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**Detection and tracking of mesoscale eddies in the
Algerian Basin from altimetric data and in-situ
measurements**

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Ai miei genitori

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Abstract

The circulation of the Western Mediterranean Sea (WMED) is dominated by highly variable and inhomogeneous mesoscale circulation. It is affected by the formation of Algerian Eddies (AEs), mainly in the Algerian Basin. These strong and large propagating structures can be both cyclonic and anticyclonic. Due to the short lifespan of cyclonic eddies, only anticyclonic ones are considered in this work.

In order to investigate the spatial and temporal distribution of eddy generation and their respective paths in the WMED, we use an automated detection and tracking method applied to 22 years of daily altimetric (SLA, Sea Level Anomalies) data (AVISO merged, delayed-time, SLA data).

The tracking algorithm provides information about the lifetime of each detected eddy, and permits the evaluation of their mean properties, such as radius, kinetic energy and translational velocity.

We treat separately the eddies with lifetime respectively under and over 100 days. We find that short-life eddies mostly occur in the northern part of the domain, above 39° N, along the North Balearic Front and we refer to them as Frontal Anticyclonic Eddies (FAEs). Most are formed in fall and winter. By contrast, longer-life eddies tend to arise in the southern part of the basin, along the Algerian Current, mainly in spring and summer. A clear spatial and seasonal complementarity of the two kinds of structures is evident.

We observe two preferred areas of formation along the Algerian slope, at 5° E and at 7° E. The southern long-life AEs are more energetic and move eastward along the coast to the Sardinia Channel. We suppose that high salinity on the surface layer hinders the transit of the eddies through the channel, forcing them to deviate northward with the cyclonic circulation.

From the perspective of eddy kinetic energy (EKE), we find that the daily MEKE in the south is higher than in the north of the domain, and has an annual periodicity, due to the seasonality of heat fluxes, and a periodicity of 4.4 years. The latter should be more comprehensively examined with a larger data set.

In order to investigate the vertical extension of the eddies and the water masses involved, we use CTD data sampled in the course of three oceanographic cruises in the WMED. We superimpose the CTD transects on the SLA maps in each eddy location. Two transects intersect southern AEs and a third intersects a FAE. In all cases, we measure a minimum level of salinity in the sub-surface layer (50-70 m depth) co-located with the eddy core. It points to the presence Atlantic Water trapped by the structure. The CTD data also provide the physical characteristics (potential temperature, salinity and potential density anomaly) of the water masses in the AEs. We found that southern AEs reach 1200 – 1500 m depth and the FAEs 600 – 700 m depth.

The detection and tracking method is a powerful instrument to study the eddies and their variability, and the combination with in-situ data allows a more complete characterization of these structures. Finally, this work helped to find the preferred areas of eddy formation and their main pathways within the basin. The interaction with the intermediate layer suggests that eddies are transported by the Algerian Gyre in a cyclonic loop below 39° N.

Several studies have shown a strong correlation between the deflection of the isopycnals, due to the eddies, and the distribution of the nutrients in the euphotic layer. The study of the relationship between hydrodynamic processes and the dynamics of the first trophic levels acquire importance in highly dynamic seas such as the WMED. The complete description of mesoscale circulation in the Algerian Basin provided by this dissertation is of fundamental importance to examine the bio-ecological processes in the WMED.

Sommario

La circolazione del Mar Mediterraneo occidentale (WMED) è dominata da una circolazione di mesoscala altamente variabile e inhomogenea. Questa risente della formazione di vortici (AEs), soprattutto nel Bacino Algerino. Tali strutture, grandi e intense, che si propagano nel bacino, possono essere sia cicloniche sia anticicloniche. A causa della breve durata dei vortici ciclonici, in questo lavoro verranno presi in considerazione solo quelli anticiclonici.

Al fine di studiare la distribuzione spaziale e temporale delle formazioni dei vortici e le traiettorie che essi compiono nel WMED, abbiamo utilizzato un metodo automatico di individuazione e identificazione delle traiettorie e lo abbiamo applicato a 22 anni di dati altimetrici giornalieri (SLA, Sea Level Anomalies) messi a disposizione da Aviso (AVISO merged, delayed-time, SLA data).

L'algoritmo di identificazione delle traiettorie fornisce informazioni riguardo la durata di ciascun vortice e permette la valutazione delle loro proprietà medie, come il raggio, l'energia cinetica e la velocità traslazionale.

Abbiamo trattato separatamente i vortici di durata inferiore e superiore rispettivamente a 100 giorni. Abbiamo trovato che i vortici cosiddetti brevi si formano principalmente nella parte nord del dominio, sopra i 39° N, lungo il fronte nord-balearico, e ci riferiremo a tali strutture con il nome Frontal Anticyclonic Eddies (FAEs). La maggior parte si formano in autunno e inverno. Al contrario, i vortici cosiddetti lunghi tendono a formarsi nella parte meridionale del bacino, lungo la corrente algerina., principalmente in primavera ed estate. Si evidenzia chiaramente una complementarità delle strutture sia dal punto di vista spaziale, sia da quello stagionale.

Abbiamo individuato due aree di formazione preferenziali lungo la costa algerina, a 5° E e a 7° E. I vortici lunghi della zona sud sono più energetici e si

muovono verso est lungo la costa fino al Canale di Sardegna. Noi supponiamo che l'alta salinità superficiale in questa zona ostacoli il passaggio dei vortici attraverso il canale, deviandoli a nord in una circolazione ciclonica.

Riguardo all'energia cinetica, abbiamo trovato che l'energia cinetica puntuale dei vortici nel sud del bacino è maggiore rispetto al nord del bacino e presenta una periodicità annuale, legata alla stagionalità dei flussi di calore, e una di 4.4 anni. Quest'ultima richiede uno studio più approfondito per mezzo di una serie di dati più lunga.

Al fine di ricavare informazioni riguardo all'estensione verticale dei vortici e alle masse d'acqua coinvolte, abbiamo utilizzato dati CTD raccolti durante tre campagne oceanografiche nel WMED. Abbiamo sovrapposto i transetti CDT sulle mappe di SLA elaborate con il metodo di individuazione dei vortici. Due transetti intersecano i vortici meridionali e il terzo interseca un FAE. In tutti e tre i casi rileviamo un minimo di salinità a livello sub-superficiale (50-70 m) in corrispondenza del centro del vortice. Si tratta di acqua di origine atlantica intrappolata dalla struttura ciclonica. I dati CDT forniscono inoltre le proprietà fisiche delle masse d'acqua all'interno dei vortici, quali la temperatura potenziale, la salinità e la densità potenziale. I vortici meridionali si estendono fino a profondità di 1200 – 1500 m mentre quelli a nord del dominio si fermano a 600 – 700 m.

Il metodo di individuazione e identificazione delle traiettorie è uno strumento molto potente per lo studio dei vortici e della loro variabilità e la combinazione del metodo con dati in-situ permette una più completa caratterizzazione delle strutture. Infine, questo lavoro ha permesso di individuare le aree di formazione e le traiettorie preferenziali all'interno del dominio. L'interazione con le acque del livello intermedio suggeriscono che i vortici siano trasportati nella loro circolazione ciclonica dal cosiddetto Algerian Gyre che si muove ciclonicamente a livello intermedio al di sotto dei 39° N.

Numerosi studi hanno mostrato una forte correlazione tra la deflessione delle isopiche, dovuta alle strutture cicloniche, e la distribuzione di nutrienti nella zona eufotica. Lo studio delle relazioni tra i processi idrodinamici e la dinamica del primo livello trofico acquisisce importanza in mari altamente dinamici come il WMED. La completa descrizione della circolazione di mesoscala nel

bacino algerino fornita da questo studio, è di fondamentale importanza per la comprensione dei processi bio-ecologici nel WMED.

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Introduction

The atmosphere and climate strongly interact with the dynamics and the biology of the oceans. The coupling of these two systems is of increasing importance considering the accelerating atmospheric variability and climate change witnessed in the last century. The rapid change of pace of the last 50 years may well be a consequence of human activity, which has a significant impact on the environment. It is widely recognised and studied by the scientific community and is documented by international protocols (Kyoto 1997, Marrakech 2001). In particular, the abnormal warming recorded on a global scale is probably caused by anthropic activities and its effects at regional and local levels are still poorly understood. The response of the marine ecosystems to atmospheric forcing has been demonstrated at different spatial and temporal scales [Olita et al., 2007]. Consequently, a deeper understanding of the intrinsic variability of the sea's physical and biological parameters is of fundamental importance to fill the gaps in the debate on climate variability.

Mesoscale eddies occur in the global ocean and they are the main cause of variability in global ocean circulation. With their non-linear dynamic, they transport water, heat content, chemical and biological properties (salt, nutrients, biomass) across the ocean, interacting with the main currents and impacting the climate and ecological processes over large distances.

The Mediterranean Sea can be seen as a small ocean, where the mechanisms of the global ocean, including deep convection, occur on a smaller scale. Despite its small size, the Mediterranean is characterised by an active thermohaline circulation and is a testbed for the advancement of knowledge on physical interactions and biogeochemical coupling at near-shore, local, sub-regional, regional and global scales [Tintoré et al., 2012].

Our area of study is the Algerian Basin, in the south of the Western Mediterranean Sea (WMED). It is a highly energetic area, whose circulation is mainly driven by the Algerian Current (AC) constituted of relatively fresh Atlantic Water flowing along the Algerian

Coast. The AC plays a key role in the thermohaline circulation of the whole WMED. Here the Algerian Eddies (AEs), the largest mesoscale structures, occur and sometimes strongly interact with the AC, blocking its eastward flow [Puillat et al., 2002]. The impact of these structures is felt all over the Mediterranean Sea and our interest lies in their formation processes and dynamics within the basin.

The influence of these eddies on thermohaline circulation is not yet well understood, as the existing numerical circulation models cannot reproduce the eddies' dynamics in the WMED. Furthermore, the eddies are also difficult to monitor by using in-situ data because of their small spatial scale and high variability.

In order to study mesoscale eddies, many instruments are widely used, from in-situ data to numerical models, from drifters to integrated systems based on satellite imageries, which provide synoptic data all over the basin. In particular, satellite altimetry has increased our knowledge of surface circulation thanks to continuous sea surface measurements provided by several altimeter missions. It is now possible to quantify the surface kinetic energy of eddies with respect to mesoscale activity using long-time periods of altimetric data [Pascual et al., 2006; Isern-Fontanet et al., 2016]. Furthermore, it is possible to identify and track the mesoscale features [Isern-Fontanet et al., 2006; Chelton et al., 2007, 2011; Halo et al., 2014] and investigate their potential impact on biogeochemical processes [Siegel et al., 2011]. It is therefore vital to continue monitoring the surface circulation in order to better understand the dynamics of the sea.

A number of studies use numerical modelling to emphasise the importance of kinetic energy in tackling the variability of sea surface circulation in the Mediterranean Sea, but only sparse data have been extracted from altimetric measurements. The first estimation of seasonal variation of EKE has been highlighted by [Iudicone et al., 1998], but only two years of data were available when the study was carried out.

The study of longer periods makes it possible to identify major changes occurring in the Mediterranean, such as the strong inter-annual and seasonal signals in the eastern basin and the seasonality of the Alboran Gyre in the western basin [Larnicol et al., 2002]. Altimetric data constitute an exceptional source of near-real time information, as their sampling rate is very frequent and the spatial and temporal coverage is large. It is also useful to merge as much as possible remote sensing and in-situ data sources to enhance the investigation of regional mesoscale dynamics. The limit of altimetric data is the low resolution of standard gridded products and the low accuracy of along-track altimetric-derived coastal

velocity fields, which prevent the detection method from identifying structures near the coast [Anzenhofer et al., 1999]. Furthermore, the ageostrophic components of circulation acquire importance at smaller scales, which altimetry typically fails to capture. Some corrections to coastal altimetric data are needed and their combination with other kinds of data is highly recommended [Isern-Fontanet et al., 2016].

In the past, the evolution of AEs in time has been examined only occasionally. The time series used were limited and the variability had not been investigated. Recent studies [Escudier et al., 2016] have successfully applied automated methods to detect eddies in the WMED and to describe their motion from the Lagrangian point of view.

However, many questions about the origin, characteristics and dynamics of the AEs are still open to debate, such as the presence of preferred areas of formation within the basin, the relation between their lifetime and physical properties (radius, kinetic energy), the seasonality of their generation and their vertical extension.

The aim of this work is to discuss some properties of the AEs, from both the Eulerian and Lagrangian point of view. To that end, we performed a statistical analysis of the spatial and temporal distribution of the formation of the eddies. AEs with a lifespan under and over 100 days respectively have been treated separately and the results present some complementarity. We also focused on the distribution of the punctual kinetic energy of AEs and their inter-annual variability, finding some periodicity in the southern basin, below 39° N.

In the first part of this work, all information has been extracted from satellite data, with the application of an automated detecting and tracking method based on both physical and geometrical properties. In part II, we have used in-situ measurements sampled during several oceanographic cruises in the WMED, to estimate the vertical extension of the anticyclonic structures and their impact on physical and biological properties of the water masses involved (temperature, salinity, density, chlorophyll). This study has promoted a better understanding of surface mesoscale circulation in the Algerian Basin. Below the surface, the general circulation is still not well understood because of a lack of in-situ data available.

This dissertation is organized as follows. In Chapter 1 we briefly review the main circulation of the WMED, as described by previous studies, with some references to global circulation. The properties of the main water masses involved are described. Then we sharpen our focus on the Algerian Basin and on the mechanism of eddy formation.

Chapter 2 begins with a brief description of various methods used to detect and track the eddies, followed by the types of data (altimetric and in-situ) used in this work. Lastly, we describe the main steps of the detection and tracking algorithm and debate some considerations about it.

In Chapter 3 we present the results of our study.

In Chapter 4 we discuss the conclusions and present some ideas for future research.

As mentioned, satellite altimetry alone provides only surface information with limited spatio-temporal resolution. To address these limitations and to better describe the mesoscale features, we feel that numerical models are necessary and useful tools, as they make it possible to access properties below the surface over long periods, facilitating the comprehension of the variability. During my PhD course I also learned some techniques in numerical modelling and in particular I applied objective analysis on CTD measurements over an area near the Island of Elba. The numerical model has been initialized with in-situ data. I participated to the writing of a paper about this study [Sorgente et al., 2016].

Chapter 1

The Mediterranean Sea

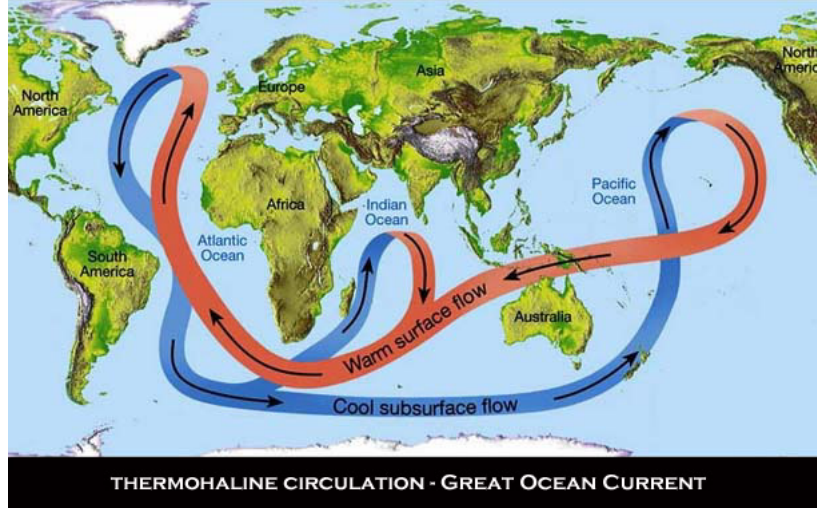
The Mediterranean Sea is located between 30° N and 46° N and 5° W and 36° E and has an area of about 3000000 km^2 .

It is characterized by high salinity, temperature and density and is a semi-closed evaporation basin, as evaporation exceeds precipitation and river inflows. The net loss of heat and freshwater of about 5 Wm^{-2} and 0.7 my^{-1} [Pinardi et al., 2015] are balanced by heat and surface fresher water from the Atlantic Ocean through the Strait of Gibraltar (anti-estuarine circulation) [Millot, 1999]. The strait is only 22 Km wide and 300 m deep and allows the salt, heat and water exchanges between the Mediterranean Sea and the Atlantic Ocean.

The Mediterranean is quite small, but is subject to strong anthropogenic pressures caused by high population density, which affects the properties of the water masses and the formation processes.

The Mediterranean is very interesting because many fundamental processes take place there, such as water masses interactions, formation of eddies, thermohaline circulation and mesoscale activities, albeit on a smaller scale than in the global ocean. The Mediterranean Sea is a sort of miniature ocean [Bethoux and Gentili, 1999] and is easier to study and sample because of the smaller spatial and the shorter temporal scales (decades vs. centuries for the global ocean).

Salty Mediterranean Water (MW) enters the Atlantic and contributes to the circulation of this ocean, representing a reserve of salt and impacting the Global Thermohaline Conveyor Belt (Figure 1.1). It is the set of the major surface and deep circulations. Thanks to the formation of deep waters, it ensures the exchange between warm surface and cold bottom waters, which governs the global climate together with atmospheric circulation [Broecker,

Figure 1.1: *Ocean Conveyor Belt*

1991]. The impact of increasing temperature and salinity in the Mediterranean Sea has been felt at mid-latitudes and on the North Atlantic heat content [Potter and Lozier, 2004]. Mediterranean Water reaches as far as the Norwegian-Greenland Sea, influencing deep water formation [Arhan, 1987; Schmitz Jr, 1996; Iorga and Lozier, 1999] and impacting its return circulation [Keeling and Peng, 1995].

The Mediterranean Sea is composed of two principal sub-basins: the Western (WMED) and the Eastern (EMED) Mediterranean Basins, connected by the Strait of Sicily. In this thesis we will focus on the WMED.

1.1 Multiscale circulation and variability

Three predominant and interacting spatial scales characterize the circulation in the Mediterranean Sea. The large-scale circulation is of thermohaline nature. The evaporation that prevails over precipitation and river run-off, and the inflow of fresher surface Atlantic Water (AW), determine the anti estuarine circulation. The regional (sub-basin) scale is dominated by sub-basin circulation, influenced by the local meteorological and topographic characteristics. Finally, mesoscale activity is highly variable and inhomogeneous, as highlighted by satellite imagery [Milot, 1987] and by the maps of Eddy Kinetic Energy (EKE). The seasonal EKE variations occur mainly in the Algerian Basin and in particular south-west of Sardinia [Pujol and Larnicol, 2005]. The Rossby radius (Appendix A), is small (10 – 14 Km) and as a consequence, so are the mesoscale structures. Given the difficulty of investigating them, high resolution datasets are needed.

At a large scale, the Mediterranean Sea is characterized by an overturning circulation (Mediterranean Overturning Circulation or MedOC, which is analogous to the Meridional Overturning Circulation, or MOC, for the global ocean) composed of three thermohaline cells: an open one, horizontal and zonal (westward) and two closed ones, vertical and meridional (southward) within both western and eastern basins. The former involves the whole sea and is driven by intermediate water formation in the Levantine sub-basin and by the light Atlantic Water inflow, while the others are driven by the deep water formation (1.2) [Pinardi and Masetti, 2000]. The two vertical cells are connected because the Levantine Intermediate Water (LIW), originated in the EMED, takes part in the formation of deep water in the western basin.

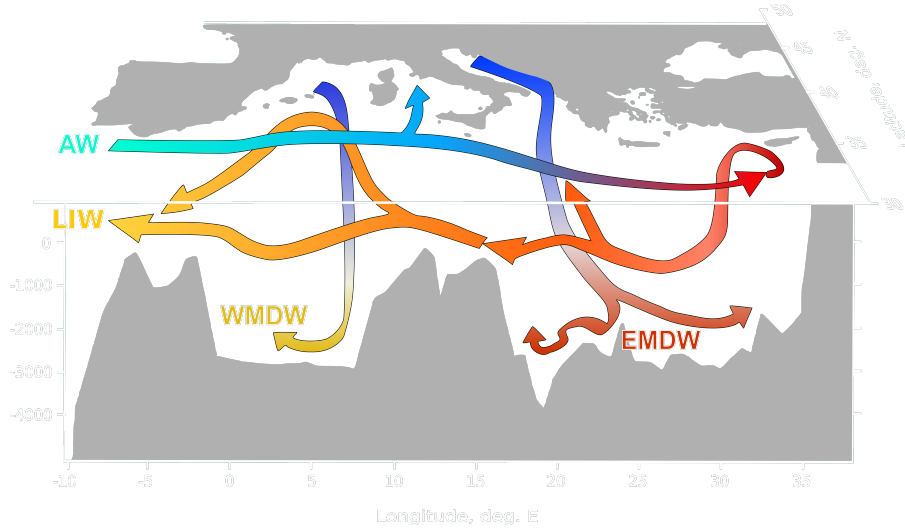


Figure 1.2: Schematic of the Mediterranean Overturning Circulation. The main regions of deep water formation are labelled. The surface circulation is shown in blue, the intermediate circulation in orange-red and the deep circulation in yellow and dark red (Courtesy of Loic Houpert) [Pinardi and Masetti, 2000]

Complexity and scales arise from multiple driving forces, from strong topographic and coastal influences, and internal dynamic processes. In the Mediterranean Sea we find free and boundary currents, jets with bifurcate, meander and vortex, permanent and recurrent cyclonic and anticyclonic gyre at sub-basin scale, and finally small but energetic mesoscale eddies. Figure (1.3) shows the pathway of the LIW from its origin in EMED.

The basin-scale general circulation of the main thermocline is composed of predominantly energetic sub-basin scale gyres linked by sub-basin scale jets.

The internal thermohaline cells existing in the western and eastern Mediterranean have interesting analogies and differences both internally and with respect to the global thermohaline circulation. Figure 1.4 shows the basin-scale thermohaline cell of WMED (top) and

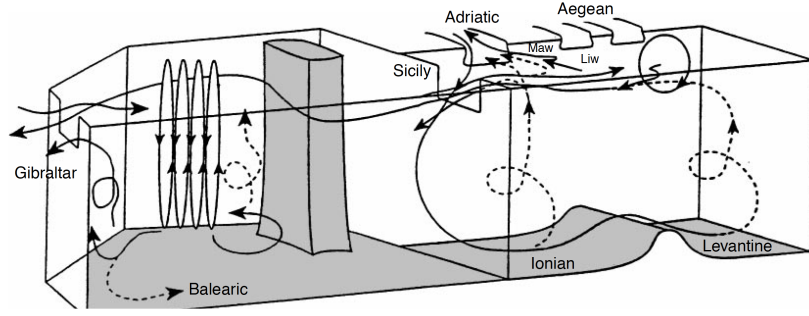


Figure 1.3: Schematic of thermohaline cells and path of Levantine Intermediate Water (LIW) in the entire Mediterranean. [Robinson et al., 2001]

EMED (bottom). The former is driven by deep water originated in the Gulf of Lions. It is possible to identify important sub-basin structures such as gyres in the main thermocline in the Alboran and Balearic seas. Along the coastal current intense mesoscale activity exists and causes instabilities and eddy formation. The latter shows the thermohaline cell.

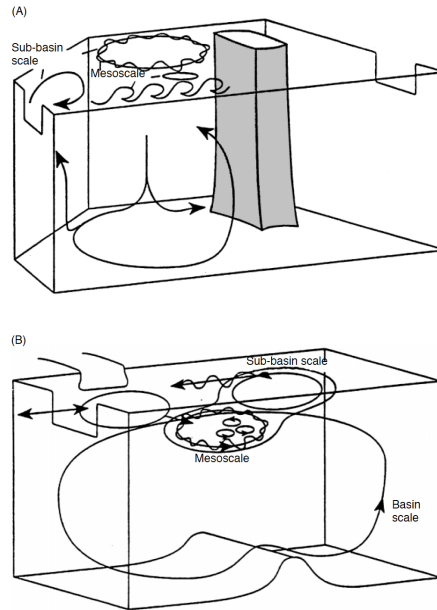


Figure 1.4: Schematic of the scales of circulation variability and interactions in western Mediterranean (A) and eastern Mediterranean (B) [Robinson et al., 2001]

The meridional transport is subject to some seasonal variations, while the zonal one to inter-annual oscillations. Both involve several temporal scales. In particular, the turnover in the Mediterranean Sea is of the order of about one hundred years, while the ocean's is one order of magnitude greater. Its high susceptibility to global climate change explains why the Mediterranean can be considered as a sensor of the global climate.

In general, the many types of water in the Mediterranean Sea can be divided in three main

classes depending on their depth: surface water, intermediate water and deep water. It is possible to track the different water masses by chemical and thermodynamic tracers such as temperature, salinity, dissolved oxygen and carbon dioxide, and nutrients.

1.2 The Western Mediterranean Sea

The Western Mediterranean basin extends from 4° W and 18° E in longitude and from 36° N and 44° N (Figure 1.5). It hosts important choke points, where the exchanges between different types of water take place, such as the Corsica, the Balearic and the Sardinia channels [Astraldi et al., 1999]. In the Gulf of Lions the salinity changes exert significant control on water dynamics, impacting the stratification and leading to the deep water formation, which occurs through open-ocean convection.

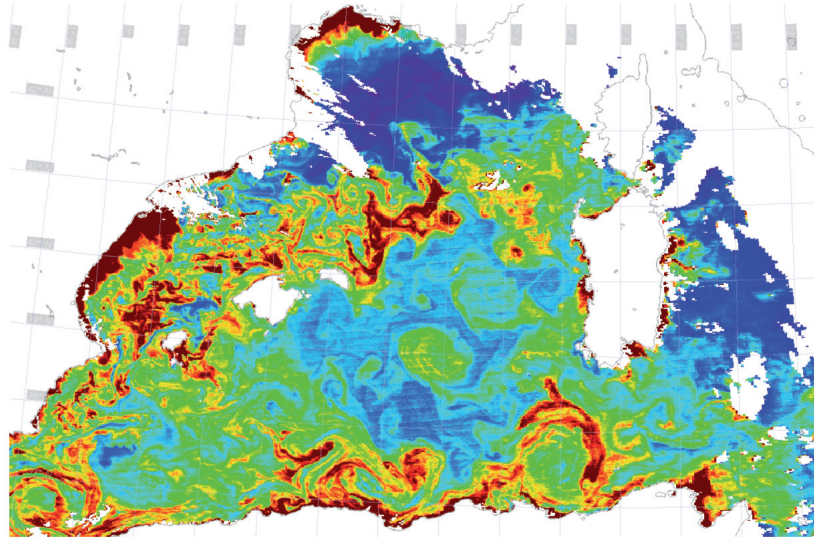


Figure 1.5: WMED, Ocean Color (Chl-a product) level 2 single swath from AQUA MODIS for March 8th, 2013

Below, you will find a detailed description of the general circulation of the entire WMED, taking into account the various water masses involved.

The Atlantic Water (AW) entering the basin is shallow and relatively fresh and flows toward the Algerian coast. It is renamed as Modified Atlantic Water (MAW) and flows all over the Mediterranean Sea in the first 100 – 200 m from the surface. It changes its characteristics as it mixes with the surrounding resident waters. Its salinity is about 36.5 at the Gibraltar Strait and reaches values of around 38.3 in the northwestern Mediterranean. It is characterized by a mean temperature, below the mixed layer, of usually 14° – 15° C. The portion of water that does not flow back into the Atlantic as intermediate water is

transformed into deep water within the basins.

The Alboran Sea is located east of the Strait of Gibraltar, between 35° N and 37° N and between 5.5° W and 1.5° E. There the AW forms a quasi-permanent anticyclonic gyre in the western part, and a more variable and cyclonic one in the eastern part. Some small cyclonic eddies are also found in this area and all around the western gyre [Tintoré et al., 1991, 1994]. Studies based on numerical models and laboratory experiments highlight the coupling between the Atlantic inflow and the surface and deep circulation in this sub-basin [Speich et al., 1996]. Several recent works present two different circulation regimes: one with only the West Alboran Gyre (WAG) in winter-spring and another one with the two gyres in summer-autumn. Renault et al. [2012] studied the annual and the inter-annual variability of these gyres, using altimetric datasets. Eddies are generated from instabilities of the Atlantic jet and of the currents along the shore around the Strait of Gibraltar. Rio et al. [2007] computed a map of the synthetic mean field (Figure 1.6) which highlights the WAG with a mean velocity ranging from 20 to 30 cm/s. A second gyre, the Eastern Alboran Gyre (EAG) is anticyclonic most of the time but more variable than its western counterpart.

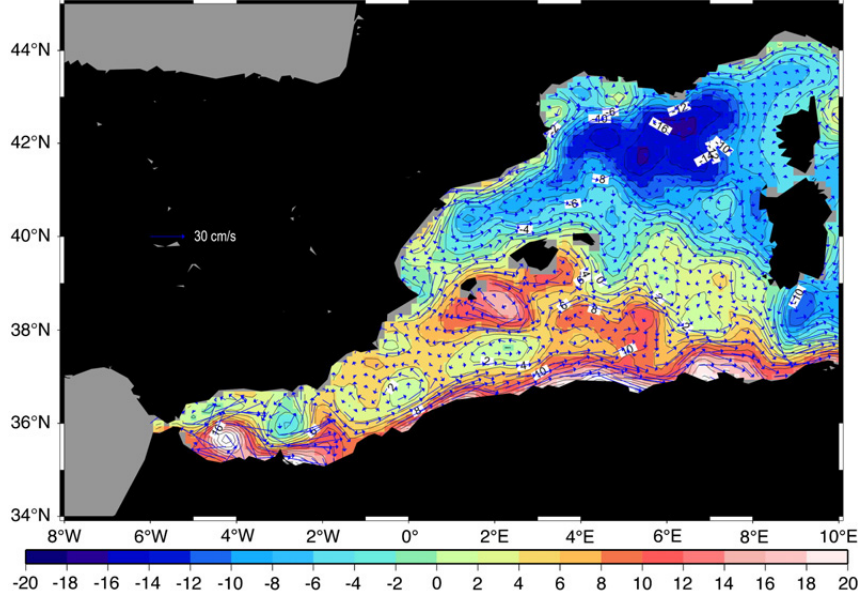


Figure 1.6: *Synthetic Mean Dynamic Topography in the Alboran-Algerian-Baleares area. The corresponding mean currents are superimposed as blue arrows. [Rio et al., 2007]*

After passing the Alboran Sea, the AW flows along the Algerian slope, forming the Algerian Current (AC), of about 0.5 Sv [Arnone et al., 1990]. It is relatively narrow (30 – 50 Km) and reaches 150 m of depth. Past the Greenwich Meridian, on its way eastward, the current

becomes shallower and wider near the Sardinia Channel. Due to the differences in density between AW and the Mediterranean surrounding water (MW) and due to other complex hydrodynamic processes, this along-slope current becomes usually unstable and meanders, generating mesoscale eddies (Section 1.3.1) [Millot, 1985, 1999; Font et al., 1998, 2004; Olita et al., 2011a], transported westward by the current, at the velocity of a few Km per day [Obaton et al., 2000] and blocked at the level of the Sardinia Channel (Figure 1.7).

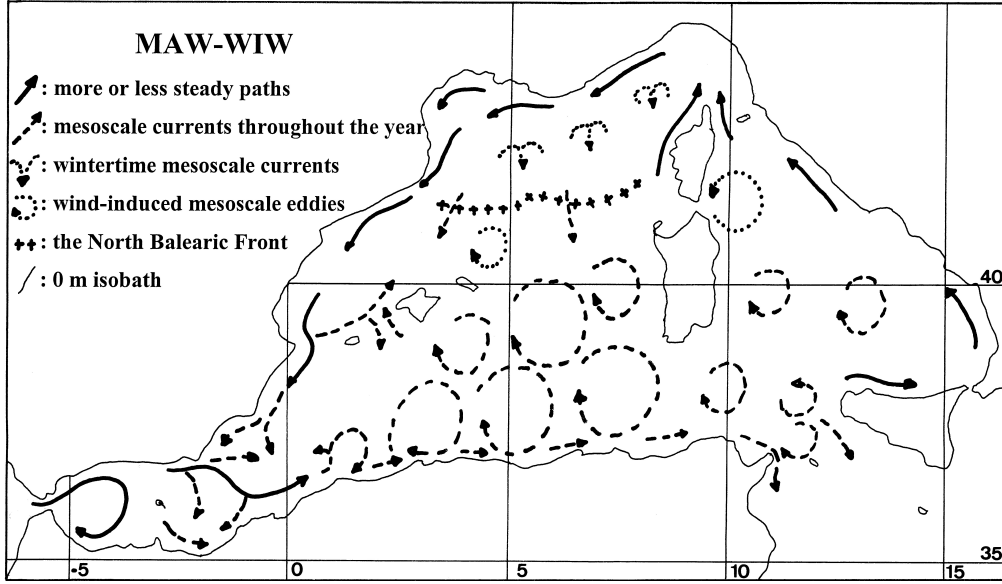


Figure 1.7: Circulation of the MAW and of the WIW in the WMED [Millot, 1999]

In proximity to the Alboran Sea, the bigger Algero-Provençal Basin plays a key role in the circulation of the entire Mediterranean Sea (Figure 1.7). Its hydrodynamics has been the object of several studies in the past [Vignudelli, 1997; Levy et al., 1999; Millot, 1999; Levy et al., 2000; Bouzinac et al., 2003; Isern-Fontanet et al., 2004]. The basin is divided into two sub-basins by the North Balearic Front (NBF), a thermal front characterized by a high seasonal variability, which separates the overall anticyclonic mean circulation of the southern part from overall cyclonic mean circulation of the northern part of the basin. The NBF is well highlighted by the Synthetic Mean Dynamic Topography (SMDT) in Figure 1.6, which assumes values close to zero. The northern basin presents mainly negative values of SMDT, associated with cyclonic structures. The opposite occurs in the southern part, characterized by anticyclonic features (positive values of SMDT). A west-east current from the Balearic Islands to the west coast of Sardinia, in correspondence with the NBF is also shown in Figure 1.6. It is known in literature as Western Mid-Mediterranean Current (WMMC) [Pinardi et al., 2013].

In winter, northwesterly winds lead the NBF to the Balearic Islands [Lopez-Garcia et al., 1994]: this is the southern position of the front. The northern sub-basin is the Provençal Basin and the southern the Algerian Basin, located along the Algerian Coast, between 2° W and 9° E in longitude and between 37° N and 41° N in latitude (Figure 1.8). There is a strong north-south density gradient between the warmer and saltier northern sub-basin and the cooler and fresher Atlantic modified water of the southern sub-basin [Olita et al., 2011b].

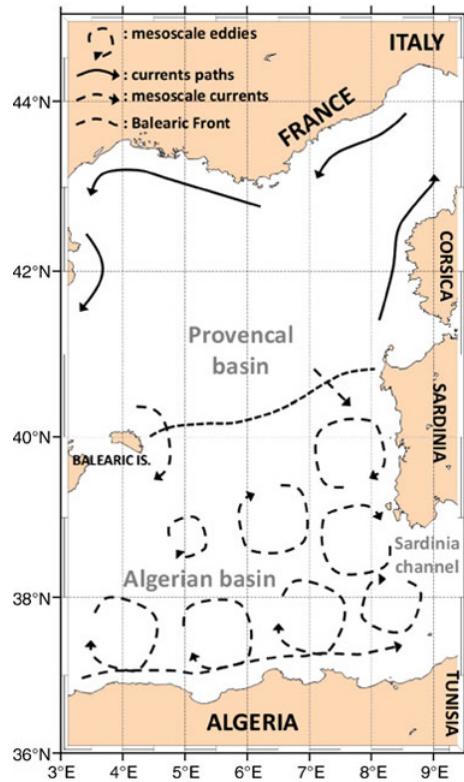


Figure 1.8: *The Algero-Provençal Basin [Olita et al., 2011a]*

A part of the AC continues to flow toward the EMED, through the Sicily Channel, and branches northward in the Tyrrhenian Sea, where the surface Tyrrhenian Current (TC) takes origin in the first 200 m.

East of the Strait of Bonifacio, in the central and northern Tyrrhenian Sea, a quasi-permanent cyclonic eddy associated with an upwelling phenomenon induced by westerly winds occurs. When the TC reaches the Island of Elba, it separates into two branches: the greater part proceeds northward along the eastern Corsica slope, to the Ligurian Sea, while the remaining part deviates southward along the eastern Sardinian coast. It does not pass through the Sardinia Channel and flows around the Tyrrhenian Sea.

In the Ligurian Sea the Northern Current (NC) originates. Several studies show that the flux is at its maximum during the winter (from December to May) when it reaches $1.5 - 2$ Sv down to about 700 m and it is not so easily distinguishable from intermediate waters. In summer, the NC is wide and shallow with limited mesoscale variability [Millot, 1999]. This current also takes the name of Ligurian Current, Liguro-Provençal Current and Liguro-Provençal -Catalan Current. The NC is part of the cyclonic circulation of the northern part of the Algero-Provençal basin (Figure 1.8).

The northern Provençal Basin is also characterized by strong mesoscale activity. To the west, the NC forms eddies, detected by hydrological and current-meter observations [Estournel et al., 2003; Millot, 1982]. The origin of the eddies is the current that separates from the coast and creates eddies from a combination of barotropic and baroclinic instabilities.

In winter northerly and westerly winds cool down the surface water in the Gulf of Lions while the Balearic Sea, protected by the Pyrenees, is characterized by warmer water. Due to the different temperatures and to the cyclonic gyre, a very intense thermal front, (the NBF), forms [Millot, 1999]. It is an unstable area where mesoscale structures often take form. A new specific water mass, called Winter Intermediate Water (WIW), originates in the Provençal Basin during this period. It is MAW that becomes denser and sinks without mixing, forming a layer between the surface MAW and the deeper LIW. This is a transformation of water with Atlantic origin to a Mediterranean Water.

The Balearic Sea occupies a central position in the WMED and is considered a transitional region between the Gulf of Lions to the north and the Algerian Basin to the south [Millot, 1999]. The NC, coming from the Provençal Basin, flows along the Catalan coast [Font et al., 1988] and enters the domain from the east. It is characterized by strong seasonal variability associated with variations of thermohaline structure rather than with wind stress. The latter is very energetic over the shelf, where dense shelf water cascading events, linked to canyons along the Catalan coast, contribute to WIW formation [Font et al., 1990; Canals et al., 2006]. Once it reaches the Ibiza Channel, depending on the presence or absence of WIW, the NC separates into two branches, one going through the Ibiza Channel and the other recirculating to the north of the Balearic Islands. In fact, when there are anticyclonic lenses of WIW, they block the channel and force the NC to flow eastward into the Balearic Current [Mason and Pascual, 2013].

As the MAW reaches the Eastern Mediterranean Basin it is subjected to evaporation for

a longer period, which raises its salinity compared to the MAW of the western basin. Dry, cold and strong winds enhance evaporation and mixing causing the development of a new water mass, the LIW. A vertical convection process occurs until the new water mass reaches 100 – 200 m depth. The LIW flows at the intermediate layer and is characterized by high salinity [Millot, 2013]. Two veins of water, coming from EMED, enter WMED through the Sicily Strait: one flowing along the Sicilian Slope and the other along the Tunisian coast. The former is the common LIW, with salinity of about 38.7 and temperature greater than 14.5°C at a depth of approximately 200 m, while the latter is about 0.1 denser but with the same salinity. It is likely that these two water masses have different origins in the EMED and do not mix because of their different velocities; furthermore, they have different masses and are deflected by the Coriolis force in different ways. [Millot, 1999].

The LIW in the Tyrrhenian Sea has a sigma-theta of about 29.1, and is thus denser than the dense waters formed in the WMED. In fact, at depths of 200 – 400 m in the Tyrrhenian Sea, the potential density assumes values in the range 29 – 29.05. It leads to a large amount of water sinking to more than 1800 m, causing a tremendous mixing not only of the inflow itself, but also of the inflow with the Tyrrhenian Sea waters [Sparnocchia et al., 1999]. This process is very complex and results in the formation of the so-called Tyrrhenian Dense Water (TDW). Finally the inflow from the Sicily Channel (200 – 400 m) changes into a 200 – 2000 m flow mainly composed of LIW in its upper part and of TDW in its lower one. The boundary between the two waters is not well defined, but the pathway is approximately the same (Figure 1.9). Hereafter we will refer to the both with the name of LIW [Millot, 1999].

The Sardinia Channel is 1900 m deep and 70 km wide at 500 m depth and provides a unique opportunity for intermediate and deep waters to communicate between the Algerian Basin and the Tyrrhenian Sea. The main core of LIW (at about 350 m depth) is characterized by high temperature and salinity maxima (around 13.9°C) [Fuda et al., 2000]. It flows westward from the Tyrrhenian Sea to the Algero-Provençal Basin along the northern side of the Sardinian Channel and turns northwards to follow the continental slope west of Sardinia. In the centre of the Algerian Basin, the LIW is generally significantly modified with typical temperature maxima half a degree lower (around 13.35°C) due to additional mixing with the surrounding waters [Testor and Gascard, 2005].

Finally, at the deep layer, the Western Mediterranean Deep Water (WMDW) fills the western basin from about 700 meter to the bottom. Its formation occurs in the Gulf of Lions

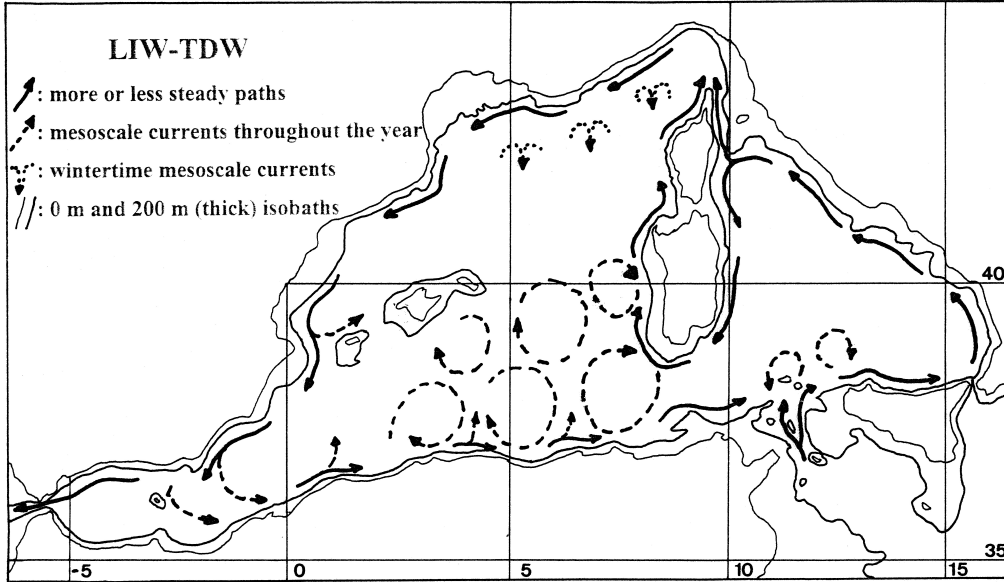


Figure 1.9: Circulation of LIW and TDW in the WMED [Milot, 1999]

during the winter. Northerly and westerly winds cool the water and cause evaporation, making the surface water denser. In sinking, it encounters the LIW and brings a part of it with it, forming a new water mass. Depending on the meteorological conditions and on the characteristics of the surface water, the depth of water formation changes.

1.3 Algerian Eddies

The Algerian Eddies are both cyclonic and anticyclonic, but the former are superficial, short-lived and do not affect the mean circulation of the basin. Hereafter we will consider only the Algerian anticyclonic eddies, indicated with the acronym AEs.

Eddy formation in the Algerian Basin usually takes place at about Long. $1^\circ - 2^\circ$ E. At 9° E, in proximity to the Sardinia Channel. Eddies are usually forced by the local topography to detach and to move to the open sea over the Algerian Basin [Milot et al., 1997]. The mean diameter is about 50 – 100 km and the vertical extension about 100 – 1000 m. The translation speed observed is of 3-5 km/day, which corresponds to a surface velocity of 30-50 cm/s [Milot, 1999]. AEs are usually generated as a result of baroclinic instabilities (Section 1.3.1) [Obaton et al., 2000] and have been widely investigated in the past [Burkov et al., 1979] with infrared and colour satellite imagery [Milot, 1985], in situ data [Benzhora and Milot, 1995], moorings, surface drifters [Font et al., 2004] and altimetry observations [Isern-Fontanet et al., 2005].

The mixing of AW and the surrounding MW is maintained by the quasi-permanency of the eddies in the sub-basin. There are several studies about the lifetime of the AEs; Benzhora and Millot [1995] and Puillat et al. [2002] proposed a duration of 3 years, but research is on-going. In spite of the current body of research, a comprehensive study of the tracking, energy and interaction of these eddies in time and space is still lacking.

A recent analysis of Escudier et al. [2016] of eddy sea level anomalies along the mean pathways reveals three preferred areas of formation. AEs form most commonly during some periods of the year and have a strong inter-annual variability over the last 20 years.

A strong correlation exists between physical mechanisms and biology, which could be better understood by studying the complex motion and dynamics of AEs [Morà et al., 2001]. The detachment of the eddies from the AC carries with it the water masses and their properties northward instead of following the estward direction of the current. Furthermore, phenomena like deep water formation and seasonal bloom in spring are strictly related: during the last phase of the formation process, when dense water sinks, a re-stratification of shallow water takes place, causing algal blooms [Olita et al., 2011a].

Gascard et al. [1999] located a gyre-type circulation which is quite different from the well-known cyclonic, along-slope, circulation in the Algero-Provençal basin (Figure 1.9). This kind of circulation has been identified with the so-called Algerian Gyre (AG), which extends from the Balearic Islands to Sardinia and North Africa at LIW layer. The mean horizontal velocity is about 5 – 10 cm/s, according to data collected by drifters [Testor and Gascard, 2005]. A full loop is completed in about 3-4 months. Some AEs leave the Algerian slope and interact with the LIW vein southwest of Sardinia, and entrap or dispatch pieces of it in the middle.

1.3.1 Baroclinic instabilities and the formation of eddies

In this section we want to explain the inner workings of eddy formation and in particular which mechanisms make a flow unstable, breaking it down into irregular small-scale motion, which lead to friction effects larger than those justified by the molecular nature of the fluid itself.

A vertically sheared baroclinic flow in a stratified fluid is characterised by a tilt of density surface. In fact a horizontal pressure gradient, and thus a horizontal density gradient, is needed for the baroclinic flow to exist. Geostrophic and hydrostatic balances combine to maintain the flow in equilibrium, which does not correspond to the lowest energy layer. In

fact, a reduction in the slope of density surfaces, with a consequent movement of the lighter fluid above the heavier one, would lower their centre of gravity and thus their potential energy. Vertical stretching and squeezing of fluid parcels is possible under the conservation of potential vorticity and thus induce a variation of the relative vorticity too. A column of stratified fluid that is stretched vertically develops cyclonic relative vorticity, and one that is squeezed develops anticyclonic vorticity. Physically, the relaxation of density surfaces liberates potential energy, whereas the simultaneous stretching and squeezing increase relative vorticity. The new motion is sustained by the transformation of potential energy into kinetic energy. Then, if the conditions are favourable, these new motions may contribute to other relaxation of the density field, making the vortices stronger, increasing the amount of velocity shear in the system, and enhancing friction. Substantially the evolution to a lower energy level leads to the growth of disturbances, to the transformation from potential to kinetic energy, to the formation of eddies and finally to the reduction of kinetic energy by friction.

Obaton et al. [2000] made laboratory experiments comparing the AC to a current created in a rotating tank. The experimental current flowed along a regular wall and over motionless denser water, with a constant flow rate and a uniform velocity at the source. The results have been compared with satellite and in situ measurements. Laboratory current and the AC are both unstable and generate meanders and cyclonic/anticyclonic eddies. The formation mechanism is schematized in Figure 1.10. The current detaches from the coast (from the wall in the laboratory) and forms an anticyclonic loop. After having impacted the coast (or wall, point P in the figure) it splits into two parts. One ($Q2$) continued downstream, constituting the main flow of the AC, while the other one ($Q1$) re-circulated within the anticyclonic loop. The latter became larger and thicker. Wind stress on the surface, baroclinic and barotropic instabilities may cause horizontal movement of water, but also lead to vertical motion. In fact, when there is a divergence of surface water, deeper water rises to take its place; conversely when there is a convergence of water on the surface, sinking occurs. Upwelling and downwelling occur throughout the oceans, both at coastal boundaries and away from them. We focus our attention on the convergence of the sea surface and consequently on the downwelling, which leads the thermocline to be lowered (Figure 1.11) [Colling, 1989].

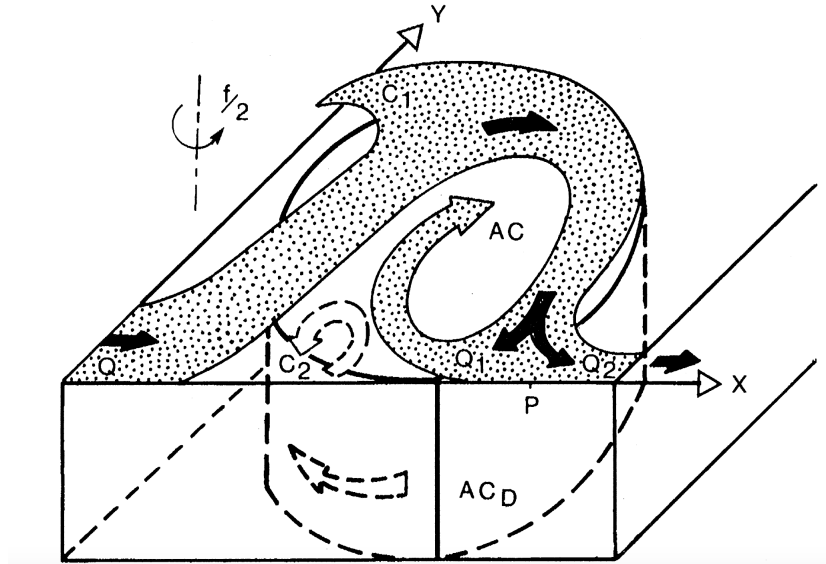


Figure 1.10: Schematic 3D-diagram of a laboratory structure showing a deep anticyclonic motion [Obaton et al., 2000]

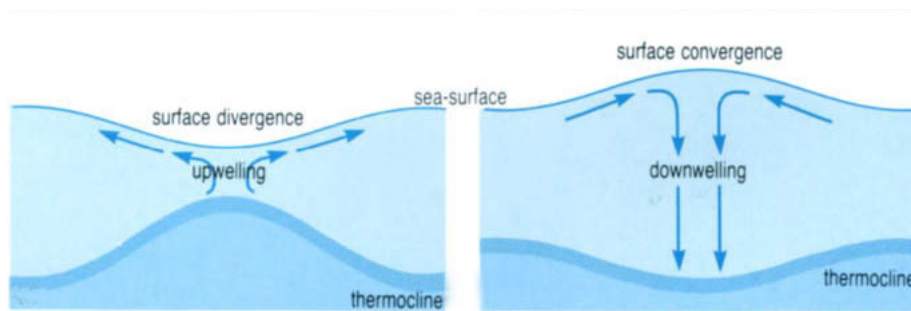


Figure 1.11: Effects of sea surface divergence/convergence on the thermocline. (Credits to Colling [1989])

Chapter 2

Materials and methods

In the past, the study of the AEs has been approached from different points of view and types of data sets. Most data on the motion of AEs is provided by infrared and colour satellite imagery, as their cores are warmer than the surrounding water except in winter, when the gradient tends towards zero or inverts [Puillat et al., 2002]. The limit of this survey technique is the need to have low cloud cover in order to record continuous data, especially in the cold winter season. The biological response associated with eddies is remarkable and is highlighted by the production of ocean colour signatures that could be used as tracer [Morà et al., 2001; Taupier-Letage et al., 2003].

To avoid the limitations associated with infrared and color satellite imagery, mesoscale phenomena can be investigated with altimetry observations, such as Absolute Dynamic Topography (ADT) and Sea Level Anomaly (SLA), which are not affected by the presence of clouds and provide the geostrophic velocity field of the selected area.

Recently, the eddy detection and tracking algorithms based on altimetry data have been widely used to investigate mesoscale structures in both space and time [Isern-Fontanet and E. Garcia-Ladona, 2003; Chelton et al., 2007, 2011]. These algorithms, applied on global and regional scales, have been successful in the characterization of several AE properties, such as polarity, propagation pathway, lifetime, radius and amplitude. They can be applied to altimetry data sets or with realistic high-resolution numerical model outputs, which also offer the opportunity to study both surface and subsurface eddies, as well as three-dimensional structure. Several comparisons have been done with both data sets [Chelton et al., 2011; Kurian et al., 2011].

Many different methods have been developed for detecting eddies, but in general they fall into two main categories: physics-based and geometrical methods. The former are

based on the calculation of some dynamic fields and define eddies based on closed contours of a threshold value. The physical fields computed are SLA, Sea Surface Height (SSH) [Chelton et al., 2011; Chaigneau et al., 2009], vorticity [McWilliams, 1999] and velocity gradient tensor (Q) or Okubo-Weiss parameter (W) [Penven and Echevin, 2005; Chelton et al., 2007; Isern-Fontanet and E. García-Ladona, 2003]. On the other hand, geometrical methods are based on the curvature or shape of the instantaneous flow field. Several studies make use of both physical and geometrical methods to better explain the structure of mesoscale eddies.

There is no preferred method for detecting eddies from water or flow properties, as the choice depends on the definition of an ideal eddy, which is different from one researcher to another. It is very subjective and thus characterized by error. In general, the SLA closed contour method combined with the Okubo-Weiss parameter remains the most popular technique due to its simplicity and computational efficiency. The algorithm used in this work has evolved thanks to many tests and has benefited from comparisons with literature and satellite imagery [Escudier et al., 2016].

2.1 Data

In the first part of the study, we used SLA data to detect the mesoscale structures with an automated method described in Section 2.2.2. After extracting some useful information about the mesoscale structures, we focused our attention on the CTD data collected during three oceanographic cruises in the WMED. The data also allows the investigation of the water column, where the algorithm has detected some eddies.

In the following subsections in-situ measurements and altimetric data, and in particular SLA data, are briefly described.

2.1.1 Altimetry data

The sea surface is characterized by bumps and depressions due to different physical characteristics such as temperature, salinity and currents and strong mesoscale activity.

The instrument best suited to sample sea-surface height is satellite altimetry. The instruments determine the distance from the satellite itself to a target surface by measuring the satellite-to-surface round-trip time of a radar pulse. The process of measurement is rather more complex and several parameters can be deduced. In fact, the amplitude and the

shape of the reflected signal contain information about the characteristics of the surface. The best results are obtained over spatially homogeneous ocean surfaces, which conform to known statistics. The spatial resolution of altimetric data is too low to allow the analysis to be performed close to the coast.

Radar altimeters continuously transmit signals and receive the echoes from the surface. Their orbits have to be tracked and their positions determined with reference to an arbitrary elliptical surface. The SSH is the range from the sea surface to that reference ellipsoid. Satellite altimetry thus measures the sea level through a combination of radar techniques to compute the distance and a positioning technique for the accurate location of the satellite in orbit.

The great potential of satellites in the observation of the global ocean is that ten days of measurements provide more detail than one hundred years of in-situ data. Furthermore, thanks to reprocessing measurements the quality of the data improves as do the continuity and homogeneity of datasets.

It is important to note that the orbit of an altimetry satellite is a compromise: it is necessary to find the right balance between spatial and temporal resolution. In practice, if a satellite revisits the same spot often, it covers fewer point than one with a longer orbital cycle. The solution has been to combine several satellites together to collect more along-track data, which is useful for data assimilation in numerical models and higher spatial resolution of mesoscale maps. Two altimetry satellites at least are needed to map the global ocean and to oversee its movement (scales of 100 – 300 Km). The resolution of SSH is greatly enhanced with just four instruments. To study mesoscale eddies, at least three altimetry satellites are needed [Marcos et al., 2015]. Special attention is reserved for

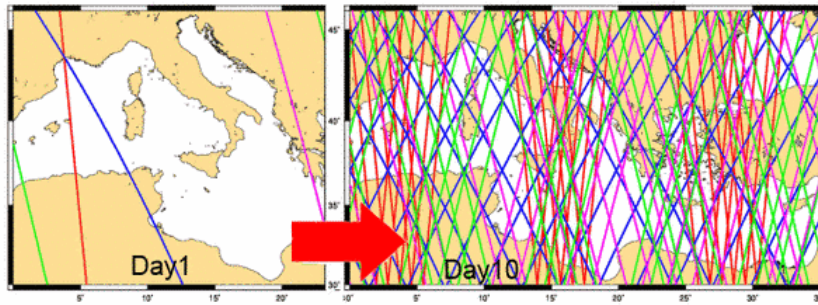


Figure 2.1: Ground tracks of four operational satellites over the Mediterranean Sea in June 2015. In blue Jason-2, in green Saral/altiKa, in red Cryosat-2 and in pink HY-2A. (Credits www.aviso.altimetry.fr)

regional altimetric gridded SSH products, as they have been developed using processing

adapted to areas which need higher spatial resolution, such as the Mediterranean Sea.

AVISO merged, delayed-time, SLA data

In this work we used merged, delayed-time grid maps of optimally interpolated SLA, available courtesy of Archiving, Validation and Interpolation of Satellite Oceanographic (AVISO) (<http://www.aviso.oceanobs.com>).

These data are produced by the SL-TAC multi-mission altimeter data processing system. Data are acquired and synchronized to produce homogeneous altimeter datasets by applying several corrections, models and references. A quality control guarantees the use of only the most accurate altimeter data. Another important step consists in the Multi-mission Cross-calibration process, which ensures that all flows from all satellites provide consistent and accurate data and removes any residual orbital or long wavelength error, as well as large scale biases and discrepancies between data flows. The altimeters used are HY2, Saral/AltiKa, Cryosat-2, Jason-2, Jason-1, T/P, ENVISAT, GFO, ERS1/2; the reference mission, to whom all the missions are homogenized, is currently Jason-2. An optimal interpolation is finally made in order to compute gridded SLA merging all the satellites flying. The reanalysis products are more precise than the Near Real Time ones and that is the reason we chose them.

The mapping procedure is based on realistic correlation functions and produces SLA maps at a given date. The along-track measurements from all available altimeter missions are merged to generate a map [Ducet et al., 2000], taking into account an updated suboptimal Optimal Interpolation parametrisation to minimize transition artefacts.

After a repeat-track analysis, a mean profile peculiar to each mission, or a Mean Sea Surface (MSS) when the orbit is non repetitive, is subtracted to compute SLA. Data are then cross-validated, filtered to eliminate residual noise and small-scale signals, and sub-sampled. The limit of the satellite is the detection of the reference ellipsoid and therefore the evaluation of the SSH. There are several means used in altimetry processing or altimetry-based studies. In particular, the MSS is a mean of several years of altimetry data, it is a reference surface. The Mean Dynamic Topography (MDT) is the previous surface minus the geoid and represents the ocean topography due to the mean currents. It is also a reference surface.

The daily maps are obtained by Optimal Interpolation (OI), as are the weekly maps in the previous release. Each map uses data selected in a temporal window of ± 49 days,

larger than the temporal correlation scale (10 days in the Mediterranean Sea). It allows an optimal correction of the long-wavelength errors [Marcos et al., 2015].

In this study, we use the *all-sat* gridded SLA fields that consider all available altimeters and therefore have higher quality levels, although not homogeneous in time due to the time-varying mission configuration. The horizontal resolution of the data is $1/8^\circ$ (about 14 Km) and data are available from January 1993.

Details of the procedures are available on the SSALTO/DUACS User Handbook <http://www.aviso.altimetry.fr/fileadmin/documents/data/duacs/Duacs2014.pdf>.

We will analyse daily data over the period from January 1993 to December 2014.

Limitations and advantages of the use of Gridded altimetric data in comparison with Along-Track data

As previously stated, the gridded altimetry data are obtained from along-track (AT) measurements by following the procedure outlined in <http://www.aviso.altimetry.fr/fileadmin/documents/data/duacs/Duacs2014.pdf>. AT geophysical products for altimetry are the product closest to the original satellite imagery and feature the maximum spatial and temporal resolution. Such high resolution of the AT data, which are unevenly spaced in time, and their synopticity would allow a better representation of the fine scales of the ocean (i.e. sub-mesoscales). At the same time, uneven sampling in both space and time, and different resolutions as a function of the different satellites and sensors providing the altimetric measurements, make those data unsuitable for the study of the seasonal and inter-annual variability of a marine system, even at mesoscale level. The use of merged and gridded data overcome the problem of the discontinuous and uneven sampling of the ocean. Nevertheless gridded data have lower spatial resolution and “time smoothing” due to the processing of the data generating the gridded maps, which cut off from the data some frequencies of potential physical interest. The gridded data are continuous in space and time and provide long and homogeneous time series (1993 – 2014), but they are no longer synoptic (even if nominally labelled as “daily” fields). The nominal resolution of the gridded data ($1/8^\circ$) is in any event sufficient to resolve the large mesoscale features on which we focus our work, so they fit perfectly our demand.

Discussion on SLA data

In the Mediterranean Sea the mean circulation is largely unknown and is characterized by small scales of low intensity. Consequently, the interpretation of SLA is sometimes difficult. In fact, a positive anomaly detected by altimetry can be interpreted as the formation of a new anticyclonic eddy, as the strengthening of a quasi-permanent one or as a meandering current [Rio et al., 2007]. Conversely, using the ADT data ($MDT + SLA$) a weak cyclonic structure in an area where the mean is anticyclonic can be interpreted as an anticyclonic structure. Vice-versa, in an area where the mean is cyclonic, a weak anticyclonic structure could be mistaken for a cyclonic structure. The Figure 2.2 shows the MDT in the domain. The north of the basin is characterized by negative values of MDT. ADT data fails to recognise some weak anticyclonic structures.

We were interested in the mesoscale circulation of the WMED, which is represented by the SLA data. It is important to underline that the Mediterranean circulation is characterized by numerous structures which were first identified punctually and whose permanent, recurrent or transient nature is still poorly understood. An accurate understanding of the MDT should help to correctly interpret the SLA measurement and to remove some remaining ambiguities on the Mediterranean variability.

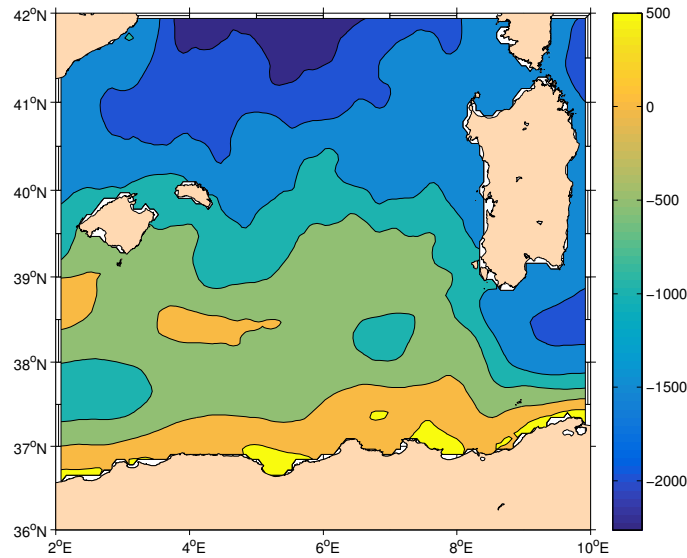


Figure 2.2: Mean Dynamic Topography (in meters) in the Algerian Basin for the period 1993 – 2012.

The access to realistic sea surface circulation variability is provided by altimetric gridded field for the Mediterranean Sea, but several *in-situ* experiments [Nencioli et al., 2011] show the limits of these data to detect small and coastal features. Some innovative strategies

to improve existing altimetry products have been implemented by Escudier et al. [2013], but this improvement is possible only at the expense of the homogeneity of the fields and the resolution can only be improved where altimetric observation are densely distributed [Marcos et al., 2015]

2.1.2 In-situ data

In this work we used *in-situ* data sampled during several oceanographic cruises in the WMED. In particular we were interested in the transects along the Algerian coast and in the Balearic transect. We analysed data from MEDGOOS09, MEDCO08 and MEDOCC07. In the following table (2.1.2) the geographic boundaries, the period and the number of casts for the three cruises are indicated.

Cruises	Lon	Lat	Casts	Period	Year
MEDGOOS09	6.8 W - 15.8 E	35.9 N - 42.4 N	74	25/05 – 12/06	2004
MEDCO08	6.2 W - 16 E	35.5 N - 43 N	63	3/11 – 24/11	2008
MEDOCC07	1.9 E - 16.3 E	36.3 N - 43.7 N	84	7/10 – 27/10	2007

The full domain of each cruise is shown in Figures (2.3, 2.4 and 2.5). The stations analysed are highlighted by the red lines.

Cruises MEDGOOS09 and MEDCO08 [Ribotti and Borghini, 2008] tookplace in October 2004 and November 2008 respectively on board R/V Urania and include stations in the southern part of the basin, where AEs form (Section 1.3). We have analysed the data sampled during MEDOCC07 in October 2007 along the Balearic Transect 7th – 27th in order to highlight the properties of the FAEs in correspondence with the NBF.

During the oceanographic cruises, a SBE 911 plus CTD have sampled data of temperature and salinity along the water column. Sensors to measure conductivity (SBE-4), temperature (SBE-3/F), pressure (4000 Digiquarz) and oxygen (SBE-13) have been installed on the probe. Chlorophyll fluorescence has been measured with a Seatech 90S fluorometer connected to the SBE carousel.

Data were archived, processed and reduced using SeaSoft. The main steps of the processing are:

- Data conversion: converting raw data into physical data, selecting the parameters on the basis of the sensor used.
- AlignCTD: manipulating data to remove misalignment of sensors.

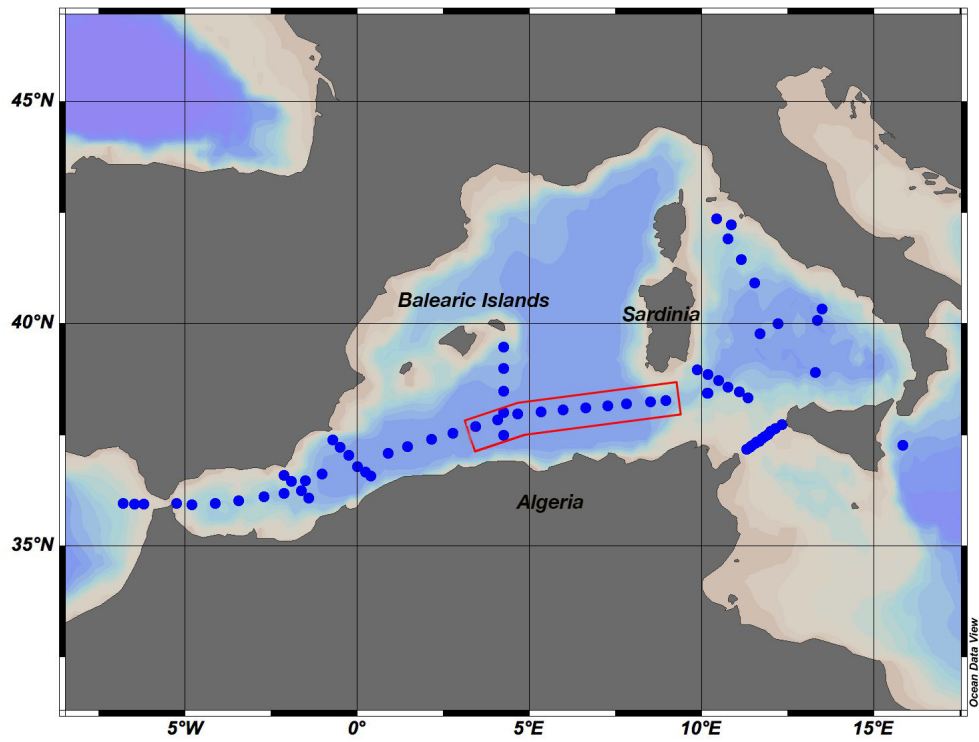


Figure 2.3: Full domain of MEDGOOS09 cruise

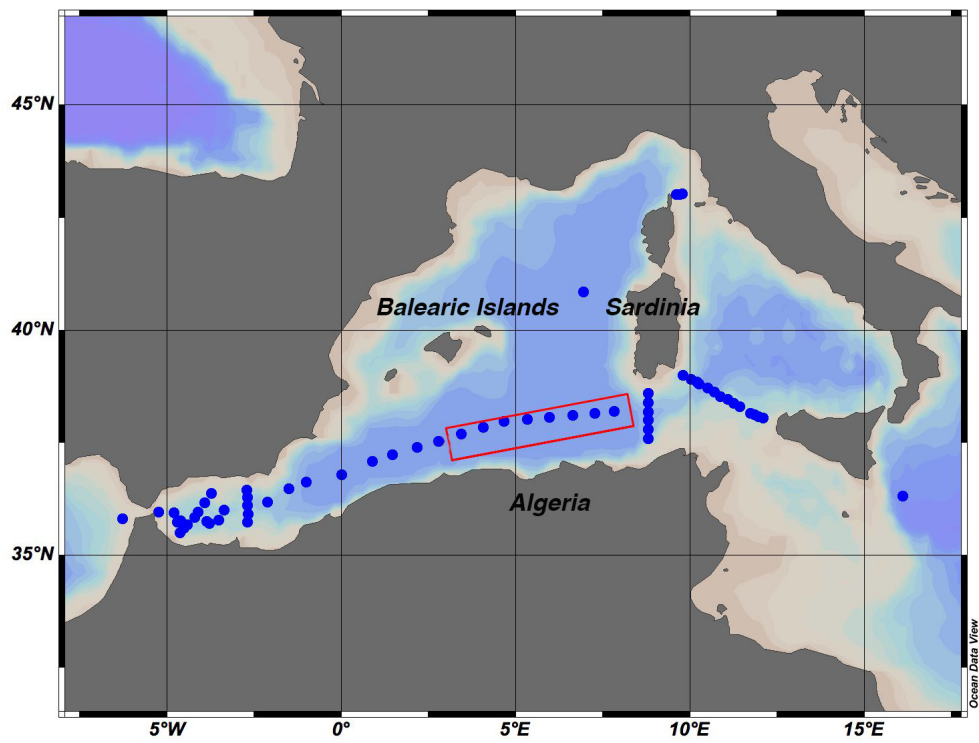


Figure 2.4: Full domain of MEDCO08 cruise

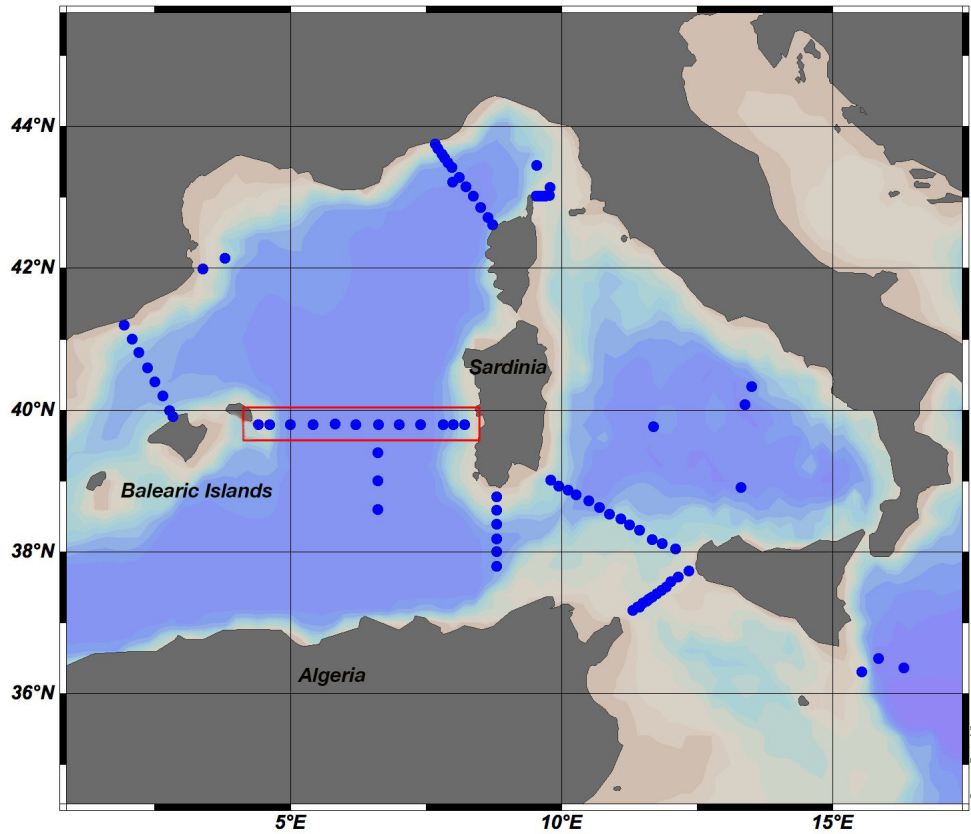


Figure 2.5: Full domain of MEDOCC07 cruise

- Cellthermalmass: as a consequence of conductivity, the glass cell stores heat. Corrections have to be introduced.
- Filter: filtering to remove bit noise in the frequency counter.
- Loopedit: removing data acquired when the CTD moves less than a minimum selected velocity.
- Wildedit: removing data outside of user-specified limits, replacing them with a bad-flag.
- Binaverage: calculating average data into desired pressure or depth bins.

At the end of these steps data are stored in *.cnv file and are ready to be analysed.

2.2 Detecting and tracking methods

There is a close link between local topology of the flow field, stirring and mixing process and dispersion of Lagrangian particles in complex flow.

The eddy detecting physical methods, based on altimetry data, use the surface velocity field calculated from SSH, imposing the geostrophic balance:

$$u_{geo} = \frac{g}{f} \frac{\partial h'}{\partial y} \quad (2.1)$$

$$v_{geo} = \frac{g}{f} \frac{\partial h'}{\partial x} \quad (2.2)$$

where h' is the sea level anomaly, g is gravity and f is the Coriolis parameter and u and v are the eastward and northward velocity components respectively.

Eulerian geostrophic velocity fields, calculated in this way, provide information about eddies tracking, whose core can be identified in an objective manner, through the horizontal velocity field.

2.2.1 The Okubo-Weiss based methods

In the past, several different methods have been used to detect eddies in the open ocean. One of the most widely adopted is the Okubo-Weiss (OW) method thanks to its ease of use and efficacy. It allows to separate the cores of the eddies from the surrounding water on the basis of physical properties.

In 1970 Okubo demonstrated that two particles moving in the ocean and initially close to each other have the shape of their trajectories correlated with the eigenvalue of the velocity gradient tensor. The theory has been completed by Weiss in 1981 [Okubo, 1970; Weiss, 1991]

The Okubo-Weiss (OW) parameter is defined as follows:

$$W = \sigma_n^2 + \sigma_s^2 - \omega^2, \quad (2.3)$$

where σ_n , σ_s are the normal and the shear components of the strain and ω is the relative vorticity of the flow and they are expressed as:

$$\sigma_n^2 = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \quad (2.4)$$

$$\sigma_s^2 = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \quad (2.5)$$

$$\omega = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}. \quad (2.6)$$

When the Okubo-Weiss parameter W is negative we are in the inner part of the eddy, the vorticity-dominated region, when W is positive we are instead in the external part, the strain-dominated region. Furthermore the $|W| \leq W_0$ with $W_0 = 0.2\sigma_W$. σ_W is the

standard deviation of the entire domain (in this case the Mediterranean Sea). It provides information about the background field.

This method has been proven to be valid to separate the eddy core from the circulation cell in terms of the sign of the Okubo-Weiss parameter W Jeong and Hussain [1995]; Pasquero and A. Provenzale [2001]; Isern-Fontanet and E. García-Ladona [2003].

The boundary of the eddy is also a barrier to the particle exchange between core and surrounding circulation cell. Water inside an eddy stays there for a long time before being ejected through a filamentation process Isern-Fontanet et al. [2004].

To demonstrate that the maximum velocity is found on the eddy boundary we have to assume a horizontally non-divergent flow:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (2.7)$$

The Okubo-Weiss parameter takes the following form:

$$W = 4 \left(\frac{\partial v}{\partial x} \frac{\partial u}{\partial y} - \frac{\partial u}{\partial x} \frac{\partial v}{\partial y} \right) = 4 \left(\frac{\partial v}{\partial x} \frac{\partial u}{\partial y} + \frac{\partial^2 u}{\partial x^2} \right). \quad (2.8)$$

Mathematically, the right side of the Eq. 2.8 is equivalent to the determinant of the velocity gradient matrix multiplied by a factor -4 . When the strain dominates in the eddies, W assumes negative values (in both cyclonic and anticyclonic cases). W is zero on the boundary, which corresponds to maximum velocity there.

Typically, the eddy detection procedures which use the Okubo-Weiss parameter or SSH methods treat the area within a closed contour as an eddy, where several properties are computed. Many methods are used to better define the eddies, for example circle/ellipse fitting or shape tests [Kurian et al., 2011].

The selected contours are made for a specific threshold value, which can be defined as 0.2 times the standard deviation (calculated at each time step over the domain) [Isern-Fontanet and E. García-Ladona, 2003] or taken as a constant [Chelton et al., 2007].

This physical method, based on the computation of W , presents three main problems. The first is the need of a threshold value of W by which eddies are identified. There is no single value that is optimal for the global ocean and too high or too low a value can lead to failure in detecting small features and to the overestimation of the size of the eddy respectively. In this case, the eddies with an unrealistic area may encompass multiple vortices, sometimes with opposite polarities. The second problem is that the need for the numerical computation of W is subject to noise in the SSH fields. In fact, the calculation of the second derivatives of SSH fields amplifies the error. Lastly, the interiors of eddies

defined by closed contours of W are different from those calculated by SSH. Eddies with opposing polarities may sometimes occur within a single closed contour of W .

2.2.2 Hybrid method: geometric and Okubo-Weiss based

In this section, we will expand briefly on the algorithm applied to the dataset [Halo et al., 2014]. It is a hybrid method: a combination of detecting the largest contours in SLA data (geometric criteria [Chelton et al., 2011]) and computing the W parameter (traditional method [Chelton et al., 2007]), which reduce the number of tunable parameters. Three tunable parameters remain in the algorithm, but some tests have demonstrated that the number of detected eddies did not change appreciably by varying these parameters [Halo et al., 2014].

The code can be divided in two main parts: the Eulerian one, dedicated to the detection of the eddies (eddy detection), and the Lagrangian one, which investigates their trajectories (eddy tracking).

Eddy detection

The Eulerian part concerns eddy detection starting from SLA data. After selecting a domain and a period of time the algorithm looks for the nearest dates of data available. In our case we had daily data available and this step was not necessary. Next the algorithm finds the local maxima and minima that correspond to anticyclonic and cyclonic eddies respectively. Here W is computed starting from geostrophic velocities (2.1) in the closed contour around the extrema and some passes of a Hanning filter are applied to reduce the grid scale noise. The Okubo-Weiss parameter allows the separation of the flow into two regions, one dominated by vorticity and the other by deformation. If the W parameter is negative inside the closed loop, the structure can be considered an eddy.

The following list summarizes the main steps of the code:

- Selection of the spatial and temporal range to analyse.
- Selection of the interval between the SLA contours, which should approximate the precision of the altimetry. We choose 0.02 m.
- An upper threshold for Okubo-Weiss parameter detection is fixed at 0.
- A minimum value for SLA is fixed at 0.

- Selection of the number of Hanning filter iterations on the Okubo-Weiss parameter. We choose 2 passes.
- The algorithm finds the local extrema in SLA.
- In each closed SLA contour, around the extrema, the algorithm computes the W parameter, the vorticity and the Eddy Kinetic Energy (EKE).
- If the SLA contour is closed and if the W parameter is negative, the algorithm computes the number of grid points inside the eddy. If this number is greater than 4, the detected structure can be considered a mesoscale eddy.
- The algorithm checks if there are other extrema in this eddy.
- The algorithm extrapolates all the properties of the eddy such as position coordinates, time, area, surface kinetic energy, vorticity, equivalent radius (computed from the area), maximum, minimum and mean sea surface height (SLA), amplitude, rotational speed [Chelton et al., 2011] and finally zonal and meridional propagation speed. (See Section 2.2.2 for details of the main parameters used.)

The hybrid method has been applied over the period from January 1993 to December 2014 on the domain between longitude 2° E and 10° E and from latitude 37° N to 42° N.

The outputs of the detection algorithm are the daily maps shown in Figure 2.6 and the properties just listed for each eddy. The dotted black circles indicate the closed contour of W inside the closed SLA contour. On the z-axis there is the SLA in m.

After the detection step, a routine selects the eddies with radius included in the range $0 - 300$ Km and amplitude greater than zero (tunable parameters). A new file with all the properties computed is written in this phase. It will be used later by the Lagrangian routines in order to track the eddies.

The main steps of the detection algorithm are summarized in Figure 2.7.

Parameters of the eddies

As described above, the algorithm finds the local extrema in the SLA field and computes the kinetic energy, vorticity and OW parameters of each point of the subgrid. It then checks if the OW parameter is ≤ 0 in the closed loops around the extrema. If this condition is satisfied, the closed contour around the extrema is classified as an eddy. The kinetic energy, vorticity, area and other parameters are then calculated inside the eddy.

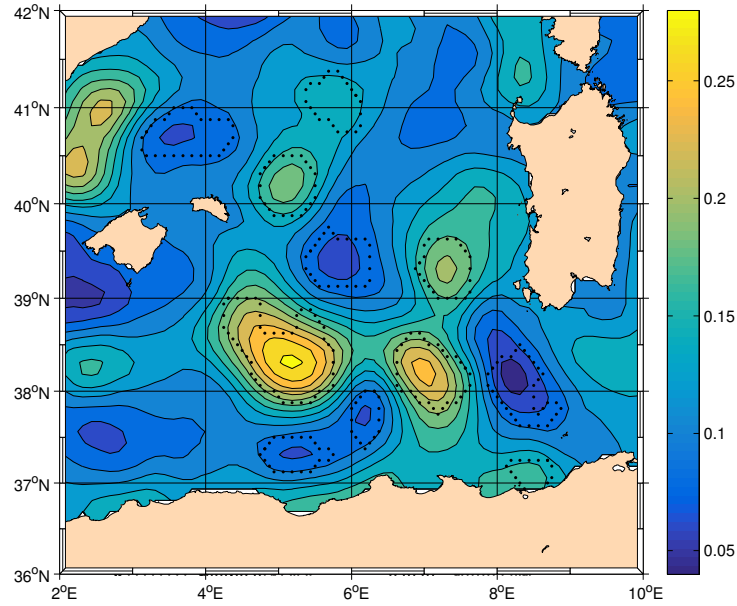


Figure 2.6: Daily output of the hybrid method. The map shows the SLA extrema in metres. The black dotted circles indicate closed W contour (with negative values) around the extrema. They are thus the eddies, both cyclonic and anticyclonic, detected by the hybrid method.

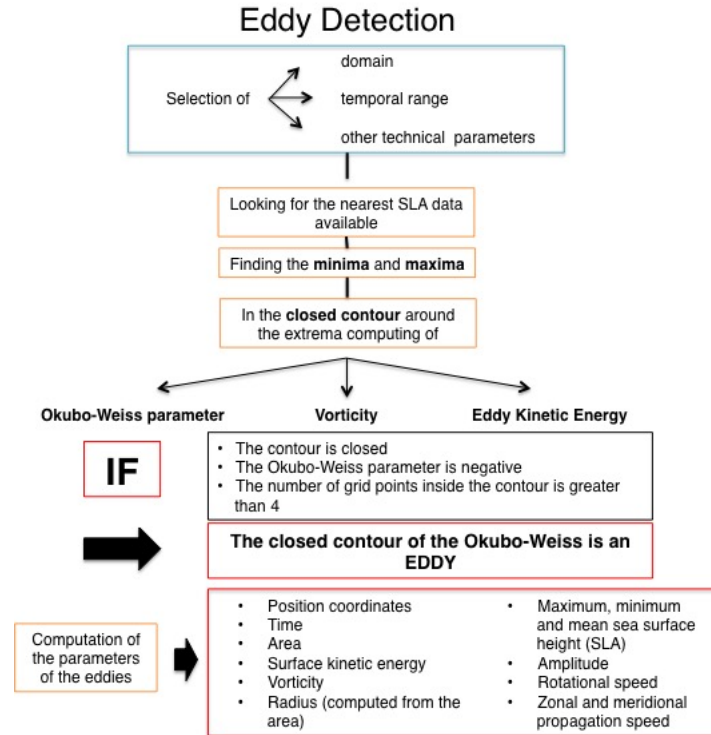


Figure 2.7: Main steps of the eddy detection algorithm

Particular attention should be paid to the kinetic energy concept. In fact, once the structures are defined, a matrix describes the kinetic energy of each point of the eddy. In all the dissertation we will refer to the kinetic energy normalized by mass. The total areal kinetic energy ($Aeke$, multiplied by unit of area), measured in m^4/s^2 , is defined as follows:

$$AEKE = \int_S EKE \, dS, \quad (2.9)$$

where EKE and dS are respectively the kinetic energy and the unit of area for each point of the eddy.

In this dissertation we will refer to the *dailyMEKE*, which is the mean kinetic energy of the daily eddies (2.11). The mean EKE of each structure is the mean of all the dailyMEKEs constituting the eddy (2.21).

The area of the eddy (S) is the sum of each $ds(i, j)$ inside the eddy:

$$S = \sum_{k=1}^N ds_k. \quad (2.10)$$

where N is the number of points inside the eddy (number of point of the subgrid inside the closed contour). S is measured in m^2 .

The dailyMEKE ($dMEKE$) is defined as:

$$dMEKE = \frac{AEKE}{S}, \quad (2.11)$$

and it is measured in m^2/s^2 .

The total daily EKE ($tdEKE$) is necessary to calculate the monthly mean EKE ($mmEKE$) used in our study, and it is the sum of the dMEKE of each one-day structure:

$$tdEKE = \sum_{i=1}^{neddies} dMEKE_i \quad (2.12)$$

where $neddies$ is the number of the eddies of each day. It is measured in m^2/s^2 .

The monthly mean EKE (m^2/s^2) is calculated as follows:

$$mmEKE = \int_{month} tdEKE \, dt \quad (2.13)$$

where dt corresponds to one day and the integral is extended to the number of the days for each month.

The other parameters are calculated as follows:

- The coordinates of the eddy centres are calculated as the coordinates of the geometric centre of the closed contour:

$$Longitude = \frac{\sum_{k=1}^N lon_k}{N}, \quad (2.14)$$

$$Latitude = \frac{\sum_{k=1}^N lat_k}{N}; \quad (2.15)$$

- The vorticity describes the local spinning motion of a continuum near some point (the tendency of something to rotate), as would be seen by an observer located at that point and travelling along with the flow. Mathematically, the vorticity of a three-dimensional flow is a pseudovector field, defined as the curl of the velocity $\mathbf{v} = (u, v, w)$ describing the continuum motion.

$$\xi = \nabla \times \mathbf{v} = \left(\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z}\right)\hat{i} + \left(\frac{\partial u}{\partial z} - \frac{\partial w}{\partial x}\right)\hat{j} + \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right)\hat{k} \quad (2.16)$$

In the algorithm, once defined the vorticity multiplied by the unit of area $b(i, j) = \xi(i, j) \cdot ds(i, j)$, the vorticity (ξ , in s^{-1}) is defined as follows,

$$\xi = \frac{\sum_{k=1}^N b_k}{S}, \quad (2.17)$$

- Radius, in m :

$$Radius = \sqrt{\frac{S}{\pi}} \quad (2.18)$$

- Amplitude, in m :

$$Amplitude = \max(h) - \min(h), \quad (2.19)$$

where h is the SLA value for the eddy, in m . It is defined as the difference between the estimated basal height of the eddy boundary and the extremum value of SSH within the eddy interior.

Eddy tracking

The second part of the code is the Lagrangian one, which provides information about the lifetime of the eddies and of their trajectories.

Penven and Echevin [2005] proposed a method to track the eddies based on a generalized distance. After having selected the structures with correct properties (minimum and maximum radius and minimum amplitude) the algorithm detects an eddy in one frame and checks its presence in the subsequent frame, comparing each eddy with the structures

present the following day, taking into account the difference in coordinates, radius, vorticity, mean height and amplitude between two successive days. For each eddy e_1 of the initial day and for each eddy e_2 of the following day, X_{e_1,e_2} is defined as an Euclidean distance in a non-dimensional property space:

$$X_{e_1,e_2} = \left[\left(\frac{L}{L_0} \right)^2 + \left(\frac{R_2 - R_1}{R_0} \right)^2 + \left(\frac{\xi_2 - \xi_1}{\xi_0} \right)^2 + \left(\frac{SSH_{mean_2} - SSH_{mean_1}}{Z_0} \right)^2 + \left(\frac{Amp_2 - Amp_1}{A_0} \right)^2 \right]^{\frac{1}{2}} \quad (2.20)$$

where L is the spherical distance between the eddies and L_0 is the typical eddy distance. R_2 , R_1 , ξ_2 , ξ_1 , SSH_{mean_2} , SSH_{mean_1} , Amp_2 , Amp_1 are respectively the radius, the vorticity, mean SSH variations and amplitude of e_2 and of e_1 . R_0 is the typical eddy radius scale, X_0 is the typical eddy vorticity scale, Z_0 is the typical eddy mean SSH variation and finally A_0 is the typical eddy SSH amplitude variation. When X_{e_1,e_2} is minimum, e_1 and e_2 are the same eddy.

The algorithm counts an eddy each day when it is detected on a map of SLA and assigns an ID to each to facilitate the extrapolation of their properties. Eddies with the same ID are considered the same eddy evolving over time (eddy tracking). The method ensures that an eddy preserves its polarity, that is to be a cyclonic or an anticyclonic structure (no cyclones become anticyclones), and that the translational velocity stays in a realistic range of speeds. If an eddy travels at an unrealistic translational speed, it is considered as two different eddies: one disappeared and a new one created (with a new ID).

We calculated for each eddy the date of formation, the date of death, the lifetime (the difference between the two dates), the translational velocity and the mean kinetic energy in order to study the main properties in relation to the lifetime.

We refer to the mean EKE ($mEKE$) of each eddy with the formula:

$$mEKE = \frac{1}{lifetime} \int_{lifetime} pEKE dt, \quad (2.21)$$

where the lifetime is calculated in days and the $mEKE$ in m^2/s^2 .

The eddy detection and tracking routines are coded in MatLab and are freely available for download at <https://sourceforge.net/projects/eddydetect/>.

The main steps of the tracking algorithm are summarized in Figure 2.8.

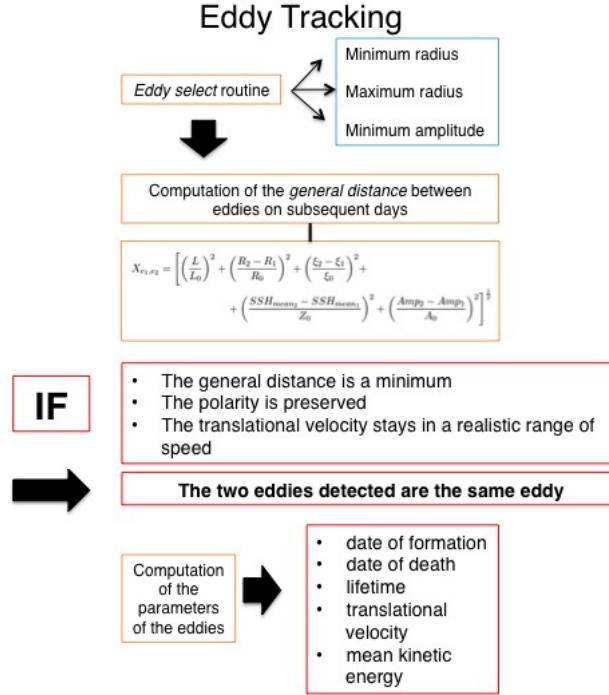


Figure 2.8: Main steps of the eddy tracking algorithm

2.2.3 Advantages and disadvantages of the methods and discussion

The main advantage of the methods described in the previous sections is that they are automated and allow a large amount of data to be taken into consideration. Several years of satellite altimetry observations are typically used to investigate the mesoscale eddy inter-annual variability.

One of the limits of whatever method chosen is the practical difficulty of defining an eddy boundary. Since eddies are fluid structures, time-dependent and continuously evolving without persistence it is difficult to clearly demarcate their boundaries. There is some arbitrariness both in the definition of mesoscale eddies and in the method selected to define their borders.

Every method based on the calculation of the OW parameter requires a threshold value of W , critical in the identification of the eddies. A threshold too high can miss the smaller structures, whereas a threshold too low could lead to unrealistically large eddies, with potentially multiple vortices, sometimes with opposite polarities.

Another serious limit with the W -based method is that numerical estimates of W are easily susceptible to noise in the SLA fields. The geostrophic velocity components are calculated from the SLA field and the computation of W requires products of numerical second derivatives of the SLA field. Consequently, the errors are amplified [Chelton et al., 2011].

These methods take into account only the geostrophic velocities, while during their formation/vanishing phases the eddies are also subjected to the ageostrophic components of velocity. Furthermore, the ageostrophic components of circulation acquire importance at smaller scales which altimetry usually fails to capture, another limit of the detection method. To avoid this kind of problem, data from drifters could be used in association with altimetric data. Although the missing of the ageostrophic components, the trajectories, related to the position of the eddy, are detectable using the SLA data and are reliable. In order to study the coalescence of eddies and the bifurcation in specific sub-areas of the basin, we will take into account also the ageostrophic velocities, sampled using drifter. Finally, the interiors of eddies defined by closed contours of W do not coincide with those defined by closed contours of the SLA data and the difference between the two is usually substantial. On the other hand, geometric methods are less problematic and produce good results.

The best results are obtained by combining geometric methods with the computation of the Okubo-Weiss parameter [Chaigneau et al., 2009], but they also require threshold levels to be set in for the SLA or criteria shape-based [Kurian et al., 2011].

As discussed in Chelton et al. [2011] and in Kurian et al. [2011] due to the high level of noise, several selected region are actually not mesoscale eddies. In the global ocean there is also the possibility that an ocean gyre is selected as a closed loop; to avoid this problem a limit diameter of 300 Km was set. The association of regions of negative W and regions embedded in SLA closed loops avoids the detection of spurious features due to noise and removes the ambiguities in multi-poles/elongated close loops [Halo et al., 2014]. Furthermore, to remove small variations of the eddy centre position due to the algorithm, structures with lifetime shorter than 7 days are not considered in the analyses.

The structures moving around the basin occasionally encounter other structures and deviate from their pathway or merge in a new stronger eddy. These two different behaviours are not always recognised by the algorithm, which can mistakenly assume the formation of a new eddy. Noise in the SLA field or temporary distortions of the shapes of the eddies contribute to the errors in the tracking phase.

Some adjustments are needed to improve the method in the WMED, but with a few exceptions it has provided good results and can be considered reliable in the tracking of eddies, as confirmed by recent results of Escudier et al. [2016].

Chapter 3

Results

This Chapter is divided into two parts. Part I will describe the results of the hybrid method of eddy detection and tracking within the area of study, with some eulerian and lagrangian statistics. In Part II we focus on specific structures detected in the basin both by the hybrid method and the analysis of CTD data sampled during several oceanographic cruises in the WMED. The combination of in-situ measurements and the output of the detecting and tracking method provides a more complete description of mesoscale eddies.

3.1 Eddy detection and tracking

The automated routines of eddy detection and tracking permit the analysis of a large amount of data and the investigation of the inter-annual variability.

The first result obtained by the application of the hybrid method is the distribution of the AEs in the domain and more particularly the distribution of their formation and kinetic energy.

The tracking algorithm permits the evaluation of the mean properties of each eddy and the distribution of formation as a function of its lifetime.

3.1.1 Eulerian statistics of the generation of eddies

In order to perform a eulerian statistics of the formation of AEs, a regular grid has been superimposed on the domain. There are 4 sectors in the grid, labelled from A to D. Each is approximately (222 by 332 Km (2° of latitude and 3° of longitude)).

The aim is to locate the areas where eddies usually form, detach from the coast and vanish. We posit that they have different pathways and lifetime depending on their area

of formation and kinetic energy.

At first look, the results of this study show different behaviour for short-life eddies (eddies shorter than 100 days) and long-life eddies (longer than 100 days). Separate statistical analysis for both short- and long-life AEs shows that the former have a homogeneous distribution within the basin and provide less information about the basin's dynamics than the latter.

Statistics of short-life anticyclonic eddies

In Figure 3.1, the histograms show the number of short-life eddies formed in each sector (panel A), both formed and vanished in the same sector (panel B) and vanished in each sector (panel C).

The higher number of births is concentrated in sector A (400 eddies), and more generally the northern part of the basin (sectors A and B) hosts almost twice the number of births of short-life AEs (almost 700) than the southern part (sectors C and D, almost 400).

We suppose that short-life eddies are caused by the baroclinic instabilities of the NBF, located between the Balearic Islands and the west coast of Sardinia, subjected to seasonal variability [Ruiz et al., 2009]. These structures have been detected in the past by Fuda et al. [2000], who labelled them Frontal Algerian Eddies (FAEs), considering only structure with lifetime up to 15 days. We use the name FAEs to indicate short- or long-life eddies, formed along the NBF. In this Section we take into account only the short-life ones.

The Figure 3.1 - panel B shows that almost all the eddies formed in each of the four sectors vanished in their sector of formation. For sector A the 85%, for B the 93%, for C 87% and finally for D 86%. Short-life eddies tend to not move around the basin, but rather remain close to their area of formation. In fact, despite their mean translational velocity of 6 Km/day and an average lifetime of 30 – 40 days, they tend to follow a random pathway and do not move far from where they originated. The results for short-life eddies are better highlighted by superimposing a double resolution grid on the basin, as shown in our poster [Pessini et al., 2016] (Appendix 4).

Figure 3.1, panel C shows where short-life eddies typically vanish. The histogram perfectly reflects the distribution of births. The tracks of the AEs in the four sectors (from A to D) are represented in Figure 3.2 (panels A-D). It is a scatter map with longitude and latitude on the X and Y axes. The colour of each point (eddy centre) indicates the daily MEKE of the structure (each day, see 2.11). As highlighted by the previous histograms, the FAEs

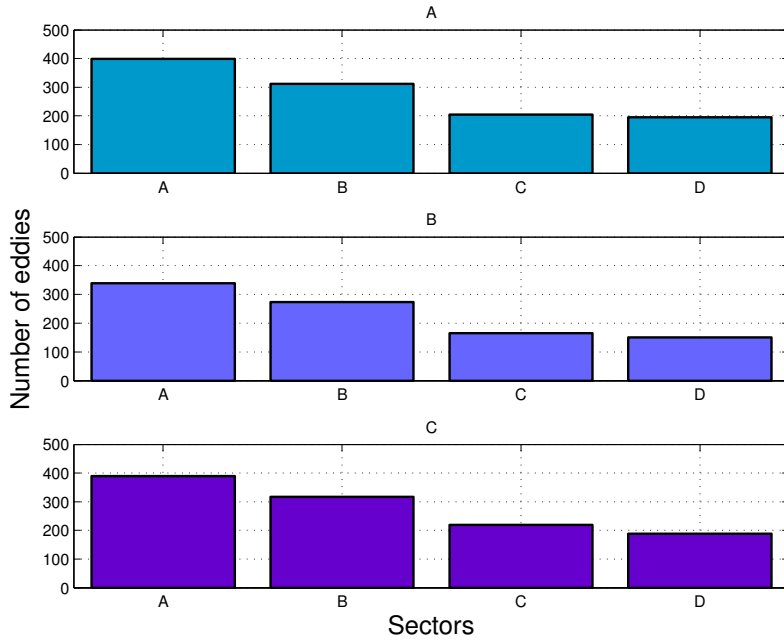


Figure 3.1: The histograms show the number of short-life eddies formed in each sector (panel A), formed and terminated in the same sector (panel B) and terminated in each sector (panel C). Sectors A and B are located in the northern part of the basin, C and D in the southern part

formed in sectors A and B are much greater in number than the others and they spend all their life in the sector of origin. Just a few eddies, usually the more energetic ones, move to another sector. As expected, the daily MEKE is higher in the southern part of the basin (Section 3.1.3), especially in sector D where it reaches values of $900 \text{ m}^2/\text{s}^2$. The EKE in sectors A and B is on average $100 - 200 \text{ m}^2/\text{s}^2$.

Statistics of long-life anticyclonic eddies

The same analysis has been performed for eddies with lifetime greater than 100 days. The results are the opposite of those obtained from the short-life eddies. Figure 3.3, panel A shows that sectors C and D host respectively 14 and 19 births, while sectors A and B respectively 5 and 7 as most long-life eddies originate in the southern part of the basin. Panel B shows the number of long-life AEs formed and vanished in the same sector. Just 1 eddy born in the northern part of the basin remained there, while 53% of the structures born in sector C died there, as well as 26% in sector D. The lifetime is long enough to allow the eddies to complete the loop around the basin and to vanish where they have formed. To better study the behaviour of these mesoscale structures, it is necessary to observe their tracks (Figure 3.4). The colour indicates the daily MEKE of each eddy

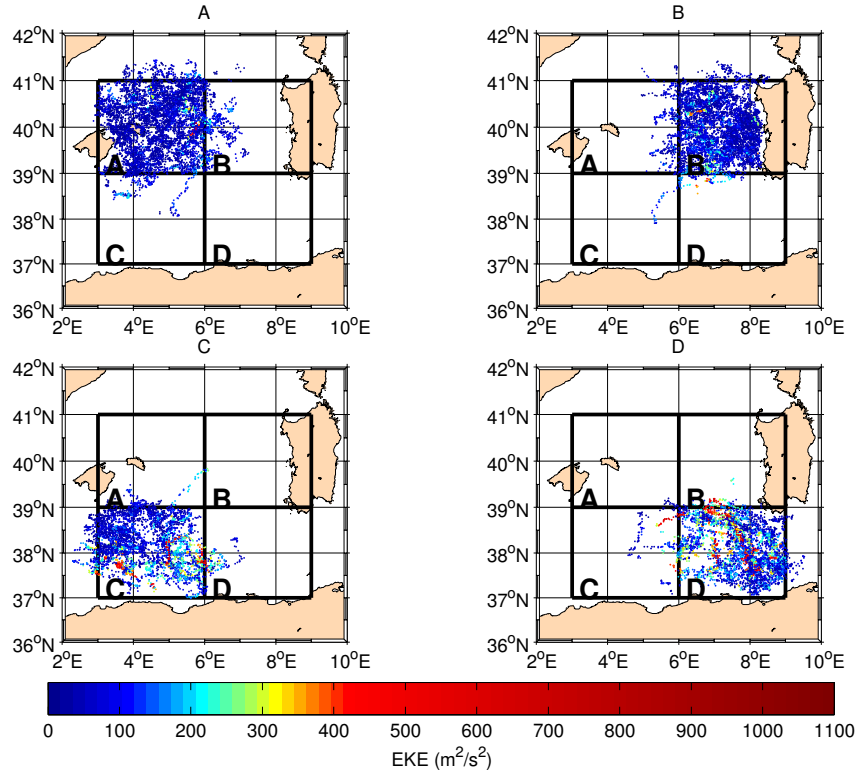


Figure 3.2: The four maps show the tracks of the short-life eddies formed in each sector (A-D). The colour indicates the daily MEKE in m^2/s^2 .

centre. In general, only about 31% of eddies die in the northern part of the basin. Most births take place in sector D but most of the eddies vanish in sector C, as they cannot complete the entire loop to return to the sector of their birth. The southern part of the basin hosts the most energetic eddies, which occupy sectors C and D, along the AC. The structures formed in sector B have energy up to values of $400 - 500 m^2/s^2$ and show cyclonic trajectories around the basin. They arise in sector B and vanish in sectors C or D, confirming the statistical analysis (Figure 3.3). These eddies have a particular behaviour because they follow a cyclonic circulation and are characterized by the highest energy level in the northern sectors.

The comparison in energy between short- and long-life structure highlights that the latter have in general higher energy than the former, especially in sectors C and D.

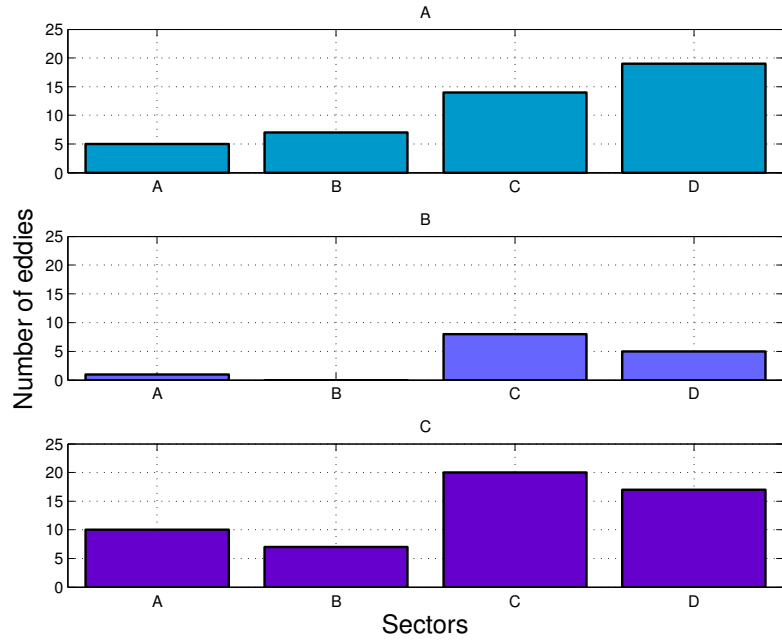


Figure 3.3: The histograms show the number of long-life eddies formed in each sector (panel A), formed and terminated in the same sector (panel B) and terminated in each sector (panel C). Sectors A and B are located in the northern part of the basin, sectors C and D in the southern part

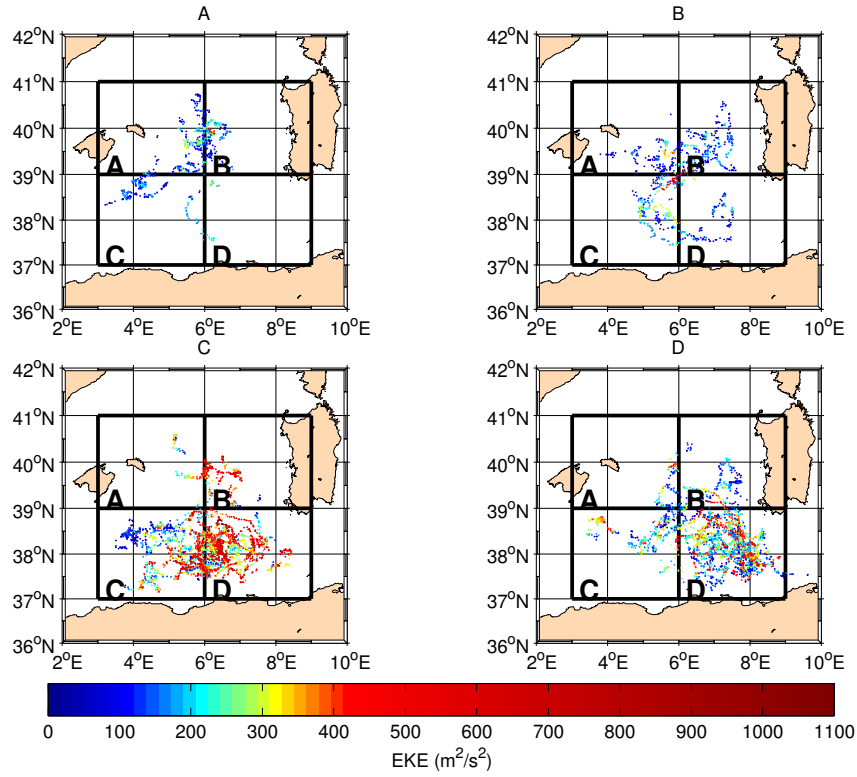


Figure 3.4: The four maps show the tracks of the long-life eddies formed in each sector (A-D). The colour indicates the daily MEKE in m^2/s^2 .

3.1.2 Seasonality of the generation of eddies

The availability of data over the long term allows the investigation of seasonality in the generation of AEs, as their distribution within the year leads to a more accurate characterization of the area of study and of its mesoscale structures. Again, short- and long-life eddies have been treated separately.

The next figures show the centres of the eddies. From the Lagrangian point of view, we define an eddy as being constituted by a number of centres equal to its lifetime in days. As an example, an eddy with a 30-day lifetime is represented by 30 centres, each of which is plotted as a single point on the track (Figures 3.2 and 3.4).

Figure 3.5 shows a homogeneous distribution of formation of short-life AEs during the year, with two peaks in fall and winter, i.e. from October to March, when births number more than 450 (panel A). Panel B shows the distribution of all the centres of the short-life AEs during the year. The centres in turn show similar peaks as Panel A, as the eddies have a lifetime shorter than 100 days and they typically form and vanish in the same season.

The result is reversed for long-life eddies, which reach the maximum number of formations in spring, 26 formations, almost 2 – 3 times the number of formations in the other seasons (Figure 3.6). It is supported by the fact that the maximum transport through the Strait of Gibraltar occurs generally in April [Beranger et al., 2005] when the AC is strongest. Panel B shows a peak of centres in summer, as expected for structures with a lifetime greater than 100 days. Long-life eddies spend most of their life between July and September.

The definition of a characteristic wavelength for the eddies due to the AC is not an easy task [Obaton et al., 2000]. There are periodic oscillation of the surface isotherms, which can be seen also from space, that indicate the serial eddies of wavelength of 50 – 100 Km and of short lifetime. Sometimes the surface features are more irregular and the formation of longer eddies, separated by larger distances, occurs. The determination of serial eddies, due to the AC instabilities, with current measurements is not easy since they are associated with intense currents at the very surface, without necessarily having a clear signature at 100 m [Milot et al., 1997]. In general, the physical parameter which supports the eddy formation is the transport of the current [Obaton et al., 2000], which increases substantially in spring. The density gradient becomes stronger and facilitates the baroclinic instabilities. The Figure 3.7 shows the tracks of short-life AEs formed in each season. The colour indicates their daily MEKE.

In winter the EKE is at its highest in the south of the basin, below 39° N of latitude, from

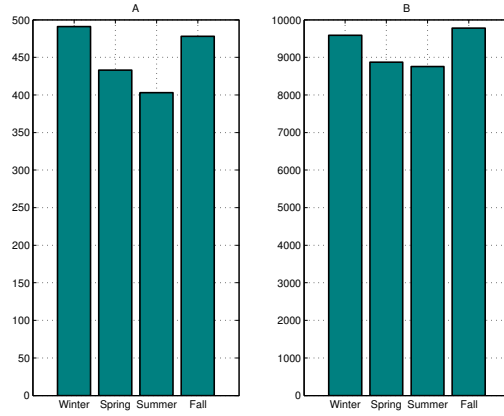


Figure 3.5: Panel A shows the number of formations of short-life eddies in each season for the period 1993 to 2014. We define the seasons as whole-month periods, as opposed to the traditional way based on solstices and equinoxes. Winter is thus from January to March, spring from April to June, summer from July to September and fall from October to December. Panel B shows the same count for all the centres of the eddies.

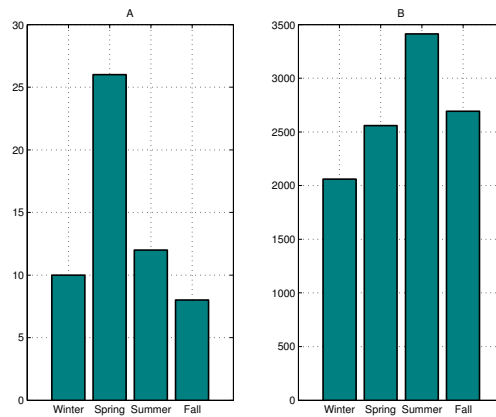


Figure 3.6: Panel A shows the number of formations of long-life eddies in each season from 1993 to 2014. We define the seasons as whole-month periods, as opposed to the traditional way based on solstices and equinoxes. Winter is thus from January to March, spring from April to June, summer from July to September and fall from October to December. Panel B shows the same count for all the centres of the eddies.

longitude 4° E and 8° E for both short- and long-life AEs (Figures 3.7, panel A and 3.8, panel A respectively).

The EKE of short-life eddies highlights a highly energetic pathway (above $400 \text{ m}^2/\text{s}^2$) corresponding with the AC and along a circle in the middle of the Algerian basin. This is the main pathway of the eddies formed in the southern part of the basin, around 7° E.

Long-life eddies are located in a small portion of the basin throughout the year except in spring (i.e. from April to June), when they cover almost the entire basin and are characterized by high EKE almost during all their life, with maxima above $500 \text{ m}^2/\text{s}^2$ and on average values of $300 - 400 \text{ m}^2/\text{s}^2$ (Figure 3.8, panel B).

In summer and autumn, when the water temperature increases and reaches its maximum, formation of long-life AEs is lower than in spring and the tracks are limited to a restricted area in the middle of the basin. Unlike in the other seasons, during this period long-life FAEs occur (above 40° N -Figure 3.8 panel C and D).

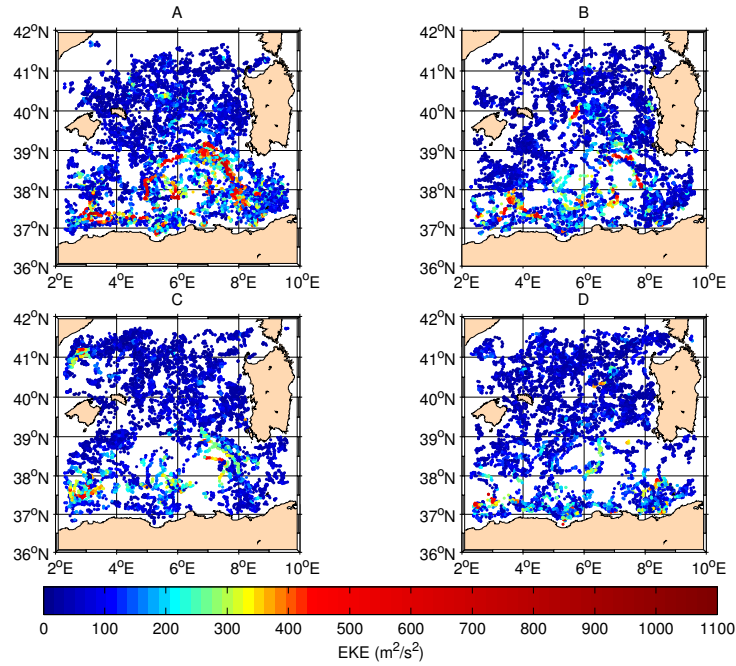


Figure 3.7: Tracks of short-life AEs born in winter (panel A), spring (panel B), summer (panel C), autumn (panel D). The colour indicates the daily MEKE in m^2/s^2 .

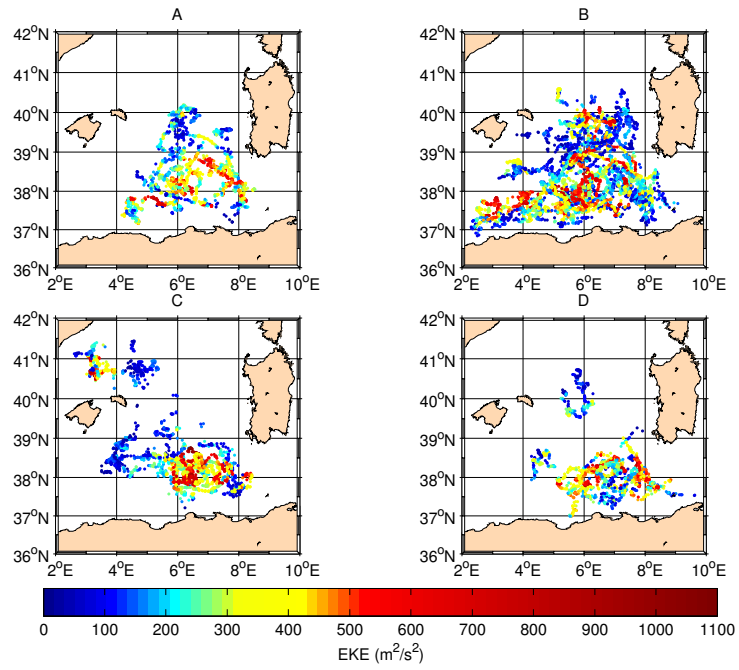


Figure 3.8: Tracks of long-life AEs born in winter (panel A), spring (panel B), summer (panel C), autumn (panel D). The colour indicates the daily MEKE in m^2/s^2 .

3.1.3 Eddy kinetic energy

The mean EKE and the mean radius of each eddy are related to the lifetime, as shown in Figure 3.9. The lifetime has been divided into 9 stages, of approximately 30 days each. The plot above shows the average values and the standard deviation of the mean EKE of all the eddies with a lifetime included in each lifetime step (indicated on the x -axis). The structures with lifetime up to 30 days have on average a mean EKE of $80 \text{ m}^2/\text{s}^2$, while the eddies with a lifetime greater than 240 days reach a mean EKE of $400 \text{ m}^2/\text{s}^2$. The relationship increases almost monotonically and for all the eddies in the basin for the period 1993-2014. The variability between the eddies in each range is very high.

The same kind of study has been conducted for the mean radius of each eddy (Figure 3.9, below). Similarly, the structures with a short lifetime have a small radius (on average 30 Km for eddies with lifetime from 7 to 30 days). Generally speaking, the longer the lifetime, the bigger the radius. The mean radius reaches values around 40 Km for eddies longer than 90 days. It increases for eddies longer than 240 days, reaching 47 Km. Studies

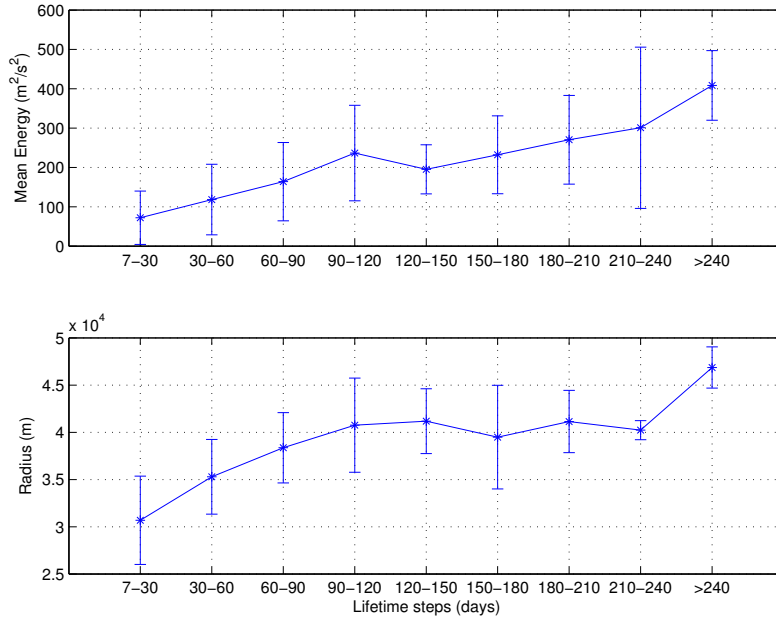


Figure 3.9: Relation between EKE (above), radius (below) and lifetime. There are 9 lifetime steps 30 days long. Averages have been computed on the basis of mean EKEs and mean radii of the eddies in the basin from 1993 to 2014.

about the spatial distribution of EKE in the Mediterranean Sea, led by Pujol and Larnicol [2005], confirmed some older studies [Larnicol et al., 2002], which describe the Alboran Sea

and the Algerian Basin, along the coast (between 5°E and 10°E), as the regions of high intensity (locally $> 200 \text{ cm}^2/\text{s}^2$) and thus strong mesoscale activity.

Awareness of the distribution of the EKE within the domain is useful to characterise the distribution and the mechanisms of eddy formation.

Due to the large quantity of data, the characterization of the EKE of the basin has been done using the monthly mean EKE.

In order to study the inter-annual variability of the kinetic energy of different eddies, we plotted the time series of the monthly mean EKE of the eddies from 39°N to 42°N (Figure 3.10 - blue line) and of the eddies from 37°N to 39°N (Figure 3.10 - red line). In particular, we computed the monthly mean of each centre's punctual energy. The values for the northern part fall in the range from 50 to $200 \text{ cm}^2/\text{s}^2$, while those of the southern part are about two or three times greater, with a mean of about $200 \text{ cm}^2/\text{s}^2$ and peaks of $380 \text{ cm}^2/\text{s}^2$. The monthly mean EKE of southern centres seems to present a periodicity

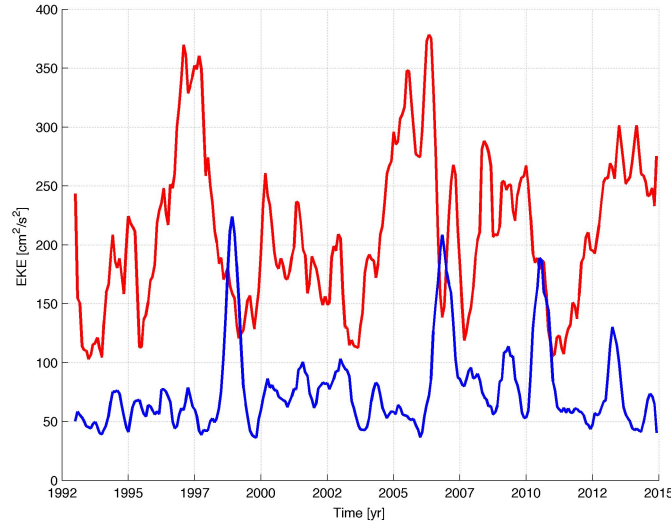


Figure 3.10: The figure shows the monthly mean EKE from 1993 to 2014. The monthly mean EKE of the southern Algerian basin (37° - 39°N) is shown in red and that of the northern basin (39° - 42°N) in blue.

which we analysed using the Fast Fourier Transform (FFT). In particular, we applied the FFT to the monthly mean value of EKE of all the eddies (the centres) found below 39°N . Northern eddies do not have specific periodicity. Southern eddies with a relatively short lifetime (from 7 to 60 days) have a periodicity of 12 months, associated with the annual variation of heat fluxes. Longer lifetime eddies (more than 60 days) show a periodicity of 52 months, corresponding to 4.4 years (Figure 3.11).

The EKE of each eddy has been computed using the geostrophic velocities anomaly u

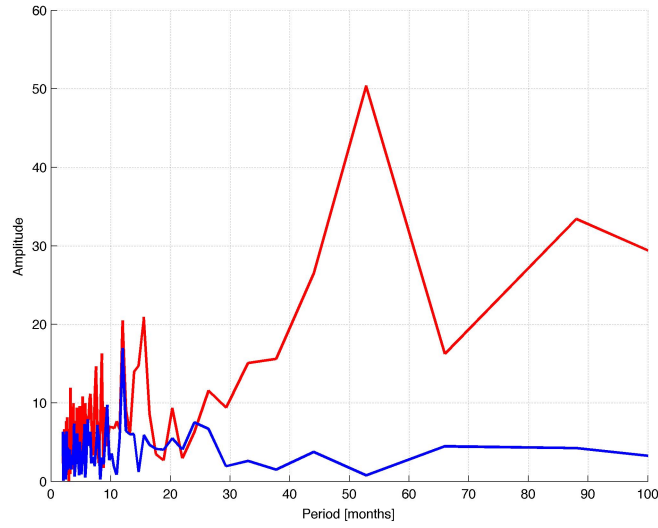


Figure 3.11: *The FFT analysis shows a peak frequency of 52 months (about 4.4 years) for eddies with lifetime greater than 60 days (red) and a peak frequency of 12 months for short-life eddies (7-60 days, blue). Only the eddies in the southern Algerian basin (37°-39° N) show periodicity. The analysis of northern eddies is not shown.*

and v (2.1). It is important to underline that the energy extrapolated from altimetry only describes geostrophic speed, whereas the kinetic energy includes ageostrophic speed components. Areas with high variability, such as the Sardinia Channel, present the greatest differences between EKE computed with geostrophic velocities (altimetry) and EKE calculated with velocities sampled by drifters (geostrophic and ageostrophic components) [Mauerhan, 2000]. We note that altimetry data underestimate EKE by half (about $400\text{cm}^2/\text{s}^2$). However, a comparison of different areas with high mesoscale activity using the same method of computation produces acceptable results.

3.2 Hydrographic results from in-situ data

To characterise the water masses involved in mesoscale structures, we used in-situ data (Section 2.1.2), sampled during some oceanographic cruises in the Mediterranean Sea.

Cruises MEDGOOS09 and MEDCO08 [Ribotti and Borghini, 2008], carried out respectively in October, 2004 and November, 2008, on board R/V Urania, include stations in the southern part of the basin, where AEs form (Section 1.3). We have analysed the data sampled during MEDOCC07 in October 2007 along the Balearic Transect 7th – 27th in order to highlight the properties of the FAEs in correspondence with the NBF.

The contour plots of the SLA data and the geostrophic velocities, provided by AVISO and computed from SLA data (Figures 3.12 3.18 3.24), show the presence of some cyclonic and anticyclonic structures in the study area. In order to be considered mesoscale eddies, these structures must have positive or negative vorticity and the Okubo-Weiss parameter must be ≤ 0 . The black closed dotted circles on the maps refer to this parameter and assure that the structures detected by the hybrid method are indeed mesoscale eddies, both cyclonic and anticyclonic.

The vertical sections of potential temperature, salinity and potential density show the deflection of the isolines where mesoscale eddies occur, as predicted by theory (Section 1.11). Uncertainties about the vertical dimension of these eddies still remain due to the lack of sub-surface measurement, but a clear indication of the water layer involved in the structures could be deduced from the analysis of in-situ data, which suggest a depth of about 1200 m for AEs and 900 m for FAEs.

CTD data between each station of the transect have been interpolated by the DIVA gridding algorithm, using the ODV software.

3.2.1 The MEDGOOS9 cruise

The MEDGOOS9 cruise took place in the Western Mediterranean Sea from 6th to 24th October, 2004,. We focus our attention on the domain where we applied the eddy detecting method and we collected temperature, salinity and density data.

Figure 3.12 shows the map of SLA and the geostrophic velocity anomalies of the 8th October when in-situ data were collected. The synoptic SLA map is representative of the mesoscale surface structures in the study area. SLA is measured in metres. The dotted black lines refer to the closed contours where the OW parameter assumes value ≤ 0 , as calculated

by the algorithm, i. e. they indicate the effective structures found by the hybrid method. Local minima in the SLA data correspond to cyclonic structures, while maxima represent the anticyclonic structures.

The algorithm detected 8 anticyclonic and 5 cyclonic eddies. We focus on the biggest AEs, hereafter called AE1 and AE2, at coordinates 38° N and 6.5° E and 37.8° N and 8° E respectively. The transect intersects the centre of AE1 and the northern border of AE2. SLA values are 0.3 m and 0.15 m respectively in the centre of the two eddies. The geostrophic velocities confirm their anticyclonic structure (Figure 3.12).

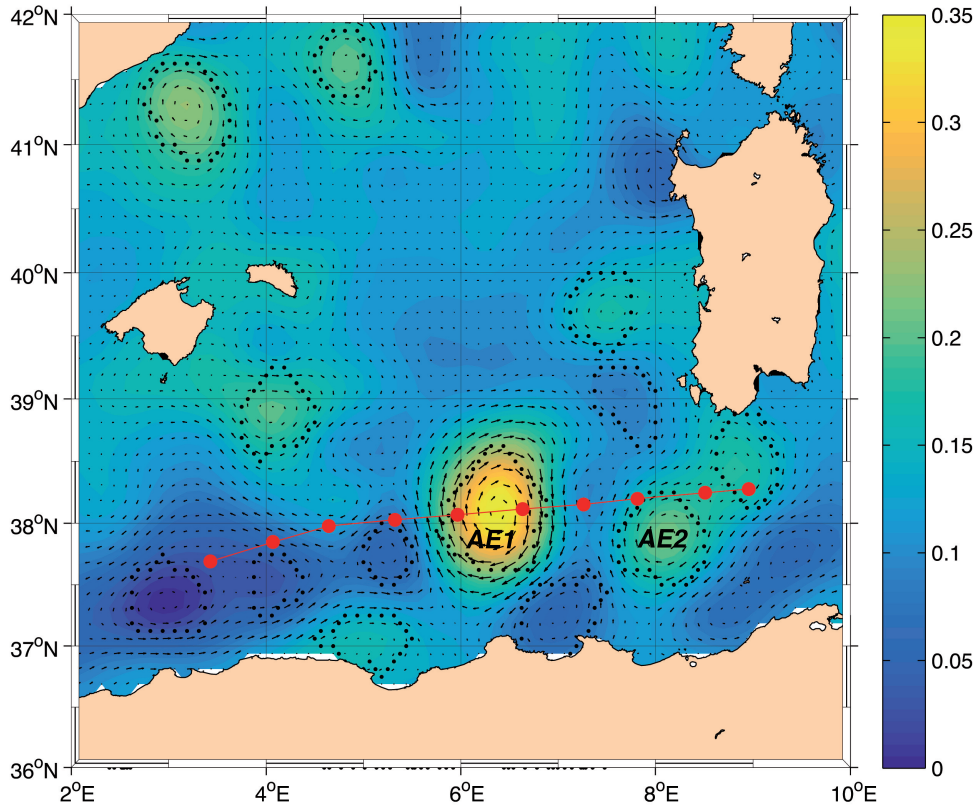


Figure 3.12: The figure shows the stations of transect (red dots), where CTD data have been collected during the MEDGOOS9 cruise, in October, 2004. The closed contours have been computed based on the SLA data and in each closed contour the Okubo-Weiss parameter has been calculated. The black dotted lines refer to the closed contours of the OW parameter computed by the algorithm.

Figure 3.13 shows the potential temperature, salinity and potential density anomaly (σ_θ) in the top 500 m along the transect on the map. The two black lines indicate the position of AE1 and AE2 as detected by the hybrid method. The shape of the isolines, in the layer of the MAW (0-200 m), dipped toward the bottom and is typical of anticyclonic eddies. At 50 m depth (sub-surface layer), in the core of the eddies salinity has values of 36.5 (AE1) and 36.8 (AE2) while in the outer edge is 37.3 – 37.5. This is surface AW

entrapped by the features. The two lenses are respectively 90 and 40 m thick.

Below 300 m the lenses of LIW are indicated by maxima of temperature and salinity. LIW comes from the Sardinia Channel and its core values are 14° C and 38.6-38.7 at 400 m, between the two eddies (similar values of Ruiz et al. [2002]). These values of temperature and salinity are the same measured in the eastern station of the transect in the Sardinia Channel. The LIW entering the basin is entrapped by the AEs and transported in the middle of the basin.

In the layer 500 – 1000 m (Figure 3.14) the deepening of the isotherms is considerable. In fact, we found the temperature of 13.1° C at 800 m in the centre of AE1 and about 200 m above on its border. The salinity rises up to 700 m, due to the presence of the LIW and then declines toward the bottom. As the LIW comes from the Sardinia Channel, the isohalines present an asymmetrical structure along the transect. The LIW is transported downward by the anticyclonic mesoscale structures and their typical values of temperatures and salinity have been measured below the LIW layer, between 600-700 m.

Despite the presence of the LIW with its high levels of salinity, the effect of temperature dominates and the isopycnals point to the presence of light water surrounded by denser waters. This structure is maintained in the deep layer (Figure 3.15, from 1000 m to the bottom). The isolines tend to become horizontal and parallel in the proximity to the bottom; below 1200 m both isotherm and isohalines show just an undulation, marking the presence of AE1, while AE2 disappeared at 900 m depth.

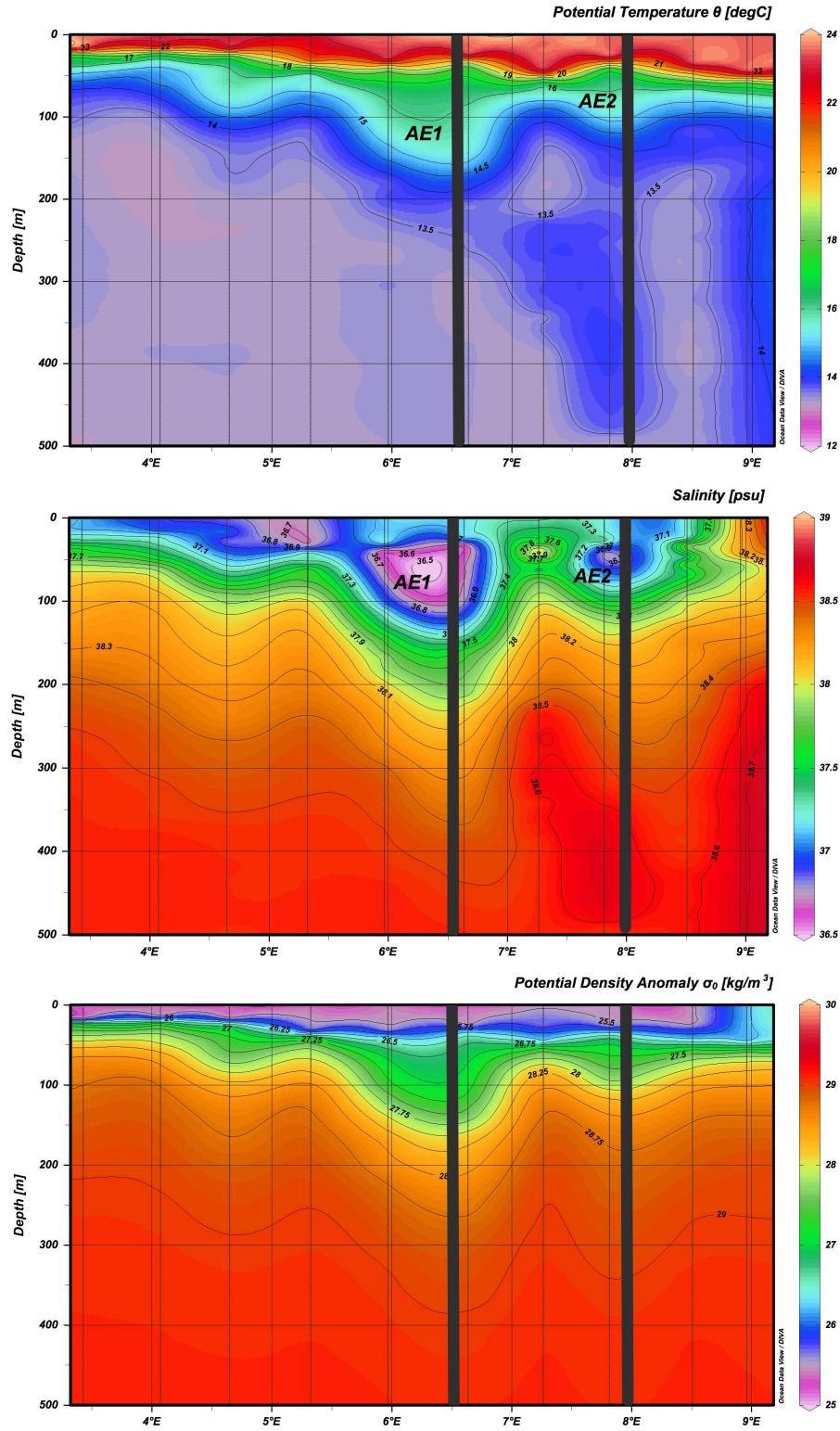


Figure 3.13: Vertical distribution from 0 to 500 m of potential temperature (top), salinity (middle) and potential density anomaly (bottom) of the transect in Figure 3.12 (MEDGOOS09) (almost W-E direction). The two black lines indicate the position of the two anticyclonic eddies AE1 and AE2 detected by the hybrid method on the SLA map.

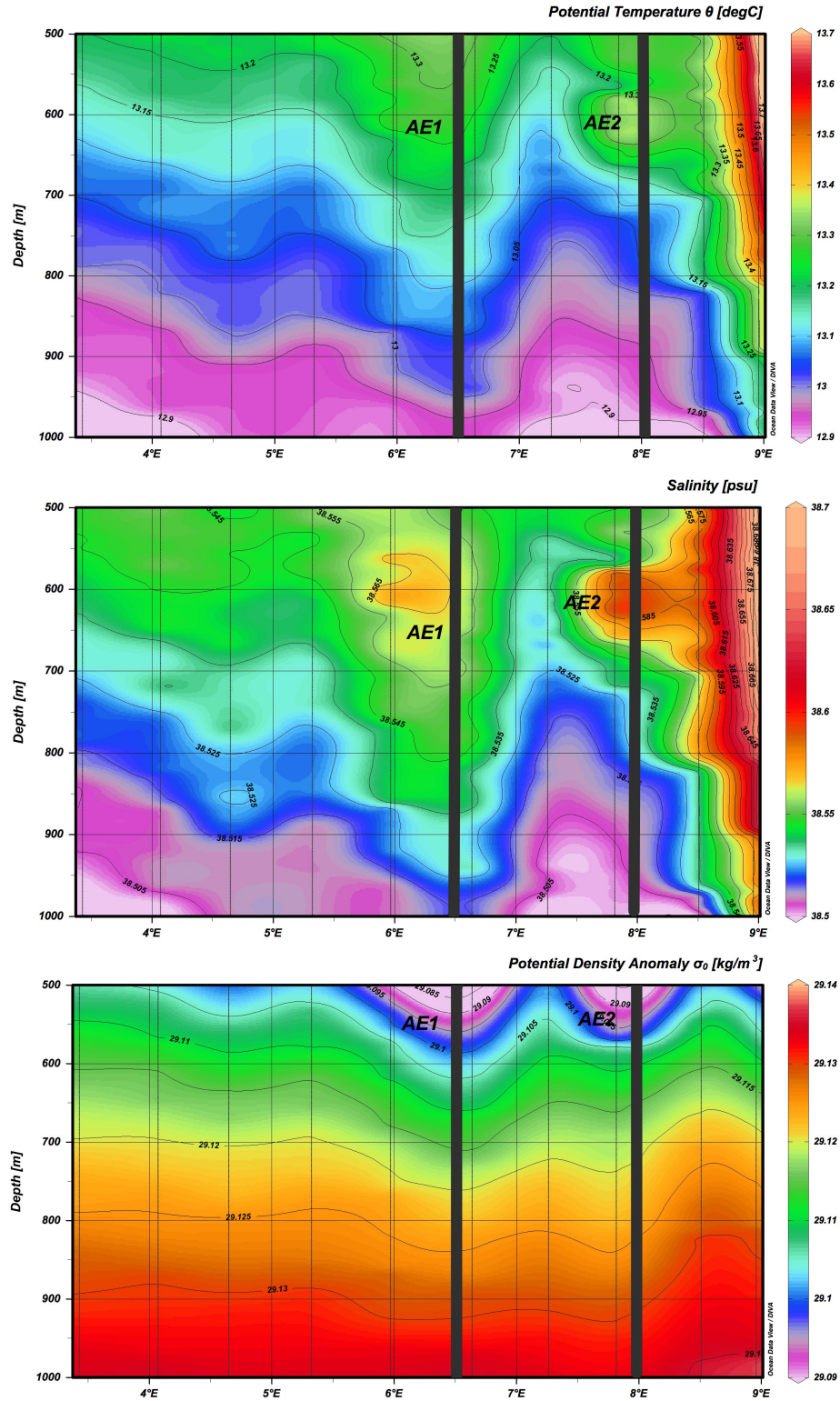


Figure 3.14: Vertical distribution from 500 to 1000 m of potential temperature (top), salinity (middle) and potential density anomaly (bottom) of the transect in Figure 3.12 (MEDGOOS09) (almost W-E direction). The black lines indicate the position of the anticyclonic eddies AE1 and AE2 detected by the hybrid method on the SLA map.

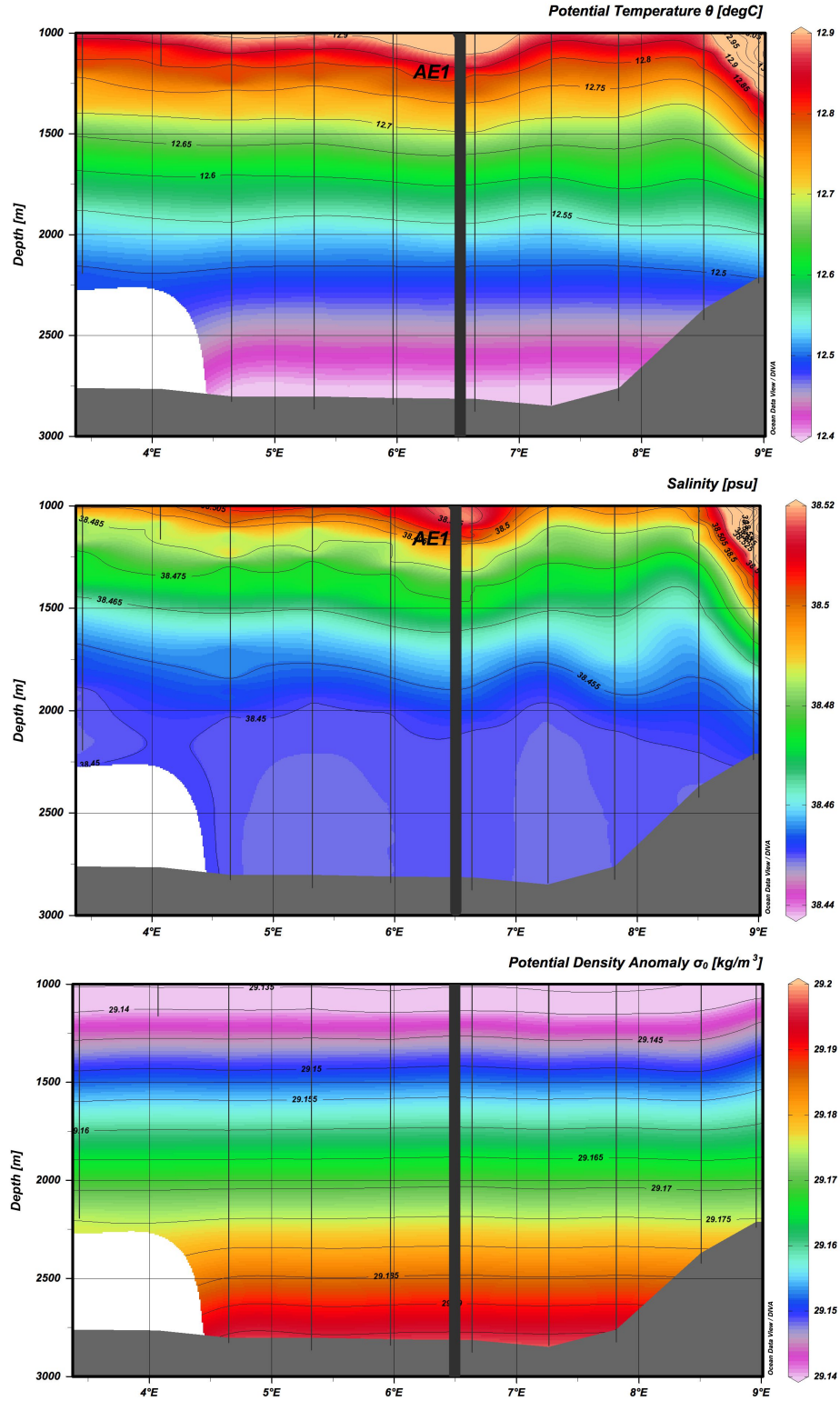


Figure 3.15: Vertical distribution from 1000 to 3000 m of potential temperature (top), salinity (middle) and potential density anomaly (bottom) of the transect in Figure 3.12 (MEDGOOS09) (almost W-E direction). The black line indicates the position of the anticyclonic eddy AE1 detected by the hybrid method on the SLA map.

The theta-s diagrams (Figure 3.16) show only the more significant stations of the transects, in order to compare the water of the mesoscale structures with the resident water of the Algerian basin and highlight the different stages of the MAW mixing.

Temperature and salinity of the water in the eddies decrease until 45 m depth, reaching 18.4° C and 36.57 for AE1 and 17° C and 36.7 for AE2. Salinity then increases until 500 m depth: this is the LIW layer. The resident water presents different values of temperature and salinity, especially until 40 m depth. It is in fact saltier, as it is not influenced by the downwelling phenomenon associated with the anticyclonic eddy. Below that depth we find the WMDW, characterized by decreasing temperature and salinity (black circle).

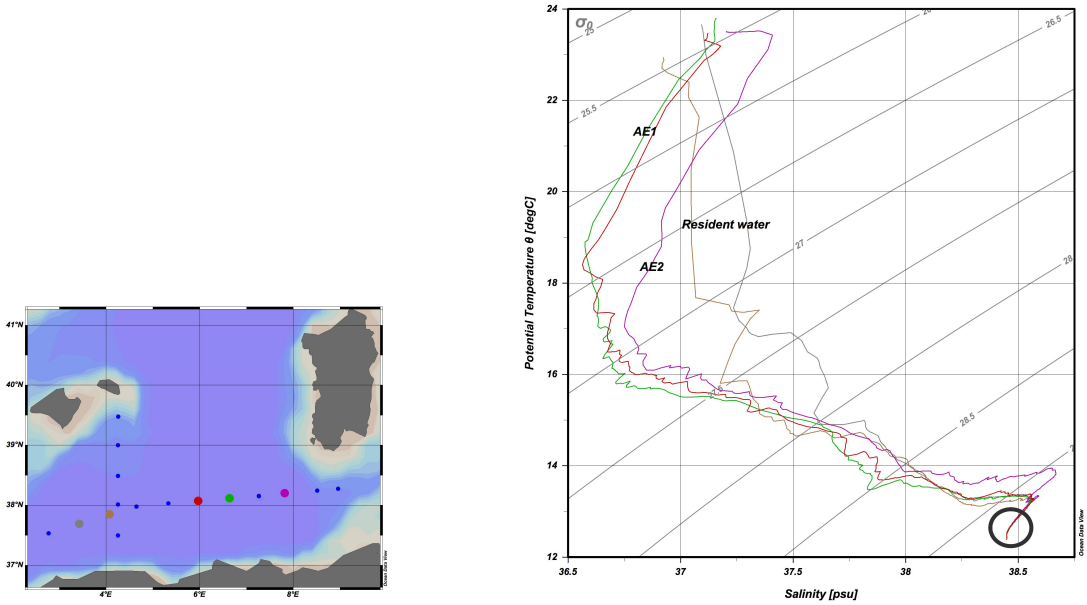


Figure 3.16: *Theta-s diagrams of stations in the centre of AE1 (red and green lines), at the northern border of AE2 (magenta line) and of the resident water of the Algerian Basin (gold and gray lines). The map of the corresponding stations is shown on the left.*

Additional information from the hybrid method

The hybrid method and the tracking method provide more information about the two structures, such as their trajectories, daily MEKE, lifetime, mean radius and mean translation velocities, which are summarized in the Table for both AE1 and AE2. In Figure 3.17 the tracks of AE1 and AE2 are shown. The colour indicates their daily MEKE.

	AE1	AE2
Formation date	30/08/2004	10/09/2004
Termination date	13/01/2006	08/12/2004
Lifetime (days)	502	90
Mean EKE (m^2/s^2)	444.7	164.9
Mean radius (km)	45.7	35.6
Mean translation velocity (Km/day)	5.05	4.9

AE1 is a long-life eddy and is on average bigger and more energetic than the short-life AE2. The maximum EKE of the former is $1120 m^2/s^2$, while the maximum for AE2 is $342.5 m^2/s^2$. Both eddies formed in summer and, as expected from the analysis of generation seasonality, their tracks are confined above $39^\circ N$ and between 6° and $8^\circ E$. The mean translational velocity of the two structures is almost the same, around $5 Km/day$ (Figure 3.8).

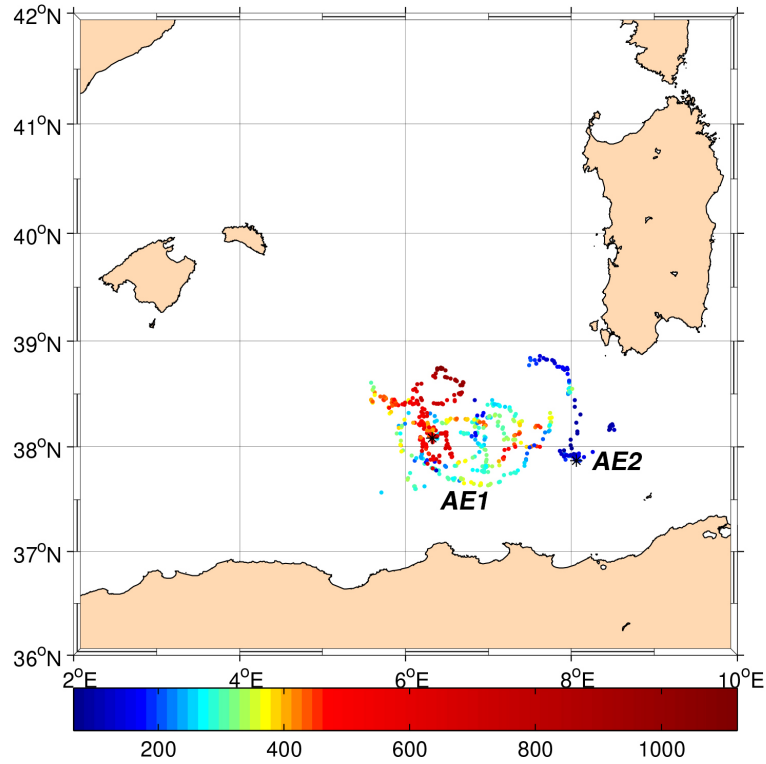


Figure 3.17: Tracks of AE1 and AE2. The colour indicates their daily MEKE (m^2/s^2). The black stars indicate the coordinates of the formation.

3.2.2 The MEDCO08 cruise

The MEDCO08 cruise has been conducted from 3rd to 11th) November, 2008, in the Western Mediterranean Sea. During the cruise, CTD profiles have been sampled along the transect in Figure 3.18 (red dots).

On the SLA map dated 9th November, 2008, the algorithm detected 6 anticyclonic eddies and 5 cyclonic eddies. The transect intersects the southern border of AE1 at coordinates 38.3° N 5.2° E and the centre of AE2 at coordinates 38.3° N 7° E. The geostrophic currents, computed from SLA data, confirm the clockwise structure of the two eddies. The value of SLA is 0.24 m in AE1 and 0.28 m in AE2.

The dotted black lines on the map indicate the closed contours where the OW parameter computed by the algorithm is ≤ 0 . It assures that the local maxima (minima) of SLA are actually mesoscale anticyclonic (cyclonic) structures. The Figure 3.19 shows the potential

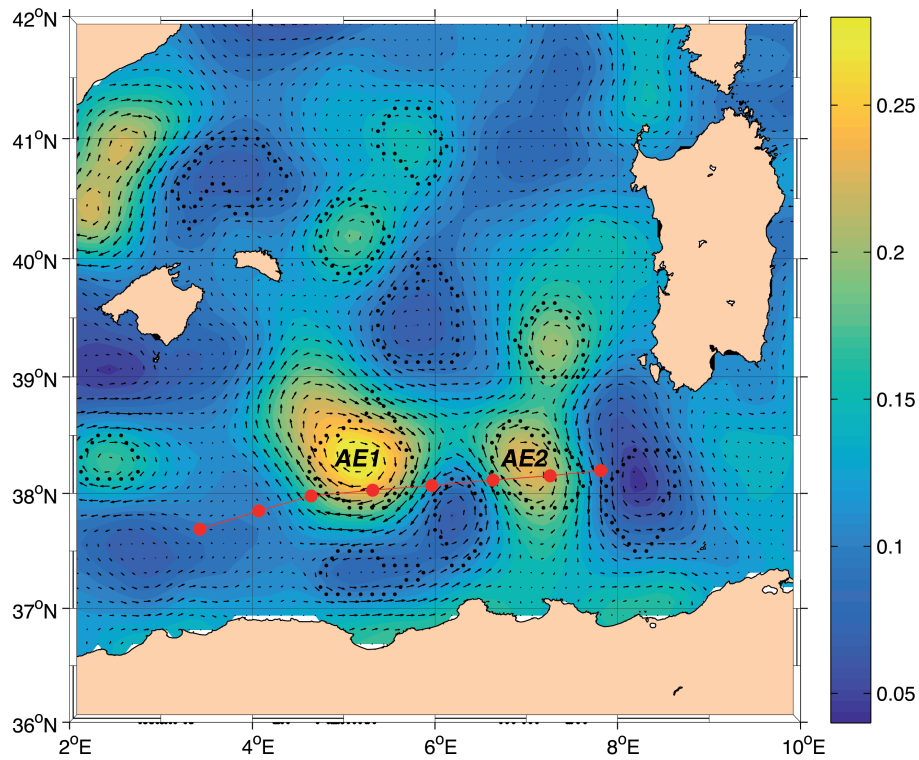


Figure 3.18: The figure shows the stations of transect (red dots), where CTD data have been collected during the MEDCO08 cruise in November, 2008. The closed contours have been computed based on SLA data and in each closed contour the Okubo-Weiss parameter has been calculated. The dotted black lines refer to the closed contours of OW parameter computed by the algorithm.

temperature, salinity and potential density anomaly (sigma-theta) in the top 500 m along the transect on the map. The two black lines indicate the position of AE1 and AE2 as

detected by the hybrid method. The structure of the isolines has been deflected by the presence of the eddies AE1 and AE2.

Like the previous case, in proximity to the core of the AEs salinity reach a sub-surface minimum (36.9 -37.1) at 50 m. The thickness of these two low-salinity lenses is 50 m for AE1 and 20 m for AE2. They show the presence of AW entrapped by the structure and transported toward the bottom. In the outer edge at the same depth salinity is 37.4. Below 300 m, the presence of LIW is highlighted by maxima of 38.55. This is the old LIW recirculating within the basin. AE2 is too far from the Sardinia Channel and does not entrain water from there. Figure 3.20 shows a considerable deepening of the isotherm in the layer 500 – 1000 m: the temperature is 13° at 930 m in proximity to AE2 and 300 m above between AE1 and AE2. The presence of a cyclonic structure between the two eddies, associated with an upwelling phenomenon, probably contributes to the deepening of the isotherms.

The salinity decreases with depth due to the presence of LIW up to 600 m, as is typical in the Mediterranean Sea. The deepening of the isohalines is very significant, with values of 38.5 in correspondence of the two eddies and 200 – 300 m above. Despite the distribution of salinity in the cores of the eddies, the effect of temperature dominates; in fact the isopycnals indicate the presence of light water surrounded by denser water. The LIW is transported downward by the AEs and its typical values of temperatures and salinity have been measured below the LIW layer to 800 m.

The structure of warmer, saltier water in the centres of AE1 and AE2 is maintained in the deep layers (Figure 3.21). The isolines become horizontal and parallel when approaching the bottom. The presence of the AEs is visible up to 1200 m.

It is interesting to note that at 1500 – 1700 m depth there is a layer with an absolute minimum of salinity. This layer separates the typical WMDW and the new formation of the same water mass (formed in years 2005 – 2006) [Schroeder et al., 2008]. Figure 3.22 shows the theta-s diagram of the stations in the centre of AE1 (green and red lines), AE2 (brown line), at the western end of the basin (longitude from 2° E to 4° E - black and blue lines), between the Sardinia Channel and AE2 (gray line) and finally in the Sardinia Channel (light blue and lilac lines). We choose only a few stations of the transect to compare resident water with eddy water.

Temperature and salinity in the core of AE1 decrease till 50 m, then the temperature continues to decrease and the salinity increases up to the end of the LIW layer. In the core

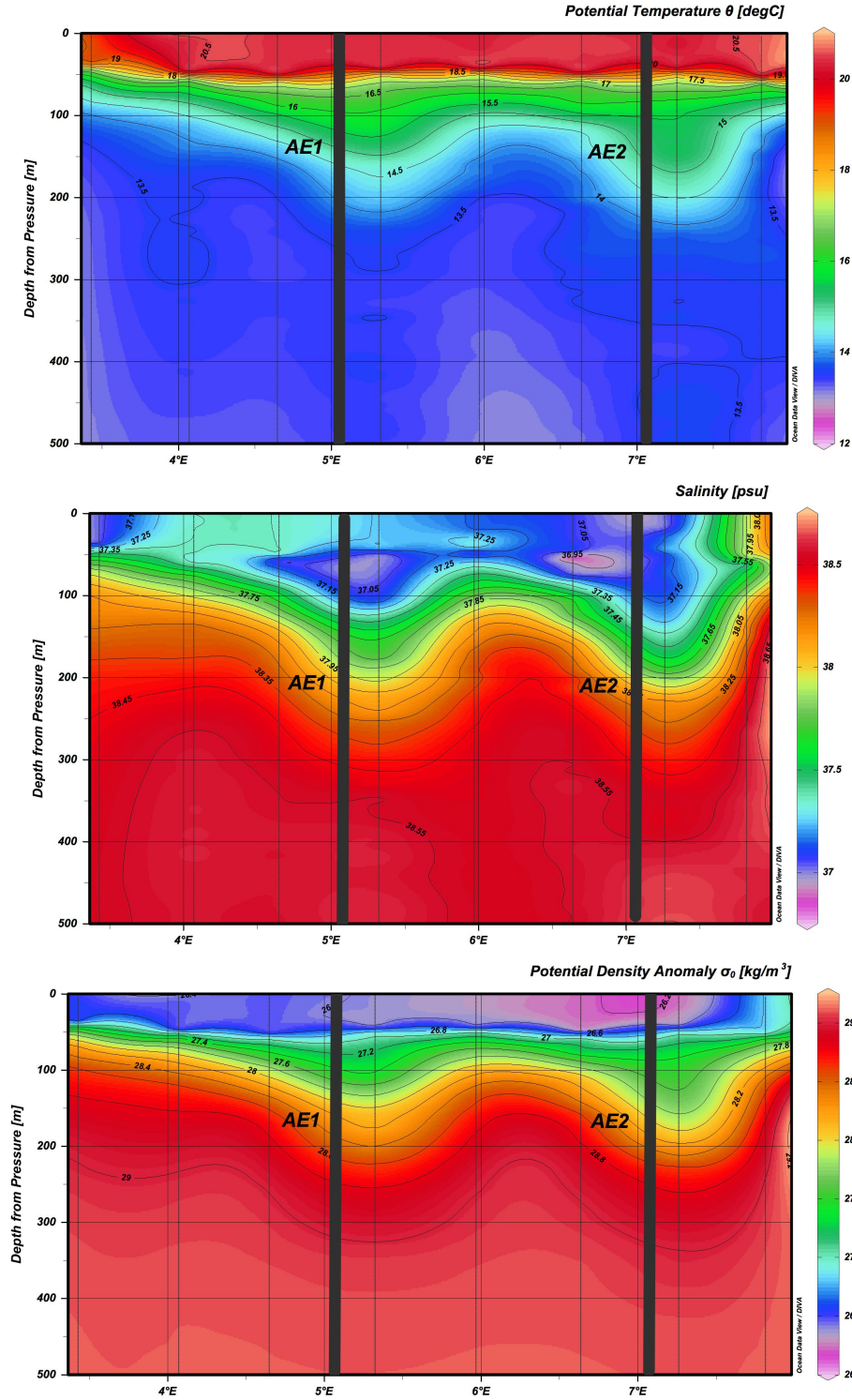


Figure 3.19: Vertical distribution from 0 to 500 m of potential temperature (top), salinity (middle) and potential density anomaly (bottom) of the transect in Figure 3.18 (MEDCO08) (almost W-E direction). The two black lines indicate the position of the two anticyclonic eddies AE1 and AE2.

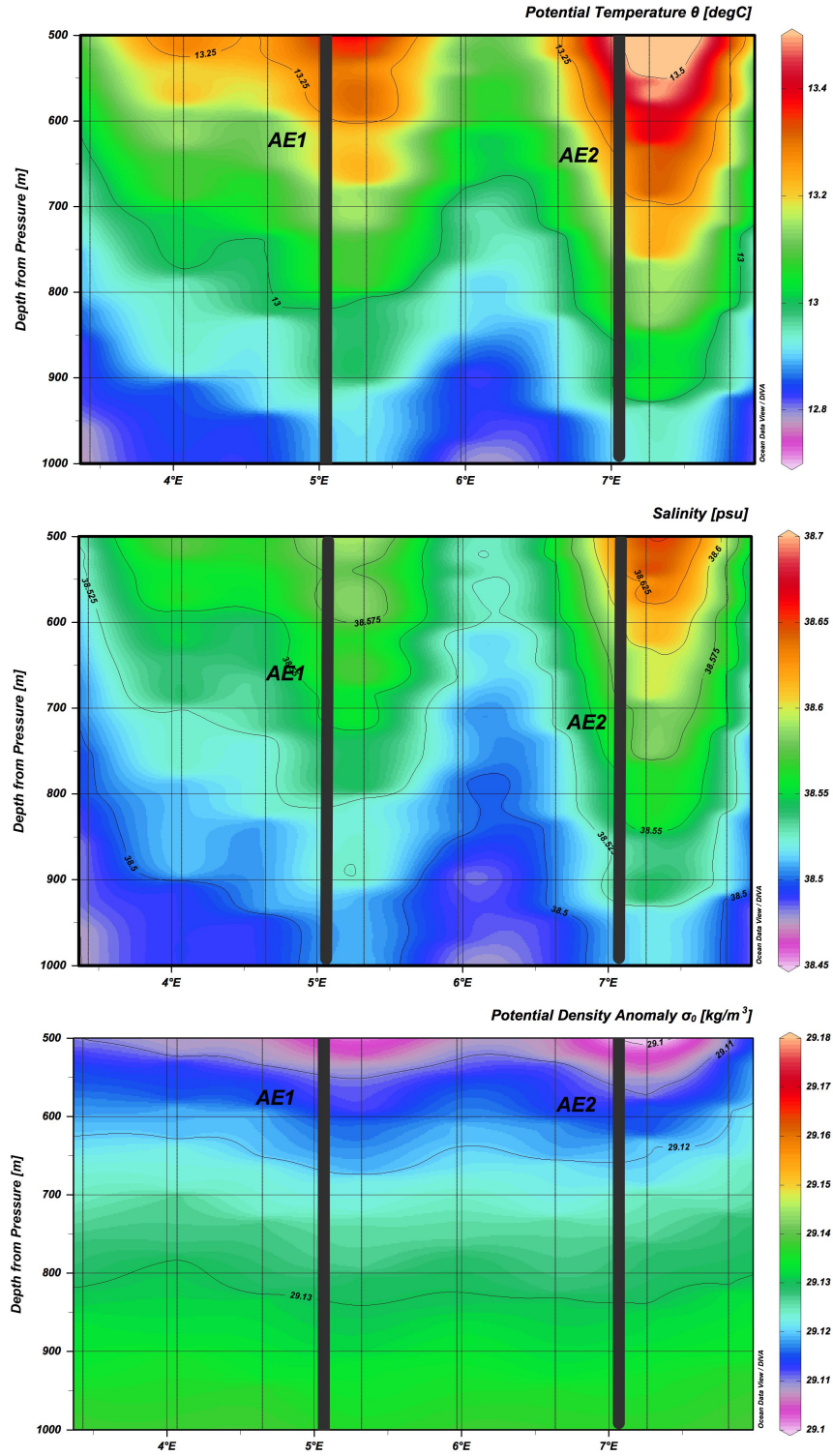


Figure 3.20: Vertical distribution from 500 to 1000 m of potential temperature (top), salinity (middle) and potential density anomaly (bottom) of the transect in Figure 3.18 (MEDCO08) (almost W-E direction). The black lines indicate the position of the anticyclonic eddies AE1 and AE2 detected by the hybrid method on the SLA map.

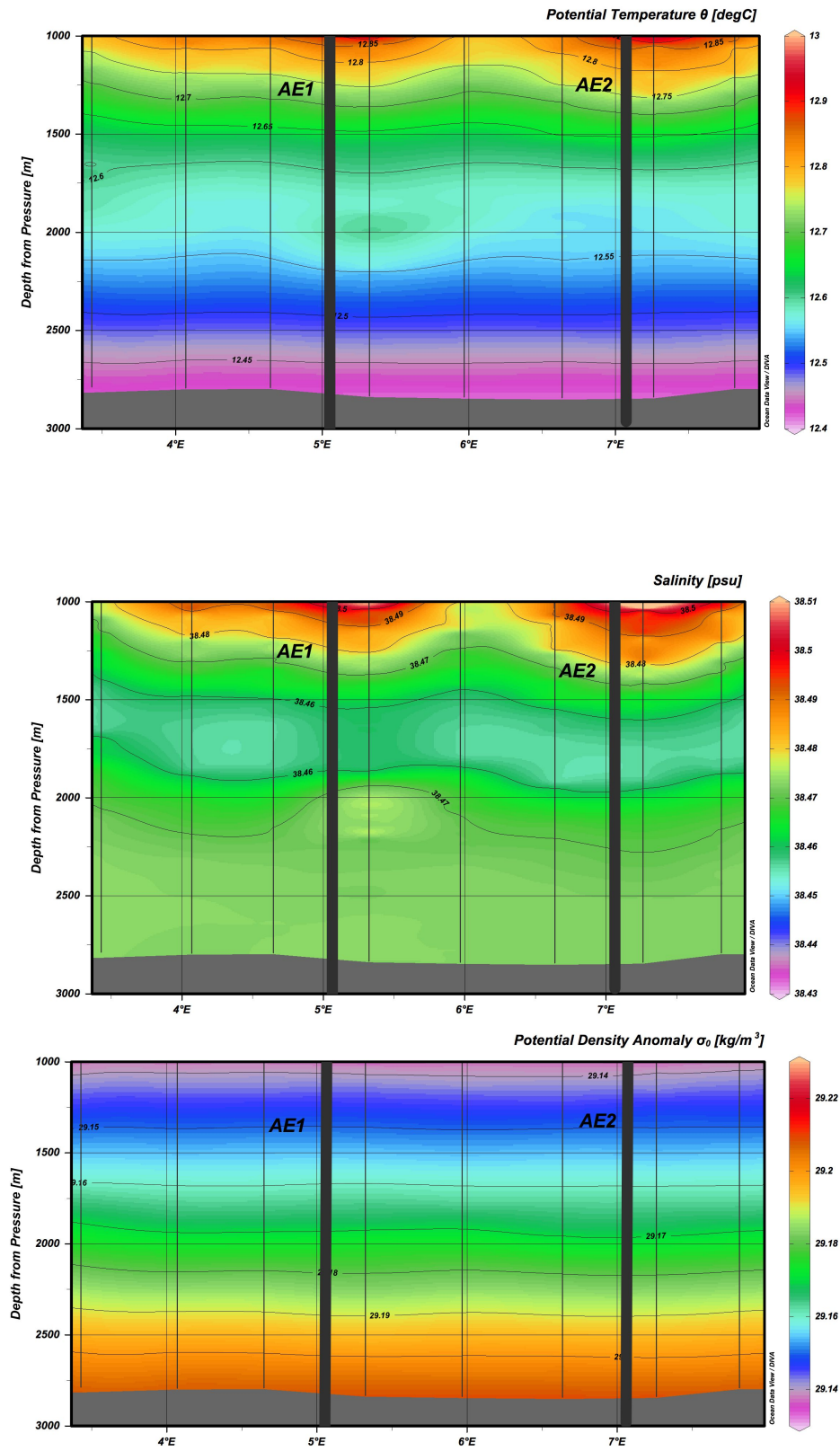


Figure 3.21: Vertical distribution from 1000 to 3000 m of potential temperature (top), salinity (middle) and potential density anomaly (bottom) of the transect in Figure 3.18 (MEDCO08) (almost W-E direction). The black lines indicate the position of the anticyclonic eddies AE1 and AE2 detected by the hybrid method on the SLA map.

of AE2, salinity declines till 50 m, remains constant till 100 before rising up to the lower boundary of the LIW layer. We suppose that the different behaviour of the two eddies could be attributed to the downwelling phenomena associated with anticyclonic structures. The resident water at the western end of the basin is stable till 500 m with decreasing temperature and increasing salinity.

The water next to the Sardinia Channel, on the eastern border of AE2 is characterized by salinity higher (37.45 at 50 m) than in the AEs (36.9 - 37.1 at 50 m).

As expected the stations in the Sardinia Channel present saltier water in every layer. The black circle in the figure highlights the effect shown in the section from 1000 m to the bottom, where we found a layer between the two formations of WMDW. It shows the effect of the new WMDW formation.

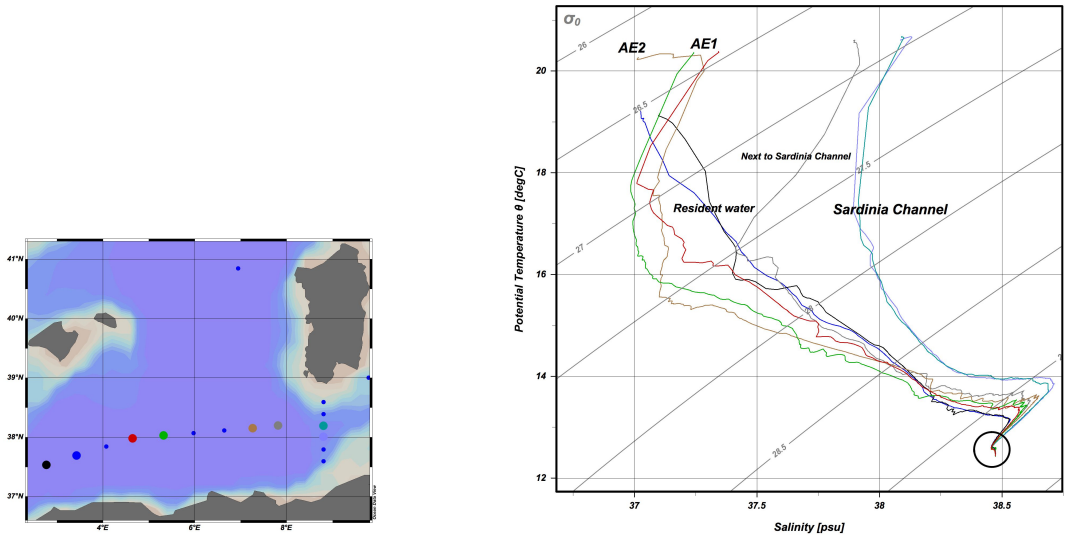


Figure 3.22: *Theta-s diagrams of stations in the centre of the eddy AE1 (green and red lines), at the border of AE2 (brown line), in the west of the Algerian Basin (black and blue lines), next to the Sardinia Channel (gray line) and in the Sardinia Channel (light blue and lilac lines). The map of the corresponding stations is shown on the left.*

Additional information from the hybrid method

The parameters extracted from the detection and tracking method are listed below Table (3.2.2).

	AE1	AE2
Formation date	20/09/2008	22/05/2008
Termination date	08/01/2009	16/11/2008
Lifetime (days)	111	179
Mean EKE (m^2/s^2)	190.7	310
Mean radius (km)	44.7	45.2
Mean translation velocity (Km/day)	6.9	3.9

Figure 3.23 shows AE1 and AE2 tracks with their daily MEKE.

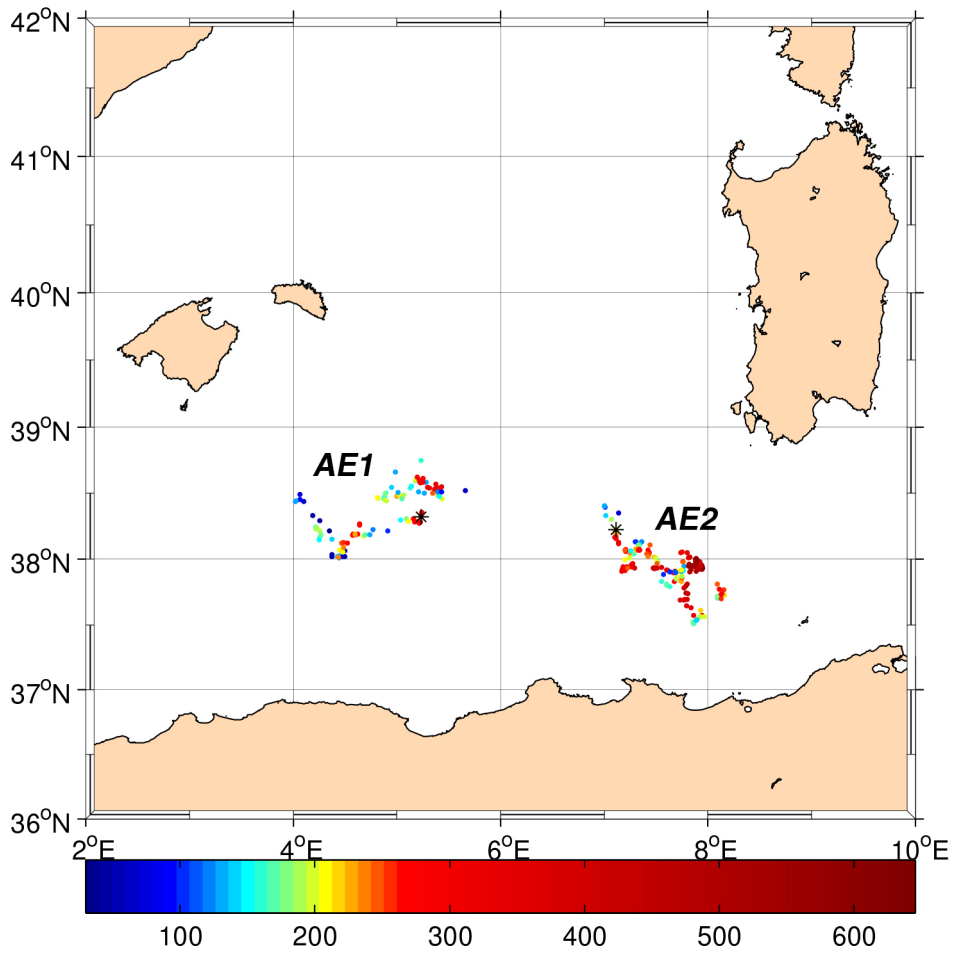


Figure 3.23: Tracks of AE1 e and AE2. The colour indicates the daily MEKE (m^2/s^2). The black stars indicate the coordinates of formation.

AE1 and AE2 are both long-life eddies, with lifetime respectively of 179 and 111 days. AE1 formed in autumn 2008 in sector C, where it also vanished. Long-life eddies arising in autumn usually form in sector D and tend to remain localized in that sector. Instead, AE1 is one of the few eddies born almost in the middle of the basin, where it stayed all its

life. Its daily MEKE is on average lower than that of AE2 and exceeds $500 \text{ m}^2/\text{s}^2$. As most long-life eddies, AE2 arose in spring in sector D. It did not move around the basin, although it was very energetic ($600 \text{ m}^2/\text{s}^2$).

3.2.3 The MEDOCC07 cruise

The MEDOCC07 cruise took place from 7th to 27th October, 2007, in the Western Mediterranean Sea. The cruise covered stations along the Balearic transect, at latitude 40° N from the Balearic Islands (longitude 4° E) to the west coast of Sardinia (longitude 8° E). This is the area where the FAEs form.

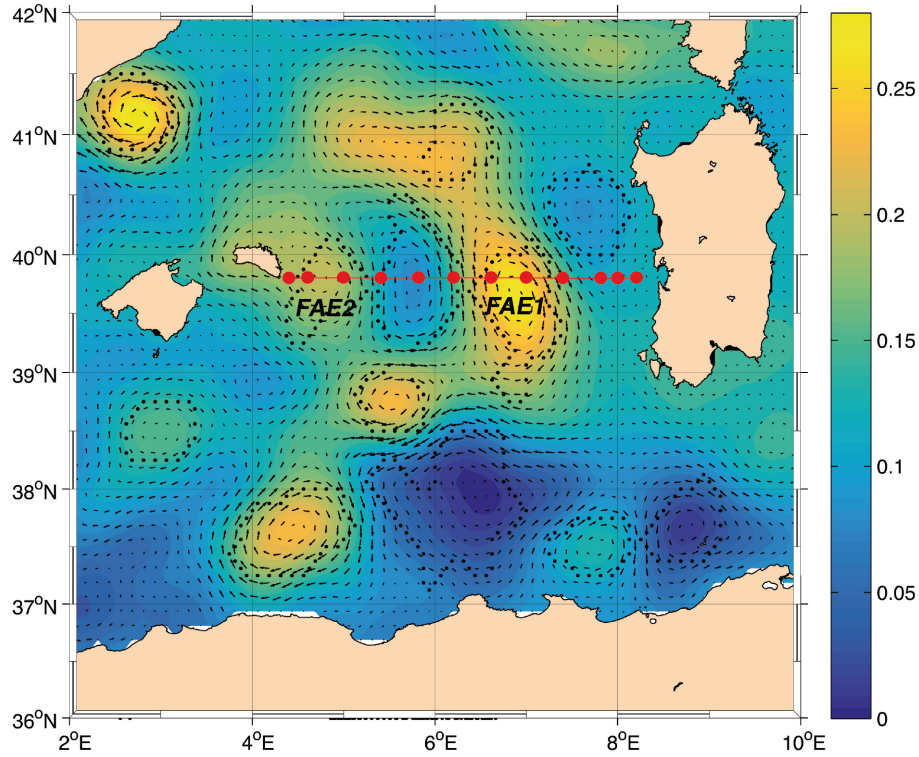


Figure 3.24: The figure shows the stations along the Balearic transect (red dots), where CTD data were collected during the MEDOCC07 cruise in October 2007. The closed contours have been computed on the basis of SLA data and in each closed contour the Okubo-Weiss parameter has been calculated. The dotted black circles refer to the closed contours of OW parameter. Lastly, the black circles indicate the effective structures found by the hybrid method (geometric and physical).

Figure 3.24 shows the map of SLA and the geostrophic velocities of 17 October, 2007. The dotted black lines refer to the closed contours where the OW parameter assumes value ≤ 0 , as calculated by the algorithm, i.e., they indicate the effective structures found by the hybrid method. The hybrid method detected 8 anticyclonic eddies and 4 cyclonic eddies. The transect intersects the structures at coordinates 39.8° N and 7° W (FAE1) and 39.8°

N and 4.4° W (FAE2). SLA assumes the values of 0.26 m and 0.21 m respectively in FAE1 and FAE2.

Figure 3.25 shows the potential temperature, salinity and potential density anomaly in the top 500 m along the transect (Figure 3.24). The black line indicates the position of FAE1 as detected by the hybrid method. The isolines are deflected due to the presence of the anticyclonic structure in correspondence with FAE1. Only the isotherms show the presence of a weak structure in correspondence with FAE2 (not shown). A lens of fresher water (36.84), probably of Atlantic origin, has been found at sub-surface depth (60 m). In the salinity plot, below 300 m, the presence of LIW is indicated by maxima of 38.7. In the layer 500 – 1000 m the deepening of the isolines is less significant than in the southern Algerian Basin. East of the transect, the LIW coming from the Sardinia Channel is trapped by FAE1. A relative maximum of temperature (13.2° C) and of salinity 38.55 are found at 700 m depth.

The salinity is decreasing with depth and the effect of the temperature, as shown by the potential density anomaly (Figure 3.26 - bottom): in proximity to FAE1 the isopycnals indicate the presence of light water surrounded by denser water. The isopycnals become almost parallel and horizontal below 700 m.

Below 1000 m there is no trace of FAE1; the isolines are almost horizontal. We observe a relative minimum of salinity (36.46) in a layer from 1250 to 2250 m (Figure 3.27). Figure 3.28 shows the theta-s diagram of the stations in the centre of the FAE1 (green and red lines), on the west of the Balearic transect (violet and gold lines) and in the middle of the Algerian Basin (black and gray lines).

Salinity in the eddy core in the MAW layer is lower than in all other stations. Salinity decreases to 60 m, then increases down to the lower boundary of the LIW layer. In the middle of the basin it reaches 37 at 40-50 m, then increases. In stations west of the transect, the minimum salinity recorded is 37.3 at 50 m.

The LIW water, characterised by salinity greater than 38.6, is present only in the stations closest to the west coast of Sardinia and in correspondence with the core of FAE1.

The black circle in Figure 3.28 highlights the new WMDW formation [Schroeder et al., 2008], characterised by a relative minimum of salinity. This phenomenon has also been observed in the MEDCO08 cruise (Section 3.2.2).

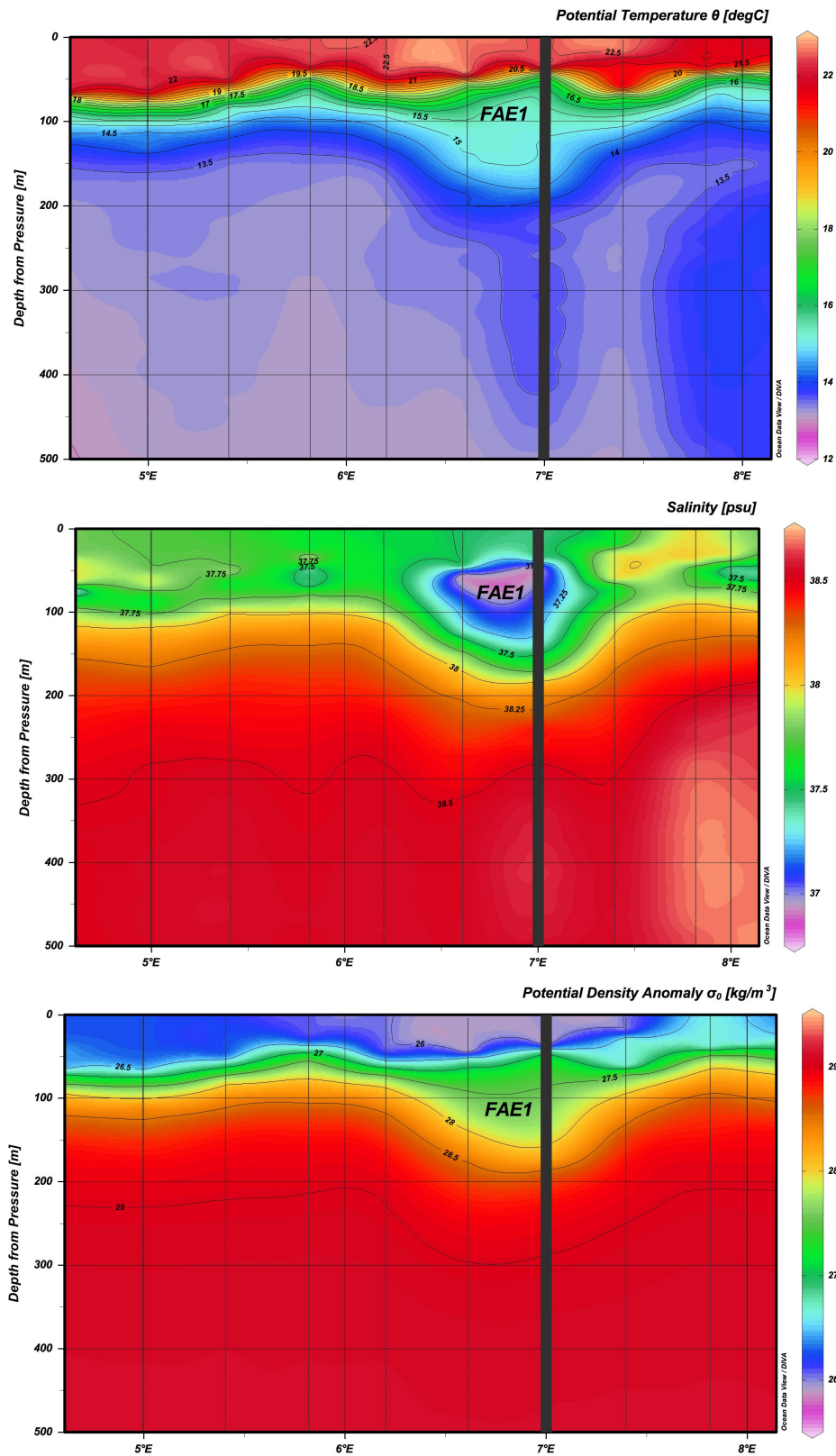


Figure 3.25: Vertical distribution ifrom 0 to 500 m of potential temperature (top), salinity (middle) and potential density anomaly (bottom) of the transect in Figure 3.24 (MEDOCC07) (almost W-E direction). The black line indicates the position of the anticyclonic eddy FAE1 detected by the hybrid method on the SLA map.

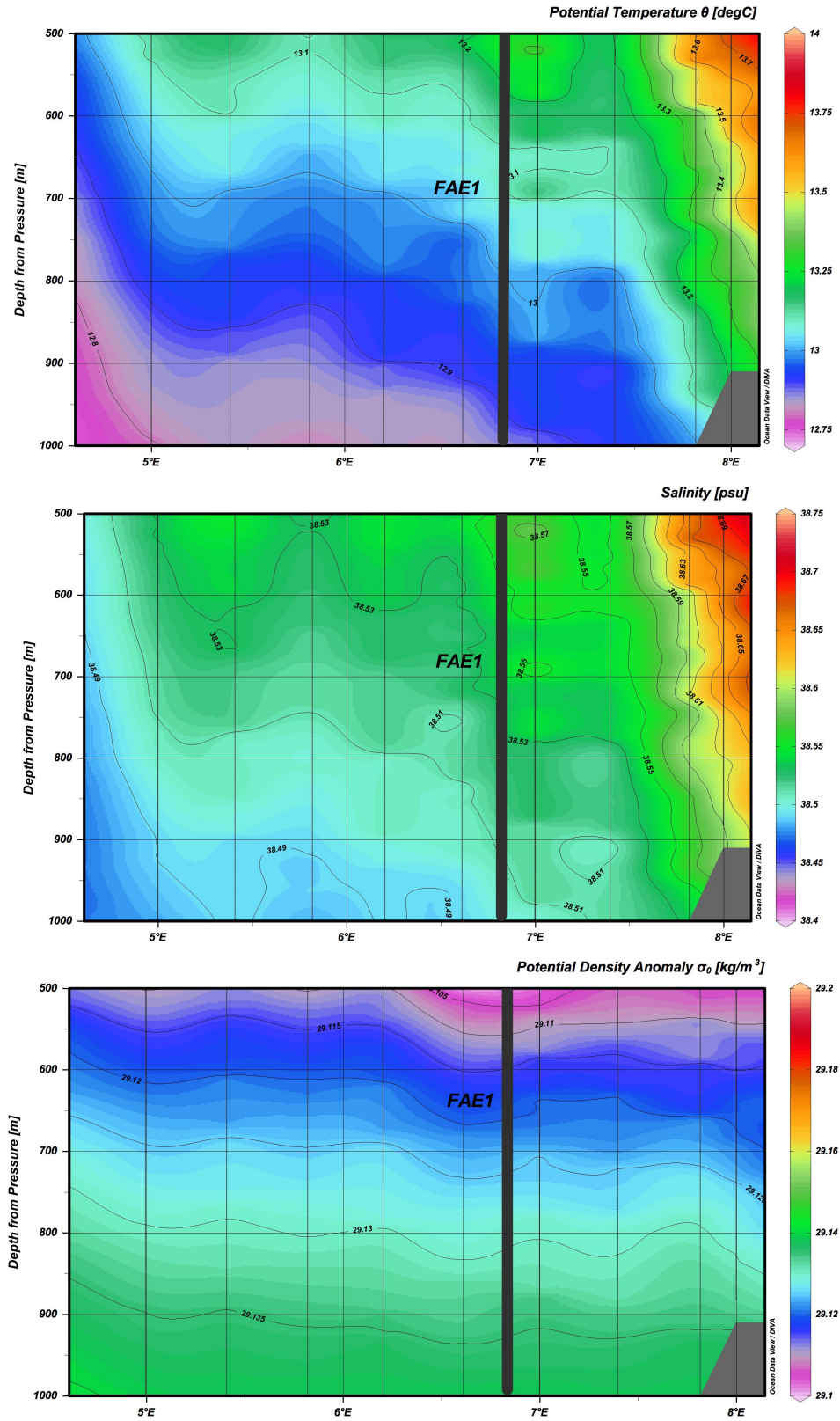


Figure 3.26: Vertical distribution from 500 to 1000 m of potential temperature (top), salinity (middle) and potential density anomaly (bottom) of the transect in Figure 3.24 (MEDOCC07) (almost W-E direction). The black line indicates the position of the anticyclonic eddy FAE1 detected by the hybrid method on the SLA map.

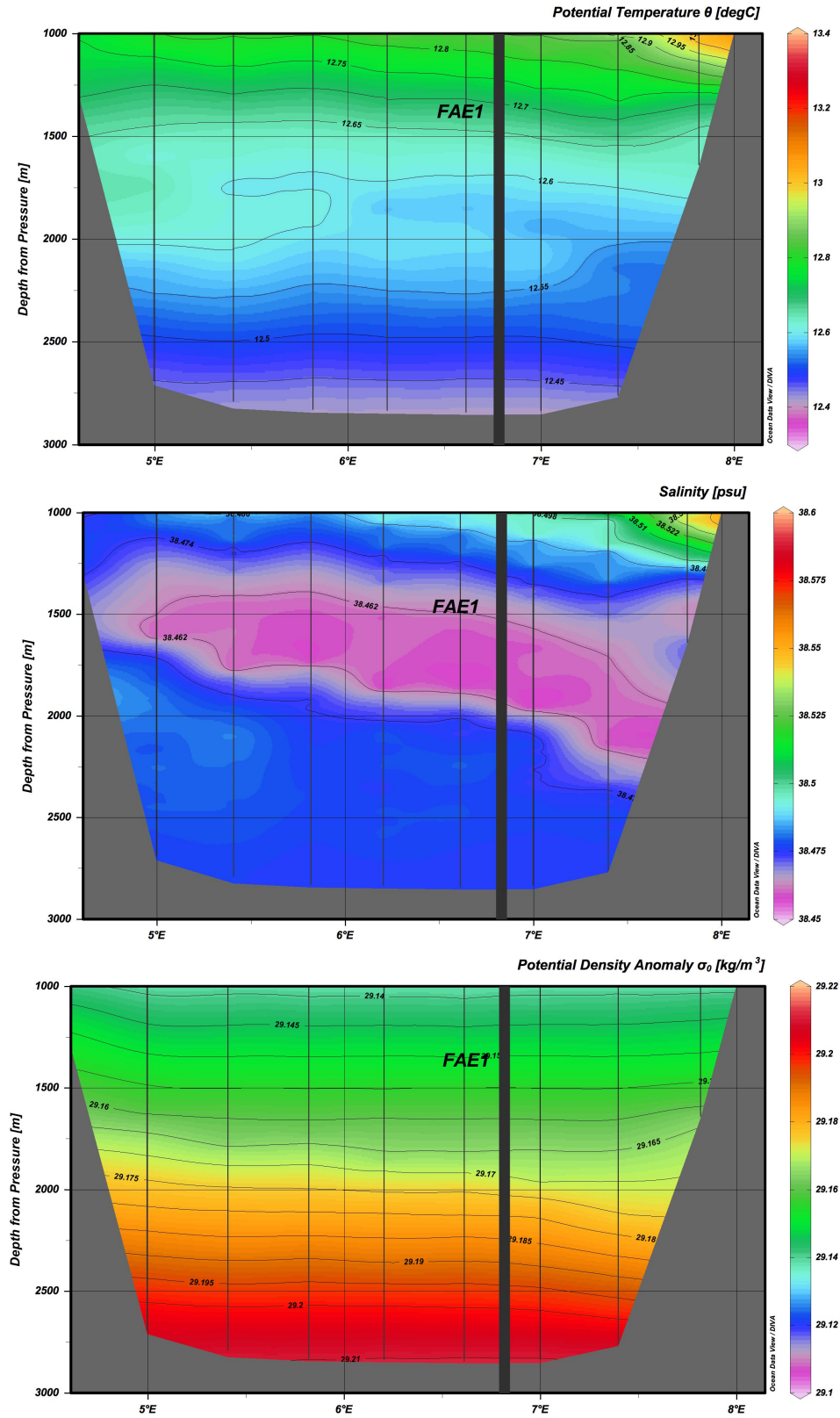


Figure 3.27: Vertical distribution from 1000 to 3000 m of potential temperature (top), salinity (middle) and potential density anomaly (bottom) of the transect in Figure 3.24 (MEDOCC07) (almost W-E direction). The black line indicates the position of the anticyclonic eddy FAE1 detected by the hybrid method on the SLA map.

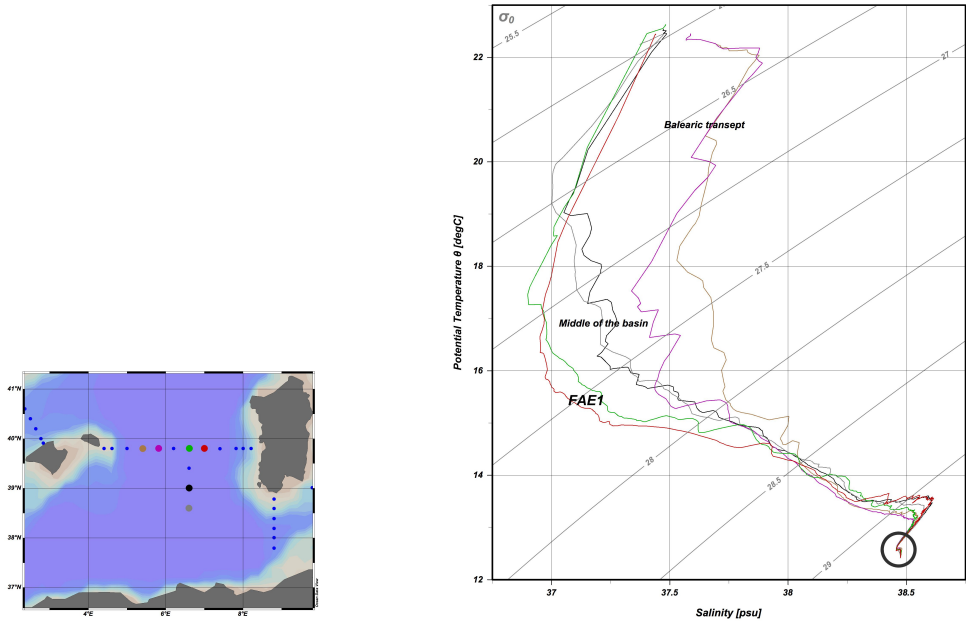


Figure 3.28: *Theta-s diagrams of station in the centre of FAE1 (green and red lines), on the west of the Balearic Transect (violet and gold lines) and in the middle of the basin (black and gray lines). The map of the corresponding stations is shown on the left.*

Additional information from the hybrid method

More parameters about FAE1 and FAE2 have been extracted from the algorithm and are listed below Table (3.2.3).

In Figure 3.29 are represented the trajectories of FAE1 and FAE2 with their daily MEKE.

	FAE1	FAE2
Formation date	03/10/2007	11/10/2007
Termination date	18/12/2007	06/11/2007
Lifetime (days)	77	27
Mean EKE (m^2/s^2)	130.4	83.6
Mean radius (km)	38.9	35.8
Mean translation velocity (Km/day)	5.7	9.5

FAE1 and FAE2 are both short-life eddies, formed in autumn 2007, with lifetime of 77 and 27 days respectively. FAE1 formed in sector B, where it also expired. The characteristics of the water involved in this structure are very similar to those of water in the middle of the basin. One possible explanation is that FAE1 was born in the southern basin and lost intensity in the middle of the basin. Here it strengthened but the detection algorithm mistakenly labelled it as a new eddy. That would explain the AW in the sub-surface layer.

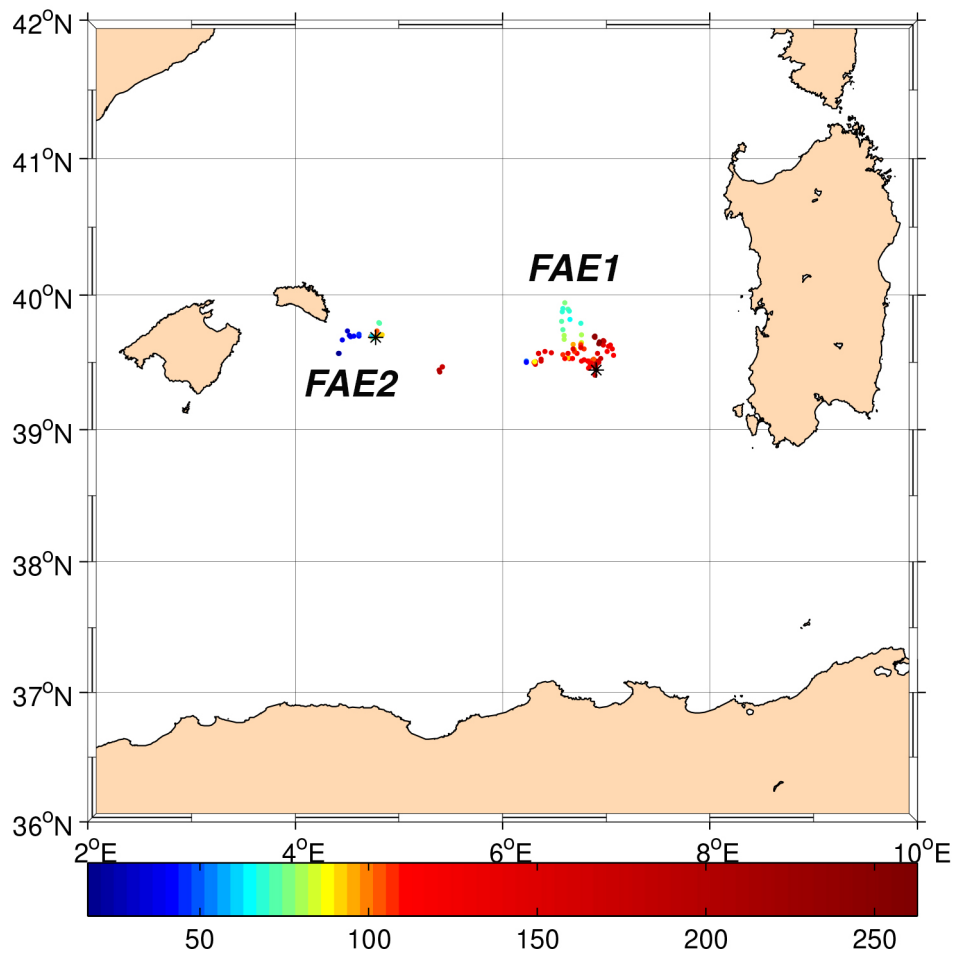


Figure 3.29: Tracks of FAE1 e and FAE2. The colour indicates the daily MEKE (m^2/s^2). The black stars indicate the coordinates of formation.

The detection method identified FAE2 as if it had formed in sector A and had vanished after 23 days. It left no traces in the vertical section, probably due to its short life.

Chapter 4

Discussion and conclusions

The automated method for eddy detection and tracking, applied over 22 years of merged altimetry SLA maps, allows us to characterize the variability of mesoscale structures and, in general, describe mesoscale circulation, which is strongly influenced by the pathways of the AEs within the basin.

As mentioned in Chapter 2, the geometric/physical method presents a number of advantages and disadvantages. The comparison with existing literature and some sensitivity tests (not shown), have demonstrated the reliability of the detection algorithm.

It is important to note that the tracking method is based on the definition of a general distance (2.20), which in turn defines the evolution of each eddy over time. In a basin as small as the Algerian one, eddies frequently encounter other eddies and deviate from their paths or merge into new, larger structures (coalescence). A significant limitation of the algorithm is that it fails to recognize these events and mistakenly assumes the formation of a new eddy. This limitation affects both the identification of a pathway and the estimate of eddy lifetime.

To overcome this limitation some tweaks have been introduced in the code, followed by several sensitivity tests. This is primarily a technical issue, which we will strive to improve in future. With the exception of some isolated cases, the method has provided usable results and can be considered reliable in tracking eddies. A comparison with the recent study of Escudier et al. [2016] confirms the results of our work.

After estimating their duration, we decided to ignore eddies with lifetime shorter than 7 days, as the algorithm may introduce spurious short-lived structures. We performed a Eulerian statistic on eddies shorter and longer than 100 days separately, in order to study their spatial distribution. We found that the short-life eddies mostly form in the northern

part of the basin (65% above latitude 39° N) and are less energetic than the others. They do not move within the basin and terminate close to their area of formation. The remaining 35% of short-life eddies, mostly to be found below 39° N, have higher kinetic energy. Due to their low persistence in the basin, short-life eddies have a limited impact on mesoscale circulation and do not appear to influence the physical, chemical and biological properties of the WMED.

This result complements that of long-life eddies, which typically form below 39° N (68%). The two areas of formation are located around 6° E and 8° E, in proximity to the Sardinia Channel. Long-life eddies absorb energy from the AC and move cyclonically around the basin, without straying above latitude 39° N. The remaining 32% of long-life eddies form between 5.5° E and 7.5° E, above 39° N. The most energetic move southward and join the southern eddy moving in the cyclonic loop. This is the only interaction between the north and south of the basin, which, despite of its small size, can be considered as composed of two distinct parts.

In observing the daily MEKE of the structures, i.e., their daily mean kinetic energy, we found a clear separation between the northern and the southern part of the basin. The latter is about three times more energetic than the former and is subject to annual periodicity related to the seasonality of heat fluxes, and a periodicity of 4.4 years (long-life eddies only), which should be more comprehensively examined with a larger data set. The northern basin does not have any periodicity in terms of kinetic energy. This result has been obtained by performing a Fast Fourier Transform (FFT) analysis of the time series of monthly mean kinetic energy.

In order to distinguish the eddies formed in the two parts of the basin, we labelled the northern structures (both short- and long- life) Frontal Anticyclonic Eddies (FAEs), as we suppose that they are caused by the instabilities of the NBF. In literature, southern eddies are commonly referred to as Algerian Eddies (AEs).

The complementarity between short- and long-life structures has also been observed in the study of seasonality. Short-life eddies form mostly in autumn and winter, while long-life eddies form preferably in spring and summer in the southern basin, when the AC is at its maximum transport.

The cyclonic loop of the eddies in the southern part of the basin corresponds to the high-energy pathway and is partly superimposed on the pathway of the Algerian Gyre (AG). The AG flows in the LIW layer. The along-slope propagation of southern AEs stops in

proximity to the Sardinia Channel, where the structures interact with the bathymetry. They remain there until they absorb from the AC an amount of energy sufficient to detach from the coast and move northward. We suppose that the salinity (and density) barrier in correspondence to the Sardinia Channel, highlighted by the CTD data, may contribute to blocking the propagation of eddies.

By examining the punctual properties of each eddy, we found that the longer the lifetime of the structures, the larger their radius and the higher their kinetic energy.

As altimetry provides only surface data, to fill the lack of information about the vertical dimension of the eddies we used in-situ CTD data sampled during three oceanographic cruises in the WMED. We combined the output of the detection and tracking algorithm with the CTD data to extract as much information as possible from the mesoscale structures. We found that southern eddies reach a depth of 1200 m, while FAEs do not exceed 700 m. The hybrid method adds information about the mean properties of the structures, such as the dates of formation and death, life span, kinetic energy, radius and translational velocity.

In the vertical section of potential temperature, salinity and potential density anomaly, we found deflections of the isolines in correspondence to the eddies. The deepening is typical of anticyclonic structures. All the features have a salinity minimum at a depth of 50 m. This phenomenon is probably associated to the downwelling of Atlantic Water due to the anticyclonic structure of the eddy. This was expected in the southern eddies formed along the AC, but not in the FAEs. The salinity value of 36.8 at sub-surface layer in the FAEs (MEDOCC07), and the comparison between the theta-s diagrams of the water in the middle of the basin and in the eddy core, suggest that this structure has originated at lower latitudes.

In proximity to the Sardinia Channel, the eddies become wider and thicker Obaton et al. [2000] and interact with the intermediate layer. In-situ data show that there they trap the new LIW (coming from the Tyrrhenian Sea) and transport it around the basin. This interaction with the intermediate layer may confirm that the eddies in the cyclonic loop are indeed driven by the Algerian Gyre.

In many areas of the global ocean and at various scales, the chlorophyll-a concentration (Chl) and the primary production are strongly related to upwelling and downwelling phenomena, which are in turn associated with the cyclonic and anticyclonic structures respectively. The deflection of the isopycnals modifies the distribution of the nutrients in

the euphotic layer [McGillicuddy and Robinson, 1997; Wilson and Adamec, 2002; KahruM et al., 2007; Olita et al., 2011a]. The study of the relationships between hydrodynamic processes and the dynamics of the first trophic levels improves the understanding and prediction of the ecological effects of hydrodynamic shifts in a climate change scenario [Somot et al., 2007; Olita et al., 2007]. This study acquires even more importance in highly dynamic seas, such as the WMED, where the hydrodynamic processes may strongly influence the distribution and the concentration of phytoplankton [Morà et al., 2001; Isern-Fontanet et al., 2004]. In particular, the relationship between eddies and the biological phenomena depends on the life history, pathways, size and vertical extension of mesoscale structures. This work provides a good description of mesoscale eddies and the circulation of the Algerian Basin in general, and aims to further a better understanding of the bio-ecological processes in the WMED.

The major results of this work have been summarized in a schematic view in Figure 4.1. It shows the areas of formation of AEs and FAEs, the pathway of Algerian Gyre, the position of the North Balearic Front, the Algerian Current and the salinity barrier. Future proposals are the improvement of the tracking method, the examination of additional in-situ data and the implementation of an eddy-resolving model to study the transport and distribution of chemical and biological components by mesoscale structures.

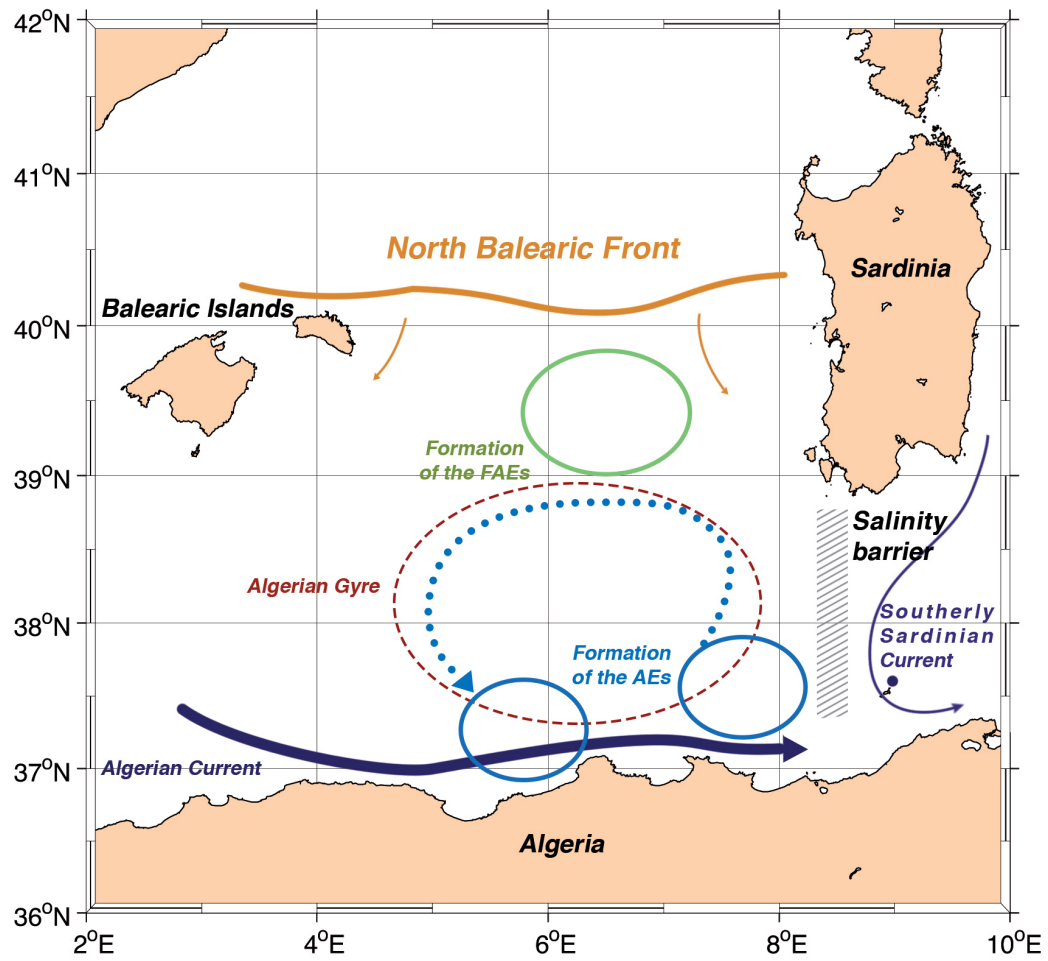


Figure 4.1: Schematic view of the results

Appendix A

Mesoscale processes

The Rossby radius of deformation, represented by L , is the distance that a wave with speed c can travel in time $1/f$, where f is the Coriolis parameter. In essence, it indicates the distance that a wave can travel before being significantly affected by the Coriolis force.

The Coriolis parameter is defined as $f = 2\Omega \sin \Phi$, where Ω is the rotation rate of the Earth and Φ is the latitude. It is identified with the angular velocity or frequency required to maintain a body at a fixed circle of latitude or zonal region. If this parameter is large, the effect of the earth's rotation on the body is significant, since it will need a larger angular frequency to stay in equilibrium with the Coriolis forces. On the contrary, if the Coriolis parameter is small, the effect of the earth's rotation is small since only a small fraction of the centripetal force on the body is cancelled by the Coriolis force.

The Rossby Radius is defined as:

$$L = \frac{c}{f}. \quad (4.1)$$

Because f is equal to zero at the Equator and reaches a maximum at the poles, Rossby Radii decrease from infinity at the Equator to a minimum at the poles. As a result, the higher the latitude, the smaller eddies, waves or other disturbances will be. It represents a manifestation of the increase in planetary vorticity with latitude.

Despite the small dimensions of the Mediterranean Sea, thermohaline circulation within the basin is very active. The internal Rossby radius of deformation is estimated to be about 10 – 14 km, which is one-fourth the typical value in the open ocean [Robinson et al., 2001].

The dimensionless Rossby number, indicated with Ro , is another useful parameter based on dynamic properties, which is used to separate mesoscale and submesoscale phenomena.

It is defined as:

$$Ro = \frac{U}{df} \quad (4.2)$$

where U is a characteristic velocity, d a characteristic length scale and f the Coriolis parameter.

It represents the ratio between inertial force and the Coriolis force due to the rotation of the Earth in the Navier-Stokes equations ([Temam, 1977]). A high value (high velocity or short length) means that Coriolis forces can be neglected, as the inertial and centrifugal forces dominate. On the contrary, if the fluid is affected by the rotational effect, Ro assumes low values. Physically the equilibrium between the pressure gradient of the fluid and Coriolis forces exists and it is called geostrophic balance.

Mesoscale processes, where the Coriolis force is dominant, are associated with small Rossby numbers. They are involved in quasi-geostrophic motions and, as a result, geostrophic velocities can be calculated from the pressure gradient, imposing geostrophic balance in the equation of motion.

There is a link between the Rossby radius of deformation and the Rossby number: in fact the latter is the length scale at which inertial forces and Coriolis forces have the same order of magnitude.

Despite the small size of the Mediterranean Sea, the thermohaline circulation within the basin is active, with values of 10 – 14 km for the associated internal Rossby radius of deformation, which is one fourth of the typical value in the open ocean [Isern-Fontanet et al., 2016].

Appendix B

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Anticyclonic eddy energy and pathways in the Algerian basin (1993-2007)

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The Algero-Provençal basin plays a key role in the circulation of the entire Mediterranean Sea. Consequently, in the past its hydrodynamics has been intensively studied with infrared and colour satellite imagery, moorings, surface drifters and altimetry observations. The basin is divided into two sub-basins by the North Balearic front, a thermal front characterized by a high seasonal variability: the Provençal sub-basin in the north and the Algerian sub-basin in the south.

The Algerian basin is dominated by mesoscale phenomena, especially anti-cyclonic eddies. The Algerian current becomes unstable and meanders; often giving rise to mesoscale eddies of both signs. The anti-cyclonic eddies (hereafter Algerian Eddies or AEs) can grow rapidly in horizontal and vertical extension. They can also detach from the Algerian slope and circulate for several months within the sub-basin, while the cyclonic ones quickly disappear. In spite of its limited dimensions, the Algerian sub-basin can contain as many as three long-life AEs, which can interact with each other and with sub-basin dynamics.

In spite of the current body of research, a study on the tracking, energy and interaction of these long-life eddies in time and space is still lacking.

In order to fill this gap, we applied the automated eddy detection and tracking method created by Penven (2005), which reveals the complex movements and dynamics of eddies in the Algerian sub-basin. The Penven algorithm combines the detection of the largest closed contours in SSH (Sea Surface Height) with a positive value of the relevant Okubo-Weiss parameter. The latter has already been successfully used in the Algerian Basin by Isern-Fontanet et al. (2003). The eddy-tracking algorithm is based on the minimization of a general distance that takes into account the difference in coordinates, radius, vorticity, mean height and amplitude between eddies of consecutive temporal steps. The code was modified and adapted in order to optimize its use in the study area.

This automated method allowed the investigation of mesoscale eddy variability using several years (1993-2007) of satellite altimetry observations. To verify the reliability of the technique, we compared the eddy pathways derived from the application of the modified Penven method with independent observations.

Preliminary results suggest that AEs, moving anticlockwise within the sub-basin, complete as many as two or three laps, depending on their lifetime, following the Algerian Gyre path. We suppose that AEs acquire kinetic energy from the Algerian current, occasionally in sufficient magnitude to cause their detachment. This phenomenon mainly takes place near the Sardinian Channel. Eddies formed on the thermal front, called Frontal Anticyclonic Eddies (FAEs), remain localized in the northern part of the sub-basin and have lower energy and shorter life than AEs. They usually don't interact with AEs.

Basic statistics on eddy trajectories and energy characteristics allow the evaluation of these mesoscale structures' relevance of on (sub-) basin circulation.

Anticyclonic eddy energy and pathways in the Algerian Basin (1993-2014)

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1 - Motivations and objectives

The Algero-Provençal basin plays a key role in the circulation of the entire Mediterranean Sea and in the past its hydrodynamics has been intensively studied with surface drifters and in situ data. The basin is divided into two sub-basins by the North Balearic front, a thermal front characterized by high seasonal variability: the Provencal sub-basin in the north and the Algerian sub-basin in the south.

The Algerian basin is one of the most energetic areas of the Mediterranean Sea and is dominated by mesoscale phenomena, especially anti-cyclonic eddies. The Algerian Current, mainly constituted by Atlantic water flowing on the surface in the Mediterranean Sea, becomes unstable and meanders, often giving rise to mesoscale eddies of both signs. Anti-cyclonic eddies can grow rapidly in horizontal and vertical extension. They can also separate from the Algerian slope and circulate for several months within the basin, while cyclonic ones tend to disappear quickly. In spite of the current body of research, a study on the tracking, energy and interaction of these eddies in time and space is still lacking. In order to better explain their behaviour, we apply an automated eddy detection and tracking method, which reveals the complex movements and the dynamics of eddies and allows dividing the basin in formation, detaching and transition zones.

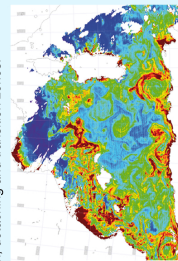


Image is Ocean Color (CH4 product) level 2 single swath from AQUA MODIS for March 8th, 2013.

References

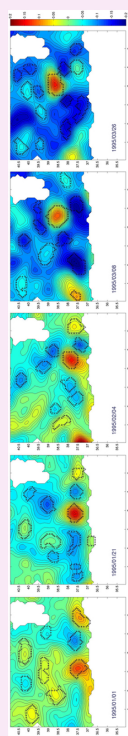
1. Millot, C. (1999). Circulation in the western Mediterranean Sea. J. Mar. Syst.
2. Perilli, A., Olita, A., Pessini, F., and Perilli, A. (2008). Monitoring of a meridian section across the western Mediterranean Sea. Deep-Sea Research I.
3. Penven, P. and Echvin, V. (2005). Average circulation, seasonal cycle, and mesoscale dynamics of the Pen Current system: A modelling approach. Journal of Geophysical Research.

2 - Materials and methods

The algorithm we used was created by Penven³. It combines the detection of the largest closed contours in Sea Level Anomaly (SLA) with a positive value of the relevant Okubo-Weiss parameter, which allows the separation of the flow in two regions, one vorticity-dominated and one deformation-dominated respectively. After detection, the algorithm uses a generalized distance between eddies belonging to consecutive time steps to track their pathways. This generalized distance takes into account the differences in latitude, longitude, radius, vorticity, mean height and amplitude.

Below is an example of five different temporal steps of eddy detection. Black closed contours in the figures refer to the Okubo-Weiss parameter. A comparison with satellite images of SST proves that this kind of method is accurate in detecting eddies in the basin.

The basin has been divided by a regular grid to better study the statistics of each area.



3 - Results and conclusions

After analysing 22 years of SLA data (1993-2014) with the Penven method, we found several kinds of eddies, with different properties and behaviours.

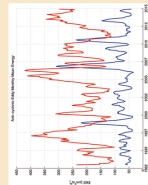
In general, in the southern part of the Algerian basin eddies have a greater Eddy Kinetic Energy (EKE) and usually a longer lifetime than in the northern part.

This method permits the identification of several different areas within the basin: formation, detachment and transition areas, where eddies respectively arise from baroclinic instabilities, detach from the coast to the open sea and move along particular pathways.

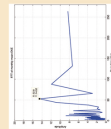
We found four different types of eddies, two with a long life span (lifetime greater than 100 days) and two with a short life (lifetime less than 100 days).

The long-life eddies arise in the southern part, mainly in sector D and M (blue bars), and we refer to them as Algerian Anti-cyclonic Eddies (AAEs) and Sardinian Anti-cyclonic Eddies (SAEs). None died in the same sector where they formed (dark red bar) and in general not many eddies (40% for M sector) die there (green bar). Rather, they tend to move cyclonically in the basin and to follow the same pathway.

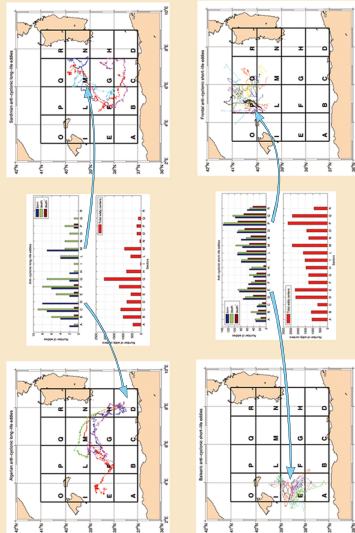
The two short-life span eddies arise mainly in sectors E and P (blue bars). They usually end their life in the same sector where they have formed (dark red bar, 70% for E and 60% for P). This implies that these kinds of eddies don't move around the basin. We refer to them as Balearic Anti-cyclonic Eddies (BAEs) and Frontal Anti-cyclonic Eddies (FAEs) respectively. Despite the small size of the basin, these long-life and these short-life eddies don't interact with each other.



The figure shows the monthly mean EKE for the entire period. The southern part of the Algerian basin (37° - 39° N) is shown in red and the northern part (39° - 42° N) in blue. Eddies born south of the latitude of 39° N are more energetic than the others.



The Fourier Transform analysis shows a peak frequency of 52 months (about 4.4 years).



The upper panel shows long-life eddies while the lower panel shows short-life eddies. Blue, green and dark red bars refer to formation and death. Red histograms present the distribution of the total number of eddy centres in each sector.

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Bibliography

- Anzenhofer, M., Shum, C., and Rentsh, M. (1999). Coastal altimetry and applications, Geodetic Science and Surveying. Technical Report 464, The Ohio State University Columbus, USA.
- Arhan, M. (1987). On the large scale dynamics of the Mediterranean outflow. *Deep Sea Research Part A. Oceanographic Research Papers*, 34(7):1187 – 1208. doi: 10.1016/0198-0149(87)90071-9.
- Arnone, A. R., Wiesenburg, D. A., and Saunders, K. D. (1990). The origin and characteristics of the Algerian Current. *Journal of Geophysical Research*, (95):1587–1598.
- Astraldi, M., Balopoulo, S., Candela, J., Font, J., Gacic, M., Gasparini, G., Manca, B., Theocharis, A., and Tintoré, J. (1999). The role of straits and channels in understanding the characteristic of Mediterranean circulation. *Progress in Oceanography*, (44):65–108.
- Benzhora, M. and Millot, C. (1995). Hydrodynamics of an open sea Algerian Eddy. *Deep Sea Research Part I: Oceanographic Research Papers*, 42(10):1831–1847.
- Beranger, K., Mortier, L., and Crepon, M. (2005). Seasonal variability of water transport through the Straits of Gibraltar, Sicily and Corsica, derived from a high-resolution model of the Mediterranean circulation. *Ocean Science*, 66:341–364.
- Bethoux, J. and Gentili, B. (1999). Functioning of the Mediterranean Sea: past and present changes related to freshwater input and climate changes. *Journal of Marine Systems*, (20):33–47.
- Bouzinac, C., Font, J., and Johnny, J. (2003). Annual cycles of sea level and sea surface temperature in the Western Mediterranean Sea. *J. Geophys Res*, (108(c3)):3059.
- Broecker, W. S. (1991). The Great Ocean Conveyor. *Oceanography*, 4.

- Burkov, V., Krivosheya, V., Ovchinnikov, I., and Savin, M. (1979). Eddies in the current system of the Western Mediterranean Sea. *Oceanology*, 19(1):9–13.
- Canals, M., Puig, P., Durrieu de Madron, X., Heussner, S., Palanques, A., and Fabres, J. (2006). Flushing submarine canyons. *Nature*, 444:354–357.
- Chaigneau, A., Eldin, G., and Dewitte, B. (2009). Eddy activity in the four major upwelling systems from satellite altimetry (1992-2007). *Progress in Oceanography*, (83):117–123.
- Chelton, D. B., Schlax, M. G., and Samelson, R. M. (2011). Global observations of non-linear mesoscale eddies. *Progress in Oceanography*, (91):167–216.
- Chelton, D. B., Schlax, M. G., Samelson, R. M., and De Szoeke, R. A. (2007). Global observations of large oceanic eddies. *Geophys. Res. Lett.*, (34).
- Colling, A. (1989). *Ocean Circulation*. Butterworth Heinemann.
- Ducet, N., Le Traon, P.-Y., and Reverdin, G. (2000). Global high resolution mapping of ocean circulation from TOPEX/Poseidon and ERS-1 and -2. *J. Geophys. Res.*, 105:19477–19498.
- Escudier, R., Bouffard, J., Pascual, A., Poulain, P. M., and Pujol, M. I. (2013). Improvement of coastal and mesoscale observation from space: application to the northwestern Mediterranean Sea. *Geophys. Res. Lett.*, 40:2148–2153.
- Escudier, R., Mourre, B., Juza, M., and Tintoré, J. (2016). Sub-surface circulation and mesoscale variability in the Algerian sub-basin from altimeter-derived eddy trajectories. *Journal of Geophysical Research: Oceans*.
- Estournel, C., de Madron, X. D., Marsaleix, P., Auclair, F., Julliand, C., and Vehil, R. (2003). Observation and modeling of the winter coastal oceanic circulation in the Gulf of Lions under wind conditions influenced by the continental orography (fetch experiment). *Journal of Geophysical Research: Oceans*, 108(C3).
- Font, J., Isern-Fontanet, J., and Salas, J. (2004). Tracking a big anticyclonic eddy in the Western Mediterranean Sea. *Scientia Marina*, (68(3)):331–342.
- Font, J., Millot, C., Salas, J., Julià, A., and O.Chic (1998). The drift of Modified Atlantic Water from the Alboran Sea to the eastern Mediterranean. *Scientia Marina*, (62(3)):211–216.

- Font, J., Salat, J., and Augusti, J. (1990). Marine circulation along the Ebro continental margin. *Mar. Geol.*, 95(3-4):165–177.
- Font, J., Salat, J., and Tintoré, J. (1988). Permanent features of the circulation in the Catalan Sea. *Oceanol. Acta*, 9:51–57.
- Fuda, J. L., Millot, C., Taupier-Letage, I., Send, U., and Bocognano, J. M. (2000). XBT monitoring of a meridian section across the Western Mediterranean Sea. *Deep-Sea Research I*, (47):2191–2218.
- Gascard, J. C., Rouault, C., and Testor, P. (1999). General ocean circulation and subsurface mesoscale eddies in the Algerian Basin. In *Fourth Mediterranean targeted project workshop*, pages 50–51. MATER, Perpignan, France.
- Halo, I., Backeberg, B., Penven, P., Ansorge, I., Reason, C., and Ullgren, J. E. (2014). Eddy properties in the Mozambique Channel: A comparison between observations and two numerical ocean circulation models. *Deep-Sea Research*, II(100):38–53.
- Iorga, M. C. and Lozier, M. S. (1999). Signatures of the Mediterranean outflow from a North Atlantic climatology: 1. salinity and density fields. *Journal of Geophysical Research: Ocean (1987-2012)*, 104(C11):25985 – 26009.
- Isern-Fontanet, J. and E. García-Ladona, J. F. (2003). Identification of marine eddies from altimetry. *J. Atmos. Ocean. Tech.*, (20):772–778.
- Isern-Fontanet, J., Font, J., García-Ladona, E., Emelianov, M., Millot, C., and Taupier-Letage, I. (2004). Spatial structure of anticyclonic eddies in the Algerian Basin (Mediterranean Sea) analyzed using the Okubo-Weiss parameter. *Deep-Sea Research II*, (51):3009–3028.
- Isern-Fontanet, J., Garcia-Ladona, E., and Font, J. (2005). Vortices of the Mediterranean Sea: an altimetric perspective. *Journal of physical oceanography*, 36:87–103.
- Isern-Fontanet, J., García-Ladona, E., and Font, J. (2006). Vortices of the Mediterranean Sea: An altimetric perspective. *J. Physical Oceanography*, (36(1)):87–103.
- Isern-Fontanet, J., Olmedo, E., Turiel, A., Ballabrera-Poy, J., and Garcia-Ladona, E. (2016). Retrieval of eddy dynamics from SMOS sea surface salinity measurements in the Algerian Basin (Mediterranean Sea). *Geophysical Research Letters*, (43).

- Iudicone, D., Santoleri, R., Marullo, S., and Gerosa, P. (1998). Sea level variability and surface eddy statistics in the Mediterranean Sea from TOPEX/POSEIDON data. *J. Geophys. Res.*, (103(C2)):2995–3011.
- Jeong, J. and Hussain, F. (1995). On the identification of a vortex. *Journal of Fluid Mechanics*, (285):69–94.
- KahruM, M., Fiedler, P., Gille, S., Manzano, M., and Mitchell, B. G. (2007). Sea level anomalies control phytoplankton biomass in the Costa Rica Dome area. *Geophys Res Lett*, (34(22)):L22601.
- Keeling, R. F. and Peng, T.-H. (1995). Transport of heat, CO_2 and O_2 by the Atlantic’s thermohaline circulation. *Philosophical transactions of the Royal Society of London. Series B: Biological Sciences*, 348(1324):133 – 142.
- Kurian, J., Colas, F., Capet, X., McWilliams, J. C., and Chelton, D. B. (2011). Eddy properties in the California Current System. *Journal of Geophysical Research*, (116).
- Larnicol, G., Ayoub, N., and Traon, P. Y. L. (2002). Major changes in Mediterranean Sea level variability from 7 years of TOPEX/Poseidon and ERS-1/2 data. *J. Mar. Syst.*, (33):63:89.
- Levy, M., Memery, L., and Madec, G. (1999). The onset of the spring bloom in the MEDOC area: mesoscale spatial variability. *Deep-Sea Res I*, (46):1137–1160.
- Levy, M., Memery, L., and Madec, G. (2000). Combined effects of mesoscale processes and atmospheric high-frequency variability on the spring bloom in the MEDOC area. *Deep-Sea Res I*, (47):27–53.
- Lopez-Garcia, M. J., Millot, C., Font, J., and Garcia-Ladona, E. (1994). Surface circulation variability in the Balearic Basin. *Journal of Geophysical Research*, 99:3285–3296.
- Marcos, M., Pascual, A., and Pujol, I. (2015). Improved satellite altimeter mapped sea level anomalies in the Mediterranean Sea: A comparison with tide gauges. *Advances in Space Research*, 56(4):596–604.
- Mason, E. and Pascual, A. (2013). Multiscale variability in the Balearic Sea: An altimetric perspective. *Journal of Geophysical Research: Ocean*, 118:1–19.

- Mauerhan, T. A. (2000). Drifter observations of the mediterranean sea surface circulation. Master of science in physical oceanography, Naval Postgraduate School, Monterey (CA).
- McGillicuddy, D. and Robinson, A. R. (1997). Eddy-induced nutrient supply and new production in the Sargasso Sea. *Deep-Sea Res I*, (44):1427–1450.
- McWilliams, J. C. (1999). The vortices of homogeneous geostrophic turbulence. *Journal of Fluid Mech.*, (401):1–26.
- Millot, C. (1982). Analysis of upwelling in the Gulf of Lions. *Hydrodynamics of Semi-enclosed Sea*, pages 143–154.
- Millot, C. (1985). Some features of the Algerian Current. *Journal of Geophysical Research: Oceans*, 90(C4):7169–7176. doi: 10.1029/JC090iC04p07169.
- Millot, C. (1987). Circulation in the Western Mediterranean Sea. *Oceanol. Acta*, (10(2)):143–149.
- Millot, C. (1999). Circulation in the Western Mediterranean Sea. *J Mar Syst*, (20(1-4)):423–442.
- Millot, C. (2013). Levantine Intermediate Water characteristics: an astounding general misunderstanding! *Scientia Marina*, 77(2). doi: 10.3989/scimar.03518.13A.
- Millot, C., Benzohra, M., and Taupier-Letage, I. (1997). Circulation in the Algerian Basin inferred from the MEDIPROD-5 current meters data. *Deep Sea Res*, (47(11)):1467–1495.
- Moràn, X. A. G., I-Taupier-Letage, Vazquez-Dominguez, E., Ruiz, S., Arin, L., Raimbault, P., and Estrada, M. (2001). Physical-biological coupling in the Algerian Basin (sw mediterranean): influence of mesoscale instabilities on the biomass and production of phytoplankton and bacterioplankton. *Deep Sea Research Part I: Oceanographic Research Papers*, 48(2):405–437.
- Nencioli, F., d’Ovidio, F., Doglioli, A. M., and Petrenko, A. A. (2011). Surface coastal circulation patterns by in-situ detection of Lagrangian coherent structures. *Geophys. Res. Lett*, 38.
- Obaton, D., Millot, C., d’Hières, G. C., and Taupier-Letage, I. (2000). The Algerian Current: comparison between in situ and laboratory data sets. *Deep-Sea Res.*, (47(11)):2159–2190.

- Okubo, A. (1970). Horizontal dispersion of floatable particles in the vicinity of velocity singularities such as convergences. *Deep-Sea Research*, (17):445–454.
- Olita, A., Ribotti, A., Sorgente, R., Fazioli, L., and Perilli, A. (2011a). SLA-chlorophyll-a variability and covariability in the Algero-Provençal Basin (1197-2007) through combined use of EOF and wavelet analysis of satellite data. *Ocean Dynamics* (2011), (61):89–102.
- Olita, A., Sorgente, R., Natale, S., Ribotti, A., Bonanno, A., and Patti, B. (2007). Effects of the 2003 European heatwave on the Central Mediterranean Sea: surface fluxes and the dynamical response. *Ocean Science*, 3(2):273–289.
- Olita, A., Sorgente, R., Ribotti, A., Fazioli, L., and Perilli, A. (2011b). Pelagic primary production in the Algero-Provençal Basin by means of multisensor satellite data: focus on interannual variability and its drivers. *Ocean Dynamics*. doi: 10.1007/s10236-011-0405-8.
- Pascual, A., Faugère, Y., Larnicol, G., and Le Traon, P.-Y. (2006). Improved description of the ocean mesoscale variability by combining four satellite altimeters. *Geophysical Research Letters*, (33):L02611.
- Pasquero, C. and A. Provenzale, A. B. (2001). Parametrization of dispersion in two dimensional turbulence. *Journal of Fluid Mechanics*, (439):279–303.
- Penven, P. and Echevin, V. (2005). Average circulation, seasonal cycle, and mesoscale dynamics of the Peru Current System: A modeling approach. *Journal of Geophysical Research*, (110).
- Pessini, F., Perilli, A., and Olita, A. (2016). Anticyclonic eddy energy and pathways in the Algerian Basin (1993-2014). EGU 2016.
- Pinardi, N. and Masetti, E. (2000). Variability of the large scale general circulation of the Mediterranean Sea from observations and modelling: a review. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 158(3–4):153 – 173. doi: 10.1016/S0031-0182(00)00048-1.
- Pinardi, N., Zavatarelli, M., Adani, M., Coppini, G., Fratianni, C., Oddo, P., Simoncelli, S., Tonani, M., Lyubartsev, V., Dobricic, S., and Bonaduce, A. (2013). Mediterranean Sea large-scale low-frequency ocean variability and water masses formation rates from 1987 to 2007: A retrospective analysis. *Progress in Oceanography*.

- Pinardi, N., Zavatarelli, M., Adani, M., Coppini, G., Fratianni, C., Oddo, P., Simoncelli, S., Tonani, M., Lyubartsevd, V., Dobricic, S., and Bonaduce, A. (2015). Mediterranean Sea large-scale low-frequency ocean variability and water mass formation rates from 1987 to 2007: A retrospective analysis. *Progress in Oceanography*, 132:318–332.
- Potter, R. A. and Lozier, M. S. (2004). On the warming and salinification of the Mediterranean outflow waters in the North Atlantic. *Geophysical Research Letters*, 31(1). doi: 10.1029/2003GL018161.
- Puillat, I., Taupier-Letage, I., and Millot, C. (2002). Algerian Eddies Lifetime can near 3 years. *Journal of Marine Systems*, (31(4)):245–259.
- Pujol, M.-I. and Larnicol, G. (2005). Mediterranean Sea eddy kinetic energy variability from 11 years of altimetric data. *Journal of Marine Systems*, 58:121–142.
- Renault, L., Oguz, T., Pascual, A., Vizioso, G., and Tintore, J. (2012). Surface circulation in the Alboran Sea (Western Mediterranean) inferred from remotely sensed data. *Journal of Geophysical Research: Ocean* (1978-2012), 117(C8).
- Ribotti, A. and Borghini, M. (2008). MedCO08 Cruise report. Technical report, CNR.
- Rio, M.-H., Poulain, P.-M., Pascual, A., Mauri, E., Larnicol, G., and Santoleri, R. (2007). A Mean Dynamic Topography of the Mediterranean Sea computed from altimetric data, in-situ measurements and a general circulation model. *Journal of Marine Systems*, (65):484–508.
- Robinson, A., Leslie, W., Theocharis, A., and Lascaratos, A. (2001). Mediterranean Sea Circulation . In Steele, J. H., editor, *Encyclopedia of Ocean Sciences*, pages 1689 – 1705. Academic Press, Oxford.
- Ruiz, S., Font, J., Emelianov, M., Isern-Fontanet, J., Millot, C., Salas, J., and Taupier-Letage, I. (2002). Deep structure of an open sea eddy in the Algerian Basin. *Journal of Marine Systems*, 33-34:179–195.
- Ruiz, S., Pascual, A., Garau, B., Faugère, Y., Alvarez, A., and Tintoré, J. (2009). Mesoscale dynamics of the Balearic Front, integrating glider, ship and satellite data. *Journal of Marine Systems*, (78):S3–S16.

- Schmitz Jr, W. J. (1996). On the world ocean circulation. Volume I. Technical report, Some global features/north atlantic circulation. DTIC Document.
- Schroeder, K., Ribotti, A., Borghini, M., Sorgente, R., Perilli, A., and Gasparini, G. (2008). An extensive western Mediterranean deep water renewal between 2004 and 2006. *Geophysical Research Letters*, 35.
- Siegel, D. A., Peterson, P., McGillicuddy, D. J., Maritorena, S., and Nelson, N. (2011). Biooptical footprints created by mesoscale eddies in the Sargasso Sea. *Geophys. Res. Lett.*, (38):L13608.
- Somot, S., Sevault, F., and Déqué, M. (2007). Transient climate change scenario simulation of the Mediterranean Sea for the twenty-first century using a high-resolution ocean circulation model. *Clim Dyn*, (27):851–879.
- Sorgente, R., Tedesco, C., Pessini, F., De Dominicis, M., Gerin, R., Olita, A., L. Fazioli and Di Maio, A., and Ribotti, A. (2016). Forecast of drifter trajectories using a Rapid Environmental Assessment based on CTD observations. *Deep-Sea Research II*, 133:39–53.
- Sparnocchia, S., Gasparini, G., Astraldi, M., Borghini, M., and Pistek, P. (1999). Dynamics and mixing of the Eastern Mediterranean Outflow in the Tyrrhenian Basin. *J. Mar. Sys.*, 20:301–317.
- Speich, S., Crépon, M., and Madec, G. (1996). A strait outflow circulation process study: the case of the Alboran Sea. *J. Phys. Oceanogr.*, 26(3):320–340.
- Taupier-Letage, I., Puillat, I., Millot, C., and Raimbault, P. (2003). Biological response to mesoscale eddies in the Algerian Basin. *J. Geophys. Res.*, (108(C8):3245).
- Temam, R. (1977). *Navier-Stokes equations. Theory and numerical analysis*. AMS Chelsea Publishing.
- Testor, P. and Gascard, J. C. (2005). Large scale flow separation and mesoscale eddy formation in the Algerian Basin. *Progress in Oceanography*, (66):211–230.
- Tintoré, J., Gomis, D., Alonso, S., and Parilla, G. (1991). Mesoscale dynamics and vertical motion in the Alboran Sea. *Journal of physical oceanography*, 21(6):811–823.

- Tintoré, J., Viudez, A., Gomis, D., Alonso, S., and Werner, F. (1994). Mesoscale variability and Q vector vertical motion in the Alboran Sea. In La Violette, P., editor, *Seasonal and interannual variability of the Western Mediterranean Sea, Coastal and Estuarine Studies*, volume 46, pages 47–71.
- Tintoré, J., Vizoso, G., Casas, B., Ruiz, S., Heslop, E., Renault, L., Oguz, T., Garau, B., Pascual, A., Martínez-Ledesma, M., Gómez-Pujol, L., Álvarez Ellacuría, A., Orfila, A., Alemany, F., Álvarez Berastegui, D., Reglero, P., Massuti, E., Vélez-Belchí, P., Ruiz, J., Gómez, M., Álvarez, E., and Manriquez, M. (2012). SOCIB: the impact of new marine infrastructures in understanding and forecasting the Mediterranean Sea. In Designing Med-SHIP: a Program for repeated oceanographic surveys. In Ed., F. B., editor, *CIESM Workshop Monographs*, Monaco.
- Vignudelli, S. (1997). Potential use of ERS and Topex/Poseidon altimeters for resolving oceanographic patterns in the Algerian Basin. *Geophys Res Lett*, (24(14)):1787–1790.
- Weiss, J. (1991). The dynamics of enstrophy transfer in two-dimensional hydrodynamics. *Physica*, (D 48):273–294.
- Wilson, C. and Adamec, D. (2002). A global view of bio-physical coupling from SeaWIFS and TOPEX satellite data, 1997–2001. *Geophys Res Lett*, (29(8)):1–4.