 15 from the narrow shelf region in front of the Kerch area, the majority of them move straight towards south into the inner basin, which it is the most successful pathway. The rest of the pathways identified in the intra-annual analysis that initially go southwards into the eastern inner basin and then either, (i) go towards southwest and arrives at the Sinop region, or (ii) go westward along the 43°N latitude to the western basin and then turn to move southeastward towards the overwintering area and arrive at the Samsun – Carsamba region. These simulations do not reproduce the result of Chapter 5, in which it was observed that starting at the end of October one pathway of Azov anchovy that moves parallel to the east coast againts the Rim Current (that carries warm waters of the south towards north). However, depending on the proximity of the Rim Current to the east coast, in the warm year (2001) the pathway was seen shifted offshore whereas in the cold year (2003) the path ran close to the shore and reached Georgia coast. This behavior has also been observed by Chashchin et al. (2015) previously, stating that in winter a larger portion of the Azov anchovy stock occupy the northeastern basin, while the rest of the stock form dense aggregations in response to northern wind observed in November and migrate along the east coast down to warmer areas (Chashchin et al., 2015) overwintering along the Georgian coast in cold years.

Earlier studies suggest that Azov anchovy migration extends further southwards from Caucasus to the Batumi region rather frequently (Chashchin, 1996). Moreover, in some particularly cold years anchovy may migrate further towards south along the east coast and approach the Turkish – Georgian border (Chashchin, 1996). However, migration towards Crimean Peninsula is thought to be less frequent and as a consequence more anchovy may be found at the Caucasus coast than the Crimean (Chashchin, 1996). The analysis in the current study suggests that the establishment of migration pathway along the complete east coast against the Rim Current may not occur very frequently as it is dependent on the occurrence of a strong temperature gradient at the Kerch Strait region and the extension of warm water along the east coast. However, the arrival of drifters released from the Kerch Strait region to the tip of Crimean Peninsula is more commonly observed in the simuations of this study within the time frame considered. For instance, the inter-annual analysis of migration pathways for the drifters released on October 30 of 2002 reveal that drfiters first reach to the offshore of the tip of Crimea and then continue towards the overwintering area. The mechanism that is likely to transport drifters to the tip of Crimea is the decreased variability related strong peripheral current that carries the warm waters of the east coast towards the south Crimea more efficiently in the November 2002 period. Moreover, the results of seasonal variability analysis indicate that the drifters come to the tip of Crimea when released in September 30 and October 15 of 2003. In the former case, the Crimea eddy that is transferring warm waters from the southern basin together with a southern anticyclone toward the tip of Crimea area during the first weeks of October and hence drifters are accumulated at the tip of Crimea. For the latter case, the reason fors accumulation at the tip of Crimea is the strengthening of the westward shifting Crimea eddy which supplies relatively warm waters in this region via its connection with a northward front at the coast of Sinop.

The high variability observed in the cold year 2003 facilitates migration of Black Sea anchovy originating on the northwestern shelf to the Turkish – Georgian border where they meet Azov anchovy migrating from Caucasus to the Batumi region. In such cases, the Azov population and the Black Sea population shoals together in this region and mechanical mingling takes place (Chashchin, 1996; Chashchin et al., 2015). This has important consequences for the summer distribution patterns of Azov anchovy species and anchovy population genetics. When co-existance of both sub-populations occur at the overwintering area, especially when the abundance of young individuals in the

Azov stock is high (as observed in 1979, 1981 and 1985), the spring migration of Azov race expands towards the Black Sea spawning grounds. As a fraction of the Azov anchovy stock stays in the northwestern shelf for feeding and reproduction, it results in formation of hybrid generations in this region. Nevertheless, the propagation of inheritable characteristics in hybrid generations is counteracted by natural selection (i.e., egg mortality) and maintenance of divergence between the populations via anchovy immigrations from the Mediterranean to the Black Sea (Chashchin et al., 2015).

Chashchin (1996) states that Black Sea anchovy migrate from the western and southwestern part of the Black Sea towards the Georgia coast. However, in both, the interannual and intraannual simulation analysis, virtual drifters are unable to reach to the overwintering area in any of the years and seasons within the time frame of interest of this study. The possible reasons this may be the very strong SST gradients occurring at the southern coast that immiditely fail the drifter migration and the no-slip boundary assumption of the current version of the model.

6.3 Conclusion

In this chapter research question 4 was answered for anchovy originating in different parts of the Black Sea, complementing the results of chapter 4 and 5. The results of the intra-annual variability analysis of anchovy migration reveal that the main factor influencing anchovy migration is the timing and strength of cooling events that are generally observed in October, no matter where anchovy originate. Depending on the intensity of cooling and the temperature gradient set up by it, anchovy experience different migration success rates. It should be noted that although the prevailing currents, as well as the strengths of eddies and the Rim Current are of importance, the overriding factor for migration success is the temperature distribution within the Black Sea in these simulations.

Starting migration long before the strong coling event may be an advantage for anchovy starting from the northwestern shelf. The main features facilitating transport are the shelf break front eddy, as well as the strong Crimea eddy connecting the north to warmer southern coastal regions. However, for later migration starts the cooling shuts down this transport pathway and migration success decreases significantly.

The analysis in this chapter also showed that migration of Azov anchovy along the east coast to the Georgian coast may be a rather rare event, as conditions that facilitate such transport are not observed frequently. Contrary to literature these simulations found that rather Azov anchovy may be transported northward towards Crimea.

Chapter 7

ORIGIN OF ANCHOVY IN OVERWINTERING AREAS AS EXPLAINED BY BACK-TRACKING MODEL SIMULATIONS CONSIDERING INTER-ANNUAL VARIABILITY

So far, this study analyzed where virtual anchovy released as drifters from specific regions would arrive within the migration period of two months in autumn and whether they succeed in arriving at the overwintering area either (i) with the aid of currents alone or (ii) with the application of behavioral movement together with advection by currents. The analyses in previous chapters 4 and 5 reveal that the advection by currents alone is not suitable for transporting the drifters from the traditional northwestern shelf spawning grounds to the overwintering area. In addition, the application of a more realistic simulation following temperature gradients towards warmer regions with five bd/s swimming speed indicated that only a small fraction of the drifters that originate from northwestern shelf area are actually able to complete a successful migration within eight weeks and the rest of the drifters are landed elsewhere.

Yet, it is known that, as the temperature in this area tends to be a few degrees higher than the western basin, the southeastern region of the Black Sea basin receives dense accumulations of anchovy schools at the end of autumn that support industrial fisheries in this region (Chashchin, 1996). In chapter 5 it was shown that drifters from other regions, mainly the eastern basin of the Black Sea may reach the overwintering region. However, to elucidate the exact source areas of anchovy accumulating in the overwinter region and their pathways for all years of interest (2001-2003), a backtracking simulations with the Lagrangian model are analyized in this chapter. This model setup exposes the source areas that facilitate anchovy's successful migration given the temperature distribution and mesoscale variability of the particular years, 2001, 2002 and 2003 in the present study.

The results of the interannual variability analysis in Chapter 4 demostrated that it takes 4 to 8 weeks to complete successful migration for the the drifters started from the northwestern shelf, the furthest geographical extent with respect to southeastern overwintering grounds. That means that drifters starting migration on October 30th arrive at the overwintering area either by the end of November or December the latest. To complement those analysis, a total of 869 drifters is initialized on 30th of December and 30th of November at the overwintering region and back-tracked for eight and four weeks, respectively, in years of 2001, 2002 and 2003. Special emphasis is given to locate possible source areas of the drifters reaching the overwintering area in 2002 as none could make it to the overwintering area from northwestern shelf area as shown in Chapter 4.

7.1 Results

The bi-weekly analysis of the source areas of the drifters released from the overwintering area on December 30 of 2001, 2002 and 2003, and back-tracked for 62 days in the advection only and temperature following simulations reveal that the eastern basin is the source area of almost all drifters in the advection only simulations (Figure 32,a-c). In the advection only simulation, in particular, the western periphery of the Eastern Gyre is observed as the primary source that supplies drifters to the overwintering area with Batumi region being of secondary importance. The extension of the source areas towards the Kerch region is closely linked with the circulation intensity and mesoscale patterns observed in each year in this region.

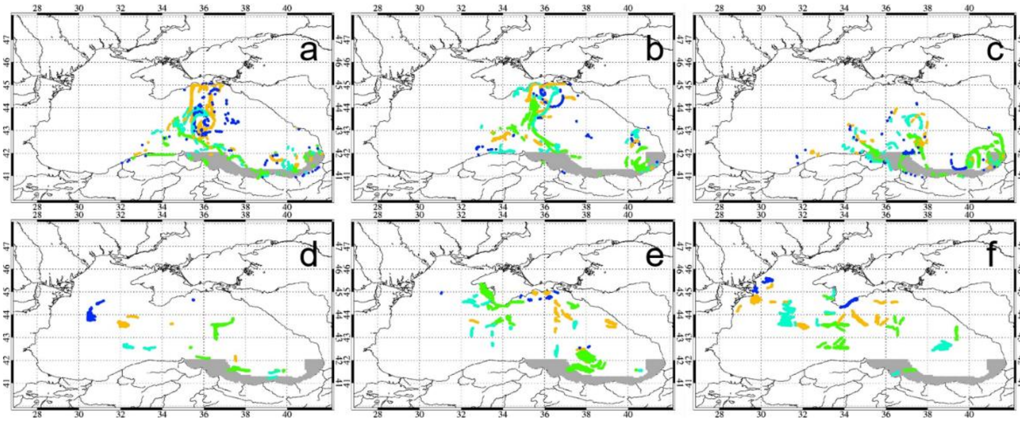

Figure 32 The end points of virtual drifters released in the overwintering area (shaded in grey) on December 30th and followed back in time until October 30th considering only advection (a-c) and movement following highest temperature with 5 bl/sec swimming speed (d-f) in years 2001, 2002 and 2003 (left, middle, right column). Endpoints of drifters after two, four, six and eight weeks are colored as green, cyan, yellow and dark blue, respectively.

In the advection only simulation, in 2001 (Figure 32,a) source areas from where the drifters are supplied to the overwintering grounds in eight weeks is the location of the big interior basin cyclone within the west half of the Eastern. Transport from the inner basin cyclone and from the Kerch Strait area takes only six weeks due to formation of a strong unstable jet that flows along the western periphery of the Eastern Gyre and extends between the southern edge of Crimea anticyclone at the north and Sinop anticyclone at the south. When the system switches into winter mode at the beginning of October, the core of the strenthened Eastern Gyre still supplies drifters to the target areas from the eastern central basin in four weeks. Then it takes two weeks for the drifters originating from the southern parts of the eastern inner basin located between the Rim Current and the Eastern Gyre to migrate. In addition, transport from the coast of central Anatolia is seen as another source region supplying drifters within only two weeks in 2001 in general. Drifters at the periphery of the Trabzon anticyclone at the beginning of December are transported in four weeks due to the high retention in this area.

In 2002, as a result of observed low mesoscale variability conditions in this period the advection only simulation results reveal that the Eastern Gyre facilitates drifter supply to the overwintering area in such a short time as two and four weeks along the western periphery extending towards the open sea at the Kerch region in the north (Figure 32,b). At the northernmost extent of the eastern basin drifters located along the coast from eastern Crimea to Kerch are transported to the overwintering area in four and six weeks, whereas it takes eight weeks for those located around the Kerch anticyclone to migrate with surface currents due to considerable retention in this area. The dipole Batumi eddy and the central Anatolia coast and open sea region are the other source regions identified in this period. Moreover, in this relatively strong flow system, some drifters originating from the middle of the Eastern Gyre, a strong retention area, are transported to the overwintering area in eight weeks.

Simulations of the high mesoscale variability year 2003 (Figure 32,c), the advection only simulation results show that unlike in 2001 and 2002, the northern extent of the source areas are the northen part of the Eastern Gyre as the eastern inner basin becomes a significant retention area for drifters transported to the overwintering areas in two, four, six and eight weeks. The coastal and open sea regions of the central Anatolia are shown to supply drifters in two to four and four to eight weeks, respectively. In this year a major source area is the Batumi region in this period that supplies drifters to the overwintering region in a very short time of two weeks due to presence of intense anticyclonic activity in the last two weeks of December. When the Batumi eddy weakens at the beginning of November considerable retention takes place and less number of drifters are supplied from this region to the overwintering area in eight weeks. Further, drifters originating from the filament in Zonguldak region are shown to be able to reach the overwintering area in six and eight weeks as a result of early establishment of Rim Current at the periphery of the southern basin, in particular.

The application of temperature following movement within the back-tracking analysis reveals a more extended and a complex orientation of the source areas that are quite variable from year to year as below. In 2001, drifters back-tracked from the overwintering areas subject to prolonged cold spell during November (Figure 32,d). Therefore, the distribution of source areas shows dense accumulations in this simulation. Drifters from the Eastern Gyre are shown to reach to overwintering areas in two weeks following the switch of the system into winter mode in the second week of December. The drifters at the offshore of Bartin – Inebolu region are seen to migrate to the overwintering area in four weeks while the Rim Current is active along most parts of the southern basin. Moreover, the drifters located within the western basin are seen to complete successful migration in six and eight weeks. In this analysis, single drifters completing migration in eight weeks from the northwestern shelf (Dniepr river plume), from northeastern Crimea and another one from the Caucasian coast arriving the overwintering area in two weeks is observed. Moreover, drifters close to overwintering area complete migration in two and four weeks in this period.

Simulations for 2002 and 2003 show that source areas distribution are more complex and scattered. The main reason is the absence of the persistent zonal cold temperature gradient. Accordingly, the source areas in 2002 (Figure 32,e) are located along the coast of Crimean Peninsula, central inner basin, northern part of the eastern inner basin, Caucasus coast and southeastern basin that complete migration in 2 to 8, 2 to 6, 4 to 6, 6 and 2 to 4 weeks is observed, respectively. Moreover, it is seen that it takes 8 weeks to complete migration for the single drifter originating from the northwestern shelf. Interestingly, the drifters along the western, southern and southeastern coast of Crimean Peninsula are migrating in 2 weeks. Comparison with the SST and SSH maps (see chapter 3) indicates that the reason for rapid relocation might be the warm temperatures extending from the Batumi region westward along the coastal zone of Anatolia, and hence creating a N-S SST gradient and the strong southwards current speeds observed in between the Western and Eastern Gyres reaching 0.25 – 0.3 m/s. Further, drifters originating from the Caucasus region are seen to follow southward along the east coast this is the region of highest SST. However, the migration in this case takes six weeks as the drifters swim against the strengthening of the northward flow intensity in the Rim Current as 0.1 m/s in November and 0.3 – 0.4 m/s in December period.

In 2003 (Figure 32,f), the distribution of source areas cover the largest area zonally compared to 2001 and 2002. Hence, the drifters that achieve successful migration from the northwestern shelf region is significantly higher. Drifters near Sevastopol on the shelf, and from the inner and outer shelf (shelf-break) region of the Danube discharge are shown to complete migration in 2, 4 to 6 and 6 to 8 weeks, respectively. The source region located within the central inner basin supplies drifters to the target area in two weeks, the drifters along the western periphery of the Eastern Gyre are influenced by the relatively high temperatures along the overwintering region and take advantage of strong southward currents at the western edge of the small cyclones within the Eastern Gyre.

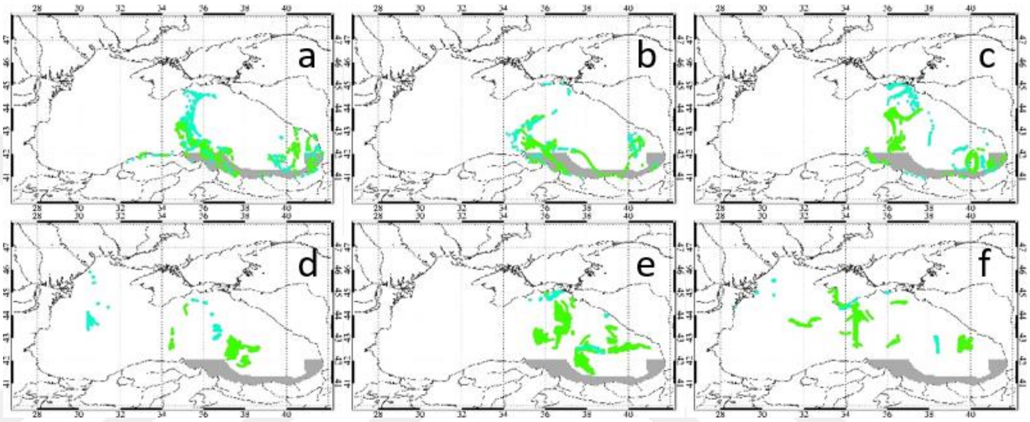

Figure 33 The end points of virtual drifters released in the overwintering area (shaded in grey) on November 30th and followed for two, four, six and eight weeks back in time are colored as green, cyan, yellow and dark blue, respectively. Simulations are considering only advection (a-c) and movement following highest temperature with 5 bl/sec swimming speed (d-f) in years 2001 (a,d), 2002 (b,e) and 2003 (c,d).

When drifters are released from the overwintering grounds on November 30th of each year and tracked for 30 days back in time in the advection only simulation, it is seen similarly to the previous results that drifters are aligning along the path of the western periphery of the Eastern Gyre (Figure 33,a,b,c), depending on the intensity of the circulation and the orientation of the Eastern Gyre during November in each year. In 2001, drifters from the periphery of the the Eastern Gyre complete migration in 4 and 2 weeks, respectively. The other source regions include the Batumi region and the coastline between Bartin and Sinop. Similar source region distribution is observed within 2002 and 2003 with respect to the Eastern Gyre and Batumi region influence. However, in

2002 the Crimea eddy is not present therefore the the region parallel to the east coast of Crimea eddy is not identified as a source region, instead, the coast of Kerch and the front around the east part of Kerch eddy are the source regions from where the drifters can be supplied to the overwintering area in 4 weeks. In 2003 the fronts around a number of mesoscale features at the west part of the Eastern Gyre and the eddy at the southern part of Crimea eddy together with the Batumi region and the eastern inner basin are the source areas identified in this period.

The application of temperature following behavior for drifters started at the end of November (30^{th}) and tracked for 30 days reveals source areas extending towards the western basin onto thenorthwest shelf area in high mesoscale variability years, 2001 and 2003, whereas in the low variability year 2002 the distribution of source areas are limited within the eastern basin (>35°E longitude) (Figure 33, d-f). The approach of cold temperatures from the west during the first two weeks of November that result in W-E temperature gradient is suggested to be the main reason for the failure of drifters from the western basin in this period. In 2001 (Figure 33,d), drifters representing anchovy arriving at the overwintering area at the end of November in four weeks are shown to originate either from the northwestern shelf, from western and eastern inner basins and from the exit of shelf of the Kerch region. Than, those arriving at the target area in two weeks are shown to originate from the southeastern part of Crimea, open sea region of the central coast of Anatolia and southern part of the eastern inner basin.

As mentioned above, the source areas of the drifters arriving at the overwintering area at the end of November 2002 (Figure 33,e) show that there is no possibility of migration success from the western basin (including the NWS) in case of low mesoscale variability conditions. However, in this year the eastern basin supplies drifters to the target areas from a larger spatial domain than shown in high variability conditions of 2001 and 2003. Then, it is seen that within the eastern basin the drifters completing successful migration in 4 weeks are originating from the region of Kerch eddy and its westward extension, Caucasus (Sochi) coastal region and from the Eastern Gyre, at the beginning of November 2002. The drifters arriving to the target areas in two weeks at the end of November are seen to originate from the western, northen and southern periphery of the Eastern Gyre, Batumi gyre and from the coast between Kerch and Novorossiysk regions and hence covering a very large area. Therefore, low variability conditions are shown to be more efficient in suppliying anchovy in the eastern basin to overwintering grounds whereas less efficient for migration success from the western basin.

In November of 2003 (Figure 33,f) show that drifters from the remote areas of Danube and Constantsa regions within the western basin, and relatively remote areas of southeastern coast of Crimea and coast of Kerch within the eastern basin can be supplied to the overwintering area in four weeks due to westward entending very warm temperatures from the east coast towards the eastern inner basin, along Novorossiysk are at the north and towards Zonguldak region along the Anatolian coast. Therefore, the increase in SST gradient at the coastal zone can be the reason for the migration success in these areas. However, it takes four weeks for the drifters to complete a successful migration from the center of Eastern Gyre close to the overwintering area. The decreased SST gradient and the strong cyclonic activity inside the Eastern Gyre could be the factors causing the delay of arrival in this period. Moreover, the drifters from the western inner basin, southwestern coast of Crimea, in between the two gyres, and open sea region of Kerch, west part of cyclonic eddy within the Batumi region and at the southern edge of the mid-basin front connecting Crimea to the southeastern coast are the observed source areas that support migration success within two weeks in this period.

7.2 Discussion

The results of the back-tracking analysis of drifters from know overwintering areas are designed to explore where all drifters located within the overwintering area domain would have come from given the interannual and seasonal variability of surface currents and SST distribution. The start dates of simulations are set on a two specific date, end of November and end of December. These dates are assigned to complement the results of the analysis of Chapter 4 that suggest that the anchovy released at the end of October from the northwestern shelf located at the furthest geographical extent of the domain, arrive at the overwintering areas in either 4 or 8 weeks, which is the end of November and December.

Accordingly, when the drifters that are back-tracked for 31 days from the end of November to the beginning, the source areas are extending towards the western basin, to the northwestern shelf in particular, in case of high variability condition of 2001 and 2002, disregarding the duration of cooling. In contrast, the low variability observed in November 2002 added to the effect of W-E gradient that resulted in a strong zonal SST gradient in the eastern inner basin resulted in no migration success in the western basin and a larger source area distribution than those observed in the other two years within the eastern basin.

When the drifters are back-tracked from December 30 for 62 days, the results show that the main spawning/source areas are located within the eastern inner basin in all simulations and they extend further east or northeast during years of high mesoscale variability (i.e., 2001 and 2003) and are more oriented along the northern regions of Crimea and Kerch in low mesoscale variability years (2002). In addition, prolonged cold SST events such as observed in 2001, are seen to restrict the spatial coverage of source areas, causing a delay in the migration duration. However, in years with short lasting cold events, the origin areas are more evenly distributed all over the basin except the southwestern basin. In addition, the orientation of source areas is mimicing the direction of cooling in each simulation year. In case of high variability conditions of 2001 and 2003 it is along a NE-SW direction whereas in low variability conditions of 2002, the orientation of source areas is along a W-E direction in the western basin and N-S direction within the eastern basin. At this point, it worths noting that rather than the overall mean temperature distributions between the (colder/warmer) years, it is actually the orientation of the temperature gradients, progression and duration of cooling that mainly influence the distribution and extent of source regions in each year. Therefore, the location of spawning grounds are dynamically changing from year-to-year and season to season depending on the flow characteristics and, more importantly, winter cooling patterns rather than the SST distribution itself.

Considering Azov anchovy, the analysis shows that the pathway that follows the Caucasus (Novorossiysk – Sochi sector) southwards to Poti – Batumi region is suggested as a common pathway (Chashchin, 1996), whereas the extended cold northern wind event can cause dense accumulations that follow the east coast of Crimea and accumulate along the southern coast of Crimea (Chashchin et al., 2015). In the present chapter's temperature following analysis (during 62 days), it is seen that it takes 2 weeks and 6 weeks to arrive at the overwintering area at the end of December of 2002 for those originating from the tip of Crimean Peninsula and coast of Caucasian (Sochi) coast, respectively. When the direction and the intensity of the currents in December are considered, a strong southward flow with a magnitude of 0.25 – 0.3 m/s is observed on the way of drifters from Crimea to overwintering area on the western periphery of the Eastern Gyre and a very strong northward flow with a magnitude of 0.3 – 0.4 m/s is observed along southward migration route of drifters originating from the Caucasus coast. Therefore, as the drifters migrate southwards to the warmer areas and hence overwintering area, arrive very fast (in 2 weeks) from Crimea to the overwintering area via swimming in the direction of the current. In contrast, those migrating along the east coast against the strong Rim Current are shown to arrive later (in 6 weeks) to the overwintering area. Knowing that anchovy evaluate the costs and benefits of performing migration via following internal, body fat content, and external cues such as temperature drops (Shulmann, 2002), the pathway that connects the Crimea to the overwintering area can be regarded as a more favorable pathway than the path from Caucasus towards the overwintering region, since it saves energy and time. Consequently, the Crimea – Anatolia migration pathway can be suggested as a major pathway and secures the transport of not only the Black Sea anchovy migrating from the NWS are but also the Azov anchovy.

7.3 Conclusions

In this chapter research question 5 was answered and the nursery areas from where anchovy arrive successfully at the overwintering area in different years (2001-2003) were investigated by applying a back-tracking model that follows drifters from their final destination, the overwintering area itself, starting in November 30th and December 30th, back to the initial locations during 31 and 62 days, respectively. Results show that source areas of overwintering anchovy vary significantly between warm and cold years as well as with different migration starting times. Simulations confirm the results of previous chapters 4 and 5 in that only x % of all drifters that were found in the overwintering areas actually originated on the northwestern shelf. Hence this region is not a viable source region for overwintering anchovy. Instead, different regions of the eastern Black Sea are the major source areas, which is confirming results of chapter 5. Small areas on the north-western deep basin may also be considered as the possible source areas.

Low mesoscale variability as observed in November 2002 help transport of passive drifters from the Azov Sea region and north-western regions of the eastern basin. High mesoscale variability in the northern basin like in 2003 shifts source areas located in the north dramatically southwards close to the overwintering area. Hence, the source areas for anchovy cannot considered to be stationary rather they are likely to be modified different environmental conditions. The results of this chapter clearly show that the contribution of currents to migration behavior is to determine the time it takes to reach the region, while the sea surface temperature distribution determines where exactly drifters reach.

Chapter 8
THESIS CONCLUSIONS

While migrating across the Black Sea, anchovy is subject to a highly variable physical environment which is characterized by rapidly changing sea surface temperatures, turbulent eddies, unstable frontal jets, coastal filaments and other mesoscale processes (i.e., cross-shelf transport). To elucidate the influence of these conditions on anchovy migration success, to evaluate their most likely source areas and common migration routes, virtual drifters representing anchovy individuals were released into the circulation field from possible nursery habitats at different times during autumn of three consecutive years of 2001-2003. This time frame spans a variety of environmental conditions in the Black Sea with 2001 being the warmest year of the century, 2002 a medium and 2003 a comparably cold year.

The analysis of satellite data showed that the presence of an eddy at the shelf-break zone and the southward frontal jet between the Eastern and Western Gyres, as well as the eddy at the shelf-break zone, its eastern adjacent cyclonic eddy, the Crimea Eddy, the quasi-stable cyclonic inner cell in the central inner basin and the cyclonic Rim Current are the likely features that facilitate efficient migration of anchovy located on the northwestern shelf (chapter 3).

However, simulated drifters cannot reach the overwintering area in the time frame of two months with the aid of advection (passive movement) alone. Including the behavior of temperature gradient following during migration at high swimming speeds of 5bl/s therefore represents the most realistic migration simulation of several tested in this study. Interestingly, these realistic simulations revealed a migration success between 0-15.3% from the northwestern shef, indicating that nursery areas on the northwestern shelf do not play a major role in supplying anchovy to overwintering grounds and that alternative source regions within the Black Sea basin must exist (chapter 4). This study is in contradiction to the theory suggesting that the northwestern shelf is the only nursery area from where the anchovies start overwintering migration (Ivanov and Beverton, 1985; Chashchin, 1996; Shulman, 2002).

In addition, the identified paths of migration pathways for the few drifters successful migrating from the northwestern shelf are (i) transport across the Western Gyre and (ii) direct transport between the two gyres. The results of this study show that due to the environmental conditions in terms of temperature and surface circulation anchovy are not likely to along the Bulgarian-Romanian coasts at all, supporting Gucu et al. (2015) and providing a possible explanation for why the route is not used anymore (chapter 4). It can be concluded that the Bulgarian/Romanian pathway (Ivanov and Beverton, 1985; Chashchin, 1995) is no longer available to virtual drifters due to the environmental connditions of the Black Sea during the time of this modeling study (2001-2003). It may even be possible that a shift in currents and cooling events has caused the collaps of this fisheries because anchovy reach overwintering regions easier via open ocean pathways.

Further simulations investigating from which other areas of the Black Sea migration to overwintering grounds is feasible, showed that the central and southern eastern basin appears to be the major source area that facilitates efficient transport of anchovy irrespective of the degree of environmental variability (chapter 5). However, the northern parts of the eastern basin, which can be assumed to be mainly occupied by Azov anchovy, are effected considerably by interannual variability. For anchovy starting migration in this area the direct pathway between Crimea and Samsun and another following the eastern coast of Black Sea against the Rim Current are found to be the major pathways which is in agreement with the literature on the migration of Azov species (Chashchin, 1996; Chashchin et al., 2015).

The investigation of seasonal variability and timing of anchovy migration and its effect on migration success showed that the most important factor shaping migration pathways, and with it success, is the intensity and timing of cooling.

More so than the intensity of currents around eddies and the Rim Current because it is contributing to forming temperature gradients across the Black Sea that determine the pathways chosen by anchovy (chapter 6). The analysis showed that starting migration long before intense cooling in October/November may increase the migration success from the northwestern shelf region. When anchovy start migration later, direct pathways to the southeastern overwintering grounds may be shut down and the migration success decreases significantly. For Azov anchovy originating off Kerch Strait migration following the temperature gradient along the eastern coast against the Rim Current depends on a strong SST gradient being established at the exit of the Kerch Strait. It is seen that this is not very common during the simulated years and seasons. Therefore, contrary to the existing literature the Crimea to Anatolia migration pathway between the two cyclones is a more advantageous pathway for these anchovy which saves time and energy.

Finally, the backtracking analysis in chapter 7 aiming at exploring the interannual distribution of the exact source areas of anchovy reaching the overwintering area within the Black Sea confirmed results of previous chapters and showed a very low contribution of northwestern shelf anchovy. The highest contribution to overwintering anchovy was made from the central eastern basin if a two month migration period is assumed. Interestingly, also some drifters from the central deep western basin supplied anchovy to overwintering grounds. When migration is thought to last only 1 months until November from the western basin contrinute more in each of the simulated years. It should be noted that the source regions were seen to be oriented along the SST gradient, within the eastern and western inner basin.

This study demonstrates that satellite data together with simple models of particle andvection and behavior can be used to explore the migration of complex organisms such as fish in the marine environment. It also demonstrates that this modeling approach is a valuable tool in understanding the process of fish migration, which is difficult to observe with conventional methods. It has proven to be a powerful tool to the complex processes of environmental variability on migration success of anchovy and may help predicting the timing and success of migration in different years, which is of importance to the fishing industry.

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APPENDICES

Appendix 1: Detailed analyses for the weekly mean sea surface temperature, geostrophic currents and absolute dynamic topography maps.

SEPTEMBER 2001:

SST

In the first week of September (Figure9a), the basin averaged SST values are changing between 23.0 and 26.9 °C. Lower SST values (<24.0°C) are observed at the northern coasts of the NWS, offshore of Crimea and Azov Sea and in the Eastern Inner Basin. The coastal regions of Eastern Anatolia (including cities of Trabzon, Rize, Artvin), inshore areas (between Batumi at the south and Kerch at the North) of eastern Black Sea and offshore Batumi region is seen to be very warm (>26.0°C). The temperature at the southern inner basin and the rest of the inshore and offshore waters of the southern (Anatolian) coast and offshore band of Eastern Black Sea is between 25.5 and 26°C. The rest of the basin SST is lower than 25.5°C. This is a typical temperature distribution for the Black Sea with the northeastern Black Sea colder than the southwestern Black Sea that is created by the heating and cooling of the Black Sea by atmospheric processes (Oguz et al., 1995; Ducet et al., 1999; Korotaev et al., 2001). The observed temperatures are rather high in comparison with other years (Mc Quatters et al, 2008), which is one of the reasons to choose this particular year for this study.

In the second week of September 2001 (Figure9d), basin averaged SST values are seen to vary between 21.5 and 26.2°C. There is a 1.5°C difference with respect to the lowest temperature of the previous week (of 23.0°C). Colder temperatures (<23.0°C) are observed over the NWS extending to the Eastern Inner Basin along/following the offshore region of Crimea. Temperatures higher than 24.7°C are concentrated at the southeastern and eastern Black Sea coasts, along the inshore and offshore waters of the region between Trabzon (at the eastern Anatolian coast) and northern Georgia and inshore waters between Georgia-Russia border and Tuapse region.

The third week of September 2001 basin average SST values (Figure9g) vary between 21.0 and 25.8°C. There is a 0.5°C drop in the minimum temperature with respect to the lowest SST value (21.5°C) of the previous week. The cold temperatures (<22.7°C) at this period prevail inside the north parts of the NWS and northeastern parts of the eastern inner basin. Similar to previous weeks, the colder temperatures (<24.3°C) are located at the southeastern and eastern coasts of the Black Sea but this time their aerial extend goes further offshore from the coast as cooling progresses. Also warm conditions (>24.3°C) exist locally at the Anatolian inshore waters.

Basin averaged SST values at the last week of September 2001 are seen to change between 20.6 and 25.4°C (Figure9j). The lowest temperature is 0.4°C colder than the coldest temperature value (21.0°C) of the previous (3^{rd}) week (Figure9g). However, cold regions (<22.2°C) at this time are seen to cover all over the NWS region and extending towards east reaching Azov Sea exit and entering Eastern Inner Basin. The warmest temperatures (>23.8°C) at this period are seen to retract towards the southeastern edge of the Black Sea following the inshore and offshore region between Trabzon and Sukhumi. The temperatures at the eastern part of the Eastern Basin and at the southern basin vary between 22.8 and 23.8°C.

Geostrophic Currents

In the first week of September 2001 (Figure9b,c), the Danube anticyclone and the Contantsa anticyclone are seen to be at formation stage within the relatively warmer (24.4-24.8 °C) regions of the NWS area. At this stage, the current speed are shown to reach 0.2 and 0.1 m/s speed within Danube Eddy and Contantsa Eddy, respectively. The other mesoscale formations in the northern part of the basin are the newly forming Kerch and active Caucasus anticyclones running with speeds of 0.1 and 0.25 m/s, respectively. Within the southeastern basin newly forming quasi-persistent Suchumi Eddy and active Batumi Eddy present each of which attain speeds of 0.15 and 0.3 m/s, respectively. The anticyclones at the Anatolian coast are the newly forming Bosphorus and Sakarya Eddies at the west and the active Sinop, Kizilirmak and the newly forming quasi-permanent eddy at the region between Giresun and Trabzon with speeds of 0.25, 0.15, 0.3, 0.3 and 0.2 m/s, respectively.

In the second week of September 2001 (Figure9e,f), the dominant mesoscale features of the turbulent basin are the newly forming Constantsa and Sevastopol Eddies and the strong Danube Eddy at the NWS area and the active and strongly flowing Kerch and Caucasus Eddies at the northeastern basin each of which attain speeds of 0.1, 0.1, 0.2, 0.1 and 0.25 m/s, respectively. When compared with the mesoscale activity of the 1st week, at the southern basin weaker Bosphorus, Sakarya, Sinop and Kızılırmak Eddies whereas stronger Batumi and quasi-permanent Suchumi Eddies persist with the speeds of 0.1, 0.15, 0.2, 0.15, 0.35 and 0.2 m/s, respectively.

Within the third week of September 2001 (Figure9h,i), the basin averaged current and SSH values indicate a weakening in the intensity of Danube, Kerch, Caucasus, Sinop and Sakarya anticyclones with speeds of 0.15, 0.05, 0.2, 0.05 and 0.1 m/s, respectively. The Constantsa, Sevastopol, Kızılırmak anticyclones are intensified with speeds of 0.15, 0.25 and 0.25 m/s, respectively. The Suchumi Eddy is seen to join with Batumi Eddy and thus attaining a high speed of 0.35 m/s.

In the fourth week of September 2001(Figure9k,l), the mean currents and SSH distribution show a decrease in the intensity of Danube, Crimea, Caucasus, Batumi and Kızılırmak Eddies and their speeds are 0.1, 0.1, 0.15, 0.3 and 0.1 m/s, respectively. Sinop, Sakarya and Suchumi anticyclones disappear. The Suchumi anticyclone vanishes due to its unison with Batumi Eddy. Sevastopol, Crimea and Kızılırmak Eddies are seen to become stronger reaching speeds of 0.3, 0.1 and 0.1 m/s, respectively. Constantsa and Kerch eddies' intensity remain the same and thus their speeds stay at constant levels of 0.15 and 0.15 cm/s, respectively.

OCTOBER 2001:

SST

The basin averaged SST values at the first (1st) week of October 2001 are seen to deviate between 18.9 and 24.3°C (Figure10a). This implies a strong drop in temperature (of 1.7°C) with respect to the SST of the previous week (Figure9j). As a continuation of the cooling process the cold regions are located along the coastal regions of NWS, extending towards the east into the Eastern Inner Basin and towards south into the Western Inner Basin in a narrow band. The regions of highest temperature (>22.6°C) are located at the southeastern basin following the coast of Giresun (Anatolia) towards the northeastern coastal Tuapse (Russia) regions and their offshore extent.

In the second week of October 2001, the basin averaged SST varies between 18.4 and 23.6°C minimum and maximum values (Figure10d). The minimum temperatures in this period are seen to drop 0.5°C with respect to the previous week values (18.9°C). The cold temperatures (<20.2°C) are spatially overlapping with the cold regions of the previous week (Figure10a).

In the third week of October 2001, the mean SST values over the Black Sea basin are seen to change between 17.2 and 22.5°C minimum and maximum values, respectively (Figure10g). This indicates for a drop of 1.7°C in the lowest temperatures over the basin with respect to the 2nd week (18.7°C) (Figure10d). The coolest temperature band (<19.0°C) at this period again dominate over the NWS area and extend towards the east coming closer to the east coast of Crimea and open sea regions of the Azov Sea exit of the Eastern Basin. Thus, the regions of high temperature are extending from Surmene (between Trabzon-Rize) to Tuapse coastal and offshore waters and also southeastern inner basin.

In the fourth week of October 2001, basin averaged SST distribution is seen to be varying between the minimum and maximum values of 15.8 and 20.9°C, respectively (Figure10j). There is a 1.4°C temperature drop with respect to the third week's temperature minimum (17.2°C) (Figure10g). However, the minimum temperature (<17.6°C) regions within the NWS are seen to get transported towards east to the coastal and open sea domains between the Sevastopol (Russia, former Ukraine) and Kerch (Russia, former Ukraine) regions and are replaced by relatively warmer waters between 18.3-17.6°C except for the residual coldest waters trapped between the land-sea boundary of the NWS. The coastal and open sea waters of Batumi (between Trabzon and Suchumi) region still remain amongst the warmest regions in the fourth week however the distribution of very warm areas are seen to decrease compared to the intensity and distribution of moderately warm (18.8-19.4°C) areas. Moderately warm areas dominate both at the southern and northeastern coastal and offshore waters and also at the west side of the very warm waters within the Batumi Region. Waters with cooler temperatures (18.1-18.8°C) exist within a narrow band between the relatively warm waters of the Batumi region, southern and northeastern coastal regions and cold open sea temperatures (<18.1°C) of the Inner Basin. In this period the Sevastopol eddy is shifted towards off-the coast of Sevastopol carrying its warm waters closer towards the NWS area.

Geostrophic Currents

In the first week of October 2001 (Figure10b,c), the current and SSH values for the Black Sea basin reveal a less turbulent mesoscale structure with respect to September 2001 values (Figure10b,c,e,f,h,I,k,l). Satellite data shows that Sevastopol, Crimea, Caucasian, Kızılırmak and Bosphorus Eddies strengthening, gaining the speeds of 0.4, 0.25, 0.2, 0.2 and 0.35 m/s, respectively. While the Batumi anticyclone weakens and Constantsa Eddy remain unchanged with speeds of 0.25 and 0.5, respectively. Moreover, in this period Kerch Eddy vanishes with Suchumi, Sinop and Sakarya Eddies stay resolved.

In the second week of October 2001, the observed SSH and current velocities (Figure10e,f) show less variation with respect to the second week of the September 2001 (Figure10e,f). In this period, Kerch and Sakarya Eddies appeared with speeds of 0.15 and 0.25 m/s, respectively. The intensity of Constantsa and Sevastopol anticyclones remain unchanged as 0.15 and 0.4 m/s, respectively. The intensity of Crimea, Caucasian, Batumi, Kızılırmak and Bosphorus Eddies decrease as they attain speeds of 0.2, 0.15, 0.15, 0.05 and 0.15 m/s, respectively. The Caucasian Eddy is resolved into two-phase structure at this period. Danube, Suchumi and Sinop eddies remain absent. In this period the Western Gyre is limited between 29.0 – 33.0°E longitudes and separated from the more turbulent Western Basin with a frontal boundary. The Eastern Basin is divided into three sections (two of which are cyclonic eddies) via two fronts along southward direction. Moreover, there is an eastward coastal front flowing between the anticyclonic eddy at Samsun region and cyclonic eddy at Rize region.

Within the third week of October 2001 (Figure10h,i), the mesoscale activity as inferred from current and SSH observations is seen to weaken. Three anticyclones that are active in this period are Sevastopol, Caucasus and

Suchumi anticyclones which reach the maximum speeds of 0.3, 0.2 and 0.15 m/s, respectively. Among those eddies, Sevastopol and Kerch Eddies seem to get weaker and Caucasian Eddy is seen to get stronger with respect to the previous (2^{nd}) week's values (Figure10e,f).

Within the fourth week of October 2001, the eddy activity remain low as in the case of third week (Figure10k,l). The active eddies are the intensified Sevastopol and Suchumi Eddies, weakened Caucasian Eddy and the newly forming Batumi and Crimea with speeds of 0.35, 0.25, 0.1, 0.15 and 0.1 m/s, respectively.

NOVEMBER 2001:

SST

In the first week of November 2001, the weekly mean SST distributions over the Black Sea vary between 13.7 and 20.1°C (Figure11a). This means a temperature drop of 2.1°C. Similar to the SST distribution of the previous week, the cold waters are distributed over the northern central basin extending from cross-shelf areas of the northwestern basin towards the central open sea area of the northeastern basin at the east and towards the Crimea coasts at the north.

In the second week of November, the SST distribution over the Black Sea varies between 12.9 and 18.2°C minimum and maximum, respectively (Figure11). This shows a 0.8°C temperature drop with respect to the basin wide minimum temperature value of the previous week. The basin wide coldest (<14.7°C) waters are concentrated around Crimean coastal and open sea regions of the northern central Black Sea and northern coasts of the NWS, while the presence of Sevastopol Eddy supplies relatively warmer (between 14.7-15.7°C) waters into the NWS basin. The highest temperatures (>16.6°C) at this period dominate again within the warmer Batumi area from Trabzon coast to Sochi both over coastal and open sea waters.

Within the third week of November 2001 (Figure11g), the basin wide SST distribution in the Black Sea is seen to be varying between 11.7 and 16.6°C, minimum and maximum values, respectively, indicating that temperatures to be 1.2°C lower than the coldest temperature of the previous week. The cooling pattern extends further from northwest to southeast and continues to do so in the fourth week as well. Then the weekly mean SST varies between 10.1 and 15.6°C minimum and maximum values, respectively, a further decrease in the coldest temperatures observed by 1.6°C. The weakening in the effect of Sevastopol eddy providing relatively warmer waters (12.0-12.5°C) for NWS and formation of two anticyclones at each side of the Sevastopol eddy causes an accumulation of very cold waters into the NWS area.

Geostrophic Currents

Within the first week of November, the mesoscale features are more dominant when compared to the 3rd and 4th weeks of the previous month (October, 2001, Figure11h,i,k,l) with the formation of new anticyclones as Constantsa, Trabzon, Kızılırmak, Sakarya and Bosphorus anticyclone with speeds of 0.1, 0.1, 0.15, 0.15 and 0.15 m/s, respectively (Figure11b,c). The Crimea eddy is intensified reaching 0.25 m/s speed and rest of the anticyclones remain at same intensity as the Suchumi Eddy or get weakened as the Sevastopol, Caucasian and Batumi Eddies with speeds of 0.25, 0.3, 0.05 and 0.05 m/s, respectively.

In the second week of November 2001, the calculated geostrophic currents and observed SSH data reveal an increase in the intensity of Caucasian, Batumi and Sakarya Eddies which are shown to reach speeds of 0.15, 0.25 and 0.25 m/s with respect to the previous week values, respectively (Figure11e,f). On the other hand Constantsa, Sevastopol, Suchumi, Kızılırmak and Bosphorus anticyclones are weakened and Crimea anticyclone remain constant. The formation of and coastal anticyclone and two offshore cyclones around Trabzon region and an inner anticyclonic cell separated from Sevastopol eddy at its southeastern part are observed. Crimea and Trabzon anticyclones remain in the same intensity as 0.25 and 0.1 m/s, respectively.

In the third week of November 2001 (Figure11h,i), the mean current and SSH distribution over the Black Sea basin reveal an increase in the strength of Sevastopol (0.25m/s) (anticyclone on the southeastern part at 0.05 m/s speed), Caucasian (0.35 m/s) and Suchumi (0.25 m/s) eddies whereas the intensity of the Crimea 0.15, Trabzon 0.05 and Kızılırmak and Sakarya 0.15 eddies decrease. Batumi eddy persist with the same intensity as the previous week with 0.25 m/s speed. In this period the Constantsa and Bosphorus anticyclones almost vanishes and become cyclonic with 15 m/s and 20 m/s speeds, respectively. A cyclonic feature appears at the northern edge of NWS with 0.05 m/s speed.

Within the last week of November, according to the surface current and SSH data (Figure11k,l), the mesoscale activity at the NWS area is weaker than the previous weeks of this month (Figure11b,c,e,f,h,i).

DECEMBER 2001:

SST

In the first week of December 2001, the weekly mean SST values are seen to vary between 8.6 and 14.7°C minimum and maximum temperatures, respectively (Figure12a), another 1.5°C decrease in the coldest temperature. There is an area of warmer waters present at the eastern boundary of NWS and western inner basin characterized by temperatures between 10.7 and 11.6°C, which overlaps the anticyclonic small eddy at the Sevastopol region and its surrounding nearly clockwise jet flow and might be related with the presence of merged Constantsa and Danube anticyclonic eddies located at the Danube coast.

In the second week of December 2001, the observed maximum and minimum temperatures over the basin are 13.4 and 7.1°C, respectively, constituting a 1.5°C drop with respect to the minimum values of the previous week. The merged structure is separated into two individual eddies, Constantsa and Danube eddy, therefore the cold waters in NWS area and around the Crimea coastal areas are replaced by relatively warmer (9.4 – 10.5°C) waters.

In the third week of December 2001, the observed maximum and minimum temperatures over the basin are 12.4 and 3.7°C, respectively. This shows a 3.4°C drop with respect to the minimum values of the previous week. In this week particularly cold SST (6.7 – 7.5°C) values are observed within a narrow band at the north part of NWS. In the fourth week of December 2001, the weekly averaged basin wide SST values are seen to vary between 4.1 and 11.8°C minimum and maximum values, respectively (Figure12j). The very cold values (<6.8°C) are only observed at the NWS coasts of the Black Sea. Within the rest of the NWS the SST varies between 6.8 and 9.1°C.

Geostrophic Currents

The first week in December shows a more settled mesoscale structure in the eastern basin is seen (Figure12b,c) compared to the previous week (Figure12k,l). However, the Rim Current is not very strong at this time as evidenced by the presence of mesoscale eddies all over the basin and hence the lack of continuous flow pattern at the eastern Anatolian offshore waters. The flow speed of this weak Rim Current is nearly 0.1 m/s. In terms of eddy activity, the appearance of a merged Danube and Constantsa eddy structure at this period and have speeds of 0.2 and 0.1 m/s, respectively. The high speeds at the Bulgarian coastal waters of 0.3-0.4 m/s are indicating Danube fresh waters discharge which seem to be reaching until the Bosphorus region. In the Sevastopol region the activity of an anticyclone and a cyclone is evident with speeds of 0.1 and 0.15 m/s, respectively. There is westwards flow around the Crimea tip (Yalta), Kerch and Caucasus region with speeds of 0.25, 0.2 and 0.15 m/s, respectively. A northwards jet is observed at Batumi region characterized by 0.30 m/s speed. There is a small anticyclone off the coast of Trabzon and the jet around this eddy has a speed 0.15 m/s. A discontinuous eastwards jet that reaches up to 0.2 m/s speed going from Bafra to Ordu is observed at the Anatolian coast. There is a small anticyclonic eddy at the Kerch offshore area.

In the second week of December (Figure12e,f), the disappearance the of anticyclone and cyclone structure at the Sevastopol area leads to a more uniform westward flow structure in this area with respect to the previous week values (Figure12b,c). Similarly, the disappearance of offshore anticyclonic eddy around Kerch increases the speed of the peripheral flow in this region thus leading to a stronger (0.3m/s) southwestward transport of warmer waters on the eastern coastal part of Crimea. Eventually the warmer waters of the eastern basin are introduced into the western basin, especially to the NWS area. Moreover, the separation of the merged Danube – Constantsa eddies into individual structures is another factor supplying warmer waters into NWS area. In the third week of December 2001 (Figure12h,i), the Rim Current flow is seen to be more stable. With respect to the previous week, the intensity of the Crimea, Kerch and Caucasus eddies increases and maintains a strong southward and northward flow at the eastern Crimea and Caucasus regions, respectively. The increase of speeds at the edge of the currents is related to linking of Batumi, Suchumi, Caucasus, Kerch eddies in the east, and Sinop and Kızılırmak eddies at the eastern Anatolian coast, and Danube and Constantsa eddies at the northwest and therefore confounds of the Rim Current flow pattern.

In the fourth week of December 2001 (Figure12k,l) a stronger flow of the Rim Current in the NWS region (0.25 m/s) is observed. However, the flow at the western coast around Bulgaria is weakened due to the decrease of the Danube fresh water discharge. Thus, the Rim Current in these regions is not as well defined as the previous two weeks (Figure12e,f,h,i). However, in the rest of the basin the contraction of mesoscale eddies helps establishment of peripheral Rim Current structure.

SEPTEMBER 2002:

SST

In the first week of September 2002, the mean temperatures over the basin are seen to vary between 22.5 and 26.1°C, minimum and maximum values, respectively (Figure13a), which means the average temperature (22.5°C) in the entire Black Sea is 0.4°C less than in the first week of September 2001. The general pattern of cooler temperatures in north-western Black Sea versus warmer temperatures in the south-east can be observed just as in 2001. In particular temperatures colder than 23.7°C are seen to spread over the whole Western Basin intruding into the Eastern basin at the north. The warmer (>24.6°C) temperatures are seen at the eastern parts of the Eastern basin and at the eastern coasts of Anatolia. Within those areas the particularly warm (>25.0°C) temperatures exist between Sochi and Gelendzhik coastal and offshore areas and partly within the northern coastal and open sea areas of Georgia. The strong cooling at the western basin that usually happens through strong cold winds blowing from the Balkans (Korotaev et al., 2001) in this period helps the formation of Rim Current early within the first week of September 2002.

In the second week of September 2002, the basin wide SST is seen to vary between 22.0 and 25.7°C minimum and maximum temperatures, respectively (Figure13d). Although there is a 0.5°C decrease with respect to the minimum temperature of the previous week the strong wind driven cooling which persisted over the Western Basin and modified the peripheral flow structure of the basin via overcoming the turbulent eddies is seen to cease in this period. Correspondingly, the geographical coverage of the coldest (<23.3°C) temperatures are seen to be retreated northwards and westwards towards the NWS region and cooling intensity decreases. Moreover, the presence of Sevastopol eddy at the west coast of Crimea is making this region of the NWS relatively warmer than its surrounding areas.

In the third week of September 2002, the weekly mean SST values are seen to vary between 20.9 and 25.2°C minimum and maximum, respectively (Figure13g). There is a 1.1°C decrease in the minimum temperatures with respect to the previous week. Further cooling is observed in the fourth week when the lowest temperature at this period is seen to decrease 0.5°C below the minimum value of the previous week. In the fourth week of September 2002, the maximum and minimum temperatures are varying between 24.8 and 20.4°C maximum and maximum, respectively.

Geostrophic Currents

The strong gradient in the sea surface heights is implying a strong peripheral current structure within the Black Sea basin (Figure13b,c). This Rim Current structure is moving at a speed of 0.15 – 0.25 m/s. The Batumi anticyclone is shown to have a speed of 0.2 m/s and the Rim Current flowing around the Batumi eddy is reaching very high speeds of 0.35 - 0.4 m/s. The current speed offshore of Samsun and Sakarya coast reaches 0.25 and 0.3 m/s, respectively. The presence wind-induced cooling introduces strong southwards flow at the coastal and offshore area of Bulgaria reaching speeds varying between 0.3 and 0.2 m/s at Bulgarian (Varna) and Turkish (Istanbul) coast, respectively. In this period, a strong, well defined Rim Current structure is apparent in the Black Sea with little mesoscale eddy activity.

In the second week of September 2002 (Figure13e,f), a significant decrease is observed in the current strength observed in the previous week (Figure13b,c). The Rim Current flow is still well established but the flow has weakened. In the third and fourth week of September, the sea surface heights data show increase in mesoscale eddies (Figure13h,i) which leads to a less structured and more eddy dominated flow (Figure13k,l).

OCTOBER 2002:

SST

The mean SST values in the first week of October 2002 are ranging between 19.0 and 24.5°C minimum and maximum, respectively (Figure14a). The minimum temperature in this week is 1.4°C lower than the minimum SST of the week before (Figure14j). The region of highest (>22.8°C) temperatures is observed at the coastal and open sea waters of the eastern and southeastern basin. Southeastern basin of the Black Sea is secure from the cold winds by the Caucasian Ridge (Chashchin, 1996). Particularly, in the presence of Batumi anticyclone is contributing to the observed highest basin wide fall and early winter temperatures.

Over the course of the month, temperatures drop further as expected, and the temperature ranges are now similar to the previous year 2001. Specifically the lowest observed temperatures decrease in intervals of 1.6°C, 1.2°C, and 0.9°C. However, the progression of the cooling process continues differently than the previous year. In October 2002 the cooling first reaches the entire western basin (Figure14) and the Black Sea is divided more into west-east (warm-cold) than in 2001, when cooling progressed northeast to southwest (Figure10-11), leaving a band of warm temperature along the western Anatolian coast.

Geostrophic Currents

In the first week of October (Figure14b,c), the dominant features of the mesoscale activity are the anticyclonic Batumi eddy, Caucasian eddy, two phase Sevastopol eddy, the cyclone-anticyclone structure at the eastern boundary of NWS, and the anticyclones at the coasts of Unye and Trabzon region. The increased mesoscale activity indicates turbulent dynamics and hence leads to development of jets. The jests observed in this period include the Caucasian jet along NW (0.2 m/s), Batumi jet along ENE (0.4 m/s) and WSW (0.15 m/s), Kızılırmak jet along SSE (0.25-0.3 m/s), Sakarya jet along ENE (0.3 m/s), Sevastopol jet along NNW (0.3 m/s), NWS jet along SW (0.2

m/s) and its continuation jet on the edge of Burgas cyclone is along SSW (0.2 m/s) direction.

Over the course of the month it can be seen that many small anticyclonic features appear along the northern coast and there is no well-defined Rim Current circulation pattern, but instead eddy associated jets and filaments (Figure14). The Batumi eddy is a strong and recurring feature. As is, southeastward flow towards is observed from the Sevastapol eddy region towards the inner Black Sea basin.

NOVEMBER 2002:

SST

In the first week of November 2002, weekly mean SST is seen to vary between 13.9 and 21.0 °C, minimum and maximum, respectively (Figure15a). The observed minimum SST value is seen to be 1.4°C lower than minimum value of the previous week (Figure15j). The geographical coverage of very cold (<16.3°C) temperatures are distributed at the western and north western coastal and offshore areas of the Western basin, the central inner basin and open sea area at the exit of the Azov Sea. In the following weeks cooling continues and over time a band of warmer waters remain along the entire Turkish coast with the Batumi region being the warmest region in the Black Sea (Figur15). Accordingly, in November 2002 the mean temperatures of the Black Sea (14.1°C) are 0.2°C colder than in 2001, which had higher temperatures in September (Figure11).

Geostrophic Currents

In the first week of November 2002, the weekly SSH variability (Figure15b,c) is seen to decrease with respect to the previous week's variability (Figure15k,l). This trend can be observed over the next 3 weeks as well, however still the Rim Current is not a very well defined feature in November 2002.

DECEMBER 2002:

SST

In the first week of December 2002, weekly mean SST is seen to vary between 8.5 and 16.3°C, minimum and maximum, respectively (Figure16a). The observed minimum SST value is seen to be 1.9°C lower than minimum value of the previous week (Figure15j). The next three weeks cooling continues and over time the familiar band of warmer waters remaining along the entire Turkish coast and the northern coast, and the Batumi region being the warmest region in the Black Sea (Figure16). Interestingly, in December 2002 the mean temperatures of the Black Sea (10.3°C) are 1.6°C higher than in 2001, which had higher temperatures in summer and September.

Geostrophic Currents

In the first week of December 2002 (Figure16b,c), the basin averaged circulation and SSH variability reveals a more defined Rim Current structure encircling the Black Sea basin which leads to stronger currents compared to the previous week (Figure16k,l). In the NWS region the Danube and Kali-Akra eddies are observed. These are accompanied by a slight increase in the activity of Sevastopol cyclone and anticyclone at the west coast of Crimea. The presence of Crimea anticyclone together with the Sevastopol leads to formation of strong westwards jet with speed of 0.25 m/s at the edge of each eddy and 0.1 m/s in the midway. Another strong southwestwards jet is observed between southern part of the NWS slope and the open sea reaching speeds of 0.2-0.25 m/s that joins with the Danube fresh water discharge at the offshore region of Constantsa and both extending towards Inebolu region following the coastline with speeds of 0.3, 0.2 and 0.3 m/s at Varna - Burgas, Kırklareli and Eregli regions, respectively.

In the second week of December 2002, the basin averaged current and SSH values (Figure16e,f) reveal elevation of sea level at the coastal areas and particularly at the NWS area and its depression in the Western and Eastern Inner Basin resulting in a stronger gradient in the SSH values and a well-defined Rim Current with stronger surface current velocities than the previous week. This process continues in the following weeks of December as well. East of the Batumi anticyclonic eddy a cyclonic eddy forms, intensifies while Batumi shrinks and then dissipates in the last week of December 2002 (Figure16). The Western and Eastern cyclonic gyres are seen to dominate over the inner basin. The Rim Current jet is seen to reach speeds of 0.25 m/s at the southern part of NWS slope, 0.4 m/s at the Bulgarian continental shelf regions, and 0.35 m/s speed along Istanbul. The Rim Current jet attains very high speeds of 0.4 m/s at the western periphery of the Batumi Eddy and Suchumi eddies. Moreover, a permanent feature in December 2002 is the southward flow observed midway between the Western and Eastern Gyres, originating from southeastern inshore region of Crimea towards Sinop Tip with speeds of 0.3 m/s at the north and 0.2 m/s at the south which then joins with the Rim Current structure.

SEPTEMBER 2003:

SST

In the first week of September 2003, weekly mean SST is seen to change between 22.6 and 26.7°C, minimum and maximum, respectively (Figure 17a). The warmest region of the Black Sea is the eastern inner basin and Batumi region and the western inner basin shows a warm pool of temperatures above 25.5°C. The coldest temperature decreases by 3.0°C, 1.8°C and 0.1°C in the following weeks and the warm pool in the western basin retreats towards the southern coast. The eastern basin continues to be the region of highest water temperatures. The mean temperature of September is 2.0°C and is thereby 1.6°C lower than in September 2001 and 2002.

Geostrophic Currents

In the first week of September 2003, the weekly mean surface current velocities and SSH values over the Black Sea basin show a cyclonic setup in which many anticyclonic eddies are located (Figure 17b,c). The Bosphorus anticyclone is observed (0.4 m/s) on the southwestern part of the basin. A cyclonic feature (0.2 m/s) is observed at the Constantsa coastal region which is accompanied by an offshore elongated filament (0.1 m/s) structure flowing along SSW direction. In this period, a weak anticyclonic cross-frontal jet (0.1 m/s) is formed at the shelf break region of NWS at the SW part of Crimea, a.k.a 'shelf-break front eddy (Shapiro et al., 2010)'. The Sevastopol (0.2 m/s), Crimea (0.25 m/s) and Caucasus (0.2 m/s) eddies are the main mesoscale features observed within the northern basin offshore regions. The Batumi eddy appears weak (0.3 m/s) in this period although the northward front at its western edge can sustain a speed of 0.4 m/s. Frontal jets are observed at the inshore of Danube Delta and Inebolu-Sinop regions generating flows along NNE and NW directions, respectively. Northward flow from the strong Bosphorus eddy is observed between Varna and the Danube coast that enables the distribution of relatively warmer southern basin waters into the Northwestern Shelf region. On the other hand, the colder shelf waters are forced into the warmer southern basin with a corresponding offshore flow (Figure 17a,b,c). This general eddy activity and associated flow patterns change only slightly in week two and three, except that anticyclonic eddy activity is increasing (Figure 17).

In the fourth week of September 2003 (Figure 17k,l), the weekly mean current velocities and SSH distribution over the entire Black Sea basin indicate the signs of alteration towards a slightly more structured Rim Current system at the northeastern and southwestern parts of the basin, in particular. In the central basin, the generation of a northward filament from Sinop towards the inner basin is observed to be coexisting with a nearby southward front which originates within the inner basin and directed towards Sinop region. The Batumi anticyclone and the anticyclone at the west side of Batumi anticyclone that first appeared in week 3 of September (Figure 17h,i) are still active with the presence of strong ENE front (0.25 m/s) surround them at their northern edge.

OCTOBER 2003:

SST

In the first week of October 2003, the mean SST is seen to vary between 17.4 and 22.2°C, minimum and maximum, respectively (Figure 18a). The observed minimum SST value is seen to be 0.3°C lower than minimum value of the previous week (Figure17j). The coldest temperatures (<19.1°C) are again observed at the northern parts of NWS while cold temperatures (19.1 – 19.6°C) are dominating at the rest of the NWS. The Batumi region is the warmest area of the entire sea. Over the course of the month the minimum temperature observed in the Black Sea decreases by 0.9°C, 1.3°C, and 1.0°C and the typical cooling pattern from northwest to southeast is observed. The mean temperature of October 2003 is 0.9°C and is thereby 0.1°C lower than in October 2001 and 2002.

Geostrophic Currents

In the first week of October 2003, the surface current velocity and SSH distribution over the Black Sea basin indicate a strengthening in the Sevastopol

(0.3 m/s) and Bosphorus (0.4 m/s) eddies (Figure18b,c). The cyclonic structure at the coastal region of Kerch observed in the previous week is seen to disappear. Crimea and Caucasus anticyclonic structures of the previous week are seen to weaken and become unstable and hence Crimea (0.15 m/s) and Caucasus (0.15 m/s) eddy change to a more elongated form. The northward filament located between the Crimea eddy and Sinop region is turned into an anticyclonic eddy (0.2 m/s) accompanied by a southward front (0.35 m/s) on its east side. The Batumi anticyclone (0.2 m/s) and the anticyclone at the west side of Batumi anticyclone (0.25 m/s) still remains this week establishing connection with the coast through surrounding fronts. The front at the western part of the basin starting at Bulgarian open sea waters (0.3 m/s) following the northern and eastern edge (0.4 m/s) of the Bosphorus eddy and approaching Sakarya coast is a rather strong one.

In the second week of October 2003 (Figure18e,f), the basin wide current patterns and SSH variability indicate 2.7 and 3.2 cm decrease in the maximum and minimum SSH values with respect to the previous week (Figure18b,c), respectively. This development continues in week three (Figure 18e,f). In the last week in October however,

In the last week of October 2003, the basin averaged current velocity and SSH distributions (Figure18k,l) reveal weaker currents and smoother SSH and therefore less variability when compared with the variability in previous three weeks (Figure 18b,c,e,f,h,i). The SW-NE front from Ordu (eastern Anatolian coast) to northern Georgia coast still remains but it is slightly weaker.

NOVEMBER 2003:

SST

In the first week of November 2003, weekly mean SST varies between 12.3 and 18.7°C, minimum and maximum, respectively (Figure 19a). The observed minimum SST value is 1.9°C lower than minimum value of the previous week (Figure 18j). The geographical coverage of coldest temperatures (<14.5°C) are seen to retreat slightly towards the north parts of NWS, both Western and Eastern Inner basin and coastal area of Kerch region. The highest temperatures (>16.5°C) are limited to the coastal areas of SE basin, mainly the coastal between Giresun (Turkey) and Batumi (Georgia) with some local patches observed at the north coast of Georgia and at Samsun (Turkey) coastal areas. Over the course of the month the minimum temperature observed in the Black Sea decreases by 0.7°C, 1.5°C, and 1.0°C and the typical cooling pattern from northwest to southeast in observed. The mean temperature of November (12.2°C) is 2.2°C and is thereby 1.9°C lower than in November 2001 and 2002.

Geostrophic Currents

In the first week of November 2003, the basin averaged geostrophic currents and SSH variability (Figure 19b,c) indicates a slightly higher gradient between the coastal and open sea waters with respect to the previous week (Figure 18k,l). This situation results in an increase in the currents at the northwestern shelf break region, northeastern and southwestern shelves. A filament like structure observed at the SE part of the Crimea Eddy of the previous weeks becomes a small anticyclone with a northeastward extension and a southward filament (0.1 m/s) that helps establishment of connection across the Eastern Inner basin (between Azov Sea exit and Sinop coast of mid-Anatolia.

Within the second week of November 2003 (Figure 19e,f), the weekly mean surface currents and SSH values reveal a significant increase in sea surface height gradient between the coastal anticyclonic regions and the cyclonic inner basin. This means that the establishment of the Rim Current takes place earlier than the other two years. In this period, there is a considerable increase in the sea level of the western coasts and at the NWS area. This implies an increased fresh water river discharge. The connection of the newly developed Sinop anticyclone with the Crimea eddy through the northwards front (0.2 m/s) between them leads to a transport along NNW direction between mid-Anatolia and the west coast of Crimea to the north. At the north, the strengthening of Kerch anticyclone at the Azov Sea exit is observed. Accordingly, the cross-basin transport originating at the southern edge of Kerch eddy towards Sinop offshore region is found to be still active. Then it joins the peripheral circulation at the southern coast. The Rim Current velocities decrease in the northern basin in week three, while in the southern basin they become stronger. In the last week of November 2003 (Figure 19k,l), basin average geostrophic current speeds and SSH gradients are slightly weaker with respect to the previous week (Figure 19h,i). The central basin is separated by the strong southeast ward from

Crimea to Sinop into a Eastern Gyre and a four-cell Western gyre. The weaker Rim Current at the western and central Anatolian inshore attains speeds of 0.25 and 0.2 m/s in this period.

DECEMBER 2003:

SST

In the first week of December 2003, weekly mean SST is seen to vary between 8.5 and 13.6°C, minimum and maximum, respectively (Figure 20a). The observed minimum SST value is seen to be 0.6°C lower than minimum value of the previous week (Figure 19j). The coldest temperatures (<10.3°C) of this period are observed at the NWS along the coastline. The highest temperature (>11.9°C) regions are located at the east part (>38.7°E longitude) of Eastern Inner Basin, central Anatolian Inner basin, and extending from Sakarya to Trabzon coasts at the south and from Tuapse to Anapa regions at the north. Over the course of the month the minimum temperature observed in the Black Sea decreases by 1.0°C, 3.5°C, and increases again by 0.8°C. There is an east-west gradient in temperature with some colder water moving towards the east in the inner basin of the Black SeaThe mean temperature of December (9.9°C) is 1.2°C higher and is thereby 0.4°C lower than in December 2001 and 2002.

Geostrophic Currents

In the first week of December 2003, the basin averaged surface currents and SSH distribution shows a more defined Rim Current structure in the Black Sea basin (Figure 20b,c) in comparison to November 2003. The sea level values at the eastern, southwestern, southeastern coastal areas and NWS is increased and therefore the increased gradient between these areas with the inner basin results in stronger and more stable peripheral circulation. The four cyclones in the Western Inner basin are united into a single cell and the extent of mid-basin jet (0.15 m/s) that previous extends from Crimea to Anatolia is decreased and its connection with the Anatolian coast is broken. The speed of Rim Current (the shelf-break front) at the NWS is observed between 0.2 – 0.25 m/s at the northern part and 0.1 m/s at the southern part. The southward front at the offshore of Bulgaria has 0.15 m/s speed at the northern Bulgaria and 0.2 m/s reaching west of Istanbul. The Rim Current jet has 0.2, 0.25 and 0.3 m/s speed along the (eastern) coast of Istanbul, Sakarya and Amasra regions, respectively. Then its speed at the central and eastern Anatolia coast decreases to 0.05 – 0.1 m/s (excluding the Batumi eddy region) with the exception that it attains 0.25 m/s southward speed at the eastern edge of the Bafra anticyclone. The Rim Current attains 0.3, 0.2 and 0.15 m/s maximum speeds while passing by the southern, northern Caucasus and the shelf boundary of the Kerch region, respectively.

Within the second week of December 2003, the geostrophic circulation fields and SSH distribution indicate a considerable increase in basin wide eddy activity (Figure 20e,f). The sea level at the coastal areas and the NWS region is decreased. The Rim Current becomes discontinuous along the Anatolia coast between Inebolu and Samsun regions. The Western Gyre is seen to sustain a stronger northwards flow (0.10 – 0.15 m/s) from Amasra region into the Western Inner basin. Formation of an accompanying southward filament-like structure (0.1 – 0.15 m/s) that establishes connection between the peripheral current at the eastern edge of the Sevastopol eddy and the eastern Amasra region is observed. In the third week of December 2003, the mean surface current velocities and SSH distribution (Figure 20h,i) indicate a more turbulent system. The basin wide Rim Current is absent in this period for the second time. This week the strong peripheral jet is seen at the western basin and it forms at the NW shelf-break zone (0.25 m/s) and extending further towards the southwest to the Burgas open sea region (0.15 m/s) and making a turn towards the east at the Bosphorus region (0.15 m/s), strengthening at the Sakarya region (0.2 m/s) and diminishing at the Zonguldak (0.15 m/s) region. The S-N connection established within the previous week between Amasra coast and the front at the eastern edge of Sevastopol eddy is not present this week. In the southeastern basin, the strengthening of the Batumi anticyclone (0.4 m/s) leads to a connection with the Suchumi meanders in this region. In the last week of December 2003, the variations in the geostrophic velocities and SSH distribution (Figure 20k,l) maps reveal a highly turbulent nature where the Black Sea Rim Current circulation is less defined and dominated by the presence of small eddies, meanders and filaments. In this time the Kerch eddy becomes stronger and the generation of a SW filament offshore of Yalta and an accompanying NE filament at the Anatolian coast establishes a connection and flow (0.15 m/s) between the Crimean Peninsula and mid-Anatolia coastal regions.

CURRICULUM VITAE

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Education:

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Ph.D., Oceanography

Middle East Technical University, Institute of Marine Sciences

Dissertation: "*Modeling the Impact of Climate Variability on Anchovy Overwintering Migration in the Black Sea*".

2010

M.Sc., Physical Oceanography

Middle East Technical University, Institute of Marine Sciences

Thesis: "*The Impact of Climate Variability on the Production of Black Sea Anchovy: A Modeling Study*"

2007

B.Sc., Mining Engineering

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Work Experience:

1/2015 – 9/2015

Project Assistant, Institute of Marine Sciences, Middle East Technical University

1/2010 – 12/2014

Research Assistant in Institute of Marine Sciences, Middle East Technical University

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Project Assistant in the EU FP-6 Project: “ECOOP (European Coastal-shelf sea operational observing and forecasting system)”

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Project Assistant in the EU FP-6 Project: “SESAME (Southern European Seas: Assessing and Monitoring Ecosystem)”

Honors and Awards:

- Won Graduate Research Scholarship from the Scientific and Technological Research Council of Turkey (1/2015 – 6/2016),
- Won Publication Award from Middle East Technical University given to early career scientists on October 1, 2014.
- Won Publication Award from The Scientific and Technological Research Council of Turkey (TUBİTAK).

Research Interests:

- Mathematical modeling of marine ecosystems
- Fish population dynamics
- Individual-Based models
- Modeling of dispersion/migration patterns of fish in the ocean

Publications:

Guraslan, C., Fach, B.A., Oguz, T. (2014) Modeling the impact of climate variability on anchovy recruitment and production. Fisheries Oceanography 23(5): 436-457. doi:10.1111/fog.12080.

Published Abstracts:

Guraslan C., Fach, B.A. , Oguz, T. (2015) Modeling The Impact Of Environmental Variability On Black Sea Anchovy Overwintering Migration. FAO Black Sea Ecosystem and Fisheries Conference 2015, Trabzon, Turkey, 18 – 20 November 2015.

Guraslan, C., Fach, B.A., Gucu, A.C. (2015) Modeling the Impact of Environmental Variability on Black Sea Anchovy *(Engraulis encrasicolus ponticus)* Overwintering

Migration. HYDROGENCONNECT Project Workshop, Mallorca, Spain, 29 – 30 June 2015.

Guraslan, C., Fach, B.A., Oguz, T. (2015) Modeling the impact of Climate Variability on Black Sea anchovy *(Engraulis encrasicolus ponticus)* recruitment and production. ICES Working Group on Small Fishes, Their Ecosystems and Climate Impact (WGSPEG), Thessaloniki, Greece, 30 March – 3 April 2015.

Guraslan, C., Arkin, S., Oguz, T., Salihoglu, B., Fach, B.A. (2014) Modeling the influence of hydrodynamic processes on Black Sea anchovy *(Engraulis encrasicolus ponticus)* overwintering migration. AMEMR Meeting IV: 'Future Challenges', Plymouth, UK, 30 June – 3 July 2014.

Guraslan, C., Fach, B.A., Oguz, T. (2013) Black Sea anchovy *(Engraulis encrasicolus ponticus)* transport pathways. 40th CIESM Congress, Marseille, France, 28 October – 1 November 2013.

Guraslan, C., Fach, B.A., Oguz, T., Salihoglu, B. (2010) The impact of climate variability on the production of Black Sea anchovy: a modeling study."Geophysical Research Abstracts", 12,), p. EGU2010-13694, Vienna, Austria, 2 – 7 May 2010.

Seagoing Experience:

- North Eastern Mediterranean, a total of 24 days aboard the *R/V Bilim2.*
- Black Sea and the Sea of Marmara, a total of 15 days aboard the *R/V Bilim2.*

Additional Information:

Computer Skills:

Linux/Unix and Windows operating systems, IDL, MATLAB, Bash/Korn-Shell, FORTRAN, MS Office

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