Ocean Sci. Discuss., 9, 2561–2580, 2012
www.ocean-sci-discuss.net/9/2561/2012/
doi:10.5194/osd-9-2561-2012

Ocean Science
Discussions

On the relationship among the Adriatic–Ionian Bimodal Oscillating System (BiOS), the Eastern Mediterranean salinity variations and the Western Mediterranean thermohaline cell

M. Gačić[1], K. Schroeder[2], G. Civitarese[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

Received: 20 June 2012 – Accepted: 11 July 2012 – Published: 31 July 2012

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

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Previous studies have demonstrated that the salinity in the Levantine depends on the intensity of the Atlantic Water inflow. Moreover, its spreading eastward or northward in the Ionian is determined by the Ionian circulation pattern, i.e. by the Adriatic–Ionian Bimodal Oscillating System mechanism. The aim of this paper is to relate salinity variations in the core of the Levantine Intermediate Water flowing through the Sicily Channel to the salt content in the Levantine and its possible impact on the Western Mediterranean Transition (i.e. the sudden salinity increase in the bottom layer of the Algero-Provençal sub-basin occurring since 2004). From the historical dataset MEDAR/MEDATLAS in the Levantine and Northern Ionian, we present evidence of decadal occurrences of extreme salinities associated with the varying flow pattern of Atlantic Water over the last 60 yr. Furthermore, we show that the salinity variations in the two sub-basins are out of phase. High-salinity events in the Levantine are a preconditioning for the potential occurrence of the Eastern Mediterranean Transient (EMT). However, there is no firm evidence of occurrences of EMT-like phenomenon prior to the one in the early 1990s. Cross-correlation between the salinity time series in the Levantine and in the Sicily Channel suggests that the travel time of the salinity signal is between 16 and 18 yr. From the timing of the Western Mediterranean Transition and the salinity maximum in the Levantine Intermediate Water core in the Sicily Channel we also conclude that the time interval needed for the signal propagating from the Levantine to reach the bottom of the Algero-Provençal sub-basin is about 27 yr.

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 characterized 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 transformation of surface water of Atlantic origin (Atlantic Water; AW) on its eastward propagation into Levantine Intermediate Water (LIW), and 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 sub-basin, 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 is the main component of the EMDW that progressively occupies the rest of the EM bottom layer. During the early 1990s, the deep water formation area switched from the SA to the Cretan Sea. This event, known as the Eastern Mediterranean Transient (EMT; see Roether et al., 1996), resulted in a series of changes involving the entire water column, especially in the Ionian Sea (Borzelli et al., 2009).

The open cell connects the WM and the EM, transporting two water masses: the AW and the LIW. 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 EMT, and the recent discovery of the Adriatic–Ionian Bimodal Oscillating System (BiOS; see Gačić et al., 2010), the concept of stationarity of the thermohaline properties and circulation in the intermediate and deep layers 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 reorganization 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 summarized 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 in 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. As opposed to the previous situation, the Adriatic is thus 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 degree than in the anticyclonic mode (Gačić et al., 2011).

The Sicily Channel (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). 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). 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. 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 most important 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 largely determined by the salt brought by the LIW from the EM. The enhancement of the salt import by the LIW from the eastern to the western basin makes the western basin more and more prone to production of warmer and saltier deep waters. We expect that the thermohaline properties of the intermediate water (the 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 determine the amount and the characteristics of the WMDW produced there. 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 by a number of authors (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 also 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 characterized by an abrupt warming and salting of the bottom layers of the WM after 2005, due to a major production of anomalously warm and salty 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 less than 50 %

of the the salinity increase within the WMT can be explained in terms of strong net evaporation (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) and thus of the LIW as well, had an important impact on the WM deep circulation as hypothesized by a number of studies (Gasparini et al., 2005; Schroeder et al., 2006).

One purpose of this paper is to document variations in the thermohaline properties of waters passing through the SC and establish whether these changes 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 at the bottom of the Algero-Provençal subbasin, and more specifically the WMT, will be discussed.

2 Data and methods

The data used here are from the new Mediterranean climatology built by Rixen et al. (2005) for the period 1945–2002. About 291 000 temperature and 124 000 salinity profiles (MEDAR Group, 2002) 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° × 0.2° grid using a Variational Inverse Model (VIM) (Brankart and Brasseur, 1998). In this new climatological approach, which can be considered statistically equivalent to objective analysis, the VIM resolved the large spatio-temporal gaps present in the original data distribution with solutions converging towards the climatic background field obtained by Brankart and Brasseur (1998). Data close to the coastline (< 15 km) and in areas shallower than 50 m were not considered in the computation.

In this study, we used salinity data spatially averaged over one area in the Northern Ionian and another one in the Levantine basin (see Fig. 1) to estimate decadal variabilities and coherences between different subbasins.

Salinity data for the SC were collected during oceanographic in situ measurements carried out by means of CTD probes in the period 1985–2011. For the sake of comparison with other areas, the yearly values were obtained by linear interpolation between experimental points.

3 Results and discussion

Salinity as a function of time and depth is shown for a location in the central part of the SC as 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, while temporally two prominent maxima, one around 1992 and the other around 2008, are evident. Their position at about 300 m depth suggests that they are associated with the LIW. The time-dependent pattern gives the evidence that LIW of varying thermohaline properties flows 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 travelling time of the signal. According to some estimates obtained by using transient tracers, the average travelling time of the signal between the Rhodes Gyre (the LIW formation site) and the SC is around eight years (Roether et al., 1997). Therefore, variations in salinity in the SC could be explained in terms of the thermohaline variability in native LIW if we consider a phase lag of around eight years between time-series.

We have calculated yearly average salinities in the Ionian, Levantine and SC, and compared them. 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 only during the anticyclonic BiOS phases. For the Levantine an area representative of the presence of the AW was chosen (Fig. 1) for calculations of the spatial mean of the vertically averaged salinities over the depth interval 50–150 m. The average salinity for the SC was calculated from in situ data from available oceanographic campaigns in the depth interval 150–500 m where the LIW core is present, as evident from Fig. 2. For comparison, the three curves 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). The 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 indications 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 salinities in the Ionian for the entire study period. This result is in agreement with other studies (Demirov and Pinardi, 2002; Gačić et al., 2011) in which it is 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. Therefore, changes in thermohaline properties of the Levantine and also of the LIW, as shown recently by Gačić et al. (2011), are determined by the Ionian circulation pattern according to the BiOS mechanism.

We will now address in detail the salinity variations in intermediate layers in the SC and try to connect them to the LIW salinity variability in the Levantine basin. The LIW salinity time series in the SC, covering the period 1985–2011, shows clear decadal variability with two maxima (in 1992 and 2008) and a minimum in about 1997. We related salinity variations in the Levantine with those in the SC, computing the moving correlation between the two time series (Fig. 4). From the correlation which displays a statistically significant maximum (at the 95 % significance level) at a phase lag of about 17 yr, we obtained an estimate of the travel time of the LIW signal between the formation area (Rhodes Gyre) and the SC. This value does not agree very well with the estimates obtained from transient tracers studies (Roether et al., 1998), which gave a travel time of about eight 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 (a factor of two) and considering errors associated with each method, we can say that the two approaches gave satisfactorily coherent results.

Our results thus suggest that the salinity maximum in the early 1990s in the Levantine reached the SC only in about 2008. Figure 3 also shows that the salinity 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) is in fact the result of the salinity increase in the SC starting in 1995. Consequently, we can infer that the travel time of the LIW from the SC to the Gulf of Lion is not longer than about nine years. Moreover, if the two features (the salinity variations in the SC and that of the WMDW) are related one to another, one could expect that the salinity increase in the WMDW will continue until 2017. 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 (16 to 18 yr) and between the SC and the Gulf of Lion, also including the time for the dense water formation and spreading in the Algero-Provençal subbasin (about nine years). Possible uncertainties in estimating the travel time between the SC and the Gulf of Lion are related to the fact that the DWF not only depends on the salt content in the LIW but also is a function of the intensity of the winter air–sea heat fluxes. Therefore, the presence of high-salinity LIW at the DWF site does not necessarily result in an immediate transfer of the high salt content to the WMDW.

In order to see how the extra salt input brought by LIW from the EM impacts the WMDW, we calculated the total salt content increase in the bottom layer of the WM from the available salinity data in the Algero-Provençal subbasin (Schroeder et al., 2010) in the period 2004–2010. The obtained estimate was then compared with the integrated extra salt imported from the EM over the six-year period, taking into account the phase lag of about nine years. The results suggest that on average the extra salt exported from the EM into the WM contributes about 40 % to the WMDW salt content increase, presumably via the DWF. Such an estimate is subject to one error arising because we used an average volume flux rate in the SC of 1.1 Sv (Astraldi et al., 1999). 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 basin (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 salinity in the surface layer of the Levantine is out of phase with the Ionian, 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; these can only take place if the pre-conditioning is followed by strong air–sea heat fluxes (Josey, 2003). The temporal variability in the LIW salinity is thus determined, as already indicated in Gačić et al. (2011), by the BiOS circulation inversions which bring larger or smaller AW volumes into the Levantine. From available salinity time series at least five EMT 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 between 16 and 18 yr. In fact, we can explain the general salinity increase in the SC between 1995 and 2008 with the salinity increase taking place in the Levantine between 1980 and 1993 and representing the EMT pre-conditioning phase. This then resulted in the salinity increase in the WM (i.e. the WMT) which occurred about nine years after the signal reached the SC. Thus, an increase in salinity in the SC starts to be felt in the bottom layer of the Algero-Provençal subbasin about nine years later, this being the time needed for the signal to be advected from the SC to the Gulf of Lion to take part in the deep water formation, and subsequently to spread over the Algero-Provençal subbasin. It was shown that about 40 % of the salinity increase in the WM bottom layer can be associated with the LIW salinity increase.

Acknowledgements. We express our thanks to Mireno Borghini (ISMAR-SP) and to the personnel of the CNR-IAMC of Mazara del Vallo for their work on in situ CTD measurements in the Sicily Channel. Isaac Mancero Mosquera calculated the accuracy interval for the cross-correlation function. The authors acknowledge Meteo-France for supplying the data and the HyMeX database teams (ESPRI/IPSL and SEDOO/Observatoire Midi-Pyrenees) for their help in accessing the data. This study is partially supported by the Italian national project RITMARE.

References

Artale, V., Calmante, S., Malanotte-Rizzoli, P., Pisacane, G., Rupolo, V., and Tsimplis, M.: The Atlantic and Mediterranean Sea as connected systems, in: Mediterranean Climate Variability, Dev. Earth Environ. Sci., vol. 4, edited by: Lionello, P., Malanotte-Rizzoli, P., and Boscoli, R., Elsevier, Amsterdam, 283–323, 2006.

Astraldi, M., Balopoulos, S., Candela, J., Font, J., Gačić, M., Gasparini, G. P., Manca, B., Theocharis, A., and Tintoré, J.: The role of straits and channels in understanding the characteristics of Mediterranean circulation, Prog. Oceanogr., 44, 65–108, 1999.

Ben Ismail, S., Sammari, C., Gasparini, G. P., Béranger, K., Brahim, M., and Aley, L.: Water masses exchanged through the Channel of Sicily: evidence for the presence of new water masses on the Tunisian side of the channel, Deep-Sea Res. Pt. I, 63, 65–81, 2012.

Beuvier, J., Sevault, F., Herrmann, M., Kontoyiannis, H., Ludwig, W., Rixen, M., Stanev, E., Beranger, K., and Somot, S.: Modeling the Mediterranean Sea interannual variability during 1961–2000: focus on the Eastern Mediterranean Transient, J. Geophys. Res., 115, C08017, doi:10.1029/2009JC005950, 2010.

Borzelli, G. L. E., Gačić, M., Cardin, V., and Civitarese, G.: Eastern Mediterranean Transient and reversal of the Ionian Sea circulation, Geophys. Res. Lett., 36, L15108, doi:10.1029/2009GL039261, 2009.

Brankart, J.-M. and Brasseur, P.: The general circulation in the Mediterranean Sea: a climatological approach, J. Marine Syst., 18, 41– 70, 1998.

Demirov, E. and Pinardi, N.: Simulation of the Mediterranean Sea circulation from 1979 to 1993: Part I. The interannual variability, J. Marine Syst., 33–34, 23–50, doi:10.1016/S0924-7963(02)00051-9, 2002.

Gačić, M., Borzelli, G. L. E., Civitarese, G., Cardin, V., and Yari, S.: Can internal processes sustain reversals of the ocean upper circulation?: the Ionian Sea example, Geophys. Res. Lett., 37, L09608, doi:10.1029/2010GL043216, 2010.

Gačić, M., Civitarese, G., Eusebi Borzelli, G. L., Kovačević, V., Poulain, P.-M., Theocharis, A., Menna, M., Catucci, A., and Zarokanellos, N.: On the relationship between the decadal oscillations of the Northern Ionian Sea and the salinity distributions in the Eastern Mediterranean, J. Geophys. Res., 116, C12002, doi:10.1029/2011JC007280, 2011.

Gasparini, G. P., Ortona, A., Budillon, G., Astraldi, M., and Sansone, E.: The effect of the Eastern Mediterranean Transient on the hydrographic characteristics in the Strait of Sicily and in the Tyrrhenian Sea, Deep-Sea Res. Pt. I, 52, 915–935, 2005.

Grignon, L., Smeed, D. A., Bryden, H. L., and Schroeder, K.: Importance of the variability of hydrographic preconditioning for deep convection in the Gulf of Lion, NW Mediterranean, Ocean Sci., 6, 573–586, doi:10.5194/os-6-573-2010, 2010.

Josey, S. A.: Changes in the heat and freshwater forcing of the Eastern Mediterranean and their influence on deep water formation, J. Geophys. Res., 108, 3237, doi:10.1029/2003JC001778, 2003.

Lacombe, H., Tchernia, P., and Gamberoni, L.: Variable bottom water in the Western Mediterranean basin, Prog. Oceanogr., 14, 319– 338, 1985.

Leaman, K. D. and Schott, F. A.: Hydrographic structure of the convection regime in the Gulf of Lions: winter 1987, J. Phys. Oceanogr., 21, 575–598, 1991.

Malanotte-Rizzoli, P., Manca, B. B., Ribera D'Alcalá, M., Theocharis, A., Bergamasco, A., Bregant D., Budillon, G., Civitarese, G., Georgopoulos, D., Michelato, A., Sansone, E., Scarazzato, P., and Souvermezoglou, E.: A synthesis of the Ionian Sea hydrography, circulation and water mass pathways during POEM-Phase I, Prog. Oceanogr., 39, 153–204, doi:10.1016/S0079-6611(97)00013-X, 1997.

Manzella, G. M. R., Gasparini, G. P., and Astraldi, M.: Water exchange through the Eastern and Western Mediterranean through the Strait of Sicily, Deep Sea Res. Pt. I, 35, 1021–1035, 1988.

MEDAR Group: MEDATLAS 2002, Mediterranean and Black Sea database of temperature, salinity and bio-chemical parameters and climatological atlas (4 Cd-roms), European Commission Marine Science and Technogy Programme, and internet server www.ifremer.fr/sismer/program/medar, SISMER (Ed.), Centre de Brest, 2002.

Ovchinnikov, I. M.: The renewal of the principal water masses of the Mediterranean, Oceanology, 23, 719–721, 1983.

Pinardi, N., Korres, G., Lascaratos, A., Roussenov, V., and Stanev, E.: Numerical simulation of the interannual variability of the Mediterranean Sea upper ocean circulation, Geophys. Res. Lett. 24, 425–428, doi:10.1029/96GL03952, 1997.

Rixen, M., Beckers, J.-M., Levitus, S., Antonov, J., Boyer, T., Maillard, C., Fichaut, M., Balapoulos, E., Iona, S., Dooley, H., Garcia, M.-J., Manca, B., Giorgetti, A., Manzella, G., Mikhaolov, N., Pinardi, N., Zavatarelli, M., and the MEDAR Consortium: The Western

Mediterranean deep water: a proxy for climate change, Geophys. Res. Lett., 32, L12608, doi:10.1029/2005GL022702, 2005.

Roether, W., Klein, B., Beitzel, V., and Manca, B. B.: Property distributions and transient-tracer ages in levantine intermediate water in the Eastern Mediterranean, J. Marine Syst., 18, 71–87, 1997.

Robinson, A., Leslie, W., Theocharis, A., and Lascaratos, A.: Mediterranean Sea circulation, in: Encyclopedia of Ocean Sciences, vol. 3, Elsevier, New York, 1689– 1705, 2001.

Roether, W., Klein, B., Manca, B. B., Theocharis, A., and Kioroglou, S.: Transient Eastern Mediterranean deep waters in response to the massive dense-water output of the Aegean Sea in the 1990s, Prog. Oceanogr. 74, 540–571, 2007.

Schroeder, K., Ribotti, A., Borghini, M., Sorgente, R., Perilli, A., and Gasparini, G. P.: An extensive Western Mediterranean deep water renewal between 2004 and 2006, Geophys. Res. Lett., 35, L18605, doi:10.1029/2008GL035146, 2008.

Schroeder, K., Gasparini, G. P., Tangherlini, M., and Astraldi, M.: Deep and intermediate water in the Western Mediterranean under the influence of the Eastern Mediterranean Transient, Geophys. Res. Lett., 33, L21607, doi:10.1029/2006GL027121, 2006.

Schroeder, K., Gasparini, G. P., Borghini, M., M., and Ribotti, A.: Experimental evidences of the recent abrupt changes in the deep Western Mediterranean Sea, in: CIESM, Dynamics of Mediterranean deep waters, N° 38 in CIESM Workshop Monographs, edited by: Briand, F., Monaco, 132 p, 2009.

Schroeder, K., Josey, S. A., Herrmann, M., Grignon, L., Gasparini, G. P., and Bryden, H. L.: Abrupt warming and salting of the Western Mediterranean deep water after 2005: atmospheric forcings and lateral advection, J. Geophys. Res., 115, C08029, doi:10.1029/2009JC005749, 2010.

Skliris, N., Sofianos, S., and Lascaratos, A.: Hydrological changes in the Mediterranean Sea in relation to changes in the freshwater budget: a numerical modelling study, J. Marine Syst., 65, 400–416, doi:10.1016/j.jmarsys.2006.01.015, 2007.

Vetrano, A., Gasparini, G. P., Molcard, R., and Astraldi, M.: Water flux estimates in the Central Mediterranean Sea from an inverse box model, J. Geophys. Res., 109, 1–24, C01019, doi:10.1029/2003JC001903, 2004.

Wu, P. and Haines, K.: Modeling the dispersal of levantine intermediate water and its role in Mediterranean deep water formation, J. Geophys. Res., 101, 6591–6607, 1996.

Zunino, P., Schroeder, K., Vargas-Yáñez, M., Gasparini, G. P., Coppola, L., García-Martínez, M. C., and Moya-Ruiz, F.: Effects of the Western Mediterranean Transition on the resident water masses: pure warming, pure freshening and pure heaving, J. Marine Syst., 96–97, 15–23, doi:10.1016/j.jmarsys.2012.01.011, 2012.

Table 1. 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

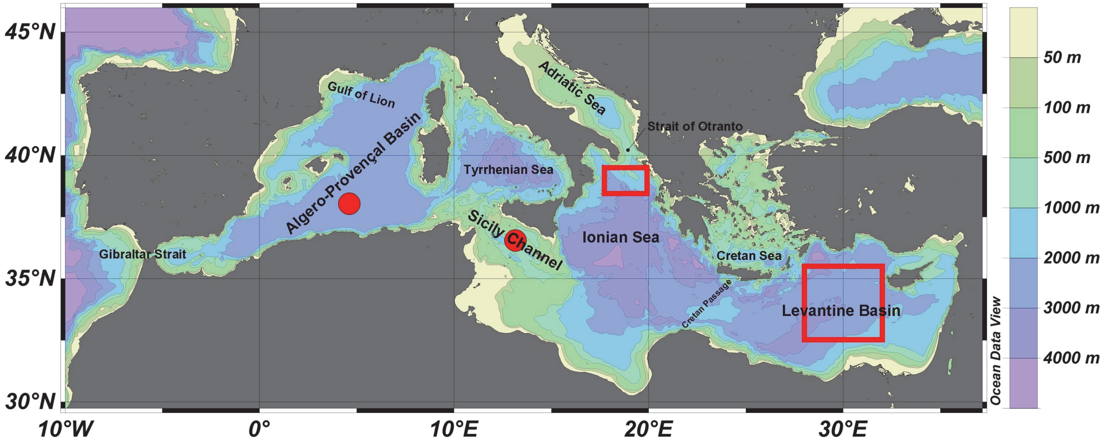

Fig. 1. Map of the Mediterranean Sea. Areas where the mean salinity values were calculated are delimited by continuous red lines. CTD measurement sites in the Sicily Channel and in the Algero-Provençal basin are denoted by a red dot.

OSD

9, 2561–2580, 2012

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
I◀ | ▶I
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◄ ►
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

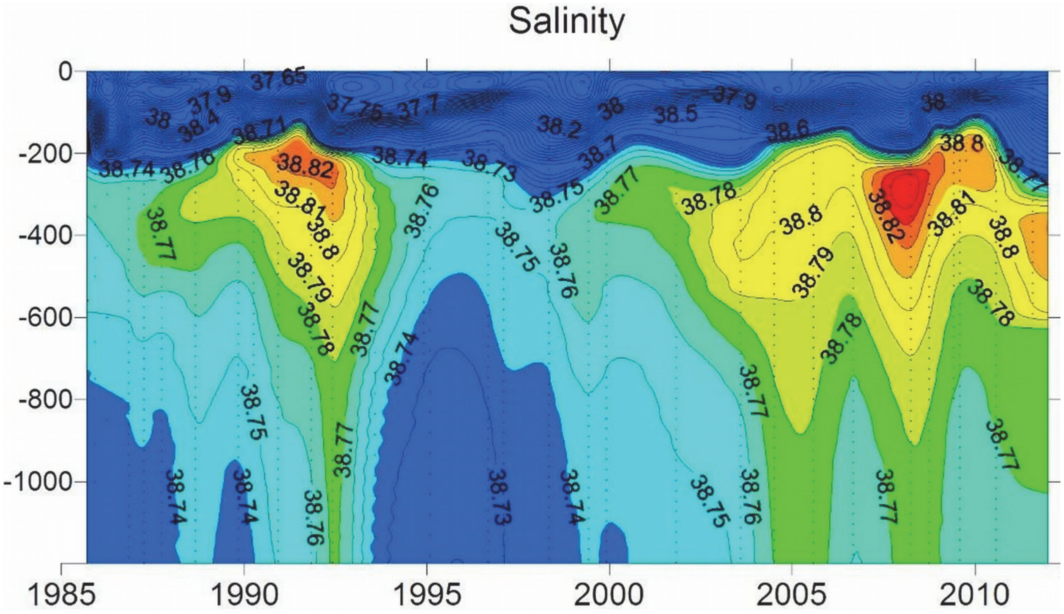

Fig. 2. Hovmöller diagram of the salinity in the Sicily Channel.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
I◀ | ▶I
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

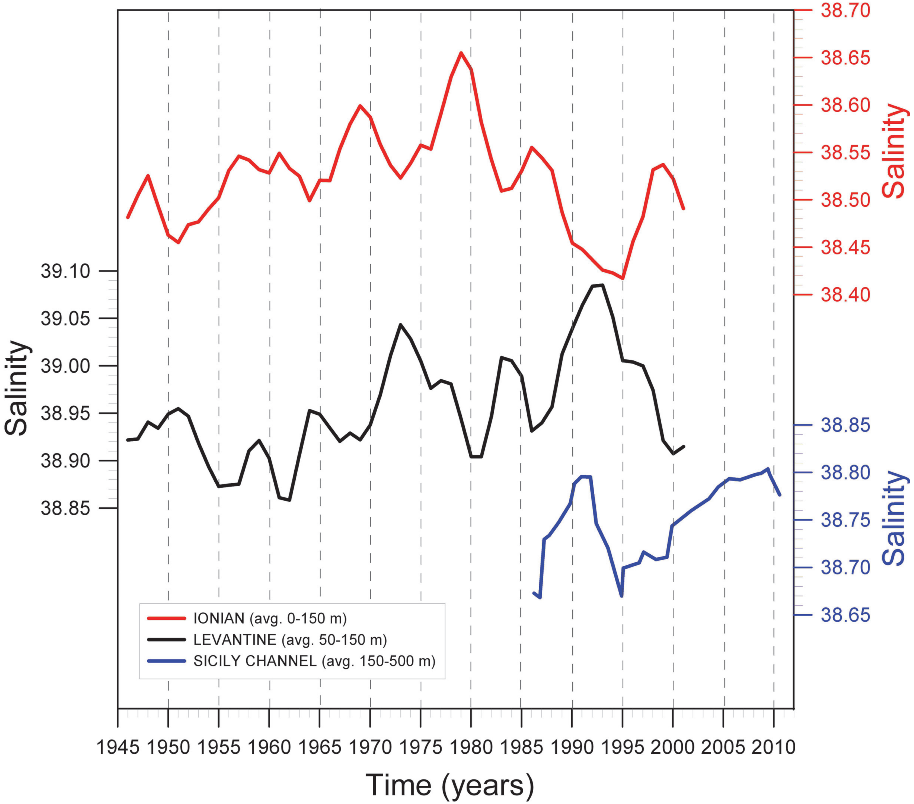

Fig. 3. Time series of the mean salinity values (see Fig. 1 for the averaging areas) for the Levantine (depth interval 50–150 m) and Ionian (surface – 150 m) sub-basins as well as for the Sicily Channnel. The data are low-pass-filtered with a three-year running average.

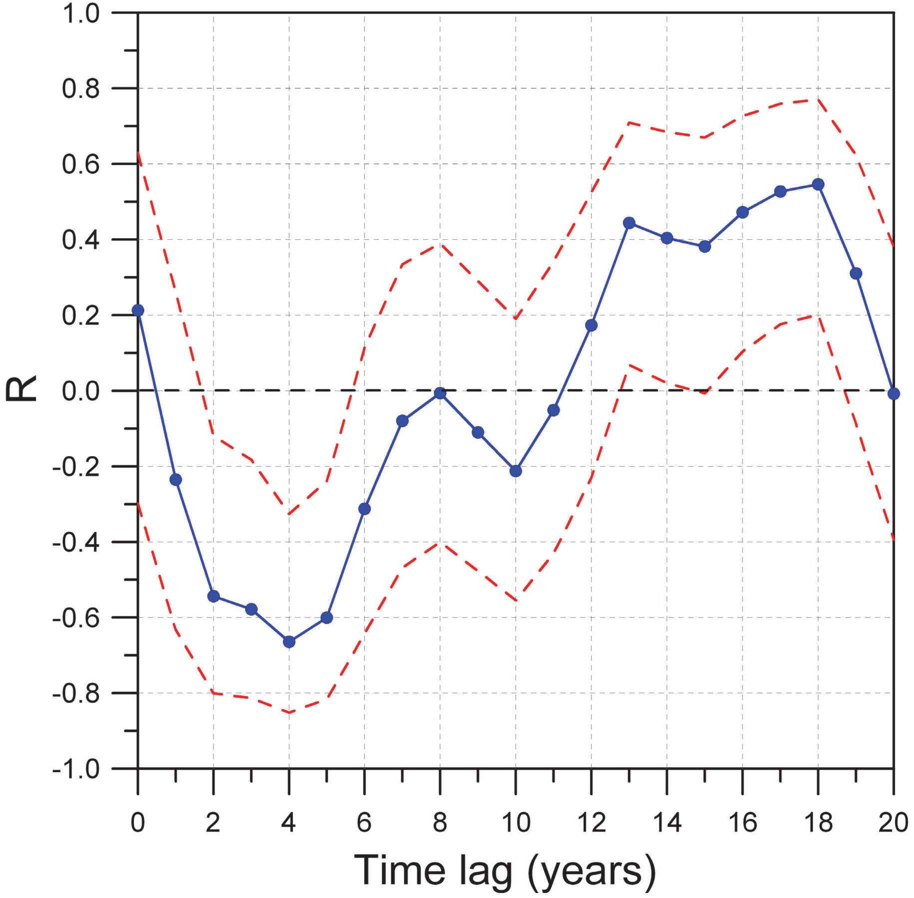

Fig. 4. Moving correlation between the Sicily Channel and Levantine Sea salinity data. Dashed lines represent 95 % confidence interval around the correlation curve.