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Observations of new western Mediterranean deep water formation using ARGO floats 2004–2006

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Abstract

The deep convection that occurs in the western basin of the Mediterranean Sea was investigated using ARGO float data over two consecutive winters in 2004–2005 and 2005–2006. The results showed deep mixed layers reaching 2000 m in surprising locations, namely the eastern Catalan subbasin (39.785° N, 4.845° E) and the western Ligurian subbasin (43.392° N, 7.765° E). Subsequently, new deep water was formed in March of 2005 and 2006 with θ=12.89–12.92°C, S=38.48–38.49 and σ_θ=29.113 kg m^{-3}. The deep water produced in the Ligurian subbasin during 2006 was more saline, warmer and denser than any historical observations of Western Mediterranean Deep Water. The results show S, θ and σ_θ in the Western Mediterranean Deep Water are higher than 1990s values, with a salinity increase of 1.5×10^{-3} yr^{-1}, a temperature increase of 3.6×10^{-3}°C yr^{-1} and a density increase of 4.0×10^{-4} kg m^{-3} yr^{-1} apparent from a dataset of WMDW properties spanning 1955-2006.

1 Introduction

Within the western basin of the Mediterranean Sea, deep convection ordinarily takes place during the winter months in localised regions of the Gulf of Lions and Ligurian and Provençal subbasins (Fig. 1). This process is important as it leads to the formation of a water mass known as the Western Mediterranean Deep Water (WMDW), which plays a crucial role in the thermohaline dominated circulation of the Mediterranean Sea (Millot, 1991). The typical water column structure of the western basin consists of three major water masses along with Mediterranean Bottom Water (at depths >3000 m), which is not of relevance to this study. The Modified Atlantic Water (MAW – S in the range 36.5 to 37.5, θ highly variable) originates from surface inflows in the Strait of Gibraltar and is recognised as a fresh, buoyant surface layer (0–200 m) which is steadily modified as it flows eastward through mixing and air-sea interactions (Bryden and Stommel, 1984; Send et al., 1999). The Levantine Intermediate Water (LIW – S in the range 38.45

to 38.75, θ>13.2°C) lies below this layer (400–600 m), it is formed in the Levantine Basin of the eastern basin and is recognised by a distinct subsurface salinity maximum in vertical profiles (Rohling and Bryden, 1992). Underlying this is the WMDW (S in the range 38.40 to 38.48, θ in the range 12.75 to 12.90°C) which, following formation by mixing of MAW and LIW during deep convection in the regions described above, spreads out through the western basin with a core at ~2000 m (La Violette, 1994).

1.1 Deep convection

Deep convection in the western basin and formation of the WMDW have been heavily studied (Leaman and Schott, 1991; Bethoux et al., 1990; Rhein, 1995; Testor and Gascard, 2006) following pioneering work by the MEDOC Group in the Gulf of Lions (MEDOC Group, 1970). Such studies suggest deep convection within the western basin is reasonably understood, with the processes involved classified under three progressive phases (MEDOC Group, 1970; Marshall and Schott, 1999):

- Initially a "pre-conditioning" phase occurs during which strong winter buoyancy losses owing to cold, dry Mistral and Tramontane continental winds (Testor and Gascard, 2006) gradually erode surface and intermediate stratification (Mertens and Schott, 1998) within a cyclonic surface gyre in the Gulf of Lions and northern Provençal subbasin (Marshall and Schott, 1999). The gyre is characterised by a doming of the σ_θ=28.8 isopycnal, with surface water densities exceeding 29.1 kg m^{-3} in late winter (Swallow and Caston, 1973). This cyclonic surface circulation is an important factor in pre-conditioning as it localises the convective region by limiting exchange of the waters exposed to persistent surface forcing with more stably stratified waters outside the gyre (Marshall and Schott, 1999; Send et al., 1999). The cyclonic circulation also draws the LIW toward the surface, to be more easily exposed to mixed layer (ML) entrainment (Schott et al. 1993) with the subsequent density increase of surface waters ultimately allowing for deeper convection of the water column (Skliris and Lascaratos, 2004). As a result the surface and intermediate waters homogenise, exposing the underlying, weakly stratified water column to strong surface forcing (Schroder et al., 2006).

- Following pre-conditioning, a "violent-mixing" phase takes place as further strong surface buoyancy loss events commence deep convection and overturning of the water column (Marshall and Schott, 1999). This process occurs in the form of "plumes" of order 1 km^2 within a convective regime reaching 1000 km^2 (Marshall and Schott, 1999). The instantaneous vertical velocities within such "plumes" have been reported to reach 10 $cm\,s^{-1}$ (Schott and Leaman, 1991) but have a net vertical transport of zero, acting more as strong mixing elements (Marshall and Schott, 1999). Typically, this phase of deep convection is fairly rapid lasting less than one week (Salat and Font, 1987). The result of this phase is the formation of "deep mixed patches" with homogenous temperature and salinity properties, varying in diameter from 10 to >100 km and reaching 2000 m into the water column (Marshall and Schott, 1999).

- As surface forcing ceases, a "sinking and spreading" phase ensues as the recently formed deep mixed patches "slump" under gravity and undergo geostrophic adjustment; with a rim current established around the patch's periphery (Jones and Marshall, 1997). Subsequently, stratification is re-established over the sinking mixed patch due to an inflow of stratified surface waters surrounding the convective region (Stommel, 1972), initiated by frontal geostrophic eddies originating within the peripheral current (Jones and Marshall, 1997). The newly convected water in the western basin forms the WMDW, which steadily sinks to a level of neutral buoyancy and is understood to spread in a general southerly direction (MEDOC Group, 1970). This dispersal of new WMDW (nWMDW) is facilitated by submesoscale vortices (Testor and Gascard, 2006) along with geostrophic eddies (Schott et al., 1993) spawned from baroclinic instabilities within the water column (Jones and Marshall, 1997). The circulation of WMDW following formation is fairly complex, but a general anticlockwise circulation of the water mass around the western basin is understood to occur (Millot, 1999).

1.2 Changes of water mass characteristics

Observations of WMDW and LIW over the past century suggest properties of both water masses are changing, with an acceleration of such trends post-1955 (Rohling and Bryden, 1992). The WMDW is described as becoming "warmer and saltier over the past several decades" by Leaman and Schott (1991) whilst the LIW has also experienced an increase in salinity (Rohling and Bryden, 1992). Mean increases in temperature and salinity have been estimated by a number of authors and are highlighted in Table 1, with estimated increases in θ and S of WMDW ranging from 8.3×10^{-4} to 5.4×10^{-3}°C yr^{-1} and 6.9×10^{-4} to 2.0×10^{-3} yr^{-1} respectively. The observed changes of both water masses are closely coupled as WMDW properties are partly governed by the properties of the water masses present in the deep convective regions of the western basin (Skliris and Lascaratos, 2004). Long term changes observed in the salinity and temperature of the LIW (and subsequently the WMDW) have been largely attributed to anthropogenic reductions in freshwater flows entering the Mediterranean (Rohling and Bryden, 1992; Bryden and Boscolo, 2002), although more recently the influence of the Eastern Mediterranean Transient (EMT) on the western basin convective regime has also been considered (Klein et al., 1999; Schroder et al., 2006). WMDW properties are also influenced by inter-annual variations in forcing and environmental conditions within the western basin (Mertens and Schott, 1998), although deep convection within the western basin is intermittent and may not occur yearly (Marshall and Schott, 1999). Nevertheless, such changes in salinity of the WMDW are predicted to significantly alter the thermohaline circulation of the Mediterranean in the coming century (Skliris and Lascaratos, 2004).

1.3 Modern observations of the western basin

Early studies of deep convection within the western basin focused on ship surveys of the convective regime in the Gulf of Lions and Ligurian and Provençal subbasins (Stommel, 1972; Leaman and Schott, 1991). However, convective regions are notoriously difficult to work in owing to strong, persistent winter storms, which can hinder ship-based sampling campaigns and such campaigns in themselves are limited by cost and manpower available. The development of neutrally buoyant profiling floats over the past half-century, outlined by Gould (2005), and the deployment of ARGO deep profiling floats (hereafter, ARGO floats) into the Mediterranean Sea in recent years (Poulain et al., 2006) represents a new approach to studying the physical oceanography of the Mediterranean Sea remotely, over periods reaching a few years. An ARGO float is capable of recording vertical profiles of temperature and salinity to pre-described depths and at pre-defined intervals, and then transmitting this data along with the float position, to global relay centres, where the data are processed and made accessible to the scientific community in near-real-time (Poulain et al., 2006). Already, data collected by ARGO floats in the North Atlantic has been presented by Ivchenko et al. (2005) in medium term monitoring of temperature and salinity variability, by Ohno et al. (2004) in observing spatial and temporal variations of the Mixed Layer Depth (MLD) in the North Pacific and by Avsic et al. (2006) in studying hydrographic properties of the Labrador Sea Water to complement ship-based CTD profiles. In relation to the Mediterranean Sea, a principal deployment of ARGO floats took place in 2003 with floats then recovered in spring 2006 (Poulain et al., 2006). Two studies have already presented data from these floats: Tallandier et al. (2006) assimilated ARGO data into a model of the Mediterranean Sea suggesting such data would be suitable for providing initial conditions for ocean circulation modelling and Lopez-Jurado et al. (2005) contrasted ARGO float data with that of CTD data in the Catalan subbasin in observing a disruption to a previously observed warming trend.

This study will examine the recent wintertime characteristics of the western basin of the Mediterranean Sea, through description and analysis of ARGO float data collected during the winter months of 2004–2005 and 2005–2006. This study will also follow seasonal evolution of WMDW production during these periods, to compare any deep convection events observed with historical observational evidence of deep convection and water mass characteristics in the western basin. From this investigation we hope to learn whether deep convection took place in the western basin between 2004 and 2006 and how the deep water properties are changing with time.

2 Data

2.1 ARGO profiling floats

The principal source of data for this study comes from temperature and salinity profiles collected by ARGO floats in the western basin of the Mediterranean Sea, over the winter months (defined as 1 November to 31 March) of 2004–2005 and 2005–2006. A total of 145 profiles from 5 floats were analysed between 0–10° E, 38–46° N. The float data presented are part of the MEDARGO Program (Poulain et al., 2006), which consisted of a total of 23 ARGO floats deployed in both the eastern and western basins of the Mediterranean Sea between 2003 and 2006. The ARGO float data we present represents real-time quality control data accessed from the USGODAE ARGO GDAC dataset on 27 November 2006. When automatic quality control flags have indicated a specific measurement of being of a poor quality, it has been excluded from this study.

The MEDARGO floats were configured to follow a 5-day profiling cycle with a neutral parking depth of 350 m and vertical CTD profiles to 700 m (9 in 10 cycles – "shallow dive") and 2000 m (1 in 10 cycles – "deep dive"). During CTD profiles the ARGO float sampled at 80 (700 m) and 106 (2000 m) depths with intervals between samples of 5 m (0–100 m), 10 m (100–700 m) and 50 m (700–2000 m). Measurements of temperature, conductivity - used to determine salinity - and pressure were made using onboard Sea-Bird Microcat CTD sensors to accuracies of 0.002°C, 0.005 and 2.4 dbars respectively.

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Initial analysis of ARGO float data coupled with discussion by Poualin et al. (2006) and Emelianov et al. (2006) suggests none of the floats experienced significant drift in any of the CTD sensors following pre-deployment calibration.

To consider differences between the pre-conditioned phases during the two winters we first assemble all available ARGO float data within two 3° ×3° cells (Catalan subbasin 39–42° N, 2–5° E and Ligurian subbasin 41–44° N, 6–9° E) between 1–30 November of the two winters and interpolate this data onto a regular 10 dbar pressure surfaces. The mean θ and S for each pressure surface were then calculated from the collated data, to create average θ and S profiles for November 2004 and November 2005. An important point to note throughout this study is that ARGO floats rarely profile the same water column more than once and may drift >30 km between subsequent profiles. However, given that processes of deep convection act over fairly large regions themselves (Marshall and Schott, 1999), we assume that the features observed in one region of a subbasin will be similar to those in adjacent locations within the same subbasin. This allows us to consider the pre-conditioning a region would most likely have undergone, despite not being directly sampled.

2.2 NCEP/NCAR

Air-sea flux data comes from the NCEP/NCAR daily reanalysis and were used to examine time-series of air-sea fluxes and heat loss (sea to air heat flux) in the regions of ARGO floats during the winters of 2004–2005 and 2005–2006. The air-sea flux data represents the net of: incoming solar radiation, back radiation, latent and sensible heat loss. The NCEP/NCAR data presented is from two separate grid cells at 3.75° E, 40.9517° N and 7.5° E, 42.8564° N (see Fig. 2), proximate to 2 of the ARGO float trajectories.

2.3 WMDW and LIW properties

Observational evidence of WMDW and LIW properties are considered to illustrate changes in the water masses properties over the past century. The dataset consists of data collected between 1909-1989 from Rohling and Bryden (1992) with additional, more recent observational data in the same regions and at the same depths taken from Mertens and Schott (1998) and Testor and Gasgard (2006), along with observational evidence from the ARGO float data presented in this study, collected in the same region as Rohling and Bryden (1992). The potential density of WMDW at 2000 m for each year has been calculated from the dataset presented with a reference pressure set to 0 dbar. The data from 1992–2006 represent properties of WMDW identified at 2000 m immediately after formation and not data averaged per vessel, per year as in Rohling and Bryden (1992). The data examined lacks observational evidence of WMDW properties between 2000–2004 when hydrographic surveys of the region were sparse. The salinity of the Levantine Intermediate Water was recorded in the region covering latitudes 41° to 43° N and longitudes 5° to 7.5° E as per Rohling and Bryden (1992) with 1° extension of region to the north to include additional ARGO float data.

This study uses implementations of the m_map toolbox made freely available by Rich Pawlowicz (http://www.eos.ubc.ca/~rich/map.html), the high resolution GSHSS Global Shoreline Data made freely available by the National Geophysical Data Centre (http://www.ngdc.noaa.gov/mgg/shorelines/data/gshhs/) and the Woods Hole Oceanographic Institution OCEANS toolbox (ftp://acoustics.whoi.edu/pub/Matlab/oceans/).

3 Results

3.1 Float observations

We first describe trajectories of ARGO floats during the 2004–2005 and 2005-2006 winter observation periods in the western basin of the Mediterranean Sea. We also examine the hydrographic conditions for the respective winters through description of 5 ARGO float datasets, with a detailed focus on 2 datasets that provide evidence of winter deep convection and formation of new western Mediterranean deep water (nWMDW).

3.1.1 Trajectories

The trajectories of the ARGO floats present in the western basin during the 2004–2005 and 2005–2006 winters are examined by using time-series ARGO float position data spanning the respective winter observation periods (Fig. 2). The ARGO float trajectories indicate 5 separate float transects (3 in 2004–2005, 2 in 2005–2006) which pass through regions where winter deep convection may be expected to take place within the western basin. The first ARGO float (6900279) profiled north of the Balearic Islands (41.120° N, 3.184° E) on 2 November 2004 and was displaced in a general south-easterly direction during the winter, initially moving into the Catalan subbasin and then in an easterly direction parallel to the coastline of the northern Balearic Islands. The float was located within the western Provençal subbasin (39.417° N, 4.658° E) in late March 2005. The trajectory of the second ARGO float (6900292) shows the float profiling along a north-easterly transect from the Provençal subbasin (42.056° N, 6.969° E) to the Ligurian subbasin (43.276° N, 9.545° E) during winter 2004–2005. During the following winter season (2005–2006) the float traces an anticlockwise loop about the centre of the MEDOC region (42° N, 5° E) moving in turn through the Gulf of Lions, northern Catalan and Provençal subbasins. The third ARGO float (69200293) remained within the central Provençal subbasin throughout the 2004–2005 winter, entrained within an anti-cyclonic eddy about 39.8° N, 6° E, with a gradual northward displacement (travelling 120 km north from initial November profile). During the following winter, the float cycled within the eastern Provençal subbasin, off the western coast of Corsica (41.161° N, 7.536° E) on 3 November 2005. The float trajectory then traces a northerly path and following initial westerly displacement, the float again became entrained within an anti-cyclonic eddy (13 December 2005–6 February 2006) and follows a path around 42.080° N, 6.500° E, before moving northward into the Ligurian subbasin on 28 March

2006.

3.1.2 Hydrographic observations (winter 2004-2005)

To examine the winter 2004–2005 hydrographic characteristics of the western basin, we first review successive profiles of θ, S and σ_θ for ARGO float 6900279, which ultimately showed deep convection occurring in the Catalan subbasin during March 2005. Time evolution of vertical profiles of θ from ARGO float 6900279 show a distinct transition from strong, surface thermal stratification in November, through to a well mixed, homogenous water column by mid March (Fig. 3a). A salinity maximum (S_{max}) is well established in vertical salinity profiles taken by the ARGO float in early winter (Fig. 3b), representing the core of the LIW at 500–600 m in the Catalan subbasin. During the early winter, surface water density is less than 28.0 kg m^{-3}. Weakening of the thermocline and a subsequent homogenous temperature profile is observed to 600 m on 10 February 2005, with significant erosion of the LIW core. This erosion of stratification is well illustrated comparing ARGO float deep-dive profiles on 2 December 2004 and 21 January 2005 where the temperature, salinity and density gradients of the upper 200 m weaken significantly (Fig. 4). As the ARGO float travelled eastward during February 2005, the MLD decreased from ~200 m on 10 February 2005 to <50 m on 20 February 2005, with vertical hydrographic profiles indicating stratified surface waters and an underlying, weakly stratified water column with θ<13.3°C. Uniform vertical temperature profiles and almost vertical isotherms (Fig. 5) were subsequently observed to maximum cycle depths of 750 m (7 March 2005) and 2000 m (12 March 2005) approximately 50 km from the coastline of Menorca (40° N, 4.5° E). Vertical profiles on 12 March indicate the MLD reaching 2000 m and "connected" to the surface, with surface water σ_θ exceeding 29.1 kg m^{-3} and salinity (0–2000 m) 38.48±0.05 with no signature of the LIW S_{max} detected. Physical properties at the maximum cycle depth on 12 March 2005 (2000 m) show θ=12.89°C, S=38.48 and σ_θ=29.11 kg m^{-3}. The water column (0–700 m) remained vertically uniform (with regards to θ and S) between 7 and 12 March 2005, whilst the float travelled south-easterly for ~100 km, with the MLDs during

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this time being ~650 and ~1900 m, much deeper than the mean MLD (97 m) observed during the 2004–2005 winter. Through the remainder of March the float travelled south into the Provençal subbasin with the MLD rapidly decreasing to 50 m, ML temperatures exceeding 13°C and an accompanying decrease in salinity of the ML occurred as the water column restratified. Below this slightly stratified surface layer, the water remained very cold (<13°C) with a weak salinity maximum apparent at 300 m (Fig. 3b).

To further examine the seasonal evolution of nWMDW during the 2004–2005 winter, we consider the progressive mixing of the water column, revealed in hydrographic properties averaged between pressure surfaces using data from ARGO float 6900279 (Fig. 6). These results show that water column cooling between November and late January was largely restricted to the upper 200 m in the Catalan subbasin (coinciding with the maximum MLD) and was characterised by four cooling "episodes", with the 0–200 m layer cooling to a uniform 13.7°C by the end of January. Over the same period, salinity in the 0–200 m layer fluctuated by a maximum of 0.1 between float cycles. By 10 February 2005 the 0–200 m layer cooled to a similar temperature of the 200–400 m layer, with subsequent prolonged cooling between late January and early March occurring in the 200–400 m and 400–600 m layers, as the MLD exceeded 200 m (after 10 February 2005). Following this prolonged cooling and increase in the MLD, a sharp increase in the 0–200 m layer salinity of 0.372 occurred between 25 February 2005 and 12 March 2005, whilst salinities in the 200–400 and 400–600 m layers decreased. These observations show surface forcing had been of sufficient duration and magnitude (by late February 2005) to overcome the density gradient and to progressively mix and entrain deeper layers. The observed salinity increase in the 0–200 m layer can therefore be explained by a reduction in salinity of the 200–400 m and 400–600 m layers through entrainment and upward mixing of the saline LIW into the ML. With continued surface forcing and deepening of the ML, the water column homogenised to 2000 m on 12 March 2005 with the 0–200 m layer having experienced a salinity increase of 0.163. In the remainder of March temperatures in all layers above 600 m increase and approach 13.2°C whilst salinity decreases between 0–200 m by 0.17, and increases by

0.035 in the 200–400 and 400–600 m layers, coinciding with the re-establishment of a sub-surface S_{max}.

The entire set of θ and S measurements recorded by ARGO float 6900279 are presented as a θ/S diagram (Fig. 7) to characterise water masses present in the western basin. Firstly, two "branches" of low salinity MAW can be identified in the surface waters (σ_θ less than 28.9 kg m^{-3}), which represent the water mass at different stages of seasonal modification and in different locations. Throughout most of the winter a strong signal of the LIW is present as a salinity maximum, with mean winter salinity of 38.556, θ~13.2°C between 450–650 m. Salinity profiles indicate the core of the LIW becomes less distinct during periods of deep MLs. A signal of Winter Intermediate Water (WIW) appears on 2 March 2005 as a potential temperature minimum (θ_{min}) of 12.821°C, with S 37.9–38.1 and σ_θ 28.6–28.8 kg m^{-3}, with the water mass occupying depths of ~60 m between MAW and LIW, close to 40.258° N, 3.628° E. Of most interest are two separate signatures of WMDW, the first is a cooler and fresher, old WMDW (oWMDW) (θ=12.86°C, S = 38.46, σ_θ = 29.108 kg m^{-3}) identified at 2000 m on 2 December 2004 and 21 January 2005, whilst the other is a warmer, more saline nWMDW (θ=12.89°C, S=38.48, σ_θ=29.113 kg m^{-3}) identified on 12 March 2005 at 39.785° N, 4.845° E. These two signals can be seen most clearly on the inset of Fig. 7, with nWMDW saltier, warmer yet denser than the oWMDW.

Having examined the data from ARGO float 6900279 we now briefly examine data from two further ARGO floats which were present in the western basin during the 2004-2005 winter, but which did not identify deep convection. Data collected within the central Ligurian and Provençal subbasins from ARGO float 6900293 reveals deep convection did not extend to this region during the winter of 2004–2005. Winter buoyancy loss events caused initially strongly stratified surface layer of MAW to cool below the temperature of the deeper waters by 6 February 2005 (Fig. 8) yet the upper water column (0–200 m) remained "fresher" than deeper waters with S<38.4 and the 0–200 m mean winter σ_θ=28.928 kg m^{-3} imposing a strong density gradient into the deeper waters. As a consequence, later cooling and vertical mixing were limited to the surface layer

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of MAW with the LIW not entrained into the ML and the MLD remaining shallower than 200 m. Similar observations from ARGO float 6900292 over the 2004–2005 winter in the southern Ligurian subbasin indicate a persistent layer of cold but "fresh" water in the upper 200 m (mean winter σ_θ=29.074 – results not shown). Layer averaged properties indicate the 0–200 m θ dropping below 13°C in February and March but salinity in the same layer remaining <38.4, with vertical mixing of the water column again inhibited by a strong density gradient and limited to those waters above the LIW core.

The ARGO float data collected over the 2004–2005 winter observation period display fascinating features of deep water formation and winter hydrographic characteristics in the western basin. 2 of 3 ARGO floats detected a low salinity surface layer of MAW, which persisted over much of the upper water column of the Provençal and Ligurian subbasins. This "fresh" surface layer prevented ML entrainment of the LIW and thus inhibited the pre-conditioning phase required for deep convection. However, the classical pre-conditioning did occur within the eastern Catalan subbasin, with ARGO float 6900279 ultimately sampling nWMDW at 2000 m during March 2005. Deep convection occurred in an unusual location (39.785° N, 4.845° E) at the border of the Catalan and Provençal subbasins, much further south than typically described. Furthermore, the nWMDW was warmer, saltier yet denser than oWMDW present in the western basin. Unfortunately, ARGO float transects did not pass through the MEDOC region or the Gulf of Lions during the 2004–2005 winter, where deep convection has traditionally been studied.

3.1.3 Hydrographic observations (winter 2005–2006)

The seasonal characteristics of the western basin during winter 2005–2006 are now examined using hydrographic data collected by 2 separate ARGO floats. We first describe seasonal characteristics of the Provençal and Ligurian subbasins from successive profiles of θ, S and σ_θ for ARGO float 6900293, which subsequently detected formation of nWMDW during March 2006 in the Ligurian subbasin.

Vertical profiles of potential temperature collected from ARGO float 6900293

(Fig. 9a) show stable stratification persists throughout the early winter at the border of the Provençal and Ligurian subbasins, with a strong thermocline in the upper 150 m, along with a sub-surface θ maximum at ~300 m. A distinct S_{max} (S=38.58) is also present in the region at 250–500 m (Fig. 9b), with the θ_{max} and S_{max} suggesting this water mass represents the core of the LIW during early winter. The thermocline becomes entirely eroded by 2 January 2006 (Fig. 10) with ML θ=13.4°C, S>38.3 and surface water σ_θ reaching 29.051 (15 m), exposing the upper water column to surface forcing. By 22 January 2006 the surface water density increases to 29.104 kg m^{-3} (15 m) and the MLD reaches 1000 m, with properties at the base of the MLD showing θ=12.94°C, S=38.48 and σ_θ=29.11 kg m^{-3}. Salinity profiles from the same cycle indicate salinity from 0–2000 m is 38.48±0.03, with the S_{max} almost entirely eroded. Surface waters briefly restratify between 1 February 2006 to 6 February 2006 as the float moves northward into the Ligurian subbasin, before again homogenising with intermediate waters as the MLD reaches 700 m on 3 March 2006. The MLD reaches 2000 m on 13 March 2006, with vertical isotherms observed in the θ time evolution plot (Fig. 11) suggesting the "violent mixing" phase of deep convection was taking place. As the MLD reaches 2000 m (~930 m deeper than the mean MLD estimated for the 2005–2006 winter in the region of the float) the hydrographic properties at the maximum cycle depth (2000 m) are θ=12.92°C, S=38.49 and σ_θ=29.11 kg m^{-3}, whilst the float is at 43.392° N, 7.765° E. The salinity at 2000 m increased by 0.04 and the density has increased by 0.01 kg m^{-3} compared to the previous deep-dive cycle on 22 January 2006, with the deep water becoming saltier, warmer but denser over winter as LIW is mixed down. These results show that although the nWMDW at 2000 m in the western basin is warmer than oWMDW, it also has a sufficiently high salt content to make it denser. It should be noted that deep water production may have occurred prior to 13 March 2006 in the Ligurian subbasin (from 26 February 2006 to 8 March 2006), as MLDs reached the maximum cycle depth of shallow-dive cycles (700 m) with similar properties in the ML to the nWMDW later produced. Surface water temperatures increase during the remainder of March to 13.1°C and a minor salinity maximum appears between 75–130 m, accompanied by a shallow MLD of 20 m as the surface waters restratify.

Having observed nWMDW formation in the Ligurian subbasin, the progressive homogenisation of the water column will now be examined to follow seasonal evolution of WMDW formation. This is accomplished by analysing time evolution of layer averaged hydrographic properties for float 6900293 over the 2005–2006 winter (see Fig. 12). A steady increase in the 0–200 m layer salinity ($\sim 7.5\times10^{-3}$ d^{-1}) is observed between the start of the observation period (3 November 2005) and 3 December 2005, accompanied by a decrease in salinity of all layers deeper than 200 m. These salinity trends coincide with cooling in the 0–200, 200–400 and 400–600 m layers measuring 1.7, 0.2 and 0.25°C respectively (relative to the first float cycle) on 22 January 2005. Such results suggest the deeper layers are progressively being entrained into an ever-deepening ML that is exposed to surface forcing and again suggest entrainment of the LIW into the ML, as the average salinity over 0–600 m reaches values typical of the LIW on 26 February 2006. Following further cooling, the 0–200, 200–400 and 400–600 m layers are uniform to within 0.1°C from 26 February 2006 to 13 March 2006 (as the float moves northward from the Provençal into the Ligurian subbasin) and as the MLD reaches 2000 m on 13 March 06, the net salinity increase in the 0–200 m layer (relative to the first float cycle) is estimated as 0.238. Salinities in the 200–400 and 400–600 m layers decrease for the remaining observation period, whilst the 0–200 m layer experiences minor warming and fluctuating salinity.

To identify the presence of water masses within the northern Provençal and Ligurian subbasins during the 2005–2006 winter, a θ/S diagram is plotted from measurements taken by ARGO float 6900293 (Fig. 13). A S_{max} can be observed close to the 29.1 σ_θ anomaly contour in most of the profiles and is interpreted as the presence of LIW in this region, with the LIW core (winter average S = 38.57, $\theta\sim$13.2°C) having salinity and density $\sim$0.0140 and $\sim$0.004 kg m^{-3} higher than the LIW core identified in the Catalan subbasin the previous winter. Data plotted above the 28.6 σ_θ anomaly contour fluctuate largely in θ and S, indicating the presence of a fresher, warmer surface layer present in early winter (MAW), which becomes saltier and cooler with progression through the winter season and movement of the ARGO float north-easterly. Measurements of θ and S at 2000 m on 22 January 2006 indicate values typical of oWMDW with θ=12.83°C, S=38.454 and σ_θ=29.107 kg m^{-3}. The following deep-dive cycle of ARGO float 6900293 on 13 March 2006 at 43.392° N, 7.765° E, identifies nWMDW present at 2000 m with θ=12.923°C, S=38.486 and σ_θ=29.113 kg m^{-3}. The nWMDW present in the Ligurian subbasin is ~0.03°C warmer and ~0.01 saltier but with indistinguishable density difference, compared to the nWMDW observed the previous winter at the border of the Catalan and Provençal subbasins. This is again evidence of a cooler, fresher oWMDW, which is later displaced by a warmer, more saline nWMDW produced during the 2005–2006 winter.

It was expected that deep convection would also have been observed in data collected by ARGO float 6900292, as the float regularly profiled within the MEDOC region during the winter 2005–2006 observation period. It appears however, that the ARGO float missed the main winter convection perhaps due to the timing of deep-dive cycles, with nWMDW subsequently detected beneath a re-establishing LIW core (Fig. 14). During the early winter, ARGO float 6900292 data indicated stable stratification was present in the Gulf of Lions, with the LIW core at ~500 m and θ exceeding 17°C in the surface waters. The LIW core was later detected at 250 m on 21 January 2006 following progressive decreases in the salinity and temperature of the surface waters. As the float profiles close to the centre of the MEDOC region, convection of the water column reached 700 m during shallow-dive cycles on 22 February 2006 and 9 March 2006 with uniform temperature and salinity profiles (results not shown). A subsequent deep-dive cycle on 14 March 2006 identifies nWMDW with θ=12.91°C, S=38.48 and σ_θ=29.114 kg m^{-3} at 2000 m (see Fig. 14). These observations strengthen the evidence that a nWMDW was formed during the 2005–2006 winter in the western basin although it may not have formed in the MEDOC region.

3.2 Air-sea fluxes

We now examine the NCEP/NCAR daily reanalysis air-sea flux data compiled in locations proximate to ARGO float transects (see Fig. 2) in order to study the surface forcing in the two deep convective regions sampled by ARGO floats (6900279 and 6900293) in March 2005 and March 2006 respectively (Fig. 15).

Winter 2004–2005 data indicates six periods (lasting <3days) when heat fluxes reach or exceed 600 W m^{-2} suggesting major meteorological forcing is taking place for short periods. Of these cooling events, three reach ~800 W m^{-2} and occur at similar times to the cooling "episodes" observed in the layer averaged θ. Intervening periods are marked by much lower heat fluxes and also correspond to observations from ARGO float 6900279 of brief surface restratification. The heat fluxes remain almost always, above 200 W m^{-2} between 12 February 2005 and 8 March 2005 during which time the MLD reached 2000 m. The heat flux remained positive for the entire winter until 10 March 2005, after which time float (6900279) observations indicate surface restratification over the newly ventilated water column.

The NCEP/NCAR data from the Ligurian subbasin over the 2005–2006 winter indicates a clear difference between the surface heat fluxes experienced the previous winter in the Catalan subbasin. Heat fluxes in the Ligurian subbasin did not exceed 400 W m^{-2} and were consistently weaker, with less distinct heat flux "episodes" observed in comparison to the previous winter. A distinct peak in the air-sea flux occurs on 6 March 2005 of 236 W m^{-2}, following which the MLD increases to reach 2000 m on 13 March 2006, despite heat fluxes quickly becoming negative.

To examine similarities between the ARGO float data and NCEP/NCAR reanalysis data, we compare the winter NCEP/NCAR heat loss with heat content changes observed by ARGO floats throughout the two winter observation periods (Fig. 16). Reasonable agreement is found between cumulated air-sea heat flux and ocean heat content with differences in total seasonal heat loss of $9.98\times10^8 \pm 6.63\times10^8$ J m^{-2} and $3.61\times10^8 \pm 3.37\times10^8$ J m^{-2} in the winters of 2004–2005 and 2005–2006 respectively.

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Differences between ARGO float 6900279 and NCEP/NCAR total winter heat loss in the 2004–2005 winter were $1.622\times10^9\,\mathrm{J\,m^{-2}}$ with the NCEP/NCAR heat loss being larger. Comparisons between ARGO float 6900293 and the NCEP/NCAR dataset for the 2005–2006 winter show similar gradients throughout the winter with stronger agreement (compared to 2004–2005 winter) and differences between total estimated heat loss of $6.976\times10^8\,\mathrm{J\,m^{-2}}$, with the ARGO cumulative heat content being larger. Interestingly, reasonable agreement was found between the datasets during both winters, with the ARGO float data "following" the NCEP/NCAR data remarkably well, despite large differences in winter buoyancy loss over the two winter observation periods.

Through analysis of the ARGO and NCEP/NCAR data it is apparent that the 2004–2005 winter experienced stronger and more prolonged surface forcing than the 2005–2006 winter, leading to a greater water column heat loss. This is highlighted in the differences between the NCEP/NCAR heat losses when deep convection was observed in the respective years. The deep convection observed in 2005 (12 March) and 2006 (13 March) occurred 2–6 days after maximum cumulative heat losses are observed in NCEP/NCAR data with the differences between these results showing an additional surface heat loss of $1.52\times10^9\,\mathrm{J\,m^{-2}}$ at the time deep convection was observed in March 2005 (compared to March 2006). As a result, the nWMDW formed during 2004–2005 was colder (and less saline), yet had indistinguishable density to the nWMDW formed the following year. Both datasets evidence a heat content increase from mid-March through to the end of the observation period, consistent with restratification of surface waters and re-establishment of a salinity maximum.

3.2.1 Differences in the pre-conditioning phases of November 2004 and 2005

An interesting question is how deep convection occurred in the 2005-2006 winter in the Ligurian subbasin, despite consistently weak buoyancy losses. To address this question we examine differences in the water column structure of the western basin during the pre-conditioning phase of 2004 and 2005. Average potential temperature and salinity profiles created from ARGO float data (Fig. 17) reveal the S_{max} of the LIW in the

Ligurian subbasin during November 2005 was saltier (∼0.007), warmer (0.005°C) and with a shallower core (at ∼400 m) in comparison to the LIW observed in the Catalan subbasin in November 2004 (LIW core at ∼540 m). Furthermore, the Ligurian subbasin was 0.359°C cooler and 0.07 saltier in November 2005 than the Catalan subbasin in November 2004 (based on 0–700 m average θ and S). The shallower, saltier LIW in the Ligurian subbasin during November 2005 would be expected to promote homogenisation of the surface and intermediate waters during winter time buoyancy loss, despite weaker buoyancy fluxes. Cooler waters persisting in the upper 200 m would also likely have assisted this homogenisation process.

3.3 Changes in WMDW properties

We finally consider an adapted version of the dataset presented by Rohling and Bryden (1992) that has been expanded to include more recent observational evidence of LIW and WMDW properties (Fig. 18), to examine long term warming and increasing salinity trends. The data show that from 1955-2006 the WMDW has warmed on average by 3.6×10^{-3}°C yr^{-1}, with accompanying increases in salinity of 1.5×10^{-3} yr^{-1} and in density of 4.0×10^{-4} kg m^{-3} yr^{-1}. The correlation coefficients (r^2) for θ, S and σ_θ were found to be 0.649, 0.734 and 0.5593 respectively. The WMDW observed in the Ligurian subbasin during March 2006 is warmer, more saline and denser than any of the previous WMDW data presented, with the data from 1955–2006 also suggesting the WMDW is experiencing accelerating increases in temperature, salinity and density compared with trends prior to 1955. The data also show the LIW has experienced a salinity increase of 9.17×10^{-4} yr^{-1} from 1900–2005 with the correlation coefficient found to be r^2=0.625, whilst a linear regression considering only post-1955 data shows a weaker co-relation coefficient of r^2=0.457. The LIW present in the MEDOC region during winter 2005–2006 was recorded as having θ=13.988°C, S=38.532 and σ_θ=28.99 kg m^{-3} (data from ARGO float 6900292) showing the LIW has experienced an increasing salinity trend, although it remains slightly less saline than in 1987 but warmer and less dense.

4 Discussion

Analysis of ARGO float data collected from the western basin of the Mediterranean Sea has indicated the distinct "three-layer" water column structure typical of the western basin (Hopkins, 1985; La Violete, 1994) throughout the Catalan, Ligurian and Provencal subbasins over the winters of 2004–2005 and 2005–2006. Regional differences noted in S and θ of the MAW are attributed to differences in residence times of the water mass in the respective float regions (Send et al., 1999), with MAW being circulated (and progressively modified) in an anticlockwise direction around the basin (Millot, 1999). The restricted deepening of the ML noted in the Ligurian and Provencal subbasins during the 2004-2005 winter is attributed to both the weaker surface forcing experienced in these subbasins (Gasparini et al., 1999) and strong stratification detected at the start of winter, with buoyancy losses in the surface waters insufficient to cause subsequent homogenisation and entrainment of intermediate waters.

Further examination of the ARGO float data reveals that two regions of the western basin (namely the eastern Catalan subbasin during winter 2004–2005 and western Ligurian subbasin during winter 2005–2006) were characterised by similar progressive deepening of a surface ML between November and January, in turn leading to entrainment and mixing of surface and intermediate waters. We find that NCEP/NCAR heat fluxes from the Catalan and Ligurian subbasins were of a similar magnitude and duration to those expected from the Mistral wind (Mertens and Schott, 1998; Leaman and Schott, 1991) leading us to conclude that the repeated winter heat and freshwater loss experienced in the two subbasins were due to cooling and evaporation by these continental winds, typical during winter in the western basin (Schott et al., 1993). Observed cooling and increases in salinity correspond well to periods of strong surface forcing, depicted in the NCEP/NCAR heat fluxes. However, sharp fluctuations in θ and S profiles taken by ARGO float 6900279 in early winter are attributed to the ARGO float moving between different water mass regimes (Ohshima et al., 2005) as the NCEP/NCAR data proximate to the floats trajectory indicates weak surface forcing in the region of the float at these times. Subsequently, stronger agreement between observed cooling and NCEP/NCAR heat loss for the 2004–2005 winter would be expected had we began cumulating heat loss after the float moved out from this warmer water mass regime.

A notable feature of ARGO float data from the Catalan subbasin in mid-February (2005) and Ligurian subbasin in late-January (2006) is the occurrence of MLDs reaching 200 m, which shallow abruptly (within 1 float cycle) and briefly remain within the surface waters before rapidly increasing during March. The NCEP/NCAR heat flux data from the two subbasins indicates weak or negative (air to sea) heat fluxes of a similar duration, which suggests restratification of surface waters is quickly initiated as surface forcing pauses between Mistral cooling events, consistent with earlier observations by Schott et al. (1996).

Following this brief restratification, MLDs reached 400–500 m in both the Catalan and Ligurian subbasin, causing an upward mixing of the saline waters of the LIW into the ML. Erosion of the LIW S_{max} thus indicates transformation of the water mass (Emelianov et al., 2006) with subsequent mixing leading to homogenisation of surface and intermediate waters. As such, the "pre-conditioning" phase of deep convection, exposing weakly stratified deeper waters to ML entrainment is concluded by early March in 2005 (Catalan subbasin) and by mid-January in 2006 (Ligurian subbasin). Typically, homogenisation of the intermediate and surface waters occurs by late February in the Gulf of Lions (Schott et al., 1993; Mertens and Schott, 1998) but interestingly, homogenisation of these waters occurred more than a month earlier in the Ligurian subbasin during 2006 despite weaker regional surface forcing than in 2004–2005 and in a region where deep convection is not traditionally seen. A combination of winter buoyancy loss, water column structure and general circulation within a region is required for pre-conditioning to take place (Swallow and Castson, 1973) and also important is the area over which consistent, strong forcing takes place (Lavender and Davis, 2002). The Ligurian subbasin was characterised by unusually shallow, saline intermediate waters (LIW) and a saltier surface MAW than typically observed, with an overall cooler and saltier water column in November 2005 compared to November 2004 in the

Catalan subbasin. Owing to these unusual characteristics of both LIW and MAW, surface and intermediate waters required lower cumulative buoyancy loss to homogenise and sufficiently pre-condition a region of the subbasin, leading to the "early" conclusion of the "pre-conditioning" phase in the Ligurian subbasin during winter 2005–2006. Pre-conditioning in the Ligurian subbasin during winter 2005–2006 is also facilitated not only by unusually shallow, warm and saline intermediate waters (and saline surface waters) but also a cyclonic surface circulation that characterises the region (Astraldi and Gasparini, 1992) and sufficiently high buoyancy fluxes from Mistral winds to entrain intermediate waters into the ML (Testor and Gascard, 2006). These processes have important consequences on the properties of nWMDW subsequently produced, which we later discuss.

Observations during early March in the Catalan subbasin (12 March 2005) and Ligurian subbasin (13 March 2006) describe well the "violent mixing" phase of deep convection (Marshall and Schott, 1999) with heat fluxes in both subbasins immediately prior to deepwater production of a similar magnitude to heat fluxes reported during convection events in the western basin from 1987 to 1992 (Marshall and Schott, 1999). The homogenous MLs extending to 2000 m in early March were far deeper than either typical wind MLs or mean winter MLDs and remained "connected" to surface waters for approximately 5 days. These observations, coupled with the appearance of a warmer, more saline (and denser) water mass at 2000 m (compared to oWMDW) means we can be confident deep convection took place during March in both the Catalan (2005) and Ligurian (2006) subbasins.

Interestingly, these findings are quite different from much of the published literature relating to formation of the WMDW. Firstly, historical observations show the "violent mixing" phase of deepwater production in the western basin occurs in mid-February (Bunker, 1972; Mertens and Schott, 1998; Marshall and Schott, 1999) or in particularly strong winters, during January (Schott et al., 1996; Schott and Leaman, 1999). Whilst the Ligurian subbasin experienced an "early" pre-conditioning phase during winter 2005–2006, heat losses (and instantaneous heat fluxes) were insufficient to trigger deep convection and production of nWMDW until March. Indeed the timing of deep convection is found to be dependent on the integrated cooling and mixing of the water column occurring over the winter period (Schott et al., 1993) with heat fluxes and associated buoyancy losses identified as the dominant factor in the timing of deep convection (Mertens and Schott, 1998). The winter of 2004–2005 in the Catalan subbasin experienced particularly severe weather (Lopez-Jurado et al., 2005) yet nWMDW production did not occur until March. It is suggested that in the Catalan subbasin the water column experienced "ventilation" during February with homogenisation of the upper water column, comparable to brief, shallow convection described by Pinot and Ganachaud (1999), which can lead to formation of a WIW. Indeed, this study identifies a WIW at depths above the LIW in the waters north of the Balearic Islands, generated by such shallow-convection and consistent with earlier observations by Salat and Font (1987) and Fuda et al. (2000). Once the intermediate waters had been entrained into the ML at the end of February 2005, a Mistral storm event in early March ultimately triggered "complete" deep convection.

Typically, studies of deepwater production in the western basin have focused on the MEDOC region and Gulf of Lions where WMDW production has consistently been observed (Leaman and Schott, 1991). We did observe nWMDW present at 2000 m in the Gulf of Lions during March 2006, however, owing to the timing of ARGO float deep-dive cycles we cannot be sure where this water mass was formed. Whilst the winters of 2004–2005 in the Catalan subbasin and 2005–2006 in the Ligurian subbasin experienced pre-conditioning and surface forcing consistent with that experienced in the MEDOC deep convective regime, MLDs have far exceeded March climatological MLD averages in both subbasins (D'Ortenzio et al., 2005). The special feature of the nWMDW formation noted between 2004 and 2006 is therefore the regions where deep convection has occurred.

In relation to the Ligurian subbasin, Stommel (1972) identified "patches" of high density surface waters in the south-west of the subbasin, with Sparnocchia et al. (1995) suggesting deep convection was possible in the Ligurian subbasin but attributing a failure to identify deep water production to weak pre-conditioning processes. Indeed, the 2004–2005 winter in the Ligurian subbasin did not experience deep convection due to a persistent layer of fresh surface water, yet the following year deepwater production did occur, which we attribute to surface forcing acting on the unusual cold and saline water column structure.

We found no previous evidence of deep convection so close to the Balearic Islands. A number of nWMDW production events occurred in the 2004–2005 winter (Lopez-Jurado et al., 2005) with Canals et al. (2006) and Schroder et al. (2006) indicating nWMDW formed off the Gulf of Lions shelf at 2000 m and detected in the Provencal subbasin with similar properties to the nWMDW identified in this study. These studies are of interest as combined with data presented in this study, show deepwater production during the 2004–2005 winter occurred in numerous regions of the western basin and was not constrained to the MEDOC region. We can assume therefore, that surface water densities exceeded 28.8 kg m^{-3} over a wider region than normal prior to deep convection during 2004–2005, else the Catalan subbasin could not have undergone the pre-conditioning required for deep convection. This leads us to that conclude that rather than a new location of deepwater production, we have observed an enlargement of the deep convective regime in 2004–2005. Furthermore, whilst unusual features facilitated deepwater production in the Ligurian subbasin the following winter, the deep convective regime of the western basin was also likely larger than usual with nWMDW detected simultaneously in the MEDOC region and Ligurian subbasin. Such nWMDW production in the Catalan and Ligurian subbasins during successive years suggests that deepwater production is regionally variable and can occur in a number of regimes within the western basin, where the meteorological and hydrographic characteristics required for deepwater production coincide.

The observations we have detailed show ARGO floats are capable of detecting some of the processes and events associated with both the “pre-conditioning” and “violent-mixing” phases of deep convection. A major limitation of ARGO floats however is that the floats can only collect data relating to water column structure within a very small region in comparison to pre-conditioned regions and deep-mixed patches that exceed 100 km^2 (Jones and Marshall, 1997). It is for instance difficult to examine the upward doming of the σ_θ=28.8 isopycnal, where the LIW is brought up into shallower waters (Schroder et al., 2006) and which typically marks the boundary of the pre-conditioned regions of the western basin (Marshall and Schott, 1999). As we were unable to map out the spatial distribution of surface buoyancy in the western basin over the two winters, we cannot examine how this distribution may have acted to localise and limit the size of the subsequent deep convection regimes.

Appearance of weak intermediate salinity maxima and minor restratification of surface waters during late March 2005 and 2006 indicates the beginning of the "sinking and spreading" phase of nWMDW formation (Madec et al., 1991). This restratification over deep-mixed patches occurs over similar time scales to those described by Jones and Marshall (1997). This reintegration of heat is enhanced in the Ligurian subbasin by a supply of warmer surface waters originating in the Tyrrhenian subbasin (Astraldi and Gasparini, 1992). The faster restratification noted in the Catalan subbasin is attributed to a combination of stronger atmospheric heating and advection of stratified fluid from coastal waters surrounding the Balearic Islands (Salat and Font, 1987). Subsequent sinking and spreading of nWMDW were not apparent in any of the ARGO float data, with the observation period and depths of sampling of the ARGO floats limiting the study in this respect.

Interannual differences between nWMDW properties in the western basin are traditionally attributed to interannual variability in surface forcing (Mertens and Schott, 1998), indeed the data presented in this study indicates the 2004–2005 winter in the Catalan subbasin experienced larger heat losses and stronger heat fluxes than the Ligurian subbasin in 2005–2006, which is consistent with observations of the particularly severe winter over the western basin in 2004–2005 (Lopez-Jurado et al., 2005). As such, nWMDW produced during 2004–2005 would be expected to be cooler than in 2005–2006. However, it should be noted that interannual variations in forcing are not the only factors influencing the properties of nWMDW. As noted, convective regimes of

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the western basin that are characterised by higher salinity intermediate waters generate warmer but more saline MLs following pre-conditioning and subsequently, produce (relatively) warm and salty deep waters. The same can also be said for higher salinity surface waters, which mix down more quickly when exposed to surface forcing. In the case of the Ligurian subbasin, unusual characteristics of both the MAW and LIW prior to deepwater formation have affected the nWMDW properties. We note MAW and LIW in the Ligurian subbasin during November 2005 recorded salinities ~0.13 and ~0.014 above that of the same water masses observed the previous winter in the Catalan subbasin, which was followed in March 2006 by production of the warmest, most saline and densest WMDW on record.

Explanations of the long-term salinity and temperature trends in the WMDW have previously focused on a higher salinity LIW present in the western basin. This has been attributed to anthropogenic reductions in the freshwater budget of the eastern basin (Rohling and Bryden, 1992; Bethoux and Gentili, 1999; Skiliris and Lascratos, 2004) and subsequent alterations to salinity of the LIW during formation in the eastern basin (Bryden and Boscolo, 2002) and also to long term changes to freshwater and heat fluxes of the Mediterranean Sea in relation to climatic cycles (Rixen et al., 2005; Send et al., 1999). Indeed, this study shows evidence of an increasingly saline LIW present in the western basin. Furthermore, changes in the dense water flowing out of the Mediterranean Sea have been observed and suggest continuing trends of temperature and salinity increase are linked to a denser (saltier) water mass produced in the eastern basin (Millot et al., 2006). What triggered formation of this denser water mass is debatable, attributed to anthropogenic influences (Skliris and Lascaratos, 2004) or ”exceptional meteorological conditions” (Millot et al., 2006). In any case, a shift in the location of deepwater formation in the eastern basin from the Adriatic to the Aegean subbasin took place post-1987 (Lascaratos et al., 1999) becoming known as the Eastern Mediterranean Transient (EMT) (Schroder et al., 2006). The notable effect of the EMT has been a further increase in the salinity of the LIW (Klein et al., 1999), which may be modulating changes to the LIW caused by reductions in the freshwater bud-

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get of the eastern basin (Rohling and Bryden, 1992). Alternative explanations to the observed trends in WMDW properties include low rainfall inputs to the Mediterranean Sea raising the salinity of surface waters (Marty and Chiaverini, 2007), consistent with the higher salinity MAW present in the Ligurian subbasin during winter 2005–2006. We suggest that production of the warmest, saline and densest WMDW during 2006 in the Ligurian subbasin was largely due to both an usually saline MAW combined with a shallower, higher salinity LIW. Previous studies identify a warming trend of 1.6–2.6×10^{-3} °C yr^{-1} and a salinity increase of 9.45–10×10^{-3} yr^{-1} of the WMDW between the 1950s and 1990s (Bethoux et al., 1990; Rohling and Bryden, 1992), with later studies showing an acceleration of trends possibly reaching 5.4×10^{-3} °C yr^{-1} and 2.0×10^{-3} yr^{-1} (Schroder et al., 2006). This study observes a similar acceleration of such trends in the WMDW to those shown in Table 1, along with an increase in the σ_θ of WMDW of 4.0×10^{-4} kg m^{-3} yr^{-1} using data spanning 1955–2006.

In the eastern Catalan subbasin and the western Ligurian subbasin nWMDW production has occurred in locations that have previously received little attention. An important factor in nWMDW production in the Ligurian subbasin has been the early winter water column structure. What remains unsure is whether the production of deep water in the two regions is a rare occurrence or have previous ship based survey sampling campaigns neglected visiting these regions in favour of investigating deepwater production in the Gulf of Lions? Without access to ARGO float data these deepwater production events could certainly have been missed, showing promise for future monitoring of deep convection and water mass properties in the Mediterranean Sea. During future ARGO based studies, a complementary ship survey during the early winter would assist in quantifying surface buoyancy distribution and water column structure prior to convection, to investigate further how these factors facilitate deep water production in the Catalan and Ligurian subbasins.

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Table 1. Estimates of mean annual increases in potential temperature and salinity of the WMDW.

Study	θ increase	S increase	Date range used in estimate
Rohling and Bryden (1992)	8.3×10^{-4} °C yr^{-1}	6.9×10^{-4} yr^{-1}	1909–1989
Rohling and Bryden (1992)	1.6×10^{-3} °C yr^{-1}	9.45×10^{-4} yr^{-1}	1955–1989
Bethoux et al. (1990)	4.0×10^{-3} °C yr^{-1}	9.45×10^{-4} yr^{-3}	1959–1989
Mertens and Schott (1998)	3.5×10^{-3} °C yr^{-1}	1.0×10^{-3} yr^{-1}	1959–1997
Bethoux and Gentili (1999)	3.5×10^{-3} °C yr^{-1}	1.1×10^{-3} yr^{-1}	1959–1996
Bethoux et al. (2002)	3.4×10^{-3} °C yr^{-1}	1.05×10^{-3} yr^{-1}	1993–2000
Schröder et al. (2006)	5.4×10^{-3} °C yr^{-1}	2.0×10^{-3} yr^{-1}	1995–2004

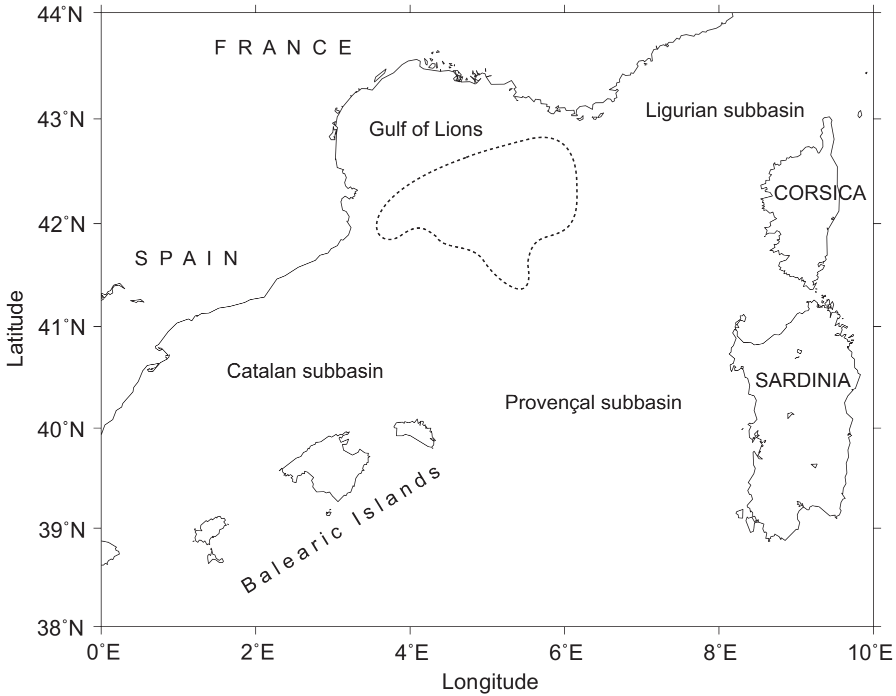

Fig. 1. The western basin of the Mediterranean Sea with the subbasins proposed by Ifremer (http://tinyurl.com/2hmnd9) and the boundary of the typical deep convection region shown (dashed region).

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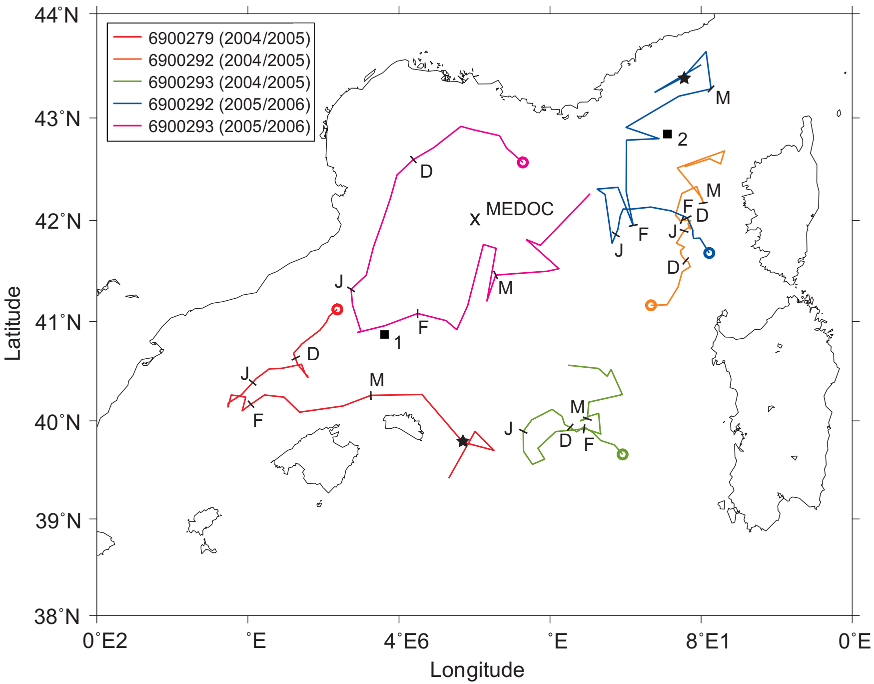

Fig. 2. Trajectories of ARGO floats within the WMed during winters 2004–2005 and 2005–2006 investigated by this study. Float locations at the start of November are circled, with subsequent tick marks denoting the first float cycle of a particular month. The locations used in the NCEP/NCAR reanalysis are shown as 1 (in relation to float 6900279 during winter 2004–2005) and 2 (in relation to float 6900293 during winter 2005/06) and the centre of the MEDOC region is also indicated as the cross at 42° N, 5° E. The locations where deep-water formation was observed are marked with a star.

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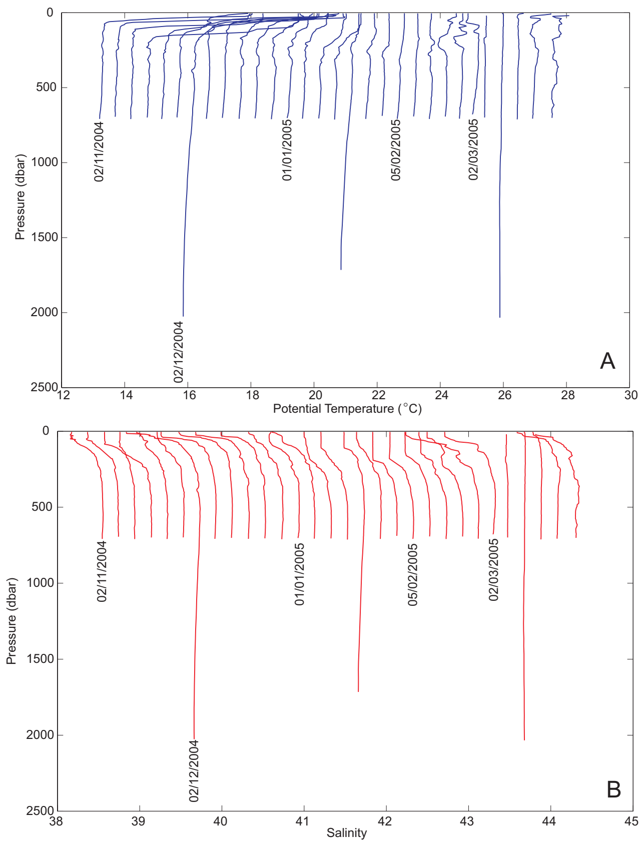

Fig. 3. All **(a)** potential temperature and **(b)** salinity profiles from float 6900279 during the winter 2004–2005 observation period. A 0.5°C offset for potential temperature and a 0.2 offset for salinity has been applied to consecutive profiles for clarity; therefore the scale applies to the 1st profile only. Dates indicate the first ARGO float profile of a given month.

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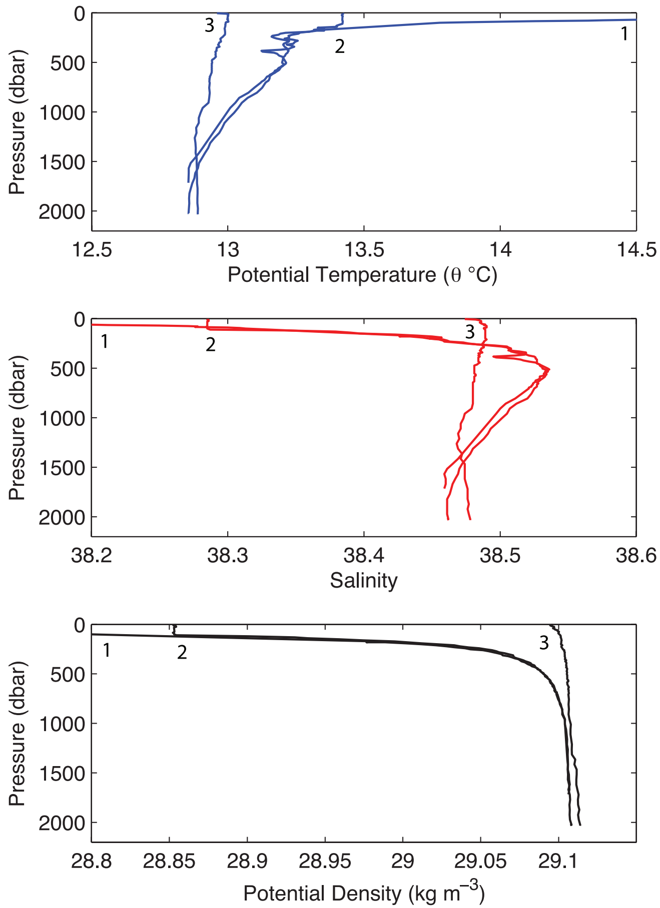

Fig. 4. Vertical profiles of potential temperature (top), salinity (middle) and potential density (bottom) taken from ARGO float 6900279 deep-dive cycles. The deep dive cycles took place at 50-day intervals on 2 December 2004 (1), 21 January 2005 (2) and 12 March 2005 (3).

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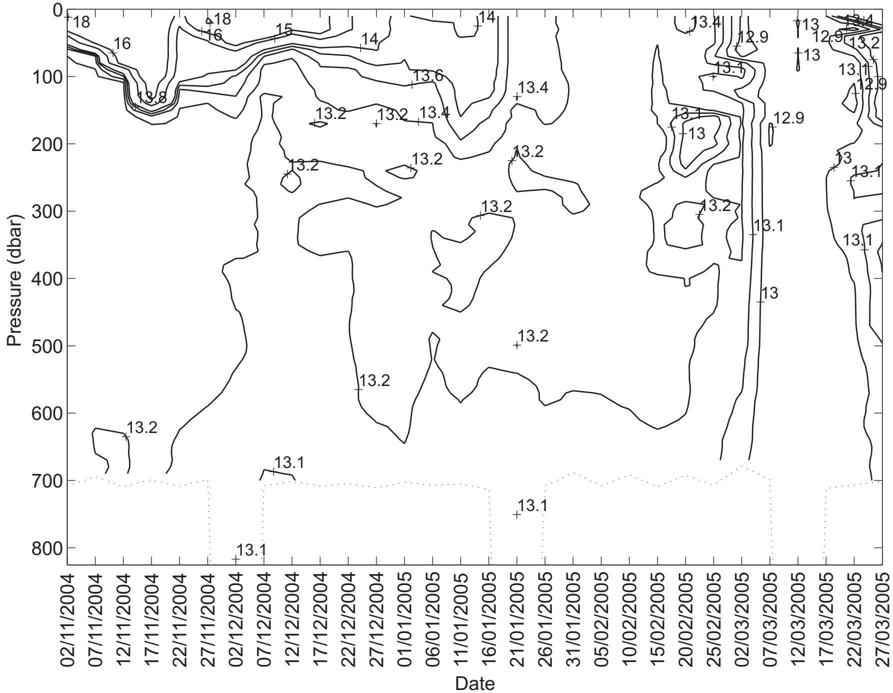

Fig. 5. Time series of vertical potential temperature profiles from ARGO float 6900279, limited to the ARGO shallow dive depth (700 m).

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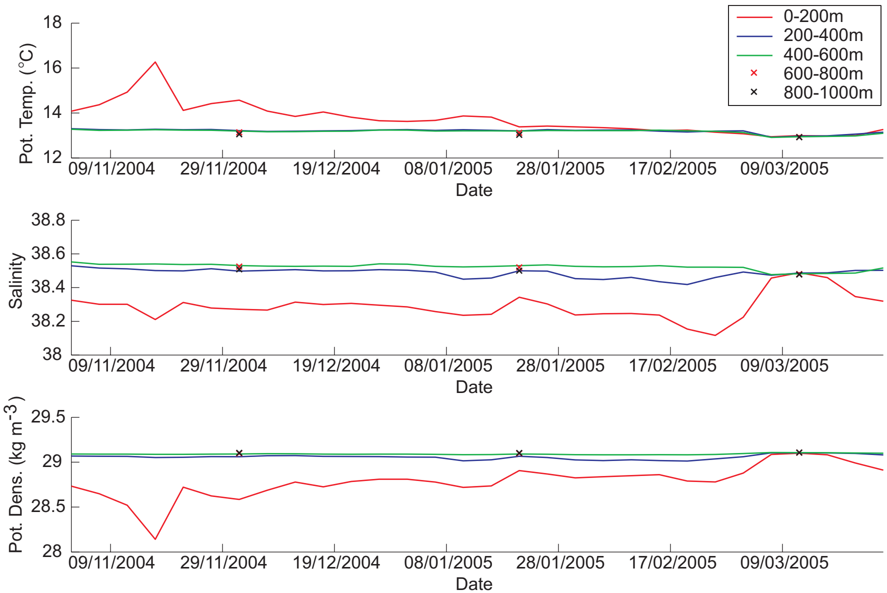

Fig. 6. Time series of potential temperature (top), salinity (middle) and potential density (bottom) averaged between pressure surfaces (see legend) from ARGO float 6900279 (winter 2004–2005). As the ARGO float profiles to 2000 m every 50 days, averages for the 600–800 and 800–1000 m layers can only be shown for these cycles and are indicated as crosses.

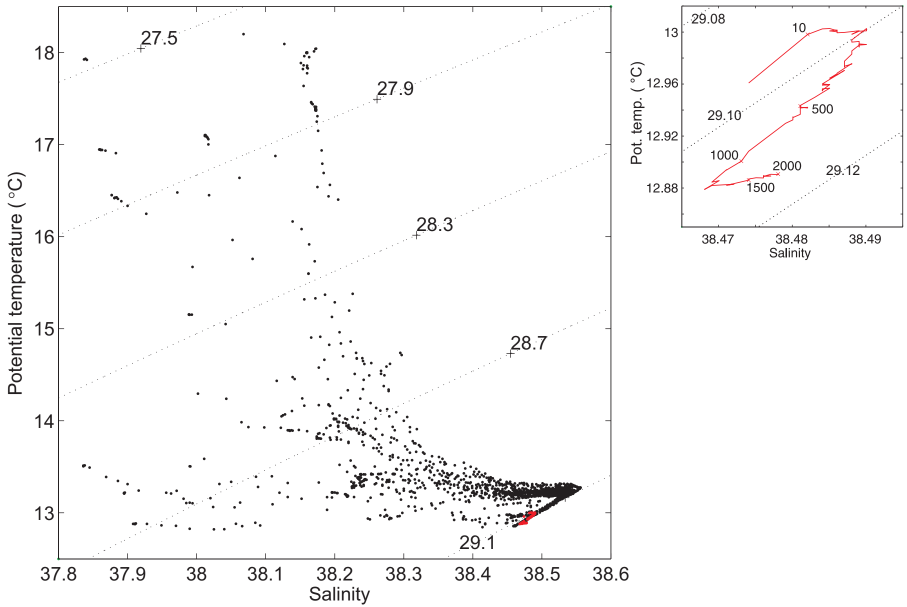

Fig. 7. θ/S diagram with potential density anomaly contours, using all measurements made by ARGO float 6900279 (large) and data collected by the ARGO float deep-dive cycle on 12 March 2005 (in red and inset right).

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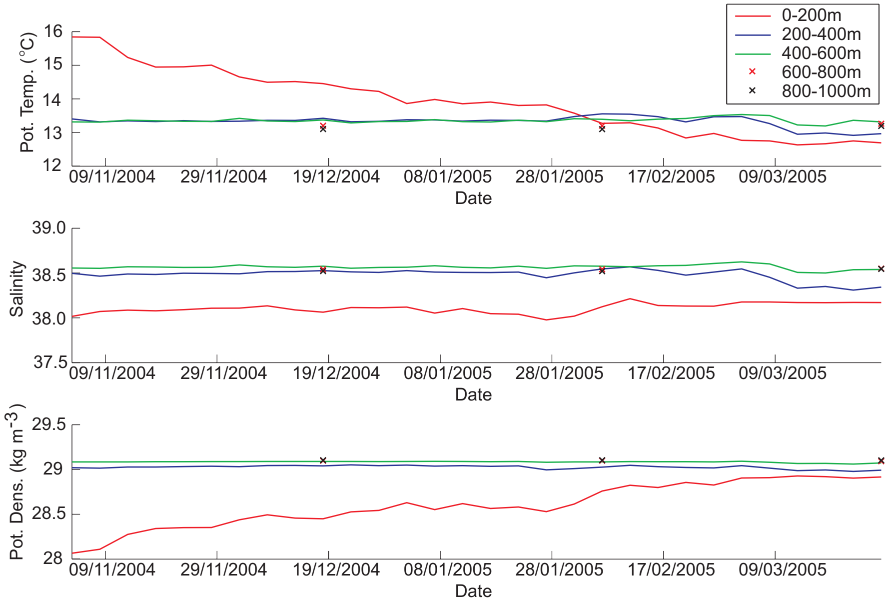
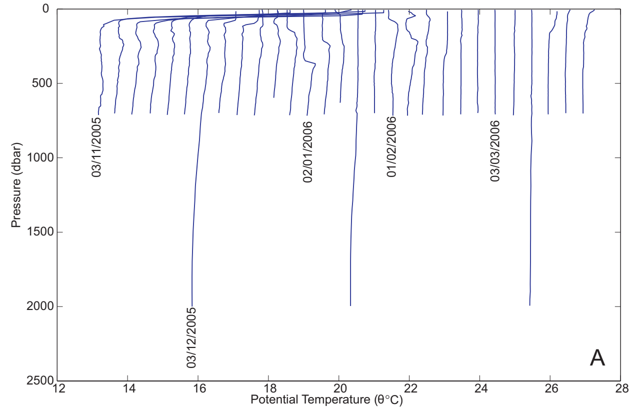


Fig. 8. Time series of potential temperature (top), salinity (middle) and potential density (bottom) averaged between pressure surfaces (see legend) from ARGO float 6900293 (2004–2005 winter). As the ARGO float profiles to 2000 m every 50 days, averages for the 600–800 and 800–1000 m layers can only be shown for these cycles and are indicated as crosses.



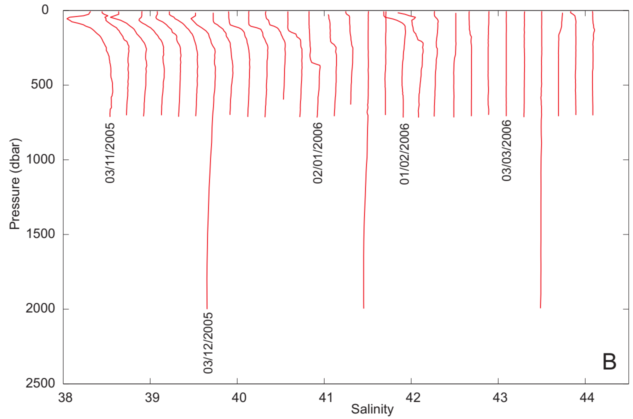


Fig. 9. All **(A)** potential temperature and **(B)** salinity profiles from float 6900293 during the winter 2004–2005 observation period. A 0.5˚C offset for potential temperature and a 0.2 offset for salinity has been applied to consecutive profiles for clarity; therefore the scale applies to the 1st profile only. Dates indicate the first ARGO float profile of a given month.

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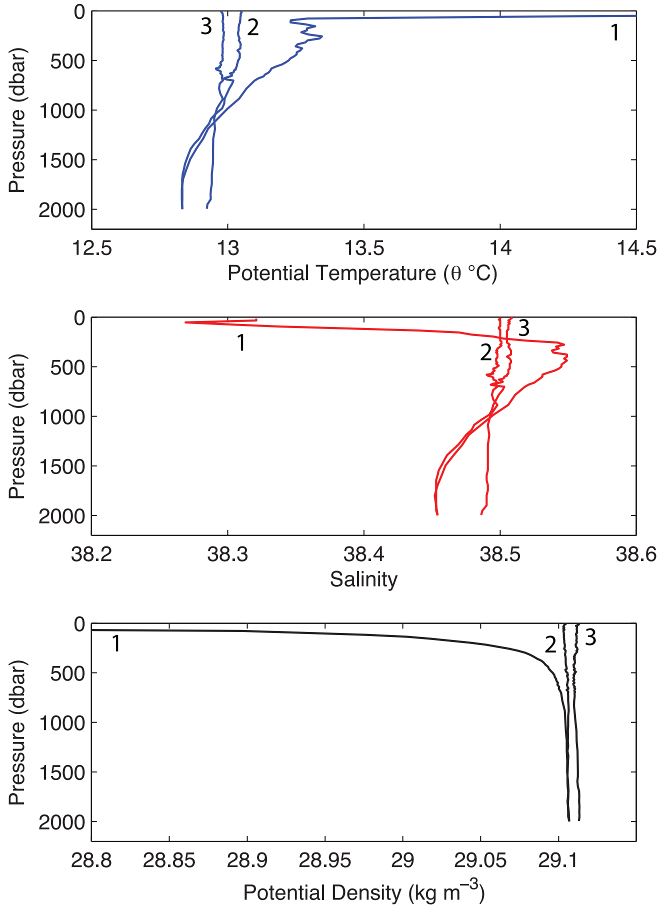

Fig. 10. Vertical profiles of potential temperature (top), salinity (middle) and potential density (bottom) taken from ARGO float 6900293 deep-dive cycles (winter 2005–2006). The deep dive cycles took place at 50-day intervals on 3 December 2005 (1), 22 January 2006 (2) and 13 March 2006 (3).

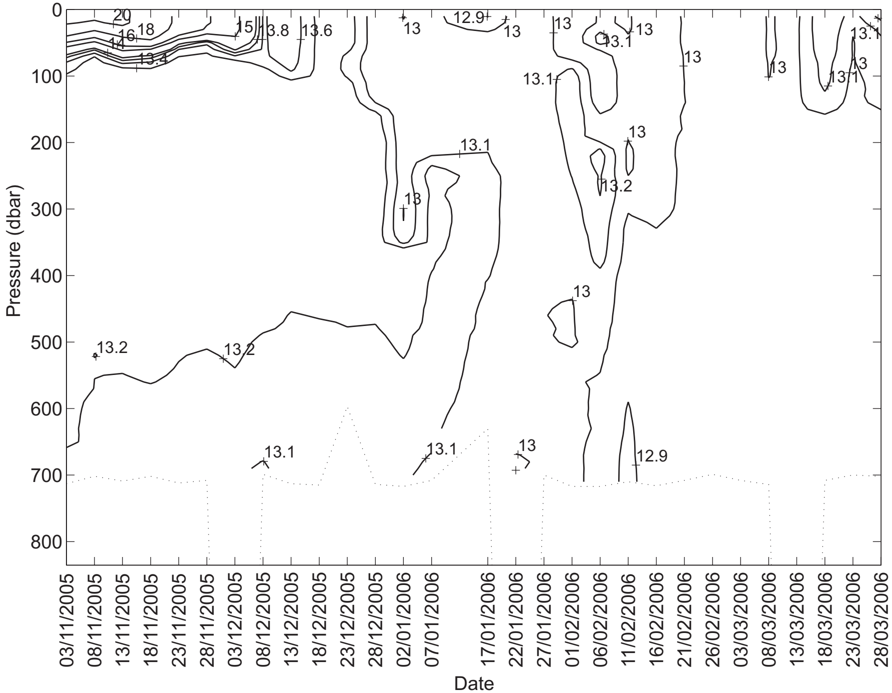

Fig. 11. Time series of vertical potential temperature profiles from ARGO float 6900293, limited to the ARGO shallow dive depth (700 m). A gap in the time series occurs between 7 January 2006–17 January 2006 when the ARGO float encountered a problem and had to make an emergency accent.

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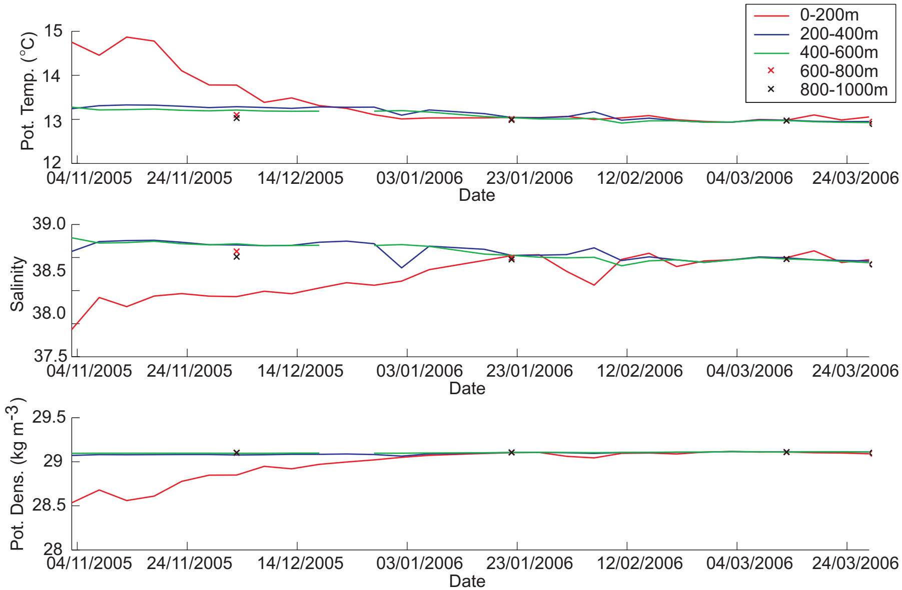

Fig. 12. Time series of potential temperature (top), salinity (middle) and potential density (bottom) averaged between pressure surfaces (see legend) from ARGO float 6900293 (2005–2006 winter). As the ARGO float profiles to 2000 m every 50 days, averages for the 600–800 and 800–1000 m layers can only be shown for these cycles and are indicated as crosses.

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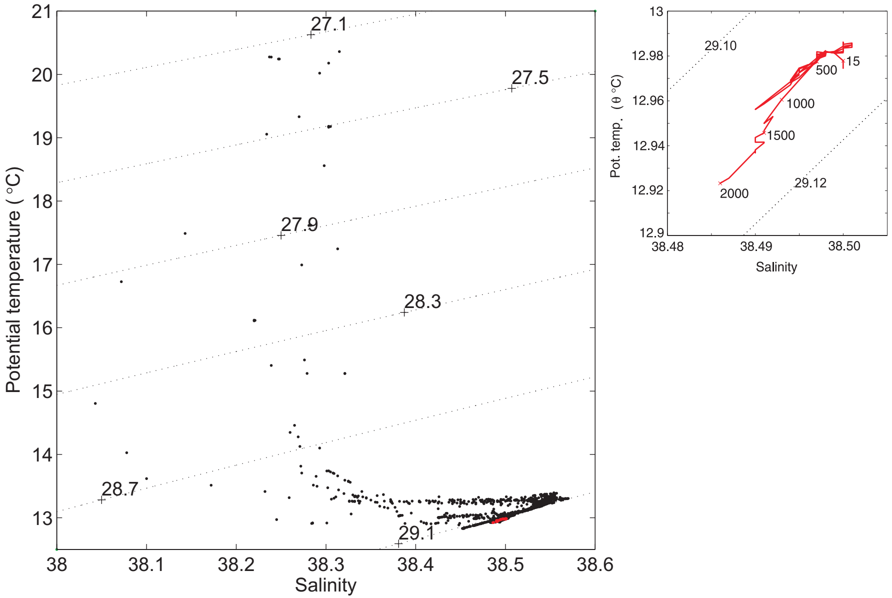

Fig. 13. θ/S diagram with potential density anomaly contours, using all measurements made by ARGO float 6900293 (large) and data collected by the ARGO float deep-dive cycle on 13 March 2006 (inset right).

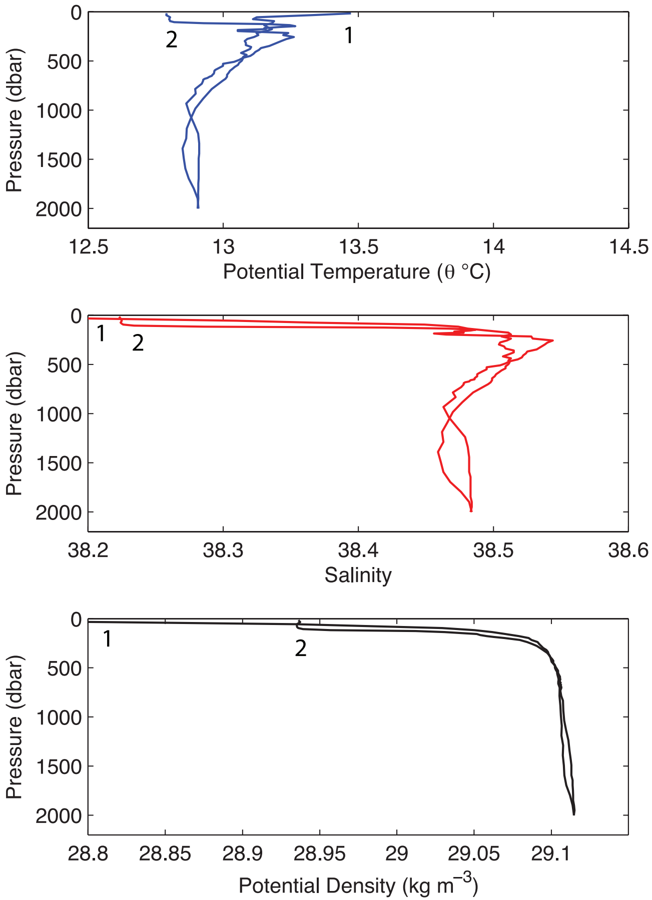

Fig. 14. Vertical profiles of potential temperature (top), salinity (middle) and potential density (bottom) taken from ARGO float 6900292 (2005–2006 winter) deep-dive cycles. The deep dive cycles took place at 50-day intervals on 23 January 2006 (1) and 14 March 2006 (2).

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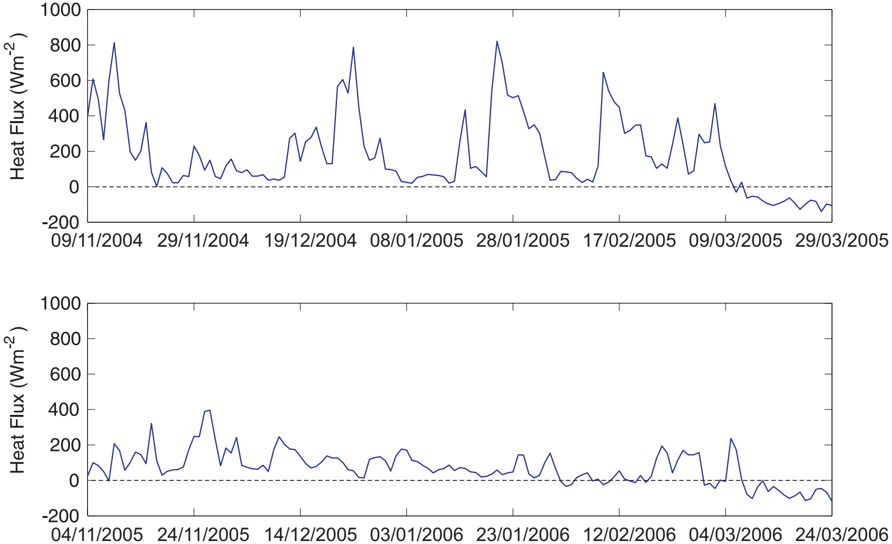

Fig. 15. NCEP/NCAR daily reanalysis air-sea flux data for the 2004–2005 and 2005–2006 winters. The locations of the reanalysis time-series are shown in Fig. 4.

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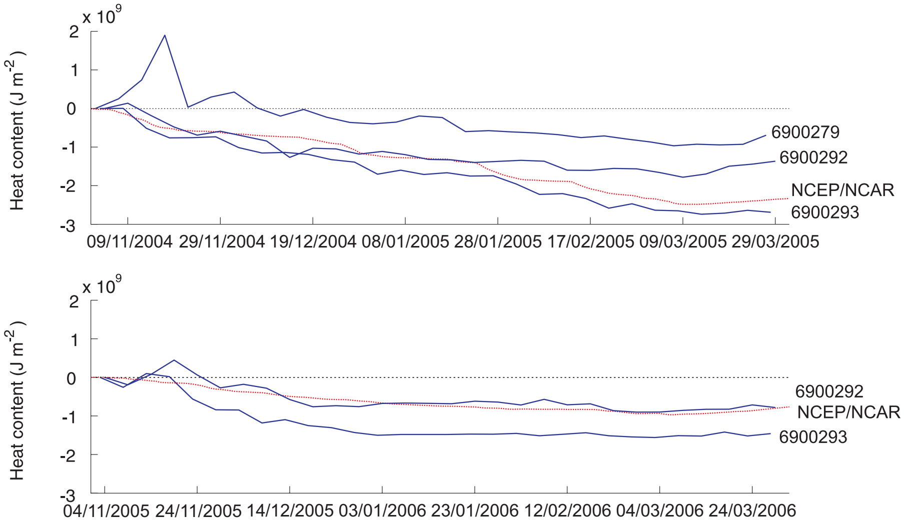

Fig. 16. Comparisons of ARGO float heat content (blue solid) and NCEP/NCAR cumulative heat loss (red dashed) for the 2004–2005 (top) and 2005–2006 (bottom) winters.

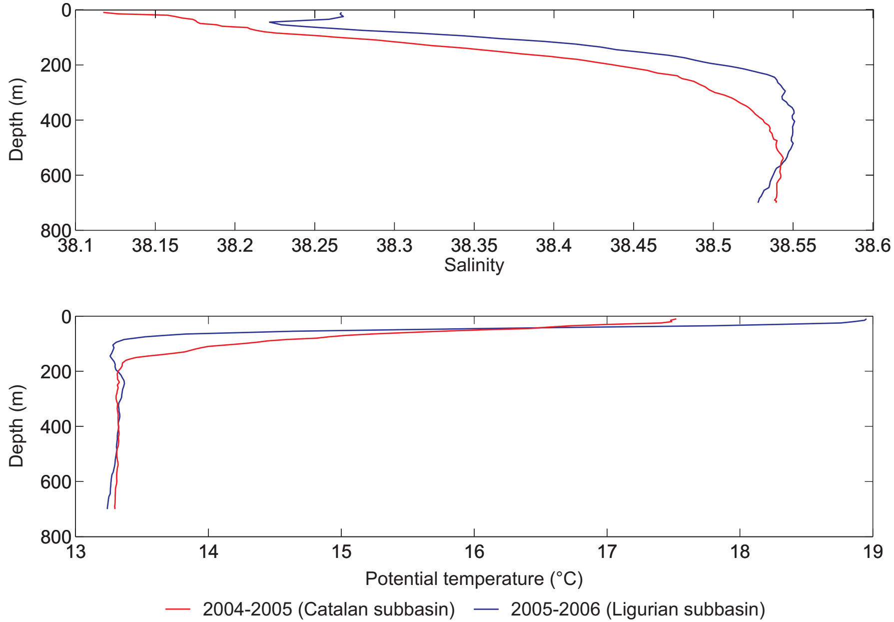

Fig. 17. Comparison of vertical salinity (top) and potential temperature (bottom) profiles in the Catalan (2004) and Ligurian subbasins (2005). Profiles represent an average of all available ARGO float data between 1 to 31 November of 2004 (532 measurements from 7 ARGO float profiles) and 2005 (368 measurements from 6 ARGO float profiles) within two + 3°×3° cells (Catalan subbasin 39–42° N, 2–5° E and Ligurian subbasin 41–44° N, 6–9° E).

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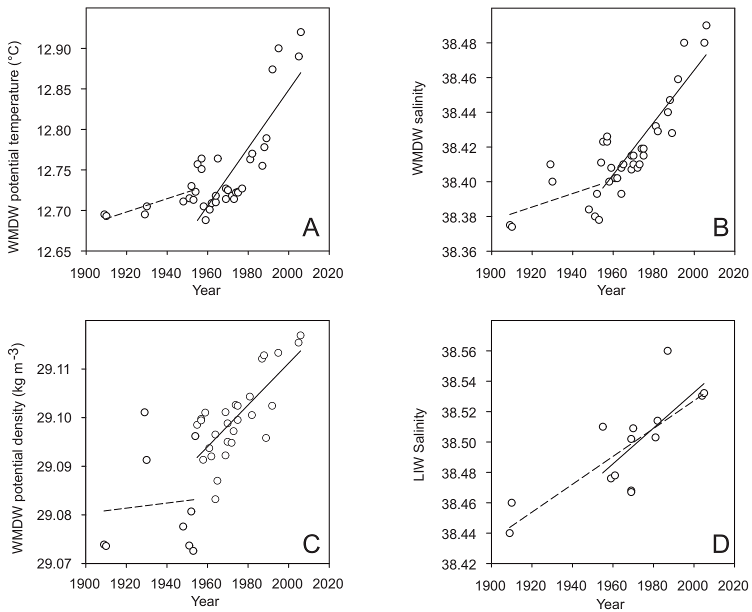

Fig. 18. Potential temperature **(A)**, salinity **(B)** and potential density **(C)** of the Western Mediterranean Deep Water, recorded in the WMed. Data prior 1990 was presented in Rohling and Bryden (1992), data from 1992 and 1995 come from Mertens and Schott (1998) and Testor and Gasgard (2006) respectively, and data from 2005 and 2006 represent properties measured by ARGO floats at the base of the deepest winter MLD in the respective winters. The dashed lines are linear regressions presented by Rohling and Bryden (1992) for data spanning 1909–1955 (with the exception of density which Rohling and Bryden (1992) did not examine), while the solid lines are linear regressions for the data from 1955–2006. The salinity of the Levantine Intermediate Water **(D)**, recorded in the region covering latitudes 41° to 43° N and longitudes 5° to 7.5° E (as per Rohling and Bryden (1992) with 1° extension of region to the north to accommodate additional ARGO float data). The dashed line represents a linear regression through the entire LIW dataset, whilst the solid line depicts a linear regression through the post-1955 data.