

Chapter 4

The Oceanographic and Climatic Context



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4.1 Introduction

The Alboran Sea is the westernmost sub-basin of the Western Mediterranean (WMED), being connected with the Atlantic Ocean through the Strait of Gibraltar. Therefore, it is the first region of the Mediterranean Sea receiving the Atlantic Water (AW) flowing through the Strait, from the nearby Gulf of Cadiz, and the last basin that the Mediterranean waters cross before exiting to the Atlantic Ocean. As a consequence of its location, the Alboran Sea is filled by a large number of water masses. On one hand, two Atlantic water masses, Surface Atlantic Water (SAW) and North Atlantic Central Water (NACW), can be distinguished, at least in the westernmost sector of the Alboran Sea (Naranjo et al. 2015). On the other hand, all the Mediterranean waters, both those formed in the WMED and in the Eastern Mediterranean (EMED), must eventually outflow (Millot 2009). Therefore, all these water masses should be present in the Alboran Sea. In fact, these water masses formed in the WMED can be clearly identified and their presence in the Alboran Sea has been described in the scientific literature. On the contrary, some of the water masses formed in the EMED can be distinguished in the Alboran Sea, whereas others have lost their signature.

The formations of the Mediterranean waters and their circulation are the result of the climatic conditions within the Mediterranean Sea, which is characterized by a freshwater deficit and a net heat loss through its surface. These conditions produce a thermohaline circulation that can be summarized in a very simple way as AW

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flowing eastwards at the surface layer, and Mediterranean waters flowing westwards at the intermediate and deep layers to finally outflow through the Strait of Gibraltar, being these currents modulated by the Coriolis force (Millot and Taupier-Letage 2005). This general circulation pattern is ultimately responsible for the circulation of the Alboran Sea, which has a very energetic dynamics at its upper layer, showing intense currents (Perkins et al. 1990), frontal areas, and mesoscale structures (Troupin et al. 2018; Olita et al. 2017; García-Lafuente et al. 1998; Tintoré et al. 1988).

The heat and water budget of the Mediterranean Sea can change on a large range of time scales, producing changes in the exchange through the Strait of Gibraltar and consequently on the properties of the water masses and their circulation patterns within the Mediterranean Sea and the Alboran Sea itself. Such time scales go from seasonal (Vargas-Yáñez et al. 2002), to inter-annual (Mihanovic et al. 2018; Renault et al. 2012), decadal and secular (Vargas-Yáñez et al. 2010a, b). The latter time scale is presumably linked to the current global warming process.

Besides this variability associated to the Mediterranean thermohaline circulation, the Alboran Sea circulation is influenced by changes in the wind and pressure fields that could alter its circulation at shorter (sub-inertial, several days to weeks) time scales. Finally, some of the shortest time scales affecting the circulation of the Alboran Sea are those associated to tidal phenomena, although these latter processes are of minor importance within the Mediterranean Sea. This circulation feature is mainly barotropic, affecting the whole water column, as internal tides, which have a large magnitude in the Strait of Gibraltar (Naranjo et al. 2014; Sánchez-Román et al. 2009) are of minor importance within the Alboran Sea (Vargas-Yáñez 1998; García-Lafuente et al. 1999).

In order to provide a brief description of the physical processes that determine the properties of different water masses and their circulation within the Alboran Sea and their time and spatial variability, this chapter is organized as follows. First, the climatic forcing, the formation of the different water masses and the thermohaline circulation of the Mediterranean Sea are described from a general perspective establishing the climatic and oceanographic context of the Alboran Sea. Then a more specific description of the water masses and their properties in the Alboran Sea are presented. Once the water masses that occupy the Alboran Sea have been described, their circulation is addressed. The first section is devoted to a brief description of the tidal currents which constitute a source of variability at short time scales. Then, the circulation of the different layers that form the Alboran Sea are analyzed. This analysis is decomposed into the upper layer, on one hand, and the intermediate and deep layers on the other. Although these two sections have been established according to the different depth levels considered, and not to the different time scales, it can be established that the time scales that affect the main traits of the Alboran Sea circulation, mainly in the upper layer, extend from the sub-inertial to the inter-annual, passing through the seasonal one. The last section is specifically devoted to long-term changes that affect the properties of the main water masses in the Alboran Sea and are very likely associated to climate change. This chapter ends with a summary and conclusions section.

Therefore the index of this chapter is as follows:

- Climate forcing, water mass formation processes and thermohaline circulation in the Mediterranean Sea.
- Water masses in the Alboran Sea.
- Currents and circulation in the Alboran Sea.
 - Tidal currents.
 - The upper layer circulation.
 - Intermediate and deep water circulation.
- Long-term variability.
- Summary and conclusions.

4.2 Climatic Forcing, Water Mass Formation Processes and Thermohaline Circulation in the Mediterranean Sea

The Mediterranean Sea is a concentration basin. When averaging over the whole basin and for a long period of time, the evaporation exceeds the freshwater supplies. Different works (Skiriris et al. 2018; Jordà et al. 2017; Criado-Aldeanueva et al. 2012; Schroeder et al. 2012; Sánchez-Gómez et al. 2011; Ludwig et al. 2009; Struglia et al. 2004; Boukthir and Barnier 2000) have attempted to estimate the terms involved in the freshwater budget of the Mediterranean Sea: Evaporation (E), Precipitation (P) and river runoff (R). Although there is a large dispersion between the different estimations (Jordà et al. 2017), for the purposes of the present review it could be stated that, if the Mediterranean was not connected to the Atlantic Ocean, the freshwater deficit would produce a decrease in the Mediterranean Sea level of between 0.5 and 1 m/year.

If the heat fluxes between the sea surface and the atmosphere are averaged for the whole Mediterranean surface, the result is a net heat flux from the Mediterranean to the atmosphere. In other words, the Mediterranean Sea losses heat through its surface. Once again it is not an easy task to estimate the average fluxes (Jordà et al. 2017; Criado-Aldeanueva et al. 2012; Ruiz et al. 2008; Bunker et al. 1982) but they can be reasonably considered to be between 5 and 7 W/m².

The Mediterranean water deficit and the net heat loss through its surface are compensated by the entrance of AW through the Strait of Gibraltar. The AW compensates for the net evaporation and it also produces a salt flux into the Mediterranean Sea. This is compensated by an Outflow of Mediterranean Water (MOW) as a deep current below the AW. The AW inflow is larger than the MOW to compensate for the net evaporation. At the same time, the net salt transport through Gibraltar must be zero in a theoretical equilibrium state. This balance is usually described by means of the Knudsen equations:

$$V_i = V_o + E \quad V_i S_a = V_o S_m$$

V_i is the annual volume of the inflow, V_o the outflow volume, S_a the salinity of the inflow of AW, and S_m the salinity of the MOW.

Finally, the AW temperature is higher than the temperature of the MOW and therefore the exchange through the Strait of Gibraltar produces a net heat flux that compensates for the losses through the sea surface.

As the AW progresses into the WMED through the surface, it becomes saltier because of the intense evaporation and mixing with resident waters. Part of it continues to flow into the EMED through the Sicily Channel. In summer, the AW which occupies the sea surface in the Levantine Basin, to the south of the Island of Rhodes and in front of the Israel and Syria coasts can reach salinity values close to 39.2 (Hecht et al. 1988). The effect on density of the salinity increase is compensated by the high summer temperatures. In winter, however, cold and dry continental winds produce the cooling of these salty waters which increase their density. A water column of 150 or 200 m is homogenized with temperature and salinity values of 15 °C and 39.1 (Lacombe and Tchernia 1972) and sinks to its equilibrium depth. After restratification of the upper water column, this water mass receives the name of Levantine Intermediate Water (LIW).

Part of the AW in the Levantine basin flows into the Aegean Sea where intermediate convection also occurs in winter. The result is an intermediate water, warmer and saltier than the LIW which is characterized by a salty and warm peak above the LIW on the θS diagrams. Although this water mass can be confused with the result of mixing between the LIW and the AW above, it is a distinctive water mass that receives the name of Cretan Intermediate Water (CIW, Millot 2013). Both LIW and CIW flow westwards decreasing their salinity and temperature by mixing with water masses above and below it. Although CIW has occasionally been distinguished at the Sicily Channel (Gasparini et al. 2005), once in the WMED the mixing of these intermediate waters originated in the EMED are simply considered in the literature as LIW (Millot 2013) and so will be done hereafter. When the LIW crosses the Sicily Channel towards the WMED, its temperature and salinity values are around 14 °C and 38.7 (Sammari et al. 1999). LIW describes a cyclonic circuit around the WMED. As it circulates within the WMED, the LIW continues reducing its temperature and salinity. When finally it gets into the Alboran Sea, these values are close to 13.1–13.2 °C and 38.5 (Vargas-Yáñez et al. 2017). Figure 4.1 shows a scheme of the LIW circulation within the WMED.

As shown in Fig. 4.1, the LIW flows over the continental slope of the northern WMED as part of the Northern Current. The general circulation in the Ligurian Sea and mainly in front of the Gulf of Lions is characterized by its cyclonic character. The cyclonic circulation produces the divergence of surface waters in the centre of such structures and the vertical movement of deep waters towards the surface. Therefore, LIW is closer to the sea surface in the centre of these cyclonic gyres, diminishing the water column stability. In winter, very cold and dry winds from the continent, cool the surface waters and increase their salinity in the Gulf of Lions area

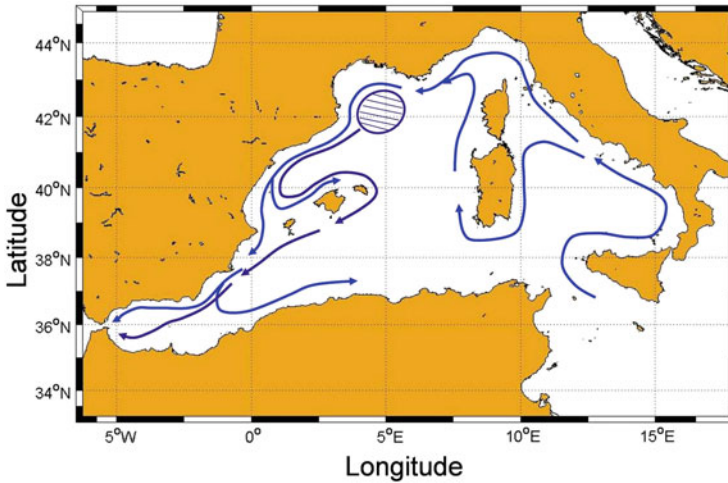


Fig. 4.1 Blue lines show the main pathways of LIW. Dark blue lines show the circulation of WMDW. The shaded area is the typical region of deep water formation in front of the Gulf of Lions

(centred around 42° N/ 5° E, Mihanovic et al. 2018; Lebeau-pin Brossier et al. 2017; Smith et al. 2008; Leamann and Schott 1991; MEDOC Group 1970; Anati and Stommel 1970). The result is the increase in the density of surface waters, which reach the potential density of LIW (~ 29.05). As a consequence, the water column mixes from the surface down to 500–600 m depth. This process is named pre-conditioning phase. At the end of the winter, the persistence of strong winds and storms are able to further cool and increase the salinity of these waters that get as dense as deep waters (~ 29.1). A violent mixing of the whole water column from the surface to 2500 m occurs (violent mixing phase). The temperature and salinity of the homogenized water column is around 12.8°C , 38.43 and this water mass is called Western Mediterranean Deep Water (WMDW). When severe winter conditions relax, the newly formed WMDW sinks and spreads around the WMED (spreading phase). Surface waters are replaced by new AW and the stratification of the upper part of the water column is restored. The WMDW follows a cyclonic circuit similar to the one followed by the LIW, but with the restrictions imposed by the WMED bathymetry. A fraction of the WMDW flows into the Tyrrhenian Sea through the Sardinian Channel where it sinks. These waters are mixed with those flowing through the Sicily Channel from the EMED. The eastern water masses taking part in this process are the LIW (Hopkins 1988) and also the Eastern Overflow Water (EOW), a mixture of LIW and the upper part of the Eastern Mediterranean Deep Water (Fuda et al. 2002). The result is the Tyrrhenian Dense Water (TDW). Finally, WMDW, TDW and LIW flow into the Alboran Sea and continue their paths towards the Strait of Gibraltar where they are mixed and outflow into the Atlantic Ocean.

According to the circulation scheme and the water mass formation processes depicted above, the WMED is usually considered a three-layer sea. The upper layer is occupied by the AW, and extends from the surface to 150 m. The intermediate

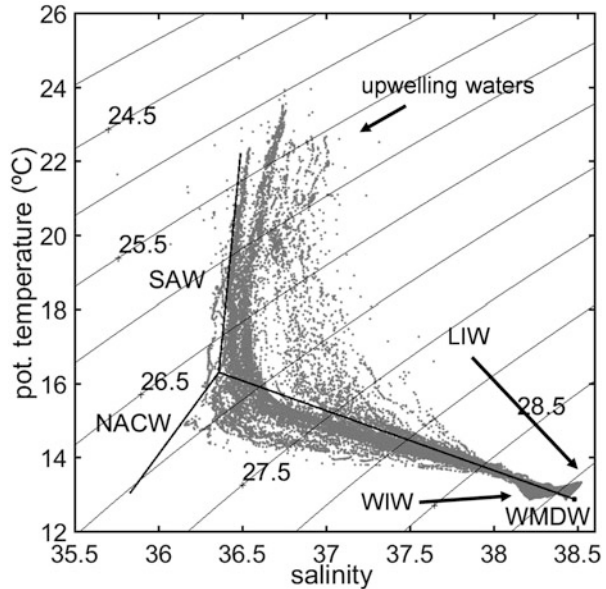
layer extends from 150 to 600 m and is occupied by the LIW. Finally, the deep layer goes from 600 m up to the sea bottom and is occupied by the WMDW and TDW. Nevertheless, the intermediate layer is not only occupied by water masses originated at the EMED, but also by others formed at the WMED. Under the influence of the strong northerly winds, in winter, the waters in the continental shelf of the Gulf of Lions and the continental shelf of the Balearic Sea can reach temperatures below 13 °C, and even close to 11 °C (Vargas-Yáñez et al. 2012a), much lower than those of the LIW and WMDW. As these waters are located over the continental shelf (200 m depth), under the influence of continental waters, and out of the influence of the LIW which flows at depths between 200 and 600 m, these very cold waters reach salinity values lower than those offshore. Therefore, a water mass with a temperature below 13 °C and salinity between 37.7 and 38.3 is formed, receiving the name of Western Intermediate Water (WIW). WIW sinks to its equilibrium depth, between 100 and 400 m, above the LIW (Juza et al. 2019; Vargas-Yáñez et al. 2012a; Pinot and Ganachaud 1999; Pinot et al. 1995; López-Jurado et al. 1995; López-Jurado 1990; Salat and Font 1987). Finally, Napolitano et al. (2019) have recently hypothesized that the Tyrrhenian Sea could also be a site of intermediate convection where Tyrrhenian Intermediate Water (TIW) would be formed. Nevertheless, according to the existent literature, this water mass has not been distinguished in the Alboran Sea.

4.3 Water Masses in the Alboran Sea

The upper layer of the Alboran Sea is filled by the AW that flows from the nearby Gulf of Cadiz through the Strait of Gibraltar. Therefore, the temperature and salinity values of the Alboran Sea upper layer are those of the waters in the Gulf of Cadiz, more or less modified. The degree of modification will depend on the distance to the Strait of Gibraltar and on the dynamics of the different areas within the Alboran Sea.

The Camarinal sill, between Point Paloma in the Spanish coast and Point Altares in Morocco, has a maximum depth of 300 m, imposing a restriction to the entrance of AW into the Alboran Sea. Data from MEDAR/MEDATLAS database (MEDAR Group 2002) have been collected from 1945 to 2000 to obtain the climatological profiles of temperature and salinity in the Gulf of Cadiz (García-Martínez et al. 2018), where the upper 300 m are occupied by the North Atlantic Central Water (NACW), characterized by the decrease of temperature and salinity with depth. In winter, temperature and salinity values at the sea surface are close to 16.3 °C and 36.4. At 300 m these values decrease to 13.1 °C and 35.8 (hereinafter, potential temperature will be written simply as θ for brevity). In summer, surface waters warm up to 22.23 °C with a slight increase of the salinity (36.49). These surface waters are named as Surface Atlantic Water (SAW). Both SAW and NACW can be clearly distinguished in the Western Alboran Sea (Naranjo et al. 2015) and are shown and labelled in Fig. 4.2 as straight black lines. This figure shows the θ S values for all oceanographic stations from the FE-92 cruise in September/October 1992 (Data obtained from MEDAR/MEDATLAS database, MEDAR Group 2002). This

Fig. 4.2 θ S diagrams for all oceanographic stations in FE-92 cruise covering the Alboran Sea



campaign has been chosen because it covers the whole Alboran Sea, with stations extending from 5.2° W to 0.13° W, and the main features of its circulation were clearly observable during the time of that cruise.

Figure 4.2 shows the different water masses already described in the previous section. Dots lying on the vertical line labelled as SAW correspond to the westernmost sector of the Alboran Sea where AW flows directly from the Strait of Gibraltar without modification. In some cases, dots are aligned around the NACW line, once again indicating no modification of the waters. The line extending from the base of the SAW to the dot labelled as WMDW represents the mixing line between Atlantic and Mediterranean waters. Waters on the left side of the θ S diagram, that is, on the Atlantic side, have salinity values around 36.5. The Mediterranean waters at the right side of the diagram (LIW, WMDW and TDW, not shown) have salinity values around 38.5 or less. Therefore, the mid-point between these two values, 37.5, is usually considered as the interface or separation layer between the AW, flowing to the east, and the Mediterranean waters flowing to the west. Those dots extending vertically, parallel to the SAW line, but displaced towards higher salinity values (~ 37) correspond to surface waters with a higher percentage of Mediterranean water. These are upwelling waters warmed by solar heating and heat fluxes from the atmosphere during summer.

The θ S values below the mixing line at the final part of the diagram correspond to the WIW with θ S values in the Alboran Sea lower than 13°C and salinity values between 38.1 and 38.2. This water mass is formed in the Northwestern Mediterranean and in the Balearic Sea and is advected to the south above the LIW and following its same pathway (Pinot and Ganachaud 1999; Pinot et al. 1995;

López-Jurado et al. 1995; López-Jurado 1990). The θ_S values above the mixing line show an absolute salinity maximum (>38.5) and a relative temperature maximum (>13.25 °C) that correspond to the LIW. WMDW is found below the LIW, filling the Alboran Sea to the sea bottom with θ_S values that range between 12.78 °C and 12.8 °C and between 38.42 and 38.43. Finally, since TDW is denser than LIW, but lighter than the WMDW it is located between these two water masses, and can thus easily be confused with the mixing line between LIW and WMDW (García-Lafuente et al. 2017).

In summary, AW, WIW, LIW, WMDW and TDW can be observed in the Alboran Sea and even in the Strait of Gibraltar (García-Lafuente et al. 2017; Naranjo et al. 2015; Millot 2009). Their spatial distribution depends on the dynamics and circulation of this basin and will be discussed in the next sections.

4.4 Currents and Circulation in the Alboran Sea

The currents in the Alboran Sea are mainly driven by the Mediterranean thermohaline circulation previously described, which is modulated by the Coriolis force, winds and bathymetry. As a result, there is a fast AW flow, usually referred to in the literature as the Atlantic Jet (AJ), flowing into the Alboran Sea through the Strait of Gibraltar. This AJ and its variability dominate the circulation of the upper 200 m of the Alboran Sea. Because of the freshwater deficit and heat losses in the Mediterranean Sea, there is a deep current that flows to the west below the AW. The position of the interface separating both the inflow and the outflow depends on the geographical location, decreasing from 250 at the western sector of the Strait of Gibraltar, to 75 m at its eastern limit (Bray et al. 1995). Nevertheless, these figures are strongly modulated by the tidal dynamics within the Strait (Naranjo et al. 2014, 2015).

The LIW, WMDW and TDW flow from 200 m depth to the sea bottom within the Alboran Sea to finally outflow to the Atlantic Ocean. The circulation of the intermediate and deep water masses is conditioned by the Coriolis force and bathymetric constrictions.

Besides this two-layer circulation scheme whose time variability is within the sub-inertial range, there are tidal currents with diurnal and semi-diurnal periodicity. Because of the periodic character of these currents they do not constitute an efficient mechanism for the net transport of water, salt, heat or any biochemical tracer in the Alboran Sea and for the rest of the Mediterranean, although a different situation could stand for the Strait of Gibraltar.

The tidal range and the intensity of tidal currents in the Mediterranean Sea are small if compared with the nearby Atlantic Ocean. Next section presents a brief description of their characteristics in the Alboran Sea. Then, the circulation of the upper layer of the Alboran Sea and its variability are addressed.

4.5 Tidal Currents

The tides in the Mediterranean Sea are a consequence of the astronomical forces directly acting on it, and the propagation of energy from the Atlantic Ocean through the Strait of Gibraltar. In a very simple way, it can be said that the tide in the WMED behaves as a standing wave with an amplitude node for sea surface elevation around $0\text{--}2^\circ$ E and maximum amplitudes in the Strait of Gibraltar and at the eastern limit of the Tyrrhenian Sea (Arabelos et al. 2011; Albérola et al. 1995). The Alboran Sea is located to the west of the nodal line and currents have a phase of 90° with respect to the sea surface, being zero for the high tide and increasing eastwards while sea level decreases. A simple explanation for this behaviour by means of a linear analytical model can be seen in García-Lafuente et al. (1994).

In the Alboran Sea, the main constituent is the M2 harmonic. Its amplitude decreases from 30 cm in the Strait of Gibraltar to 10 cm at Cape Gata (Arabelos et al. 2011, Albérola et al. 1995). The tidal currents associated to the M2 harmonic are of the order of 2 cm/s, increasing with depth to 4 cm/s, very likely because of the effect of topography on contracting streamlines (Albérola et al. 1995). More recently, observations of Lagrangian currents from drifters have evidenced energy peaks at the K1 (diurnal) and M2, S2 (semi-diurnal) frequency bands (Poulain et al. 2013).

Although the barotropic tide has a low amplitude in the Mediterranean Sea, it produces large internal tides in the Strait of Gibraltar which enhance mixing between the incoming AW and the outflowing Mediterranean Waters. As a result of these mixing processes, the long-term exchange between the Atlantic Ocean and the Mediterranean Sea is enhanced and the properties of the AW within the Alboran Sea are modified (Naranjo et al. 2014).

4.6 The Upper Layer Circulation

As already described, the AJ is a fast current of AW flowing through the Strait of Gibraltar into the Alboran Sea. Although the speed of the AJ can be modulated within the Strait by the tidal currents, its average value is around 1 m/s (Perkins et al. 1990).

Figure 4.3 shows the most common features of the Alboran Sea upper layer circulation. The circulation of the Alboran Sea is very complex and many different situations can be observed. Nevertheless, from a very simplistic point of view, two main different modes of circulation can be defined. The first one, probably the most frequently described in the scientific literature, is the two-gyre circulation mode (light grey lines in Fig. 4.3, Vargas-Yáñez et al. 2002). The second one is the coastal circulation mode (dark grey lines in Fig. 4.3, Vargas-Yáñez et al. 2002). In the first circulation mode, two anticyclonic gyres are well developed occupying both the Western and Eastern Alboran sub-basins (Western Alboran Gyre, WAG, and

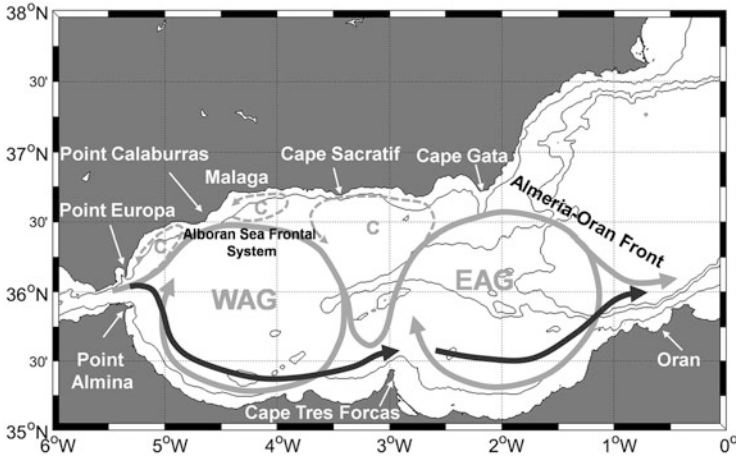


Fig. 4.3 Grey lines are a sketch of the two-gyres circulation mode. The Western Alboran Gyre (WAG), Eastern Alboran Gyre (EAG), the Alboran Sea Frontal System and the Almeria-Oran Front are labelled. The black line is a sketch of the coastal-circulation mode

Eastern Alboran Gyre, EAG respectively). In this case, the AJ flows into the Alboran Sea in a northeast direction, due to the orientation of the longitudinal axis of the Strait. It continues in this direction until approximately $4^{\circ} 30' W$, flowing close to the Spanish coast. Then it turns to the southeast impinging on the African coast to the west of Cape Tres Forcas. Part of the AJ then turns to the northeast, once again approaching to the Spanish coast, while another part re-circulates to the west along the Moroccan coast forming an anticyclonic gyre in the western sub-basin. The branch of the AW that turns to the northeast at Cape Tres Forcas describes a new anticyclonic gyre within the Eastern Alboran Sea.

The inner parts of the anticyclones are areas of convergence of surface waters. Therefore, AW sinks and the thickness of this layer increases within the gyres. The result is that the surface waters have a marked Atlantic character (low salinity values), and the interface between AW and Mediterranean waters, which can be identified as the 37.5 isohaline, deepens. The AJ surrounds the gyres. Its geostrophic adjustment produces the tilting of isopycnals and the elevation of deep waters to the left of the current (according to the sense of the movement, see Figs. 4.4, 4.5 and 4.6). As a consequence, strong temperature and salinity differences between the waters to the north and to the south of the jet can be observed. This thermohaline front extends all along the AJ from the Strait of Gibraltar to at least $1^{\circ} W$. It was named by Cheney and Doblar (1982) as the Alboran Sea Frontal System. When the EAG is well developed, the easternmost part of the frontal system extends from Cape Gata to Oran (Algeria), coinciding with the limits of the Alboran Sea. This frontal area creates a natural frontier between the AW recently advected into the Mediterranean Sea through the Strait of Gibraltar and the AW which has re-circulated within the WMED and, consequently, has a larger degree of modification. Although the Alboran Sea frontal system is a continuous feature, its eastern part has received a

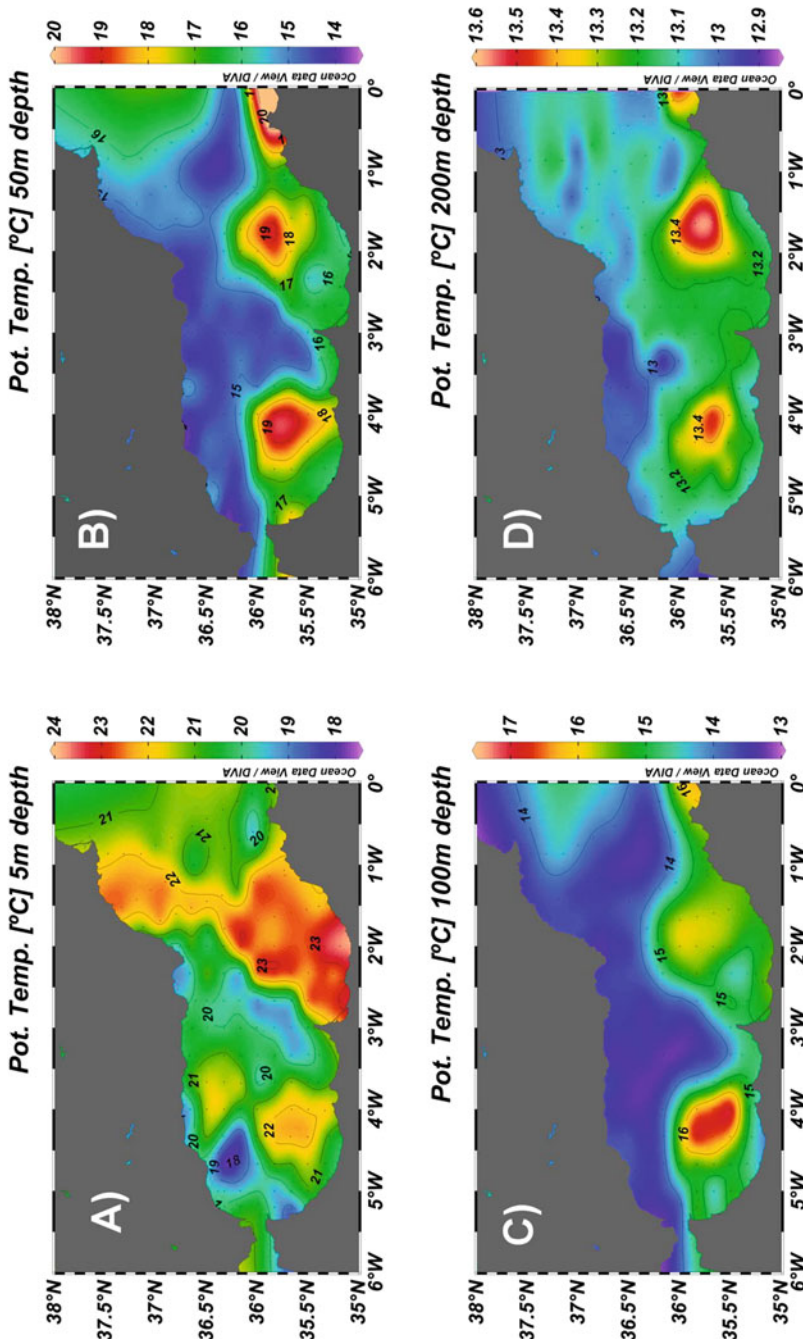


Fig. 4.4 Horizontal distributions of potential temperature at 5 m depth (a), 50 m (b), 100 m (c) and 200 m (d)

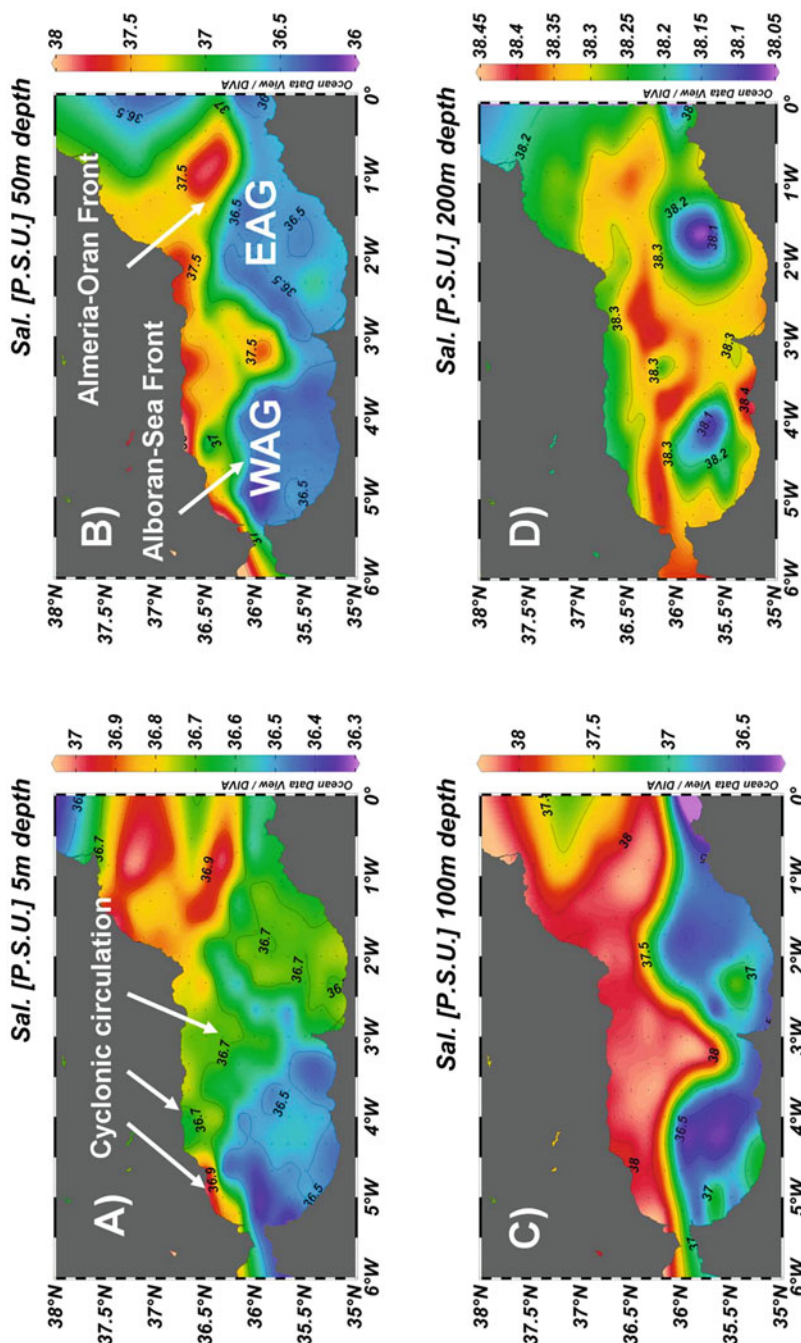


Fig. 4.5 Horizontal distributions of salinity at 5 m depth (a), 50 m (b), 100 m (c) and 200 m (d)

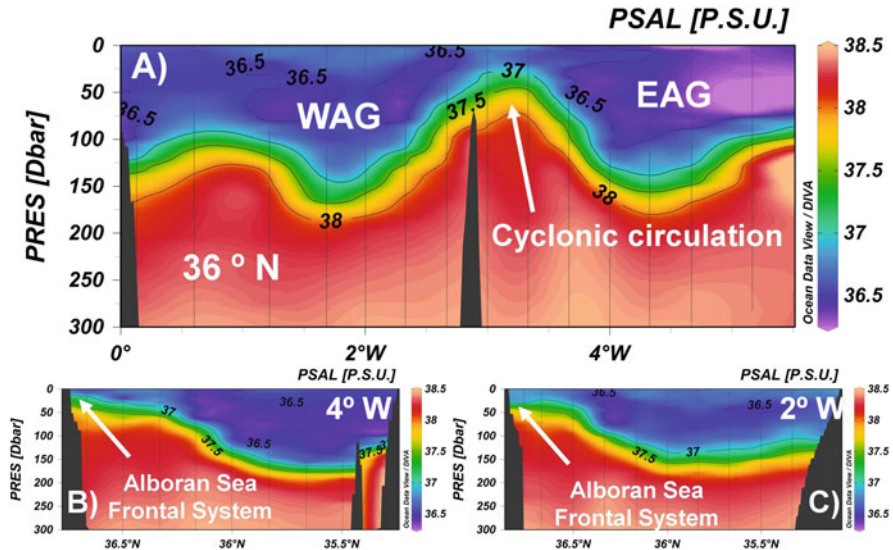


Fig. 4.6 (a) is a zonal salinity vertical section along 36° N. (b) and (c) are north-south salinity vertical sections along 4° W and 2° W, respectively

differentiated name and is usually referred to in the literature as the Almeria-Oran Front (Troupin et al. 2018; Olita et al. 2017; Tintoré et al. 1988).

The area between Point Europa and Point Calaburras (see Fig. 4.3) and the areas in front of Malaga Bay and between Cape Sacratif and Cape Gata, in the northern coast of the Alboran Sea, are frequently occupied by cyclonic circulation cells. These structures produce the divergence of surface waters at the inner part of the gyres and the upwelling of deep waters. The effect of the Alboran Sea frontal system and the cyclonic circulation areas is the presence at the sea surface or close to it, of waters saltier and cooler than the AW which is already flowing through the Strait of Gibraltar (see Fig. 4.2).

Figures 4.4 and 4.5 show the temperature and salinity horizontal distributions at 5, 50, 100 and 200 m depth. The data used correspond to the cruise FE-92 (MEDAR/MEDATLAS database). These distributions illustrate the two-gyre circulation mode and the generation of down and upwelling areas within the Alboran Sea.

Figures 4.4 and 4.5 show the presence of waters with a surface temperature higher than 22 °C and salinity values lower than 36.5 in the areas of the WAG and EAG. The position of the temperature and salinity frontal system is especially clear in the 50 m depth distribution. It is also clear the salinity increase and the low-temperature values in the areas between Point Europa and Point Calaburras and in the sector to the north of the frontal system, mainly in front of Malaga Bay and Cape Sacratif. These regions have been marked in Fig. 4.5a, b.

The vertical extension of the AW upper layer is also modulated by the different circulation structures. Figure 4.6a shows a zonal salinity section along 36° N. The

interface separating the AW from the Mediterranean waters is between 150 and 200 m at the centre of the anticyclonic gyres. It is shallower than 50 m close to $3^{\circ} 30' W$ coinciding with the cyclonic circulation area located in front of Cape Sacratif and to the north of the Alboran Sea frontal system. Figure 4.6b, c are north-south transects along $4^{\circ} W$ and $2^{\circ} W$. These figures also show the upward tilting of isohalines to the north, reaching depths lower than 50 m at the position of the Alboran Sea frontal system.

The circulation scheme described by means of Figs. 4.4, 4.5 and 4.6, and sketched with light grey lines in Fig. 4.3, is the most frequently described in the literature. Nevertheless, this circulation pattern is far from being stationary and it has a strong temporal variability.

One of the first descriptions of the water masses and geostrophic circulation for the whole Alboran Sea, was the one made by Lanoix (1974) using data from a summer cruise in 1962. In his work, the WAG was fully developed, while the EAG was absent and the AJ flowed in the eastern Alboran sub-basin along the African coast. It is very likely that because of this early work, the WAG was initially considered as a permanent feature of the Alboran Sea while the EAG was considered a more elusive circulation pattern. The use of thermal infrared images, mainly from the early 1980s, revealed that both the WAG and EAG could disappear and it could be established that the disappearance of any of them had the same frequency (Heburn and Laviolette 1990). Other works, using SST images and Empirical Orthogonal Function decomposition showed that the dynamics of the Alboran Sea is very complex and has a strong temporal variability on a sub-inertial scale (Baldacci et al. 2001).

Renault et al. (2012), Flexas et al. (2006), Vélez-Belchí et al. (2005), Vargas-Yáñez et al. (2002) observed that the circulation of the Alboran Sea could develop more complex structures. In some situations, the AJ does not surround the WAG. Instead of it, the AJ impinges on the WAG and then turns to the right flowing close to the African coast. The AJ finally develops a new anticyclonic gyre that pushes and displaces the “old” WAG. During several days or weeks, three anticyclonic gyres can coexist within the Alboran Sea, until a new two-gyre system is re-established. In some cases a more dramatic change can be observed. The AJ, instead of flowing in a northeast direction after getting out of the Strait of Gibraltar, turns to the southeast, surrounding Point Almina (black lines in Fig. 4.3), and then flows along the African coast. In this case, the northern shore of the Alboran Sea is not affected by the AW and its temperature/salinity takes lower/higher values. Renault et al. (2012), using altimetry data, classified the monthly circulation patterns from 1993 to 2010. The different situations described included the existence of one anticyclonic gyre (the western one), two gyres, three gyres, and a coastal jet. The two-gyre circulation situation and the coastal circulation mode are depicted in Fig. 4.3. Several hypotheses have been proposed for explaining these changes in the direction of the AJ and the migration or disappearance of the Alboran Sea gyres. These hypotheses include changes in the AJ velocity or blocking of the AJ caused by the size increase of the WAG (Flexas et al. 2006; Velez-Belchi et al. 2005; Bormans and Garrett 1989). In

any case, after their disappearance, the development of the WAG and EAG requires several weeks or even months (Vargas-Yáñez et al. 2002).

Besides the WAG migration episodes and the transition to the coastal circulation mode, other processes with shorter spatial scales can be observed at the sub-inertial scale (with periods of several days). These processes would include the north-south oscillations of the AJ (Sarhan et al. 2000) which can induce the upwelling of Mediterranean waters at the northern sector of the Alboran Sea, and the advection of mesoscale structures (~20 km diameter) around the anticyclonic gyres (García-Lafuente et al. 1998; La Violette 1984).

The circulation of the upper layer of the Alboran Sea seems to be also subject to a seasonal variability, although the studies and information concerning this time scale are scarce. García-Martínez et al. (2018) and Vargas-Yáñez et al. (2017) have revealed the existence of a salinity seasonal cycle in the continental shelf and slope waters of the northern coast of the Alboran Sea. This cycle exhibits lower salinity values and a higher influence of the AW in autumn. Salinity would reach maximum values during winter and spring. It has been hypothesized that this cycle could be linked to the wind seasonal cycle in the Alboran Sea. Westerly winds are the prevailing ones during winter and spring. This would favour wind-induced upwelling at the northern coast of the Alboran Sea. During summer, the wind intensity decreases considerably and the easterly winds are more frequent. This could explain the observed decrease of salinity during summer. Nevertheless, westerly winds recover during autumn when the salinity reaches its minimum value in the northern waters. This phase difference between winds and salinity could be linked to the different time resolution of wind and salinity time series used, or to a recent extension of the summer season during the 1990s and beginning of the twenty-first century, when TS data were collected in the mentioned literature (García-Martínez et al. 2018; Vargas-Yáñez et al. 2017). Another possibility is that the Alboran Sea anticyclonic gyres have a larger size and affect in a much more direct way to the Spanish coast during summer and autumn.

The transport through the Strait of Gibraltar and the AJ speed is a factor that could affect the development of the Alboran Sea gyres (Velez-Belchí et al. 2005). Therefore, it is important to consider the existence of a seasonal cycle for the exchange through Gibraltar (García-Lafuente et al. 2007), with maximum outflow in April. These authors relate this increase of the outflow to the formation and replenishment of deep waters during winter. Although it is very speculative for the moment, we suggest that the seasonal changes in the volumes exchanged through Gibraltar could influence the circulation of the Alboran Sea.

4.7 Intermediate and Deep Water Circulation

The circulation of intermediate and deep waters in the Alboran Sea is not as well known as that of the upper layer. Much of the information concerning the upper layer circulation comes from geostrophic calculations. These estimations require the

knowledge of a no motion reference level which is usually considered as the 200 or 300 dbar level. Bryden and Stommel (1982) considered that the anticyclonic circulation of the upper layer extended to the intermediate and deep layers below, and the sea bottom should be used as the reference layer for geostrophic calculations. Nevertheless, the velocity of the currents at the deep layers is of the order of a few centimetres per second, while the AW velocities can reach 1 m/s. Therefore, the error induced by the selection of the no motion reference level does not affect the description of the main features of the upper layer circulation. In the case of the LIW, WMDW and TDW circulation, the low-velocity values make it difficult to extract conclusions from geostrophic calculations. Our knowledge about the pathways followed by these water masses is inferred from their θ_S values and from direct measurements using current meters or drifters.

Lanoix (1974) considered that the LIW is divided into three branches within the Alboran Sea. One of them would flow to the north because of the Coriolis force. The other two branches flow to the north and south of the Alboran Island. Auffret et al. (1974) concluded that the intermediate and deep waters flow close to the Spanish coast. These authors, once again, invoked the Coriolis force as the responsible mechanism. Bryden and Stommel (1982) deployed a current meter at the Moroccan continental slope close to the Strait of Gibraltar (between 4° and 5° W). The instrument depth was 500 m and the average speed was 4.6 cm/s, directed to the Strait of Gibraltar, along the direction of the isobaths. According to these results and using hydrographic measurements, these authors considered that the WMDW flows along the African slope, uplifting as it approaches the Strait of Gibraltar. The presence of the LIW was also stronger at the central and southern parts of the Alboran Sea. The results concerning the behaviour of the WMDW were confirmed by Gascard and Richez (1985) using free drifters deployed between 600 and 800 m depth at the Moroccan continental slope. The average speeds found in this work were around 4 cm/s with peaks that could reach 12 cm/s. Kinder (1984) and Parrilla et al. (1986) analyzed time series from several current meters deployed in the central and northern sectors of the Western Alboran Sea. At 540 m, the currents were directed towards the Strait of Gibraltar with average speeds between 1 and 3 cm/s. According to these results, the authors concluded that the LIW does not follow an anticyclonic circuit, but flows as a slow current (1–2 cm/s) across the central and northern parts of the Alboran Sea, not being so clear the LIW behaviour in the southern sector. Concerning the deep water circulation, results in Parrilla et al. (1986) coincide with previous ones and show that the WMDW flows in an SW direction to the north of the Alboran Island because of bathymetric constrictions. Then it flows along the Moroccan slope uplifting to 400–500 m as it approaches the Strait of Gibraltar. According to these authors, it is not clear if the WMDW partially recirculates anticyclonically in the northern sector of the Alboran Sea. More recently it has been accepted that the deep currents in the Alboran Sea that finally outflow through the Strait of Gibraltar because of Bernoulli's aspiration (Kinder and Bryden 1990; Kinder and Parrilla 1987), are not formed just by WMDW, but they also have an important contribution from TDW (Naranjo et al. 2015; Millot 2009).

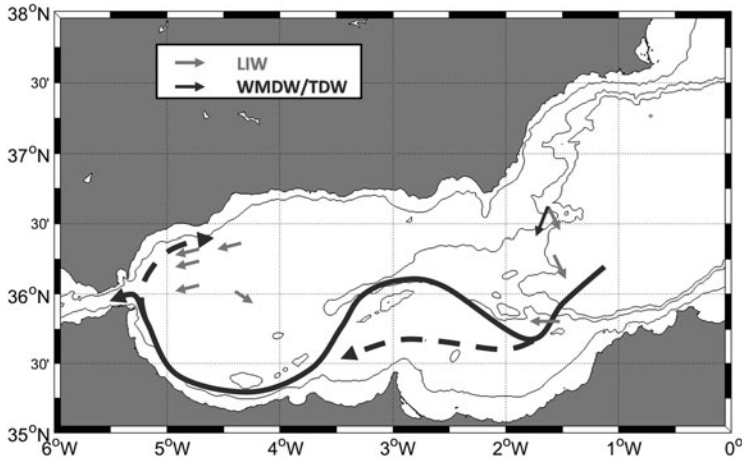


Fig. 4.7 Some features of the intermediate and deep circulation in the Alboran Sea. The dark line is a sketch of the WMDW/TDW circulation within the Alboran Sea. Dashed lines are used when some controversy exists in the literature. The grey arrows show the average current direction for the LIW estimated from current meters or drifters at the 500–700 m depth range. A black arrow shows the average direction for the deep layer (>1000 m) from one of the current meter measurements

Current measurements in the Alboran Sea (Fabres et al. 2002) show a westward current at 470 and 974 m depth at the northwestern sector of the Alboran Sea ($4^{\circ} 15.4' W$, $36^{\circ} 14.4' W$). The average velocity in this case was between 3.7 and 5 cm/s, with peaks of 22 cm/s close to the sea bottom. Sánchez-Vidal et al. (2005) analyzed three lines of current meters at a section at the eastern limit of the Alboran Sea ($1^{\circ} 30' W$). These lines were located at $36^{\circ} 40.5' N$, $36^{\circ} 13.1' N$ and $35^{\circ} 55.5' N$. At 680 and 645 m depth, the average current was directed to the SE in the northern and central lines. The deep current meters at 1190 m at the northern line and at 1170 and 2210 m at the central line also showed a SE average direction. The average velocities ranged between 2 and 4 cm/s. Currents at 510, 1050 and 2070 m at the southern line were directed to the West (see Fig. 4.7).

Figure 4.7 attempts to sketch the mean features of the WMDW/TDW circulation, according to the review presented above. For the LIW, discrepancies between different works prevent us from proposing a circulation scheme. Average directions from direct observations using current meters or drifters in the depth range 500–700 m are included. Black lines correspond to the WMDW/TDW circulation. Dashed lines are used when the works reviewed do not show conclusive results as could be the case for the recirculation in the northwestern sector of the Alboran Sea. According to results from numerical models in Parrilla et al. (1986), the WMDW would flow to the south of the Alboran Island. Nevertheless, Vargas-Yáñez et al. (2002) found that the average current between the Alboran Island and Cape Tres Forcas at 770 m depth was close to zero. For this reason this branch of the WMDW/TDW is presented using dashed lines. The grey arrows show the average directions

for the 500–700 m layer from the works: Fabres et al. (2002), Sanchez-Vidal et al. (2005), Parrilla et al. (1986) and Kinder (1984).

As already stated, all the Mediterranean waters must finally get out of the Mediterranean Sea. The contribution of each water mass to the Mediterranean outflow is variable and our perception about it has changed over the last decades. Initially, it was assumed that most of the outflow was made of LIW. Kinder and Parrilla (1987) showed that deep waters would also contribute to the outflow as they were sucked by the swift Mediterranean current within the Strait (Bernoulli's aspiration). More recently, García-Lafuente et al. (2017) have shown that the proportion of the different water masses contributing to the outflow could be variable and dependent on the circulation pattern in the upper layer of the Alboran Sea. Well-developed anticyclonic gyres would help to evacuate deep water masses, whereas a coastal mode circulation would inhibit their outflow, favouring the flow of LIW.

4.8 Long-Term Variability

Since mid-1980s, many works have revealed changes in the temperature and salinity of the water masses of the WMED. Lacombe et al. (1985) compared the results from different campaigns carried out during the twentieth century and concluded that the WMDW had increased its potential temperature and salinity from 12.66 °C/38.38 to 12.712 °C/38.406 from 1909 to 1977. The warming and salinification of the WMDW were confirmed by Bethoux et al. (1990) who considered that the warming of the Mediterranean waters was the result of the climate change affecting the world oceans. Leamann and Schott (1991) and Rohling and Bryden (1992) also observed the warming and salting of the WMDW and reported the salinity increase of the LIW. According to these authors, the LIW salinity increase was the result of the damming of the river Nile and of those rivers draining into the Black Sea. The salinity increase of the LIW would be the cause for the warming of deep waters. As the LIW takes part in the WMDW formation, saltier waters would reach the deep water density with temperature values higher than those from the beginning of the twentieth century. Krahnemann and Schott (1998) detected positive linear trends for the temperature and salinity of the WMDW, but not for the LIW. These authors considered that the warming of deep waters was caused by the salinity increase of the AW, associated with the damming of the river Ebro.

Vargas-Yáñez et al. (2010a, b, 2012b, 2017) showed that the WMDW had increased its temperature and salinity along the second half of the twentieth century and that the LIW had increased its salinity. These authors showed that the changes in the WMDW were robust, and were not sensitive to the data analysis methods. On the other hand, the LIW results were influenced by the methodology used for the construction of the annual time series. Nevertheless, more recent works have clearly shown the temperature and salinity increase of LIW in the Sicily Channel, at least from 1992 (Schroeder et al. 2017).

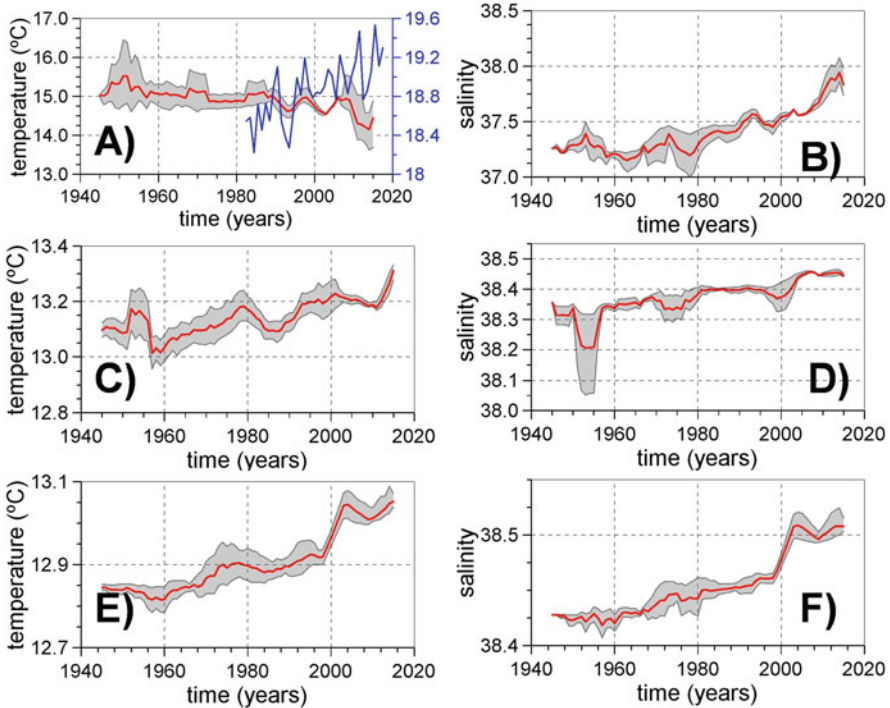


Fig. 4.8 Time series for SST and potential temperature and salinity at the upper, intermediate and deep layers of the Alboran Sea. (a) Blue line is the Sea Surface Temperature obtained from satellite data averaged for the Alboran Sea. Red line is the annual time series of potential temperature for the upper layer of the Alboran Sea (0–150 m). The shaded grey area in all panels represents the uncertainty associated to the different data analysis methods. (b) Red line is the annual salinity time series for the upper layer of the Alboran Sea. (c) and (d) are respectively the same as (a) and (b) for the intermediate layer (150–600 m) and (e) and (f) are for the deep layer (600 m to the sea bottom)

The sensitivity of the results to the data processing methodology seems to be caused by the data scarcity. Llasses et al. (2015), Jordà and Gomis (2013), Beuquier et al. (2010) showed that the oceanographic data available during the twentieth century and the existing monitoring programs were not adequate for the detection of temperature and salinity long-term trends at the different layers of the WMED. Vargas-Yáñez et al. (2010a, b, 2017) pointed out that the detection of trends in the upper layer of the WMED was not possible because of the data scarcity and the high temporal variability at short time scales, but considered that the existence of warming trends in the deep waters could not be explained only on the basis of the salinity increase of the AW and/or LIW. Garcia-Martinez et al. (2018) showed by means of a simple box model that the salinity increase of the AW and LIW, which contribute to the WMDW formation, could partially explain its warming, but the temperature increase of the upper layer was also necessary to explain the observed trends. The use of SST data from radiometers operated from satellites has shown

that, at least since the beginning of the 1980s, the surface temperature of the WMED has warmed with linear trends higher than $1\text{ }^{\circ}\text{C}/100\text{ year}$ (Skliris et al. 2011; Nikjaer 2009).

Figure 4.8 shows the evolution of the temperature and salinity for the upper (0–150 m), intermediate (150–600 m) and deep (600 m bottom) layers for the Alboran Sea. These time series have been constructed using data from MEDAR/MEDATLAS (MEDAR 2002) database and from the monitoring program RADMED, operated by the Spanish Institute for Oceanography (Lopez-Jurado et al. 2015).

The intermediate layer of the Alboran Sea (Fig. 4.8c, d) has increased its temperature and salinity at rates of $0.22 \pm 0.05\text{ }^{\circ}\text{C}/100\text{ year}$ and $0.24 \pm 0.04/100\text{ year}$. The linear trends estimated for the deep layer of the Alboran Sea are $0.30 \pm 0.04\text{ }^{\circ}\text{C}/100\text{ year}$ and $0.13 \pm 0.01/100\text{ year}$ for the temperature and salinity, respectively. The salinity of the upper layer has increased at a rate of $0.81 \pm 0.11/100\text{ year}$. Nevertheless, no warming is observed for the upper layer from in situ data. This latter result seems to be the consequence of the data scarcity and the strong variability of the surface layer. If satellite data from 1982 to 2017 are considered, there is a clear positive trend of $2.1 \pm 0.7\text{ }^{\circ}\text{C}/100\text{ year}$ which is coincident with the results obtained in other areas of the Mediterranean Sea (Nikjaer 2009) and with the upper layer warming of the world ocean (Levitus et al. 2012).

4.9 Summary and Conclusions

The main water masses and their circulation within the Alboran Sea are the results of the exchange between the Mediterranean Sea and the Atlantic Ocean through the Strait of Gibraltar. This exchange is the consequence of the freshwater deficit and the heat losses to the atmosphere in the Mediterranean Sea, but is also conditioned by the geometry and the intense mixing within the Strait, associated to internal tides.

The intermediate and deep layers of the Alboran Sea are occupied by intermediate waters of both Eastern (LIW) and Western (WIW) origin, and by deep waters: WMDW and TDW. These water masses have a slow circulation within the Alboran Sea with velocities around a few cm/s. Their pathways are not very clear, but it seems that the LIW flows preferentially to the north of the basin, forced by the Coriolis force, whereas WMDW and TDW flow close to the African coast at the Western Alboran Sea, because of topographic restrictions, and then they are uplifted by Bernoulli's aspiration to finally outflow through the Strait of Gibraltar.

The upper layer of the Alboran Sea is filled by waters of Atlantic origin: SAW and NACW. This layer occupies the upper 150–200 m and has a very energetic dynamics. A frontal thermohaline system is associated with the fast Atlantic Jet (AJ), which describes anticyclonic and cyclonic structures. The circulation scheme of this upper layer can present different situations: two anticyclonic gyres at the western and eastern Alboran Sea sub-basins, only one anticyclonic gyre at the western sub-basin,

three anticyclonic gyres, and a coastal mode circulation with the AJ flowing close to the African coast. These different circulation patterns do not only affect the Alboran Sea itself, but also influence the water exchange through Gibraltar. The two-gyre circulation system would favour the outflow of deep Mediterranean waters (WMDW and TDW) whereas the coastal mode circulation would favour the LIW outflow.

Several cyclonic gyres are frequently found in front of the northern coast of the Alboran Sea. These structures, mainly between Point Europa and Calaburras and in front of Malaga Bay and Cape Sacratif are responsible for the upwelling of sub-surface waters.

The different circulation schemes briefly depicted above are subject to time variability at sub-inertial, seasonal and inter-annual time scales. Long-term changes in the temperature and salinity of the water masses that fill the Alboran Sea have also been observed since, at least, mid-twentieth century, showing warming and salting of the whole water column.

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Chapter 5

A Geological History for the Alboran Sea Region



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