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Ocean Science

Salinity in the Sicily Channel corroborates the role of the Adriatic–Ionian Bimodal Oscillating System (BiOS) in shaping the decadal variability of the Mediterranean overturning circulation

M. Gačić[1], K. Schroeder[2], G. Civitarese[1], S. Cosoli[1], A. Vetrano[2], and G. L. Eusebi Borzelli[1]

[1]Istituto Nazionale di Oceanografia e di Geofisica Sperimentale – OGS, 34010 Sgonico (Trieste), Borgo Grotta Gigante 42/c, Italy
[2]Istituto di Scienze Marine – ISMAR, Consiglio Nazionale delle Ricerche (CNR), Arsenale – Tesa 104, Castello 2737/F, 30122 Venice, Italy/Forte Santa Teresa, 19032, Lerici (SP), Italy

Correspondence to: M. Gačić (mgacic@ogs.trieste.it)

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Abstract. Previous studies have demonstrated that the salinity in the Levantine basin depends on the intensity of the Atlantic water (AW) inflow. Moreover, its spreading eastward (to the Levantine basin) or northward (to the Ionian Sea) is determined by the Ionian circulation pattern, i.e. by the Adriatic–Ionian Bimodal Oscillating System (BiOS) mechanism. The aim of this paper is to relate salinity variations in the Levantine basin to the salt content variability in the core of the Levantine Intermediate Water (LIW) passing through the Sicily Channel (SC) and its possible impact on the Western Mediterranean Transition – WMT (i.e. the sudden salinity and temperature increase in the deep layer of the Algero-Provençal subbasin occurring since 2004). From the historical data set MEDAR/MEDATLAS in the Levantine and northern Ionian, we present evidence of decadal occurrences of extreme salinities associated with the varying influx of AW over the last 60 yr. Furthermore, we show that the salinity variations in the two subbasins are out of phase. High-salinity episodes in the Levantine are a pre-conditioning for the potential occurrence of the events like the Eastern Mediterranean Transient (EMT). Cross-correlation between the salinity time series in the Levantine basin and in the SC suggests that the travel time of the LIW is between 10 and 13 yr. Comparing the timing of the salinity increase associated with the WMT and the salinity in the LIW core in the SC, we estimate that the total time interval needed for the signal propagating from the Levantine to reach the deep mixed layers of the Algero-Provençal subbasin is about 25 yr. We also showed that the extra salt input from the eastern Mediterranean contribute up to about 60 % to the salt content increase in the bottom layer of the western Mediterranean.

1 Introduction

The Mediterranean Sea (MS) (Fig. 1) consists of two connected mid-latitude basins, the Western and the Eastern Mediterranean (WM and EM, respectively) and is characterised by a limited exchange with the Atlantic Ocean. The thermohaline circulation of the MS is generally described as an open basin-wide cell, resulting in the gradual salinification of surface water of Atlantic origin (AW) while propagating eastward, and in its transformation into LIW. In addition, there are two closed secondary cells, one in the EM and the other in the WM, which involve the transformation of surface and intermediate water into eastern and western Mediterranean deep waters (EMDW and WMDW, respectively).

The WMDW forms in the Gulf of Lion and spreads over the entire basin (Robinson et al., 2001). In the EM the deep water formation area is situated in the Southern Adriatic (SA), where the Adriatic Deep Water (AdDW) originates. The SA is located outside the main subbasin, and is connected with the rest of the EM through the Otranto Strait (80 km wide, with a sill depth of about 800 m). The AdDW spreads into the Ionian abyss and represents the main

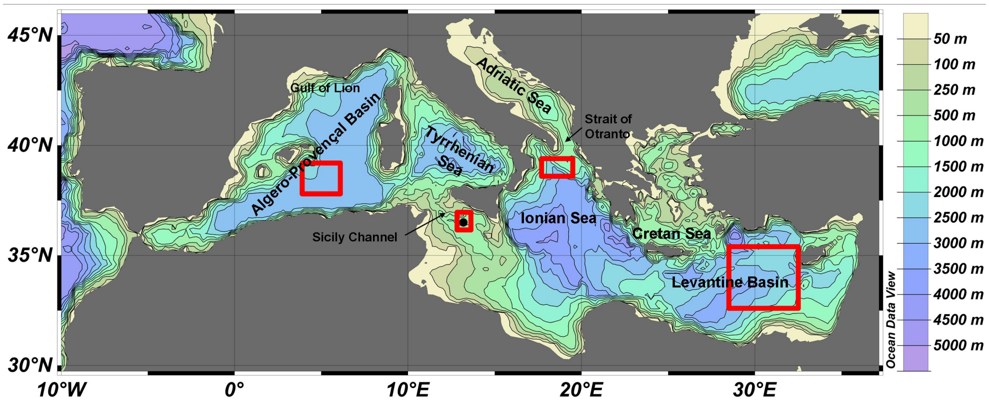

Fig. 1. Map of the Mediterranean Sea. Areas where the mean salinity values were calculated are delimited by continuous red lines. CTD measurement site in the Sicily Channel is denoted by a black dot.

component of the EMDW which occupies the EM deep layer. During the early 1990s, the deep water formation area switched from the SA to the Cretan Sea. This event, known as the EMT (see Roether et al., 1996), resulted in a series of changes involving the entire water column (see e.g. Borzelli et al., 2009).

The open cell connects the WM and the EM, transporting two water masses in opposite directions: the AW eastward and the LIW westward from the formation site (Rhodes Gyre) toward the SC and the WM. The role of the LIW is particularly important since it is the preconditioning agent for the formation of both the AdDW and WMDW. After the recent discoveries of the EMT, and of the BiOS (see Gačić et al., 2010), the concept of stationarity of the thermohaline cells of the EM is no longer applicable. The EMT showed that, under favourable conditions, the dense water formation area can switch from the Adriatic to the Cretan Sea, with a consequent change in the EMDW properties and the restructuring of the entire thermohaline cell. Furthermore, it has been demonstrated that the upper layer circulation in the Ionian (Borzelli et al., 2009; Gačić et al., 2010), the thermohaline properties of the AdDW-EMDW (Gačić et al., 2010), and the salt distribution over the EM (Gačić et al., 2011) are interconnected through the BiOS, a feedback mechanism which is briefly summarised here. During the last 25 yr it has been observed that the upper-layer circulation in the Ionian reversed on decadal time scales, from anticyclonic to cyclonic and vice versa. Reversals result in two different AW pathways in the Ionian. The anticyclonic Ionian circulation mode brings fresher AW into the northern Ionian interior, diminishing the salt content. Consequently, the result of this circulation pattern is the inflow of relatively fresh Ionian waters into the Adriatic, increasing the buoyancy of the water column and obstructing the vertical convection. At the same time the anticyclonic mode weakens the spreading of the AW into the Levantine subbasin, resulting in an increase in the salinity of the entire basin including the Cretan Sea. Therefore, the anticyclonic mode represents a preconditioning mechanism for the dense water formation processes in the Aegean and eventually for EMT-like events (Demirov and Pinardi, 2002; Gačić et al., 2011). Conversely, the cyclonic Ionian circulation mode favours the spreading of the Levantine high-salinity waters in the northern Ionian interior and consequently into the southern Adriatic. Thus as opposed to the Ionian anticyclonic circulation, the Adriatic is more prone to vertical convection and dense water production. AW, on the other hand, reaches the Cretan Passage via the shortest pathway, diluting the upper layer of the Levantine and Cretan Sea to a greater extent than in the anticyclonic mode (Gačić et al., 2011).

The SC, a topographically complex and dynamically active region situated between southern Sicily and the Tunisian–Libyan coast, is composed of a deep interior basin (maximum depth 1700 m) bounded by sills at the western and eastern edges. The western part of the channel, between Sicily and Tunisia, represents the shallowest passage (about 450 m maximum depth) as well as the narrowest (140 km). It is already known (Artale et al., 2006) that the volume and the thermohaline properties of the water flowing through the SC modulate the decadal variability of the Mediterranean thermohaline circulation.

From a dynamic point of view the SC is a two-layer system, with the topography playing an important role. The upper layer (about 200 m thick) is occupied by the AW flowing eastward, and is dominated by intense mesoscale variability (Astraldi et al., 1999; Ben Ismail et al., 2012). In the channel the AW follows different routes, flowing along the Tunisian side (the freshest vein) or crossing the bank in the northern part of the Channel (Vetrano et al., 2004). The lower layer is composed of LIW and of the upper part of the EMDW (the transitional EMDW, or tEMDW), both flowing towards the western basin. Topographic steering seems to prevail in this subsurface layer, maintaining a fairly constant direction of the deep and bottom currents. Due to the Coriolis effect, the tEMDW crosses the deep channel on the Sicilian side (Millot, 1999). Many studies provide information about water exchange rate (Manzella et al., 1988; Astraldi et al., 1999; Vetrano et al., 2004; Ben Ismail et al., 2012), indicating an annual mean of ~ 1 Sv.

One of the key factors controlling the deep water formation in the Gulf of Lion and in the northern part of the WM in general is the salt distribution over the water column and, more specifically, the salinity in the incoming LIW (Lacombe et al., 1985; Schroeder et al., 2010). Therefore, the thermohaline properties of the bottom layer of the WM are in part determined by the salt brought by the LIW from the EM. The increase of the salt input by the LIW from the eastern to the western basin makes the western basin more prone to production of warmer and saltier deep waters. In addition, Roether and Lupton (2011) showed EMT-related enhanced mixing of the waters overflowing the Sicily Strait into the Tyrrhenian Sea deep waters due to stronger salt input from the EM.

We expect that the thermohaline properties of the intermediate water (mainly LIW) entering the WM through the SC should vary following the salt redistribution operated by the BiOS between the EM subbasins. As already mentioned, because the LIW salt content is a preconditioning agent for the convection in the Gulf of Lion (Lacombe et al., 1985; Grignon et al., 2010), variability in its thermohaline properties should influence the amount and the characteristics of the WMDW produced. Therefore, the WM deep circulation and thermohaline properties of deep water masses are modulated by the thermohaline properties of the water entering the basin from the Ionian, as already demonstrated in a number of studies (Artale et al., 2006; Wu and Haines, 1996). A continuous increase in LIW salinity would result in production of warmer WMDW, and this was indeed one of the explanations of the observed long-term increasing temperature trend in the WM. According to Leaman and Schott (1991), if the LIW has been accumulating salt over several decades then the upper layers in the Gulf of Lion do not have to be cooled as much during winter to reach a density high enough to allow the water to sink to great depths. This is what happened during the event which has been called the Western Mediterranean Transition (WMT; see CIESM, 2009 and Zunino et al., 2012). The WMT was characterised by an abrupt warming and salinity increase of the bottom layers of the WM after 2004, due to a major production of warmer and saltier waters. The bulk of the new saltier and warmer WMDW between 2004 and 2008 occupied an abyssal layer hundreds of meters thick and, by the end of 2008, this new deep water extended over the entire WM basin below 1500 m depth (Schroeder et al., 2010). Recent studies have demonstrated that slightly less than 50 % of the salinity increase within the WMT can be explained in terms of net evaporation variations (Schroeder et al., 2010), whilst the rest is associated with an advective contribution. The EMT, the event which changed the thermohaline properties of the EM (Roether et al., 2007), had an important impact on the WM deep circulation as hypothesised by a number of studies (Gasparini et al., 2005; Schroeder et al., 2006). However, no detailed analysis of the mechanism of the impact of the EM on the WM deep thermohaline properties has been carried out so far.

One purpose of this paper is to document variations in the thermohaline properties of waters passing through the SC and establish whether these changes in general can be related to decadal variability in the thermohaline properties of LIW. Furthermore, we have studied the connection between the WM and the EM, relating the recorded variations in the thermohaline properties of the LIW passing through the SC to the recent (50 yr BP) oceanographic history of the Levantine basin. The variations in thermohaline properties of the LIW will be interpreted in terms of the inversions of the Ionian circulation (i.e. the BiOS) and the salt content in the Levantine. Subsequently, possible relationships between such changes and the variability in thermohaline properties in the deeper layers of the Algero-Provençal subbasin, and more specifically the WMT, will be discussed.

2 Data and methods

The data used here are from climatology for the period 1945–2002 built by Rixen et al. (2005). About 291 000 temperature and 124 000 salinity profiles have been quality checked according to international standards and interpolated at 25 standard vertical levels. Subsequently, the in situ data were interpolated on a $0.2^\circ \times 0.2^\circ$ grid using a variational inverse model (VIM) (Brankart and Brasseur, 1998). In this study, we used MEDAR gridded salinity data spatially averaged over four areas in the northern Ionian, Levantine seas, SC and Algero-Provençal subbasin (see Fig. 1) to estimate decadal variabilities and coherence between different subbasins.

For a detailed description of the temporal evolution of the LIW characteristics in the SC following the EMT, salinity data were collected during several oceanographic campaigns by Consiglio Nazionale delle Ricerche (Italy), mainly on board of R/V *Urania*. In situ CTD profiles in the period 1985–2011 at one location (see Fig. 1 for the station position) were used.

3 Results and discussion

In situ SC salinity as a function of time and depth (Hovmöller plot) is shown in Fig. 2. The thermohaline evolution at this location has already been discussed in Gasparini et al. (2005) and in Schroeder et al. (2009). At any moment the salinity profile shows a maximum at around 300 m depth. Its position suggests that it is associated with the LIW. The temporal evolution reveals two prominent maxima, one around 1992 and the other around 2008. The time-dependent pattern gives the evidence that LIW of varying thermohaline properties flows

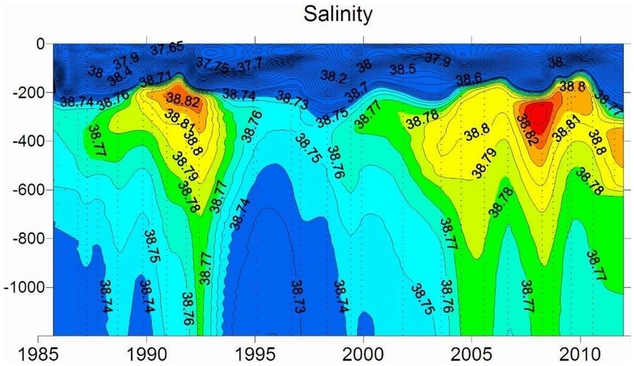

Fig. 2. Hovmöller diagram of the in situ salinity in the Sicily Channel.

through the SC. In order to relate variations in the LIW properties at the source area and those at the SC, one should consider the travel time of the signal. According to some estimates obtained by using transient tracers, the average travel time of the signal between the Rhodes Gyre (the LIW formation site) and the SC is around eight years (Roether et al., 1998). Therefore, variations in salinity in the SC could be explained in terms of the thermohaline variability in native LIW if we consider a time lag of around nine years between time series.

Yearly average salinities from the MEDAR gridded data in the Ionian, Levantine, SC and the Algero-Provençal subbasin were compared. The average salinity for the northern Ionian was calculated for an area (Fig. 1) and depth interval (0–150 m) presumably occupied by the fresher water of WM origin during the anticyclonic BiOS phases. For the Levantine an area representative of the LIW formation was chosen (Fig. 1). The vertical average was calculated within the 150–300 m depth limits. The average salinity for the SC was calculated for the area centered at the location of the in situ sampling as noted in Fig. 1 for the depth interval 150–500 m. In the WM the central part of the Algero-Provençal subbasin was chosen for the calculation of the spatially averaged salinities (Fig. 1) within the 1200–2500 m depth range. For comparison, the resulting yearly time series are displayed in Fig. 3. Ionian average salinities show a very prominent minimum in the mid-1990s which is associated with the experimentally demonstrated anticyclonic mode of the Ionian circulation (Borzelli et al., 2009 and references cited therein). Other two minima occurred in 1983 and in 1973, presumably also being associated with a massive presence of AW in the northern Ionian due to the anticyclonic circulation mode of the BiOS. In contrast, the two most recent maxima, in 1987 and in 1999, are associated with the cyclonic mode in the Ionian and the more pronounced presence of the LIW in its northern portion, as confirmed from experimental and numerical studies (Malanotte-Rizzoli et al., 1997; Pinardi et al., 1997). For the other two maxima (in 1979 and in 1969) there are no experimental evidences of the circulation pattern in the Ionian but, according to the BiOS mechanism, it can be assumed that the circulation was cyclonic. The salinity time series in the Levantine subbasin is out of phase with respect to the Ionian salinities for the entire study period. This result is in agreement with other studies (Demirov and Pinardi, 2002; Gačić et al., 2011) in which it was shown that a more intense spreading of the AW into the Ionian due to the anticyclonic circulation is associated with the weakening of its spreading into the Levantine. In contrast, the cyclonic circulation in the Ionian brings LIW in directly, causing higher salinities, while the AW is almost entirely diverted by the shortest pathway to the Levantine, resulting in an increased surface water dilution (Gačić et al., 2011).

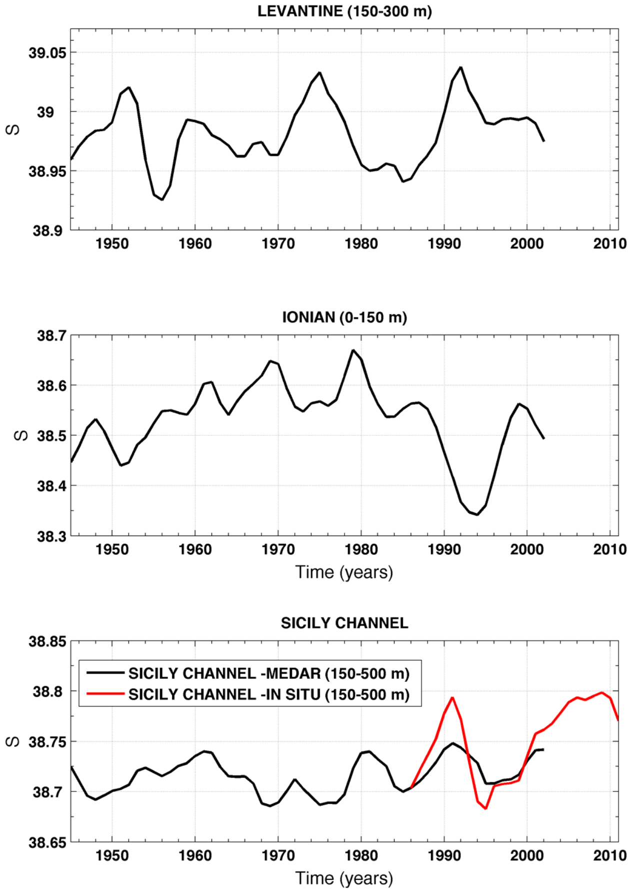

Fig. 3. Time series of the mean salinity values (see Fig. 1 for the averaging areas) for the Levantine (depth interval 150–300 m) and Ionian (surface – 150 m) subbasins as well as for the Sicily Channel (150–500 m). The data are low-pass filtered with a three-year running average.

We will now address in detail the salinity variations in intermediate layers in the SC and try to associate them to the LIW variability in the Levantine basin computing the moving correlation between the two gridded MEDAR time series (Fig. 4). From the correlation which displays a statistically significant maximum (at the 95 % significance level) at

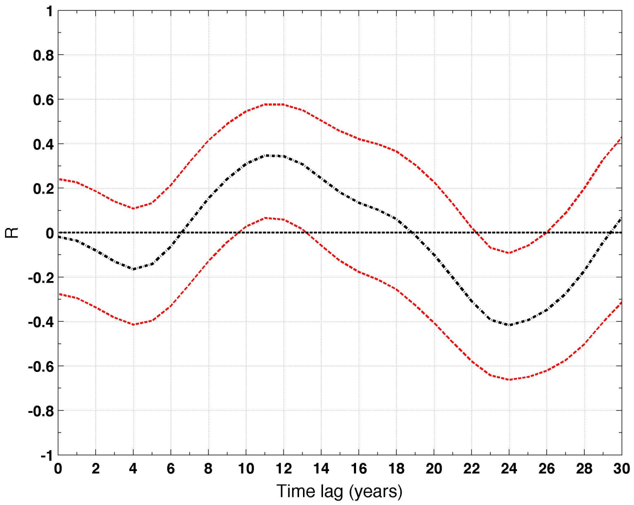

Fig. 4. Moving correlation between the Sicily Channel and Levantine Sea spatially averaged salinity data (for the averaging area see the Fig. 1). Dashed lines represent 95 % confidence interval around the correlation curve.

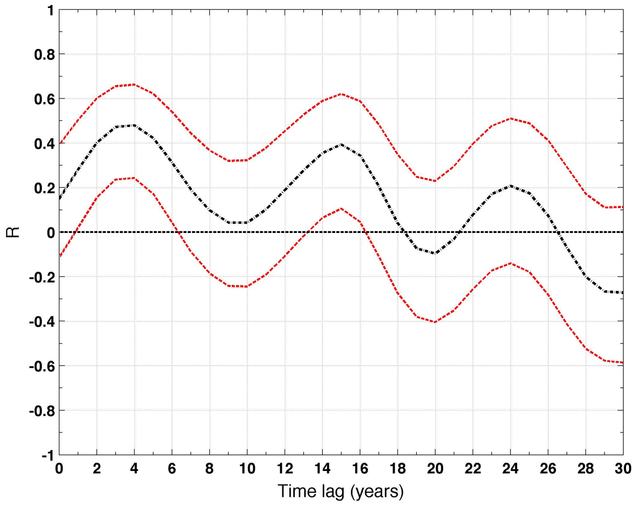

Fig. 5. Moving correlation between the Algero-Provençal and Sicily Channel spatially averaged salinity data (for the averaging area see the Fig. 1). Dashed lines represent 95 % confidence interval around the correlation curve.

a time lag of about 11 yr (between 10 and 13 yr), we obtained an estimate of the travel time of the LIW signal between the formation area (Rhodes Gyre) and the SC. This value slightly differs from the estimates obtained from transient tracers studies (Roether et al., 1998), which gave a travel time of about nine years. In interpreting this discrepancy, we have to consider that the transient tracer results were based on the assumption of the absence of mixing and did not take into account the effect of the BiOS phase on the transport speed (W. Roether, personal communication, 2012). Nevertheless, despite the difference between the two estimates and considering errors associated with each method, we can say that the two approaches gave satisfactorily coherent results.

Further propagation of the salinity signal from the SC to the WM (Algero-Provençal subbasin) can be obtained by comparing LIW salinity changes in the SC with the timing of the WMT. Figure 3 shows that the salinity (and temperature, not shown) increase in the SC preceding the maximum in 2008 started around 1995. Therefore, the salinity increase associated with the occurrence of the WMT in winter 2004/2005 in the Algero-Provençal subbasin (Schroeder et al., 2010) can be associated with the salinity increase in the SC starting in about 1995 as postulated earlier by Schroeder et al. (2006). From these qualitative considerations, we can thus infer that the time of the LIW travel from the SC to the dense water formation (DWF) and its spreading southward is about ten years.

In order to determine more precisely a time lag between the LIW salinity variations in the SC and the salinity in the deep mixed water column in the Algero-Provençal subbasin, we calculated the lagged correlation between the LIW core layer salinity in the SC (150–500 m depth) and the average salinity in the Algero-Provençal subbasin for the layer 1200 and 2600 m depth using in both areas MEDAR gridded data set. For comparison between the MEDAR gridded and in situ salinity data for the LIW core, in Fig. 3 we show average values of the two data sets between 150 and 500 m. The two curves show satisfactory agreement both in absolute values and in the temporal evolution of the MEDAR gridded and in situ data. The lagged correlation function (Fig. 5) between the SC and the Algero-Provençal subbasins shows maximum values for the time lag of about four and 15 yr. The time lag of about four years is probably due to the local vertical mixing of the LIW and underlying portion of the water column during its passage over the area where averages were calculated. The 15-yr time lag can be considered as the sum of the advection transit time of the salinity anomaly between the SC and the DWF site, and the WMDW spreading time from the formation site to the Algero-Provençal subbasin. The LIW pathway in the WM according to various studies (see Menna and Poulain, 2010 and papers referenced therein) follows the Sicilian coast towards west-northwest, loops in the Tyrrhenian Sea up to about 40° N, exits along the Sardinian coast and then turns northward into the Algero-Provençal subbasin. According to M. Menna, personal communication (2012), the northward LIW flow in the Algero-Provençal subbasin covers large portion of the Sardinia–Balearic Islands passage and thus the major part of our averaging area (see Fig. 1) is directly influenced by the passage of the LIW.

Here, we should mention that Ovchinnikov (1983) estimated that the renewal time of the LIW is about 26 yr, which agrees rather well with the sum of the LIW travel time between the Rhodes Gyre and SC (about 11 yr) and between the SC and the Gulf of Lion, including the time for the dense water formation and spreading in the Algero-Provençal subbasin (about 15 yr).

In order to estimate to what extent the extra salt input brought by LIW from the EM impacts the WMDW, we computed the total salt content increase in the bottom layer of the WM from the available in situ salinity data in the Algero-Provençal subbasin (Schroeder et al., 2010) in the period 2004–2010. The salt content increase in the Algero-Provençal subbasin was calculated as a spatial integral of the salinity anomaly in 2010 with respect to 2004. The obtained estimate was then compared with the integrated extra salt imported from the EM over the six-year period, taking into account the time lag of about ten years obtained from the qualitative comparison of the salinities in the SC and in the Algero-Provençal subbasin. In these calculations we considered that the average water volume inflow from the EM was 1.1 Sv (Astraldi et al., 1999) and then we multiplied it by the salinity anomaly with respect to the year 1994. The results suggest that on average the extra salt exported from the EM into the WM over the six-year period (6.764×10^{12} kg) contributes about 60 % to the WMDW salt content increase, mainly via the DWF. This estimate is subject to an error arising from the use of an average and constant volume flux rate in the SC of 1.1 Sv. Another source of error is that the estimate of the salt content increase in the WMDW was obtained by extrapolating results of the salinity measurements at the single location in the Algero-Provençal subbasin (see Fig. 1) to the entire volume of the WM deep layer. Nevertheless, this result agrees rather well with those of Schroeder et al. (2010) and Skliris et al. (2007), who showed that about 50 % of the salt increase in the WMDW can be associated with lateral advection.

4 Conclusions

The analysis of historical salinity data for the second half of the last century has revealed that in the Ionian subbasin several low-salinity events occurred. These events are associated with the anticyclonic mode of the BiOS mechanism, i.e. the anticyclonic basin-wide circulation bringing fresher AW into the northern Ionian. In contrast, high salinity events are associated with the cyclonic BiOS mode generating intense spreading of Levantine waters into the northern Ionian. It has also been shown that the LIW salinity in the Levantine is out of phase with the Ionian surface water salinities, the low-salinity events in the Ionian coinciding with the EMT pre-conditioning in the Levantine. Not every high-salinity occurrence in the Levantine necessarily results in an EMT-like event such as the one that happened in the early 1990s; this can only take place if the pre-conditioning is followed by strong air–sea heat fluxes (Josey, 2003). From available salinity time series at least five pre-conditioning events (high surface salt content episodes in the Levantine) were recorded during the last half century. We do not have any strong indication of EMT-like events which may have taken place, with the exception of the one recorded in the early 1990s. There are, however, some numerical studies which show convection events in the Aegean Sea (i.e. a possible EMT-like phenomenon) in the early 1970s (Beuvier et al., 2010) corresponding to the Levantine salinity maximum in our data set (see Fig. 2). Cross-correlation analysis between the Levantine and the SC salinities suggests a travel time of the signal of about 11 yr. In fact, we can relate the general salinity increase in the SC between 1995 and 2008 to the salinity increase in the Levantine associated with the EMT preconditioning phase. Calculations of the time lag between the SC and Algero-Provençal subbasin salinities reveal two temporal scales (∼ 4 and ∼ 15 yr). A shorter time-scale of the propagation of the salinity signal from the SC to the Algero-Provençal subbasin (∼ 4 yr) is presumably related to the local vertical mixing during the LIW passage over the area. The longer time-scale (15 yr) is probably associated with the sum of the advection travel time between the SC and DWF sites, and the dense water spreading time. However, the recent salinity increase in the WM (i.e. the WMT) occurred about 10 yr after the signal had reached the SC which we interpret as the combination of the time-lag associated with the local mixing, and the advection and spreading time. It was shown that about 60 % of the salinity increase in the WM bottom layer can be explained in terms of the LIW salinity increase.

Table A1. List of acronyms.

AdDW	Adriatic deep water
AW	Atlantic Water
BiOS	(Adriatic–Ionian) Bimodal Oscillating System
EM	Eastern Mediterranean
EMDW	Eastern Mediterranean deep water
EMT	Eastern Mediterranean Transient
LIW	Levantine intermediate water
MS	Mediterranean Sea
SA	Southern Adriatic
SC	Sicily Channel
tEMDW	Transitional eastern Mediterranean water
WM	Western Mediterranean
WMDW	Western Mediterranean deep water
WMT	Western Mediterranean Transition

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