An extensive western Mediterranean deep water renewal between 2004 and 2006

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The deep waters of the western Mediterranean are known to have an almost constant trend towards higher salinity and temperature values since the 1950s. Recent observations have shown an acceleration of this tendency, which has been attributed by some authors to the effect of the propagation of the signal of the Eastern Mediterranean Transient, from east to west. From 2004 to 2006 five basin-scale oceanographic cruises evidenced a relevant change in the deep structure of the western Mediterranean. In less than two years almost the whole deep basin has been filled with highly saline and warm new deep water, which substantially renewed the resident deep water. The paper shows evidence of the rapid basin-wide extension of the event, giving insights into the origin and the propagation of the new deep water towards the basin interior and showing the evolution of the deep characteristics. Citation: Schroeder, K., A. Ribotti, M. Borghini, R. Sorgente, A. Perilli, and G. P. Gasparini (2008), An extensive western Mediterranean deep water renewal between 2004 and 2006, Geophys. Res. Lett., 35, L18605, doi:10.1029/2008GL035146.

1. Introduction

For many decades the western Mediterranean (WMED) heat and salt contents increased almost steadily. Past studies have demonstrated the tendency of the deep waters in the WMED towards higher temperatures and salinities since the 50s, with an acceleration after 1985 [Béthoux et al., 1990; Rohling and Bryden, 1992; Krahmann and Schott, 1998; Rixen et al., 2005]. More recent observations have shown further significant heat and salt increases, both in the deep and intermediate layers, in several WMED subbasins, which have been attributed [Gasparini et al., 2005; Schröder et al., 2006] to the propagation of the Eastern Mediterranean Transient (EMT), from the eastern Mediterranean (EMED) to the WMED. The EMT, which has been extensively investigated by several authors (see Roether et al. [2007] for a review), was characterized by a change in the internal thermohaline cell of the EMED, which substantially modified the water column characteristics. Its signature, crossing the Strait of Sicily, reached the WMED and propagated through it reaching the northern basin, one of the most critical regions of the WMED, since it constitutes a site of deep water formation (DWF hereafter) processes [MÉDOC Group, 1970].

During winter 2004/2005 an unusual and remarkable deep water production has been observed, extending from the Gulf of Lions to the Catalan subbasin. This event gave origin to a newly formed deep water mass, which was characterized by a complex structure and high heat and salt contents [López-Jurado et al., 2005; Schröder et al., 2006; Canals et al., 2006; Font et al., 2007]. Different hypotheses have been investigated to give an explanation to this DWF event: while López-Jurado et al. [2005] and Font et al. [2007] evidenced that the winter 2004/2005 was the most dry and severe winter of the last 40 years, Schröder et al. [2006] related it to a progressive increase of heat and salt content in the intermediate and bottom layer, due to the EMT propagation from the EMED to the WMED.

During winter 2005/2006 the DWF occurred mainly in the Ligurian subbasin [Smith et al., 2008], leading to a new WMDW with even higher salt and heat contents than in the previous year. With respect to winter 2004/2005, the successive one was less severe: the NCEP/NCAR reanalysis data in the north-western Mediterranean show significantly lower heat fluxes between ocean and atmosphere and the DWF event in winter 2005/2006 in the Ligurian subbasin has been attributed to the presence of a shallower LIW vein [Smith et al., 2008].

In both winters it seems that a key role was played by the higher heat and salt contents in the water column, advected from the EMED to the WMED as consequence of the EMT [Gasparini et al., 2005]. The observed signature has been successively transferred to the deep layer of the WMED as a result of the deep convection processes taking place in the Gulf of Lions during winter. In particular the transfer of the EMT signal from the intermediate to the deep layer occurred in winter 2004/2005 [Schröder et al., 2006] and continued further in winter 2005/2006, as is demonstrated by the great anomaly observed in the deep layer after these two winters.

The aim of the paper is to verify the extent of these events, which were able to completely modify the water characteristics of the deep layer.

2. Data and Methodology

Five surveys (MEDOOS09, MEDOCC05, MEDG-OOS10, MEDOCC06 and MEDGOSOS13) were carried out respectively in October 2004, April-May 2005, June 2005, June 2006 and October 2006 with the R/V Urania, owned by the Italian National Research Council (CNR). At all hydrological stations (Figure 1a) pressure, salinity, potential temperature and dissolved oxygen were measured with a CTD SBE 911+. Dissolved oxygen was also measured with Winkler titration and the CTD oxygen was calibrated against the titrated samples. Temperature measurements were performed with a SBE-3/F thermometer (resolution 10⁻³°C) and conductivity measurements with a SBE-4...
sensor (resolution $3 \times 10^{-4}$ S m$^{-1}$). The probes were calibrated before and after each cruise at the NURC in La Spezia, Italy.

3. Results

The available data permit to follow the deep WMED hydrographic conditions before and after the DWF events described in literature, from the formation area to other regions of the basin. In 2004 the WMED hydrographic conditions appeared coherent with climatology and the deep layer situation was characterized by the ‘classical’ WMDW structure. Looking at the $\theta$–$S$ diagram in Figure 1b, which refers to the transect shown in Figure 1a, we may note that the water column exhibits a monotonic decrease of potential temperature ($\theta$) and salinity ($S$) with depth, at a nearly constant density ($\sigma_0$) of 29.1. Two years later peculiar deep $\theta$–$S$ diagrams (Figure 1c) have been observed along the
same transect, indicating the presence of a newly formed deep water mass, which was characterized by a complex structure and high heat and salt contents.

The deep structure began to change after winter 2004/2005, not only in the DWF region in the northern WMED but also in the Provençal and the Algerian subbasins (see the $\theta$–S diagram by López-Jurado et al. [2005, Figure 3e] and Schröder et al. [2006, Figure 2]), suggesting a rapid propagation of the newly formed dense water mass from its formation region towards the interior of the basin. Figure 2a shows the stations visited in 2005 (April-May and June 2005), distinguishing between those where no new deep water was observed and those which have been recently ventilated: the new WMDW was found in a wide area of the WMED, along its spreading pathway, even in the northern part of the Algerian subbasin and in stations near the entrance of the Alboran subbasin. Since the deep water spreads south- and westward through the basin [Send et al., 1996], only a weak signal of this newly formed deep water was present east of the DWF region. As for 2005, Figure 2b shows the stations visited in 2006 (June and October 2006), indicating where the new WMDW (formed in both winters 2004/2005 and 2005/2006) has been observed: it is clearly evident that the new WMDW is now present in almost the whole WMED, excluding the Tyrhenian and the western Alboran subbasins. We should mention that comparing the

![Figure 2](image-url)
three years, no significant changes have been detected westward of 4°W.

[10] To give a comparative description of the situations in 2004, 2005 and 2006 a zonal transect from Gibraltar to the Tyrrenian entrance, which has been investigated during the MEDGOOS09, MEDGOOS10 and MEDGOOS13 cruises (red dashed line in Figure 1a), is analyzed. The 2004 situation is prior to the intense DWF in winter 2004/2005. The deep layer is occupied by a homogeneous water (Figure 3a), with almost constant \( \theta \), \( S \) and \( O_2 \) values (\( \theta \leq 12.83 \, ^\circ C, S \leq 38.45 \) and \( O_2 \leq 4.48 \, ml \, l^{-1} \) below 2000 m depth). One year later, in 2005, the vertical sections along the same transect (Figure 3b) indicate higher \( \theta \) and \( S \) values (12.85 \( ^\circ C \) and 38.46, respectively) in some stations near the bottom. The simultaneously increase in the \( O_2 \) concentration (up to 4.54 ml \, l^{-1}) suggests the arrival from the north (the DWF region) of a salty, warm and recently ventilated deep water. The dramatic changes involving the deep layer of the WMED became clearly evident in 2006 (Figure 3c): the whole deep layer below 2000 m depth in the southern WMED is now filled with the newly formed deep water, which has further increased its heat and salt contents (\( \theta = 12.85 - 12.88 \, ^\circ C \) and \( S = 38.455 - 38.47 \) below 2000 m depth). Oxygen reached concentrations up to 4.64 ml \, l^{-1}, mainly at the eastern edge of the transect. These observations permitted us to conclude that in 2006, below 1800–2000 m depth, the resident deep water has been completely renewed by the newly formed deep water.

[11] Examining the hydrographic properties it was possible to define the volume occupied by the new WMDW, assuming the sharp edge in the \( \theta-S \) diagram (Figure 1c) as its upper limit. From the volumetric distribution of the \( \theta-S \) properties [Schroeder et al., 2008] for the whole period 2004–2006 we estimated a total volume of new WMDW of 1.5 \( 10^{14} \, m^3 \), corresponding to a mean production rate during the two winters (2004/2005 and 2005/2006) of about 2.4 Sv. This estimate, even if very approximated, is significantly higher than previous estimates (e.g., Rhein [1995] indicates an annual deep water formation rate comprised between 0.14 and 1.2 Sv), confirming that recently the WMED experienced intense deep water formation events [López-Jurado et al., 2005; Schröder et al., 2006; Smith et al., 2008].

[12] As it was the case of the EMED, where the production of dense water in the Aegean Sea during the 90s, i.e. during the EMT, had induced a significant uplifting of the isopycnals in the Ionian subbasin, the recent huge new deep water production in the WMED seems to have had similar consequences. A comparison of the depth of the \( \sigma_{1000} = 33.477 \) isopycnal (which approximately corresponds to the sharp edge in the \( \theta-S \) diagram of Figure 1c) in 2004, 2005 and 2006 is shown in Figure 4. In 2004 it was found in the southern part of the WMED at a depth of about 1500-1600 m (Figure 4a), which maintains almost the same during 2005 (Figure 4b), in agreement with the hydrographic displacement shown in Figures 3a and 3b. In the northern part of the basin the same isopycnal was found at significantly shal-
lower depths (between 500 and 1000 m depth in the Gulf of Lions and the Balearic Sea). A remarkable change, involving the whole region, can be observed examining the 2006 displacement, with an uplifting in the southern part of 100–150 m (Figure 4c), and in the northern part of 200 m, up to 1000 m in the Ligurian subbasin. If the northern uplifting can be attributed to the DWF during winter 2005/2006, the southern is mainly due to the migration of the 2004/2005 production.

In order to determine the type of changes in the $\theta$ and $S$ structure responsible for the observed changes along the transect shown in Figure 1a, we tried to verify whether the prevalent contribution was due to vertical motion of isopycnals or to water mass modifications related to $\theta$/$S$ changes [Bindoff and McDougall, 1994]. Along the transect the changes along isopycnals resulted 3 orders of magnitude smaller than those along isobars, indicating that most of the observed variability in the deep layer was due to pure heave (isopycnal uplifting). This result confirms our hypothesis that these intense modifications are due to the arrival of a new dense water mass from its formation regions, and not to an in situ water mass change, leading to a huge uplifting of the resident deep water, as was discussed above.

4. Discussion and Conclusion

Previous studies demonstrated the tendency towards higher heat and salt contents of the deep water of the WMED since the 1950s [Béthoux et al., 1990; Rohling and Bryden, 1992; Krahmann and Schott, 1998]. A comparison between the vertical hydrographic conditions in an extended region in 2004, 2005 and 2006 evidences the fast and massive renewal of the deep layer of the WMED. This has lead to a dramatic increase in $\theta$ and $S$ within a very short period of time, which is not comparable to the previously reported trends in the WMDW. In fact, Béthoux and Gentili [1999] indicated an increasing trend for $\theta$ and $S$ of 3.5$\times10^{-3}$ °C yr$^{-1}$ and 1.1$\times10^{-3}$ yr$^{-1}$, respectively, for the period 1959–1996. Slightly lower values have been proposed by Krahmann and Schott [1998] for the 1955–1994 period, i.e., 1.6$\times10^{-3}$ °C yr$^{-1}$ and 0.8$\times10^{-3}$ yr$^{-1}$, respectively for $\theta$ and $S$. Recently, Rixen et al. [2005] reported that between 1950 and 2000 the bottom layer...
showed a monotonic increase of $\theta$ and S in the WMED, with a sharp acceleration in the last 15 years (1985–2000) to values of $5.5 \times 10^{-3}$ °C yr$^{-1}$ and $1.2 \times 10^{-3}$ °C yr$^{-1}$, respectively for $\theta$ and S. However, our analysis shows that between 2004 and 2006 the deep layer of the WMED has experienced a $\theta$ increase of about 0.038 °C and a S increase of 0.016, which are 5 to 7 times greater than the increasing trends indicated by Béthoux and Gentili [1999] and about 4 times greater than the estimates given by Rixen et al. [2005] for the 1985–2000 period. Since the 90s in the intermediate and deep waters of the WMED an increase in heat and salt contents has been observed and attributed to the propagation of the EMT signal, which crossed the sill between the EMED and the WMED by the end of 1992 [Gasparini et al., 2005].

[16] The recent sudden change in the deep layer structure, heat and salt contents, may be related to two different effects, acting at two different scales. There is a decadal salt and heat accumulation at intermediate levels, induced by the arrival of the EMT signal first in the Tyrrhenian and then in the Ligurian Sea [Gasparini et al., 2005; Schröder et al., 2006]. The salt content of the LIW is an important factor controlling the DWF in the northern WMED [Lacombe et al., 1985], and can explain the high heat and salt contents of the new deep water formed in winter 2004/2005. Along with this long-term modification of the water column, particularly severe weather conditions [López-Jurado et al., 2005] were responsible for the extensive DWF in winter 2004/2005. There are quite a lot open questions with regard to the new WMDW characteristics. Further investigations are needed in order to verify when, if ever, the new deep water will pass the complex topography of the Central Mediterranean, with a sill depth of about 1900 m, to reach also the Tyrrhenian. The vertical property distributions in 2006, along the zonal transect (Figure 3c), gives evidence on the ongoing upwelling of the new WMDW layer towards the sill region in the Tyrrhenian entrance. But, above all, it will be necessary to assess the effect on the Mediterranean Outflow Water (MOW) towards the Atlantic Ocean and when this will be visible. Stommel et al. [1973] showed that water from about 700 to 1000 m depth may participate directly in the outflow, while Kinder and Parrilla [1987] evidenced that there is a presence of WMDW on the Atlantic side of the Strait. The comparison of data collected in 2004, 2005 and 2006 suggests that, starting from 2005, almost the whole WMED is filling up with these particular water masses, significantly accelerating the ventilation of the deep WMED. Considering that in the EMED the EMT produced an uplifting of the old Eastern Mediterranean Deep Water (EMDW) of about 500 m [Lascaratos et al., 1999], what we are observing now in the WMED seems to be significant as well (300 m displacement of the resident WMDW in two years on average).

[17] By analogy with the Strait of Sicily, the connecting point between the EMED and the WMED, we may envisage some effects: as it was the case of the Eastern Mediterranean Outflow, probably the first effect would be a MOW with a higher percentage of old WMDW, with a consequent decrease of $\theta$ and S and a $\sigma_\theta$ increase. Successively, when the new WMDW will be able to reach the Strait of Gibraltar, a significant increase of $\theta$ and S is very likely. Indeed García Lafuente et al. [2007], observing a $\theta$ decrease in the Strait of Gibraltar by the end of March 2005 and in March 2006, have attributed it to a remote signature of the deep convection in the Gulf of Lions, which replenishes the WMDW reservoir and raises its interface with the water above, making cooler water available for suction. This happens almost every year, with a drop in $\theta$ in early spring, but in 2005 and 2006 a very sharp decrease was registered [García Lafuente et al., 2007].

[18] The rapid change in deep water properties in the WMED as a response to a dramatic event in the EMED, one decade earlier, is an example of instabilities in the thermohaline circulation and how different subbasins interact with each other. It is important that other disciplines as biology and chemistry are aware of these changes and interpret biogeochemical data in the context of these changes.

**References**


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