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MEDARGO: A drifting profiler program in the Mediterranean Sea

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Abstract

In the framework of the EU-funded MFSTEP project, autonomous drifting profilers were deployed throughout the Mediterranean Sea to collect temperature and salinity profile data and to measure subsurface currents. The realization of this profiler program in the Mediterranean, referred to as MEDARGO, is described and assessed using data collected between June 2004 and March 2006 (including more than 1500 profiles). Recommendations are provided for the permanent future implementation of MEDARGO in support of operational oceanography in the Mediterranean Sea.

More than twenty drifting profilers were deployed from research vessels and ships-of-opportunity in most areas of the Mediterranean. They were all programmed to execute 5-day cycles with drift at a neutral parking depth of 350 m and CTD profiles from either 700 or 2000 m up to the surface. They stayed at the sea surface for about 6 h to be localised by, and transmit the data to, the Argos satellite system. The temperature and salinity data obtained with pumped Sea-Bird CTD instruments were processed and made available to the scientific community and to operational users in near-real time using standard ARGO protocols, and were assimilated into Mediterranean numerical forecasting models.

In general, the cycling and sampling characteristics chosen for the MEDARGO profilers were found to be adequate for the Mediterranean. However, it is strongly advised to use GPS and global cellular phone telemetry or the future Argos bi-directional satellite system in order to avoid data compression and losses, for the continuation of the Mediterranean drifting profiler program.

1 Introduction

Freely drifting autonomous oceanographic instruments reporting data through satellite links have become increasingly used since the 1980's to monitor the world oceans and seas. Nowadays, numerous surface drifters and subsurface floats or profilers are being used to collect physical, biogeochemical and optical data. Autonomous drifting instruments are generally cost-effective and allow monitoring over extended geographical areas (e.g., whole oceans or seas) for long time periods (months to years). They also provide data in areas where harsh weather conditions and political reasons preclude ship-based measurements. Since they follow the currents, the freely-drifting instruments are often referred to as Lagrangian systems. To be more accurate, they are considered as quasi-Lagrangian when their drift is affected by winds and waves at the surface (e.g., surface drifters and profilers during their surfacing periods). This Lagrangian nature can also be exploited to estimate dispersion statistical properties.

Data provided by drifters, floats and profilers have become abundant over the last couple of years in all oceans and most marginal seas, mostly through international efforts to organise their operation at international level as part of the Global Drifter Program (GDP, see Lumpkin and Pazos, 2006) and the Array for Realtime Geostrophic Oceanography (ARGO, see Gould et al., 2004) program. GDP consists of a global array of satellite-tracked drifters to measure surface currents and other parameters such as surface temperature (T), salinity (S), optical properties and winds. ARGO is an international effort initiated in 1999 to collect T and S profiles at typically 10-day intervals from the upper 2000 m of the ice-free world oceans and currents from intermediate depths. The data are provided by drifting profilers equipped with CTD sensors. At each surfacing, data are telemetered via satellites to data centres where they are processed and made available in near-real-time (NRT) to the community. The number of ARGO profilers worldwide should be reaching its target of 3000 operating instruments by the end of 2006.

In the Mediterranean, drifters, floats and drifting profilers have been operated in specific areas mainly as part of national projects since the mid-1980's. The surface circulation in the Algerian and Adriatic subbasins (Salas et al., 2001; Poulain, 2001; respectively) and the Sicily Channel (Poulain and Zambianchi, 2006[1]) have been studied

[1]Poulain, P.-M. and Zambianchi, E.: Near-surface circulation in the central Mediterranean Sea as deduced from Lagrangian drifters in the 1990's, Cont. Shelf Res., submitted, 2006.

with drifters, to mention a few examples. Acoustically tracked floats (Testor and Gascard, 2003, 2005), neutrally buoyant at depths between 250 and 1450 m, have been used to study intermediate circulation in the northwestern Mediterranean (1994-1995) and in the Algerian subbasin (1997–1998). The latter study focused on the large scale flow separation and the mesoscale eddy formation contributing to the spreading of the Levantine Intermediate Water (LIW) in the Western Mediterranean basin. Pioneering use of drifting profilers in the Mediterranean started in 1995–1996 when ALACE (Davis et al., 1992) and MARVOR (Ollitrault et al., 1994) profilers were deployed at the entrance of the Adriatic Sea (Eastern Otranto Channel) and were configured to measure the intermediate circulation near the LIW core (300–400 m) and to profile with a 3-day interval (Poulain and Zanasca, 1998). The profilers provided subsurface current and T profile data in both the Adriatic and the northern Ionian (Poulain et al., 2003). Starting in 2000, the United States Naval Oceanographic Office (NAVO) deployed profilers in the Eastern Mediterranean basin in support of military operations. The first units were programmed to drift near 650 m and to measure T and S profiles every 5 days.

As part of the EU-funded Mediterranean Forecasting System Toward Environmental Predictions (MFSTEP) project, PAN-Mediterranean collaboration was organised to collect T, S, and subsurface current data with drifting profilers throughout the Mediterranean Sea, and to make these data available in NRT to the scientific community and to operational users, and in particular, for assimilation into MFSTEP numerical prediction models (see Pinardi et al., 2003; Coppini et al., 2006[2]). This effort, referred to as MEDARGO and corresponding to workpackage 4 of the MFSTEP project (Poulain et al., 2004a; Poulain, 2005), is thoroughly described in this paper. The focus is more

[2]Coppini, G., Pinardi, N., Manzella, G. M. R., Tziavos, C., Nittis, K., Larnicol, G., Poulain, P.-M., Send, U., Testor, P., Raicich, F., Griffa, A., Crispi, G., De Mey, P., Tonani, M., Lascaratos, A., Sofianos, S., Kallos, G., Katsafados, P., Pytharoulis, I., Zavatarelli, M., Triantafyllou, G., Zodiatis, and Petit de la Villeon, L.: The Mediterranean Forecasting System second phase of implementation: marine core and downstream services, Ocean Sci. Discuss., in preparation, 2006.

on the design and implementation of the profiler program to the Mediterranean Sea than on the analysis of the data collected. A detailed analysis of the CTD profiles and subsurface velocities provided by the MEDARGO profilers will be presented in separate papers. The manuscript is organised as follows. Details about the profilers are first given (Sect. 2), followed by a discussion on the sampling strategy adopted for the Mediterranean (Sect. 3). Preparatory tests and operational deployments are explained in Sect. 4 while T and S data are presented and briefly discussed in Sect. 5. The effectiveness of the MEDARGO profiler array is assessed in Sect. 6 and recommendations are offered for its future permanent implementation.

2 ARGO profilers

Two types of battery-powered profilers are operated in ARGO, one called APEX (manufactured by Webb Research Corporation, USA) and the other one PROVOR (produced by Martec, France). The APEX is the successor of the ALACE (Davis et al., 1992) whereas the PROVOR is based on the MARVOR technology (Ollitrault et al., 1994; Loaec et al., 1998, 1999). They were developed in the 1990's as part of the World Ocean Circulation Experiment (WOCE). Most profilers are equipped with Sea-Bird CTD sensors (model 41 pumped MicroCAT with accuracies of 0.002°C, 0.005 and 2.4 dbars for T, S and pressure, respectively). In the world oceans, they are programmed in the "Park and Profile" configuration with a neutral parking depth near 1000 m and a maximum profiling depth of 2000 m. At typically 10-day intervals, fluid is pumped into an external bladder to increase the profiler volume and make it ascent while measuring T and conductivity (C), from which S is calculated. When at surface (typically during 6 h), the profilers are located by, and transmit data, to the Argos system onboard polar-orbiting satellites (mostly from the National Oceanic and Atmospheric Agency, NOAA), before they deflate their bladder and descent to their parking depth and repeat the cycle. Profilers are generally designed to perform ~150 cycles. The ARGO data are transferred to one of the ARGO Data Assembly Centres (DAC) where they are processed and made available in NRT. The data are then sent to one of the Global Data Assembly Centre (GDAC; in Monterey, California or in Brest, France) where they are centralised for easy access by the scientific community and by operational centres. The two GDAC synchronise their data contents on a daily basis and disseminate them on the Global Telecommunication System (GTS). The ARGO data are finally archived at the United States National Ocean Data Centre (US-NODC). All ARGO profilers have two identification numbers: the Argos Platform Terminal Transmitter (PTT) identification number and the World Meteorological Organization (WMO) number used for GTS dissemination.

3 MEDARGO cycling characteristics and sampling strategy

Given the reduced size of the Mediterranean Sea relative to the world oceans, and of its specific morphology, bathymetry and circulation structures, profilers programmed with the ARGO standard characteristics (i.e., cycles of 10 days with neutral and maximum depths of 1000 and 2000 m, respectively) are not adequate for the MEDARGO program. The specific characteristics chosen for the MEDARGO profilers are explained and motivated below.

We have chosen 350 m as the neutral parking depth because it corresponds approximately to the depth of the LIW core in most of the Mediterranean Sea. Drifts at that depth allow to study the LIW pathways from its origin in the northern Levantine subbasin to its outflow through the Strait of Gibraltar. It is important to note that the LIW, clearly identified by its subsurface S maximum, is an important Mediterranean water mass and a crucial component of the Mediterranean thermohaline "conveyor belt" circulation. Concerning the maximum profiling depth, alternate values of 700 and 2000 m were selected. The first value (700 m) is near the maximum depth of the T-7 XBT probes and 65% of the Mediterranean bathymetry is deeper than this value. The second, 2000 m, below which there is only 40% of the Mediterranean area, is the standard ARGO profiling depth. In order to limit the occurrence of grounding on the sea bed, this deeper profiling depth was only programmed every ten cycles.

The second problem is the determination of the cycle length to obtain robust and useful estimates of subsurface currents. Indeed, the profiler's horizontal displacements during descent and ascent, and its surface drift after (before) the last (first) satellite fix, introduce errors on the mean current estimate. The choice of the cycle length was made following the indications from two preliminary studies based on statistical results obtained from historical currentmeter data and based on numerical results derived from an Ocean General Circulation Model (OGCM).

Historical data on current profiles in selected areas of the Mediterranean, including the major current systems such as in the Algerian subbasin, were used to estimate relative error on the currents near 350 m as observed by the MEDARGO profilers (Griffa and Molcard, 2003). Typical velocity profiles inspired from the data in the selected areas were used, along with their variance, in a simple statistical model to calculate the profiler mean displacements, and their standard errors, in the water column above 700 m during cycles of 3.5 and 7 days. In addition to the drift time at the parking depth, these time intervals include the periods while the profiler is ascending, descending and drifting at the surface after (before) the last (first) satellite fix (about 7.5 h) and the surface time while it is transmitting data to, and tracked by, the satellites (4.5–6.5 h). The errors appeared to be highly dependent on the current regimes. In strong currents with fluctuations highly correlated in the vertical (e.g., in the Liguro-Provencal and Catalan subbasins) the relative errors on the subsurface mean currents are rather low (<20% and <40% for cycles of 7 and 3.5 days, respectively). For currents more confined to the surface and less correlated in the vertical (e.g., the current system in the Algerian subbasin), the expected error can reach 100% (60%) for a cycle length of 3.5 (7) days, during specific events. As expected, the longer the interval, the smaller is the error, but long cycles have two disadvantages: (1) the corresponding mean currents between two points separated by a long distance are not adequate to represent the circulation in the vicinity of the intricate coastlines and the numerous Mediterranean islands, and (2) the assimilation of profiler displacements (currents) becomes inefficient to correct modelled velocities if the cycle length is longer that the typical Lagrangian integral time scale characteristic of the circulation at 350 m (Molcard et al., 2003).

Numerical simulations of the motions of the MEDARGO profilers were done by Rupolo (2003a) using off-line velocity fields provided by the OGCM developed for the Mediterranean as part of the Mediterranean Forecasting System Pilot Project (MFSPP; Pinardi et al., 2003). The Lagrangian integration is based on the method developed by Blanke and Raynaud (1997). A total of four numerical experiments were conducted with times for the drift at the neutral depth (350 m) of 3, 6, 15 and 30 days. As many as 40 000 numerical particles uniformly deployed in most Mediterranean areas deeper than 700 m were integrated for about a year (52 weeks) using the MFSPP model 3-day mean hindcast velocity fields for year 2000. In general, the probability density functions of the relative mean error have a peak around 20–30% and are characterised by long tails due to the presence of cycles (about 10%) in which the subsurface displacement of the profiler is very small (a few km). Consequently, in several areas the mean relative error is high (greater than 100%), and the variance is larger than the mean. In contrast, when considering only cycles characterised by subsurface displacements larger than 10 km (which are more realistic with respect to real in-situ data), the mean relative error on the inferred subsurface speed can be reduced to ∼30%. Finally, the numerical simulations do not suggest any geographic criterion to exclude observations characterised by small subsurface displacements, even if a relative minor concentration of such cycles is observable in the northern part of the western basin.

In brief, the statistical and numerical approaches described above indicate that short cycles (e.g., 3 days) yield reliable estimates of the subsurface currents only in areas with fast currents and limited vertical shear. Choosing 5 or 6 days helps to decrease the relative error but erroneous results can be obtained in regions with slow currents and/or strong shear. Numerical simulations suggest that with a cycling period of 5–6 days, and considering only cycles characterised by a displacement larger than 10 km, the probability of having a relative accuracy on the inferred subsurface speed smaller than 50% is about 80%.

The above-described Lagrangian numerical simulations using the MFSPP OGCM were also used to study the geographical coverage of the MEDARGO data following various deployment strategies. Experiments using several different cycle lengths and two deployment scenarios, one with 40 000 profilers deployed uniformly throughout the deep (>700 m) Mediterranean and the other using 20 units deployed along planned lines of the MFSTEP VOS program (Manzella et al., 2006), were carried out (Rupolo, 2003b). The motions of the profilers were integrated for about a year using the MFSPP mean hindcast velocity fields (year 2000) mentioned above. The main conclusions that emerged from this work are: (1) after a drift of a year, most of the profilers stay confined in the subbasins where they were deployed. Using four tracks of commercial ships in the western basin enables a relatively good sampling of the basin, while deploying profilers along the unique commercial track in the eastern basin leads to a poor sampling of the Ionian and of the southern Levantine subbasins. So if data are highly required in such regions, plans have to be made to deploy the profilers there; (2) deploying profilers, with cycle length of 6 days, in strong (>10 cm/s) current systems result in larger geographical coverage and higher number of independent T and S profile data.

4 MEDARGO profiler deployments and tracks

4.1 Pre-TOP deployments

Four profilers were operated in fall 2003 to test their cycling and sampling characteristics before the Targeted Operational Period (TOP) of MFSTEP (Table 1). Two APEX profilers were deployed in the Catalan subbasin on 26 September 2003. A week later, on 2–3 October 2003, two PROVORs were deployed with the R/V *Garcia del Cid* in the vicinity of the APEX profilers. All units were equipped with Sea-Bird MicroCAT CTD sensors (model 41) and were configured to drift at a parking depth of 350 m and to profile between 700 m and the surface. They were operated until 7 November 2003, providing a total of 35 ascending T and S profiles. Thereafter, the profilers remained at surface until they were recovered. Note that the PROVOR also record T and S during the first descent. Since these measurements might be affected by the profiler itself (the sensors being downstream of the tubular body), they are not considered in this paper. Ship-based CTD measurements were made in the vicinity of the profilers upon deployment and recovery. Cycle lengths varied between 3 and 7 days, surfacing times were chosen between 6 and 10 h, and the number of sampling depths were set between 60 and 80 depths to span the water column above 700 m. The periodicity of the Argos transmissions was 45 s. Details about these deployments can be found in Font et al. (2003), Le Bras and Poulain (2004) and Poulain et al. (2004b).

The comparison between profiler and ship CTD data confirmed that the profilers were well calibrated during their entire period of operation. In particular, deep values of salinity agreed within 0.01. The calibration issue triggered the idea to profile once in a while to deep depths (e.g., 2000 m) to intercalibrate the profiler instruments drifting in the same area, and to compare the deep T and S measurements to climatological values. It was recommended to program a deep profile down to 2000 m every ten cycles. Cycles of 5 days appeared as a good compromise to obtain useful subsurface velocity estimates. A detailed examination of the frequency of transmissions (Poulain et al., 2004b) revealed that, out of 5 days, 10 h at the surface are enough to transmit successfully 100 T and S pairs. If the Argos transmission period can be reduced from 45 s to 30 s, the surfacing time can be reduced to 6–8 h. Based on the above tests, it was decided to program the MEDARGO floats with the parameters listed in Table 2. For the APEX profilers, shallow and deep profiles include 80 and 106 sampling depths, respectively, spanning the water column with 5 m intervals above 100 m, 10 m between 100 and 700 m, and 50 m intervals below 700 m. For the PROVOR, 71 sampling depths were programmed between 5 and 705 m, with 10 m intervals, and 26 depths between 725 and 1975 m (50 m interval).

4.2 TOP deployments

A total of 23 profilers (10 PROVOR and 13 APEX) were acquired and were programmed with the above-described parameters (see Table 2 and schematic diagram of the MEDARGO cycling characteristics in Fig. 1). The chronology of the deployments is listed in Table 3, along with other details on the profiler operations. The deployment locations of all MEDARGO profilers are depicted in Fig. 2. All releases were carried out in sea areas deeper than 2000 m. The operational phase of MEDARGO started in summer 2003 with the deployments of two APEXs in the Catalan subbasin on 30 June 2003. By the start of the MFSTEP TOP period (1 September 2003), five APEXs were operational in the Catalan and Tyrrhenian subbasins. Five PROVORs were subsequently released in the Liguro-Provencal and Algerian subbasins. All of these deployments were carried out onboard research vessels (R/V *Garcia del Cid*, R/V *Urania* and R/V *Tethys II*). Deployments from ships-of-opportunity were organised starting in November 2004 in collaboration with the MFSTEP VOS program (Manzella et al., 2006). Profilers were deployed while the ships were steaming at speeds of up to 20 knots using specifically designed deployment cardboard boxes so as to protect the instrument and soften the impact with the sea surface. Profilers were deployed in the Levantine and northern Ionian from the *Britain Star* container ship along the VOS line connecting Haifa, Israel to Salerno, Italy, whereas two PROVORs were released from the *Annabella* Liquefied Petroleum Gas (LPG) ship along the route between Barcelona, Spain and Benghazi, Libya. Eleven profilers out of 23 were deployed from ships-of-opportunity with minimal logistical problems and reduced costs between November 2003 and May 2005. The first APEX deployed in June 2003 was recovered in summer 2005 on the Spanish coast. After inspection, this profiler was redeployed in the Catalan subbasin in September 2005. The last two MEDARGO profilers were released in the southeastern Ionian and southern Levantine subbasins from R/V *OGS-Explora* in November 2005 (Poulain et al., 2006). The recovery of APEX WMO 6900279 on Majorca Island in October 2005 gave us the opportunity to have the instrument refurbished

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and the CTD calibrated by the manufacturer. A comparison between the calibrations before the deployment and after 93 cycles (about one year and three months in the water) indicates that there is no significant drift of the pressure, T and C sensors.

4.3 TOP basic statistics

Discarding two units (WMO numbers 6900283 and 6900296) that failed right after deployment and never provided any data, and taking into account the profiler that was deployed twice, both the western and eastern basins were equally seeded with 11 profilers in each (Fig. 2). Between 30 June 2004 and 31 March 2006, 1579 cycles were executed with good transmission and positioning. Only two cycles did not yield any data and, hence, there is no proof that the float actually surfaced or stayed at depth for more than five days. Presumably due to the low power of the signal transmitted to the satellite, the profilers were sometimes not localised successfully by Argos although they transmitted the data while drifting at the surface. A total of 15 cases of this kind occurred, especially for profiler WMO 6900286 that was not located for a maximum of 20 days (3 cycles) in March 2006.

In the rest of the paper, all results correspond to the MEDARGO profilers operated between 30 June 2004 and 31 March 2006 and exclude the two profilers that provided no data. Out of 22 profilers (13 APEXs and 9 PROVORs), about 50% (9 APEXs and 3 PROVORs) were still operating on 31 March 2006, including 5 units that have performed 114–118 cycles during 570–590 days. The histogram in Fig. 3a indicates that 11 profilers carried out 50–100 cycles and that 6 instruments performed less than 30 cycles. Note that the short-lived profilers include PROVOR WMO 6900297 that performed only two cycles before drifting continuously at the sea surface and ultimately beaching on the northern coast of Cyprus. If we restrict the histogram to the profilers that have stopped working before 31 March 2006, it can be seen that 4 units stopped after less than 30 cycles, one unit after 53 cycles and 5 profilers after 72–93 cycles (Fig. 3b and Table 3). Six of these ten profilers were picked up by seafarers in coastal waters or ended up ashore, whereas the other four (1 APEX and 3 PROVOR) stopped transmitting for unknown reason.

Given the 350-m parking depth of and the intermittency of 700-m and 2000-m profiles, it is interesting to examine the incidence of grounding on the sea bed. Considering all the 1579 cycles performed between 30 June 2004 and 31 March 2006, about 11% are associated with grounding. If shallow (1411) and deep (168) cycles are separated, about 10% and 31% of the cycles touches the sea bottom, respectively. These numbers were estimated by interpolating the Smith and Sandwell (1997)'s 2-min Mediterranean bathymetry to the first Argos position after the ascent of each cycle, and comparing then to the programmed profiling depths. This means that about 11% of the T and S profiles are truncated, that is, shorter than expected, due to grounding. The water depth can also be less than 350 m, in this case (occurring for 57 cycles, ~4%), the profiler sits or is dragged on the sea floor and its displacements cannot be used to estimate subsurface currents.

Statistical information on the profiler cycling characteristics are presented in Table 4, for both the APEXs and PROVORs. The surfacing time was estimated approximately from the time difference between the first and last Argos fixes while the profiler is drifting at the sea surface. This is an underestimate (by 1–2 h) of the real surfacing time due to the temporal distribution of the satellite passes. The time span between the first and last Argos positions during each cycle was calculated in the same way. The positions and times before and after each dive are used to estimate the duration, displacement and mean speed while the profiler is submerged. During the surfacing periods of typically 5–6 h (with a maximum of 12 h), we obtain a mean number of satellite passes of 8–9, with a maximum of 18. These are the typical values expected using the Argos system onboard six polar-orbiting satellites (NOAA 12, 14, 15, 16, 17 and 18). The mean number of Argos positions per cycle is 5–6, with a maximum of 17 good positions, whereas the mean time difference between the first and last Argos positions is about 5 hours. Excluding the cycles longer than ~5 days (17 cases, see above), the mean submergence period is 4.8 days, corresponding to a mean displacement of 15–16 km and to a mean speed of about 4 cm/s (with maxima of 125 km and 30.4 cm/s for

APEX WMO 6900279).

4.4 TOP profiler trajectories

In terms of geographical coverage, some MEDARGO profilers sampled almost entire subbasins of the Mediterranean. For instance, profiler WMO 6900292 covered a large northwestern portion of the western basin including the Liguro-Provencal and the Catalan subbasins (Fig. 4a), profiler WMO 6900299 drifted over most of the Ionian in about 500 days (Fig. 4b) and profiler WMO 6900302 circled cyclonically southeast of Rhodes before heading to the south and getting trapped for some time in an anticyclonic eddy southeast of Crete (see Fig. 4b). Other profilers spent a significant portion of their operating life in the same area, such as APEX WMO 6900301 in the northern Levantine subbasin. Some units were caught by the currents on the continental slope along the periphery of the Mediterranean (part of the basin-scale gyres): APEX WMO 6900285 in the northern Ionian (Fig. 4b), profilers WMO 6900278, 6900279 and 6900300 off Spain and profiler WMO 6900292 off Italy and France (see Fig. 4a). Likewise, profiler 6900282 followed the continental slope around southern Sardinia. Some profilers spent a long time period on the continental shelf or in shallow waters, including APEX WMO 6900287 off Egypt (Fig. 4b) and the three profilers deployed in the Tyrrhenian (Fig. 4a). Another noteworthy track is that of profiler WMO 1900630 that was deployed in a strong anticyclonic eddy in the southern Levantine subbasin and that stayed and circled around such a feature for about 20 cycles (100 days) before proceeding its course towards the northeast (Fig. 4b, see also Poulain et al., 2006). Other interesting trajectories are those of three profilers that operated in the southern part of the Western Mediterranean, describing looping and eastward drift between the Alboran subbasin and the Sicily Channel (Fig. 4a).

5 CTD profiles

5.1 Data processing

The MEDARGO data transmitted through the Argos satellite system were received simultaneously at both the MEDARGO Thematic Expert Data Centre (TEDC) at OGS in Trieste, Italy and at the MFSTEP centralised Archiving and Dissemination Data Centre (ADDC) at IFREMER in Brest, France. At the TEDC, profiler statistics and graphical summaries were produced in NRT and were posted on the World Wide Web in a dedicated MEDARGO site (http://doga.ogs.trieste.it/WP4/). At the ADDC, which is also an ARGO GDAC and also known as CORIOLIS Operational Oceanography Data Centre, the Argos messages were decoded, the data were quality controlled and were archived in a user-friendly web-based database (http://www.coriolis.eu.org/cdc/projects/mfstep.htm). The MEDARGO data were disseminated on the GTS using the profiler's WMO numbers. In general, processed and quality-controlled data were available within 4 h of the actual measurements. MEDARGO and other Mediterranean profiler data were downloaded from the ADDC on a weekly basis to be assimilated into the MFSTEP numerical forecasting models (Dobricic et al., 2006[3]). MEDARGO data were also distributed to non-MFSTEP modelers such as the French MERCATOR group and to the European-funded Marine Environment and Security for the European Area (MERSEA) project. The final (delayed-mode) quality control and processing of the MEDARGO data is still in progress at both the ADDC and TEDC. Final data will be disseminated on a CD-ROM in the near future.

The MEDARGO profiler data extracted from the ADDC between 30 June 2004 and 31 March 2006 (1366 profiles) represents 70% of the expected data amount estimated taking into account the drifts of some profilers into shallow areas corresponding to trun-

[3]Dobricic, S., Pinardi, N., Adani, M. Tonani, M., Fratianni, C., Bonazzi, A. and Fernandez, V.: Daily oceanographic analyses by the Mediterranean basin scale assimilation system, Ocean Sci. Discuss., submitted, 2006.

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cation of the CTD profiles. The main causes for the missing data are transmission and decoding problems, and/or insufficient transmitting times at the surface. It is hoped to decrease somehow the number of missing data via delayed time decoding and manual editing so as to provide a more complete final dataset for scientific applications. The MEDARGO data as extracted from the ADDC in early April 2006 are briefly described in the rest of the paper.

5.2 Data distribution

The spatial coverage of the MEDARGO T and S profiles is illustrated in Fig. 5. Most of the Mediterranean areas are covered, except the Adriatic and Aegean subbasins. Note the availability of T and S profile data in the southern Ionian and southern Levantine where historical data are rather scarce mainly because of political reasons. Temporarily, the distribution of the number of CTD profiles per month (Fig. 6) reaches a plateau between 50 and 90 after a few months following the first deployments (from October 2005 to March 2006). July 2005 corresponds to the maximum concentration of observations with 94 profiles. Since profilers were first released in the western basin, the majority of the data are localised in this basin in summer and fall 2005. From December 2004 to March 2006, the number of profiles per month in the western basin decreases from 53 to 25, while the eastern basin concentration varies between 22 and 35 profiles per month.

5.3 Global data description

The CTD data collected by the MEDARGO profilers between June 2004 and March 2006, downloaded from the ADDC in early April 2006, are plotted separately for the western and eastern basins in Figs. 7a–c. The potential temperature (θ) profiles (Fig. 7a) show substantial variability (mostly seasonal) in the upper sea with near surface values ranging in 12.7–27.4°C and 13.4- 28.3°C in the western and eastern basins, respectively. Near 2000 m, θ values converge to 12.8–13.4 °C (west) and 13.4–

13.7°C (east). Hence, as expected, the eastern basin is generally slightly warmer than the western basin. Note that below 100–200 m, θ profiles in the western basin are separated in two groups, the cooler corresponding to the Liguro-Provencal, Catalan, Alboran, Algerian subbasins, and the warmer to the Tyrrhenian.

Salinities are also highly variable in the upper 100 m of water due to the advection of low-salinity Atlantic Water (AW; Fig. 7b). Near-surface salinity values range in 36.5–38.5 in the west, and in 37.4–39.6 in the east. The subsurface salinity maximum corresponding to LIW is seen in both basins, although it is more evident in the west due to the reduced salinities related to the AW lying above it. Again, the salinities below 100–200 m are divided into two groups in the western basin, with higher salinities corresponding to the Tyrrhenian subbasin. At 2000 m, the range of salinities reduce to 38.4–38.6 in the western basin, whereas it is 38.7–38.8 in the eastern basin.

Potential temperature and salinity (θ/S) diagrams (Fig. 7c) excluding the seasonally varying near-surface values show clearly the subsurface salinity maximum associated with the LIW (especially in the western basin, ~38.78). Maximum density at 2000 m depth, reaches 29.11 and 29.20 (in sigma-θ units), in the western and eastern basins, respectively.

5.4 Potential temperature and salinity contour diagrams

The CTD data provided by the MEDARGO profilers can also be illustrated in the form of contour diagrams following the profilers along their trajectories. Examples of such contour diagrams, in which θ and S are shown as coloured tiles in the time-depth plane, are depicted in Figs. 8 to 12, for 5 profilers in selected Mediterranean areas. Due to the intermittency of the deep profiles, values are only represented between the sea surface and 700 m.

In the Catalan and Alboran subbasins (Fig. 8), APEX WMO 6900278 reveals the maintenance, deepening and erosion (or decay) of the seasonal near-surface mixed layer in summer and fall 2004. The seasonal thermocline is centred near 40 m, deepening to ~80 m in October 2004. Thereafter, the thermal structure remains quasihomogenous through winter 2005, before the new formation of the mixed-layer starting in April–May 2005. In early summer 2005, the thermocline is centred near 20 m when the profiler is looping cyclonically in the eastern Alboran subbasin. In summer 2004, there is a weak signature of a halocline near 40 m in correspondence to the thermocline. The following spring and summer, in the Alboran, the profiler encountered near-surface AW with salinity as low as 36.51. In the cyclonic eddy, this low-salinity feature extends as deep as ~100 m. At depth, between 300 and 700 m, there is a weak and broad salinity maximum all along the profiler trajectory, which is related to modified LIW.

PROVOR WMO 6900292 released west of Sardinia, generally drifted cyclonically in the northwestern part of the western basin, passing through the Liguro-Provencal and Catalan subbasins (Fig. 9). After about one year and a half, the profiler ended up in the vicinity of its deployment location. The thermal structure sampled by this profiler shows the expected seasonal variations of the surface mixed layer and thermocline. There are numerous signatures of near-surface low salinity AW extending as deep as 100 m and mostly concentrated northwest of Sardinia in fall 2004 and winter 2005. The LIW subsurface salinity maximum prevails throughout the entire operating life of the profiler.

PROVOR WMO 6900299 was deployed on 12 November 2004 in the southern Ionian (Fig. 10). After some southward drift, it generally moved to the north and northeast, crossing the central Ionian subbasin, and eventually reaching the Greek coastal waters in March 2006. Again, the expected seasonal variability is seen in the upper-sea thermal structure. In the first 100 m of water, the low-salinity AW persists until January 2006 when the profiler reaches the northeastern Ionian more saline near-surface waters. The LIW salinity maximum is striking near 300 m. As the profiler is moving northeastward and is approaching the Levantine subbasin, the salinity in the LIW core increases and reaches ~39.

We finish our qualitative description of the T and S data collected by selected MEDARGO profilers with two APEX units operated in the Levantine subbasin. The first

(WMO 6900302, Fig. 11) spin cyclonically southeast of Rhodes before progressing to the southwest and being caught by a anticyclonic eddy southeast of Crete. Maximal θ and S values (reaching 28.3°C and 39.5, respectively) occur at the surface southeast of Rhodes where the warm and salty mixed layer remains shallow (the thermocline and halocline are centred near 20 m). The eddy southeast of Crete is a relatively warm (~21°C) and high salinity (~39.2) homogeneous structure extending as deep as ~150 m. Underneath this feature (near 200 m), there is a remarkable signature of low-salinity water (~38.7), presumably related to the trapping of AW. Following the profiler after it leaves the area southeast of Rhodes, we can see that the subsurface high salinity (~39) waters are deepening and stabilizing at a depth near 300 m, hence forming the LIW subsurface salinity maximum.

The profiler APEX WMO 1900630 was deployed in an anticyclonic eddy in November 2005 and swirled around it several times before escaping to the northeast in March 2006 (Fig. 12). In late fall 2005, there is a strong warm and salty mixed layer persisting above ~50 m. In winter, this layer is deepening down to 300 m, with corresponding decrease in T and S. In March 2006, as the profiler exits the eddy, the near-surface temperature decreases. There is a striking signature of low-salinity AW lying between 70 and 300 m, prevailing in the eddy in late fall and slowly fading away through the subsequent winter. Below this feature, we have the expected LIW salinity maximum centred at ~400 m and enduring as long as the profiler is trapped in the eddy. In late February and March 2006, as the float has moved northeastward in the Levantine subbasin, the salinity maximum extends over the entire water column above ~400 m.

6 Conclusions and recommendations

More than twenty MEDARGO drifting profilers were operated throughout the Mediterranean Sea starting in June 2004 to provide T and S profile data in near-real time to operational forecasting models of MFSTEP and to measure intermediate currents. They were programmed to execute cycles of 5 days with a neutral parking depth near

350 m and maximum profiling depths of 700 m (or 2000 m every ten cycles). CTD data were obtained at ~100 sampling depths separated by 5–10 m above 700 m and 50 m between 700 and 2000 m. Between June 2004 and March 2006, more than 1500 profiles were obtained, and some profilers had performed as many as 118 cycles.

The cycling and sampling characteristics chosen for the MEDARGO profilers turned out to be satisfactorily adequate for the Mediterranean Sea. Five-day cycles correspond to submerged displacements of less than ~100 km, only one (three) out of ten shallow (deep) profiles are truncated because the profilers grounded, and only 4% of the cycles occur in water depths less than 350 m and are useless to estimate parking depth mean currents. There is some data loss (about 30%) mainly due to transmission and decoding problems, and to the insufficient surfacing period for satellite data telemetry.

It was estimated that, excluding man power, the mean cost of a MEDARGO CTD profile is less than 200 EUR, which is significantly less costly than ship-based CTD data. The disadvantage of MEDARGO profiles is the reduction of data in the vertical and the lack of control on their exact positions. But this drawback is compensated by the fact that drifting profilers can operate autonomously for years and cover wide geographic areas, including zones where oceanographic measurements from ships are difficult to obtain. In fact, ship-based and profiler CTD data are complementary and should be used jointly to study the water mass properties of a sea area. Thanks to the relatively easy deployments from research vessels and ships of opportunity, the MEDARGO profilers sampled most areas of the Mediterranean.

The MEDARGO T and S data will be used in a upcoming paper to characterise the thermohaline properties throughout the Mediterranean, and to compare them to climatological values. In the meantime, the MEDARGO data in the western basin, including the pre-TOP (September-November 2003) and the TOP (June 2004–February 2006) profiles, were already used by Emelianov et al. (2006) to investigate the thermohaline structure of the LIW with a clustering method. The trajectories of the MEDARGO floats, and in particular their subsurface displacements, were assimilated in a numerical circulation model in the northwestern Mediterranean by Taillandier et al. (2006) to test the importance of these data for operational forecasting systems. Significant impact of the assimilation was found on the large scale circulation of the basin.

It is recommended to use the same cycling characteristics, i.e., 5-day cycle length, 350-m parking depth, and 700 m (2000 m every ten cycles) maximum profiling depth, for the permanent implementation of a Mediterranean ARGO program as part of the operational Mediterranean Operational Oceanography Network (MOON) program. In order to avoid data loss and decrease the surfacing time to a few hours (and eventually transmit full CTD profiles sampled with 1-m vertical resolution) it is crucial to use the future Argos bi-directional telemetry or satellite-based cellular phone networks (such as Iridium or Globalstar). It is hoped that future funding will be secured at national and EU levels so as to maintain a permanent array of 20–30 profilers by releasing 10–20 units per year. A total of 20–30 profilers in the Mediterranean corresponds approximately to the ARGO targeted density of one float in $3^{\circ}\times3^{\circ}$ bins.

Acknowledgements. MEDARGO is supported by the European Commission (V Framework Program – Energy, Environment and Sustainable Development) as part of the MFSTEP project (contract number EVK3-CT-2002-00075). We wish to thank all the scientists, captains and crew members for their skilled and enthusiastic assistance with the float deployments. In particular, we are grateful to F. Bignami and L. Santoleri for the releases from R/V Urania, and to M. Emelianov and A. Julià for the deployments off Spain. Thanks to G. Constantini, R. Gerin, G. Notarstefano and L. Ursella for their help with the deployment logistics and with the data processing.

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Table 1. Basic statistics for the four pre-TOP MEDARGO profilers. The last column shows the cycle length in days. These profilers were deployed by the Consejo Superior de Investigaciones Cientificas (CSIC) in the Catalan Sea. Hours are in GMT.

Model	WMO	Argos	Deployment Date		Lat	Lon	Institute	Cycles	Last Date		Lat N	Lon E	Cycle
APEX	6900226	35503	26-Sep-2003	15.25	41.75	3.72	CSIC	12	07-Nov-03	15.30	41.16	3.62	3.5
APEX	6900227	35504	26-Sep-2003	15.06	41.73	3.72	CSIC	6	11-Nov-03	7.24	41.32	2.26	7
PROVOR	6900228	35505	2-Oct-2003	17.27	41.6	3.77	CSIC	11	07-Nov-03	15.30	41.17	3.81	3-4
PROVOR	6900229	35506	2-Oct-2003	18.33	41.6	3.73	CSIC	6	07-Nov-03	15.32	41.28	3.92	7
TOTAL								35					

Table 2. Specifications of the MEDARGO profilers.

Profiler Type	APEX	PROVOR CTS2
Cycle length (days)	5	5
Neutral parking depth (m)	350	350
Sensors	Sea-Bird 41 pumped MicroCAT	Sea-Bird 41 pumped MicroCAT
Maximum profiling depth (m)	700 and 2000*	700 and 2000*
Number of sampling depths	106 (2000 m) and 80 (700 m)	97 (2000 m) and 71 (700 m)
Sampling depths (m)	4,10,15,...,100,110,...,700,750,2000	5,15,...,695,705,725,775,...,1975
Surfacing time (h)	–	6
Up times (h)	14 (2000 m) and 8 (700 m)	–
Down times (h)	106 (2000 m) and 112 (for 700 m)	–
Ascent times	9 (2000 m) and 6 (700 m)	–
Argos repetition rate (s)	30	40

* Every ten cyles.

Table 3. Basic information on the operation of the MEDARGO profilers in the Mediterranean Sea. Status in the last column is dead (D) or alive (A) as of 31 March 2006. The institutes responsible for the deployments are: Consejo Superior de Investigaciones Cientificas (CSIC), Centre National de la Recherche Scientifique (CNRS), Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS), Consiglio Nazionale delle Ricerche (CNR) and Israel Oceanographic and Limnological Research (IOLR). Hours are in GMT.

Model	WMO	Argos	Deployment Date		Lat	Lon	Institute	Cycles	Last Date		Lat N	Lon E	Status
APEX	6900278	35503	30-Jun-2004	13.43	41.61	3.94	CSIC	77	30-Jul-2005	14.01	37.4	–1.4	D
APEX	6900279	35504	30-Jun-2004	12.18	41.75	3.82	CSIC	93	8-Oct-2005	11.11	39.47	3.29	D
APEX	6900280	50762	16-Aug-2004	10.00	38.85	12.97	OGS/CNR	118	29-Mar-06	10.24	41.98	11	A
APEX	6900281	50763	15-Aug-2004	20.08	39.61	12.42	OGS/CNR	117	28-Mar-06	22.10	41.81	10.9	A
APEX	6900282	50764	15-Aug-2004	10.46	40.17	11.98	OGS/CNR	116	28-Mar-06	10.50	38.6	8.67	A
PROVOR	6900291	35505	7-Sep-2004	2.14	41.68	6.1	CNRS	82	19-Oct-2005	6.41	42.1	8.12	D
PROVOR	6900292	35506	7-Sep-2004	8.32	40.67	6.1	CNRS	114	29-Mar-06	6.16	42.29	6.52	A
PROVOR	6900293	50770	7-Sep-2004	15.23	39.65	7.12	CNRS	114	28-Mar-06	8.18	43.52	7.98	A
PROVOR	6900294	50771	8-Sep-2004	4.27	38.63	7.12	CNRS	72	05-Sep-2005	7.24	38.42	13.36	D
PROVOR	6900295	50769	26-Oct-2004	9.15	37.86	0.68	CSIC	30	22-Mar-05	8.22	37.58	5.3	D
APEX	6900283	50756	1-Nov-2004	6.00	36.24	21.66	IOLR	0	1-Nov-2004	6.00	36.24	21.66	D
PROVOR	6900299	50768	12-Nov-2004	13.15	33.1	16.42	CSIC	96	04-Mar-06	3.05	36.39	22.37	D
APEX	6900287	50760	6-Dec-2004	8.23	34.64	26.66	IOLR	53	02-Sep-2005	7.54	30.99	28.74	D
APEX	6900286	50759	7-Dec-2004	0.15	36.02	21.18	IOLR	83	07-Mar-06	1.10	36.4	17.92	A
APEX	6900285	50758	7-Dec-2004	6.05	36.7	19.19	IOLR	94	27-Mar-06	11.21	39.65	16.95	A
APEX	6900284	50757	7-Dec-2004	11.00	37.28	17.49	IOLR	95	27-Mar-06	14.53	34.99	18.02	A
PROVOR	6900296	50765	08-Jan-2004	5.21	33.58	31.3	IOLR	0	08-Jan-2004	5.21	33.58	31.3	D
PROVOR	6900297	50766	08-Jan-2005	12.24	34.13	28.58	IOLR	2	02-Feb-05	8.02	35.05	30.64	D
PROVOR	6900298	50767	08-Jan-2005	14.15	33.14	16.95	CSIC	15	21-Mar-05	8.01	32.16	17.35	D
APEX	6900301	50754	20-May-2005	18.55	34.71	31.35	IOLR	62	31-Mar-06	22.34	35.13	30.59	A
APEX	6900302	50755	21-May-2005	3.47	35.09	28.4	IOLR	62	27-Mar-06	8.46	34.38	25.44	A
APEX	6900300	35503	27-Sep-2005	10.45	41.17	2.61	CSIC	29	19-Feb-06	06.21	38.42	0.37	D
APEX	1900630	50761	16-Nov-2005	21.21	32.82	28.79	OGS	27	31-Mar-06	22.34	33.85	30.43	A
PROVOR	1900629	50772	14-Nov-2005	9.06	35.02	21.22	OGS	28	31-Mar-06	5.31	34.49	20.58	A
TOTAL								1579					

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Table 4. Cycling statistics for the two types of TOP MEDARGO profilers. The mean (± the standard deviation) and the maximum value are listed for the number of satellite passes, the number of Argos positions, and the time spans of these values when the profiler is at the sea surface. Likewise, the statistics are listed for the time period, displacement and speed for the profilers at the neutral parking depth. See text for more details.

Model	Number of cycles	Number of satellite passes	Number of positions time (hours)	Data surfacing time (hours)	Position surfacing	Submergence time (days)*	Submergence Distance (km)*	Submergence mean speed (cm/s)*
APEX	1026	8.0±2.5, 18	5.3±2.1, 17	5.5±1.4, 12.2	4.8±1.7, 11.5	4.8±0.1, 5.2	15±13, 125	3.7±3.2, 30.4
PROVOR	552	9.1±1.6, 15	6.0±1.7, 13	5.4±0.8, 10.0	4.8±1.1, 9.7	4.8±0.4, 5.8	17±13, 82	4.1±3.2, 19.4

* Excluding 17 cycles longer than ∼5 days.

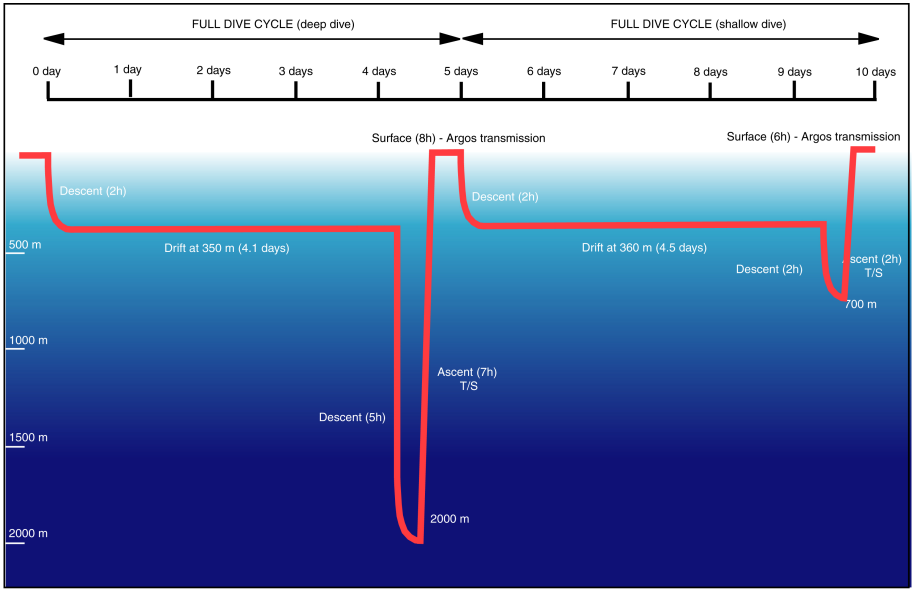

Fig. 1. Cycling characteristics of the MEDARGO profilers with "Park and Profile" configuration.

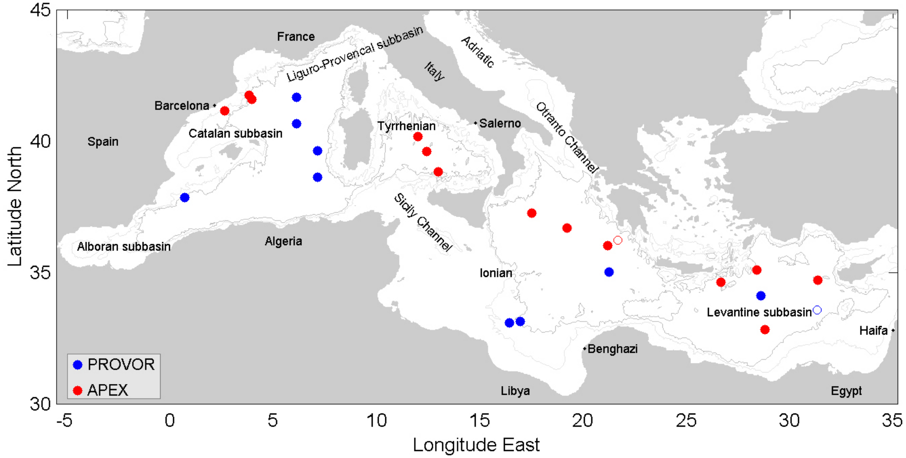

Fig. 2. Deployment locations of the MEDARGO profilers released between July 2004 and March 2006 throughout the Mediterranean Sea. The 1000 and 2000-m isobaths are shown with grey curves.

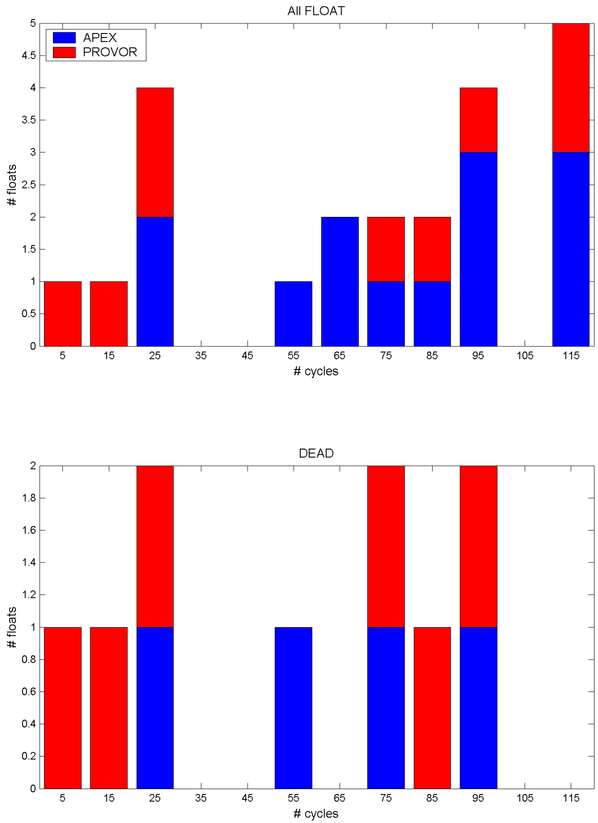

Fig. 3. Histograms of the number of cycles carried out by all the MEDARGO profilers between July 2004 and March 2006 **(a)**. Same histogram for the profilers that stopped transmitting before 31 March 2006 **(b)**.

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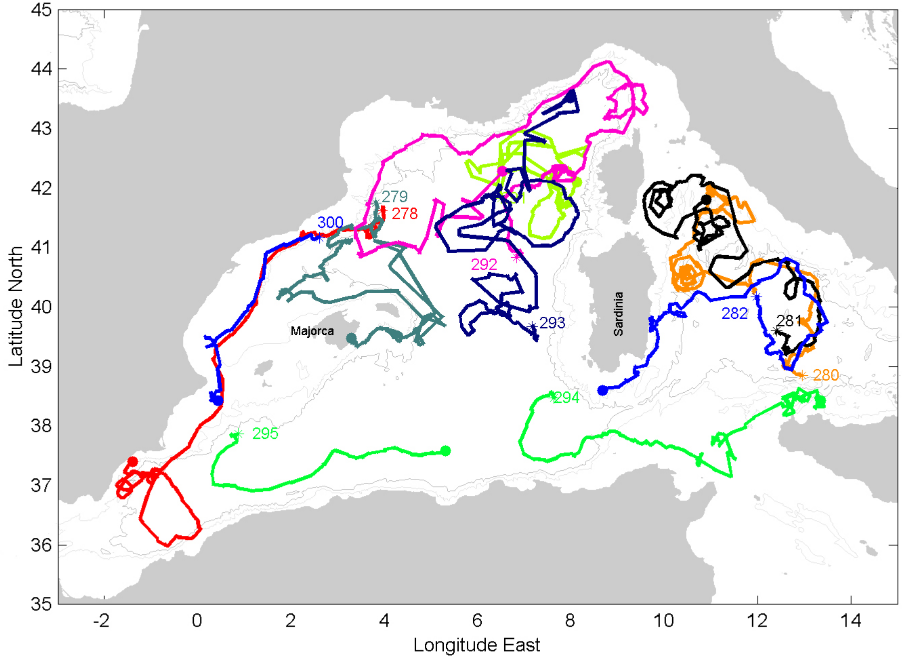

Fig. 4a. Trajectories of the MEDARGO profilers between July 2004 and March 2006 throughout the Western Mediterranean basin. The 1000 and 2000-m isobaths are shown with grey curves. WMO numbers (last three digits) are posted near the deployment locations (shown with star symbols).

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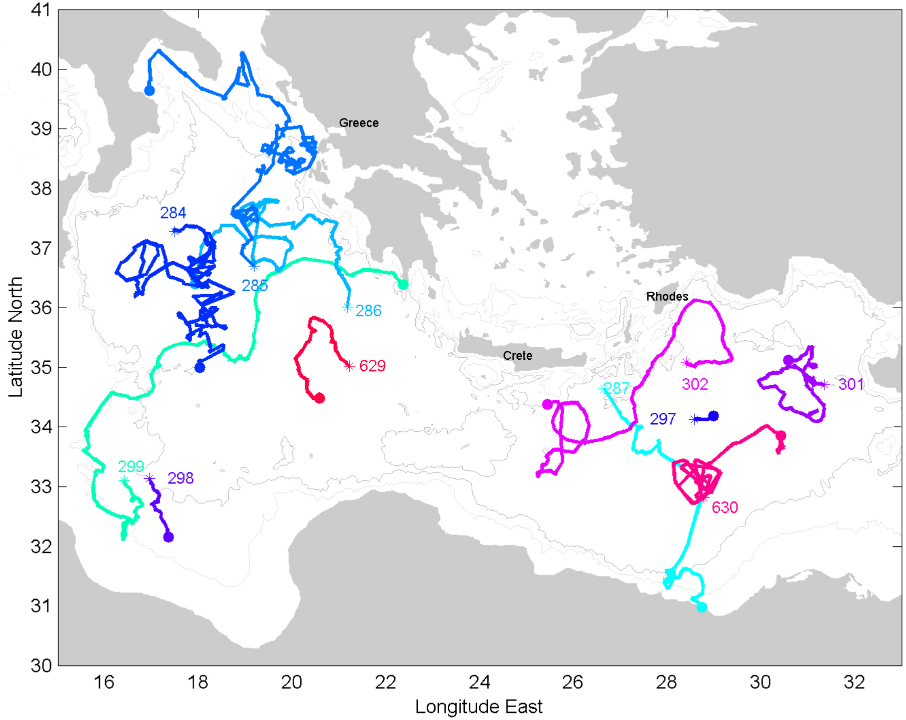
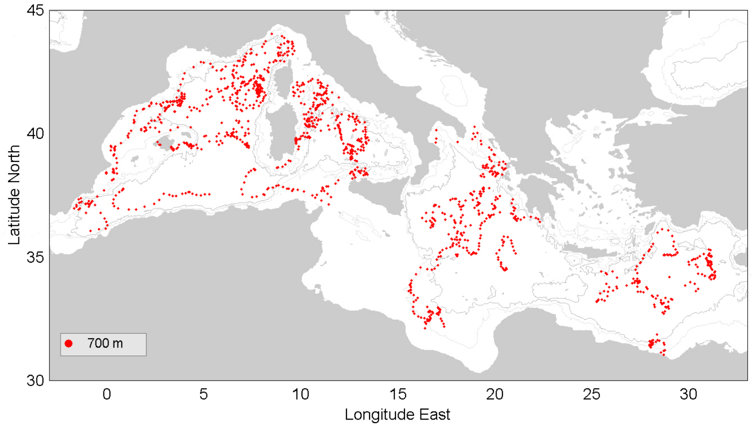


Fig. 4b. Same as in Fig. 4a but for the Eastern Mediterranean basin.



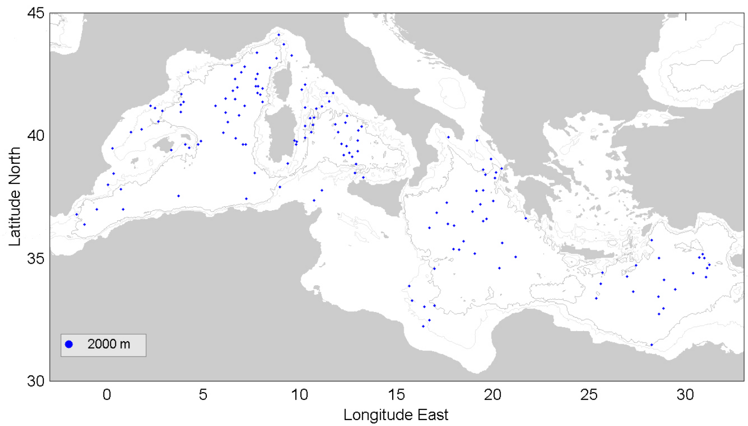


Fig. 5. Locations of the CTD casts obtained from the MEDARGO profilers between July 2004 and March 2006 throughout the Mediterranean Sea: shallow (700 m; top panel) and deep (2000 m; bottom panel). The 1000 and 2000-m isobaths are shown with grey curves.

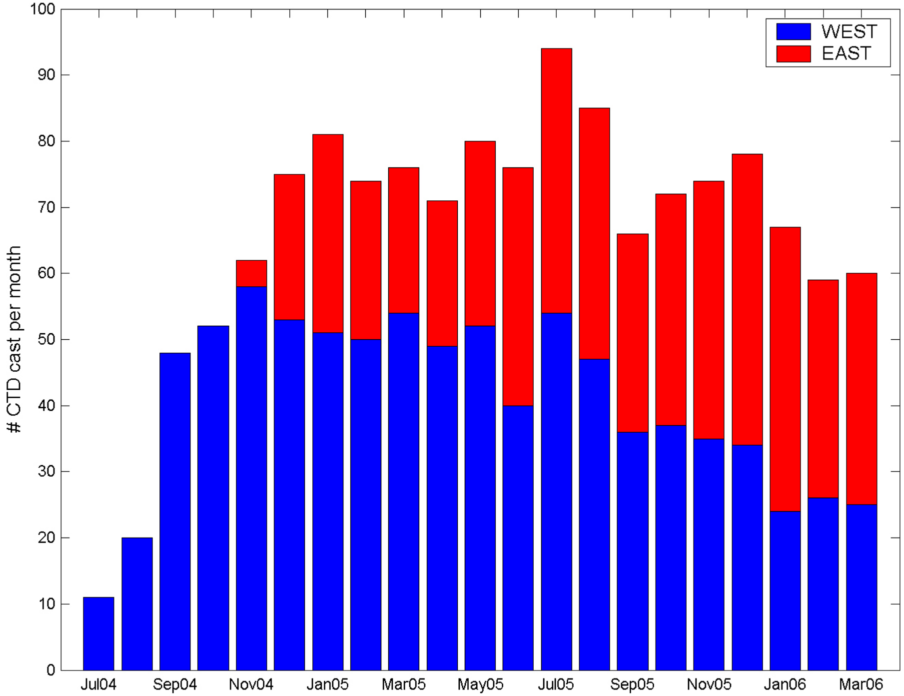


Fig. 6. Number of MEDARGO CTD casts per month for the Western and Eastern Mediterranean basins between July 2004 and March 2006.

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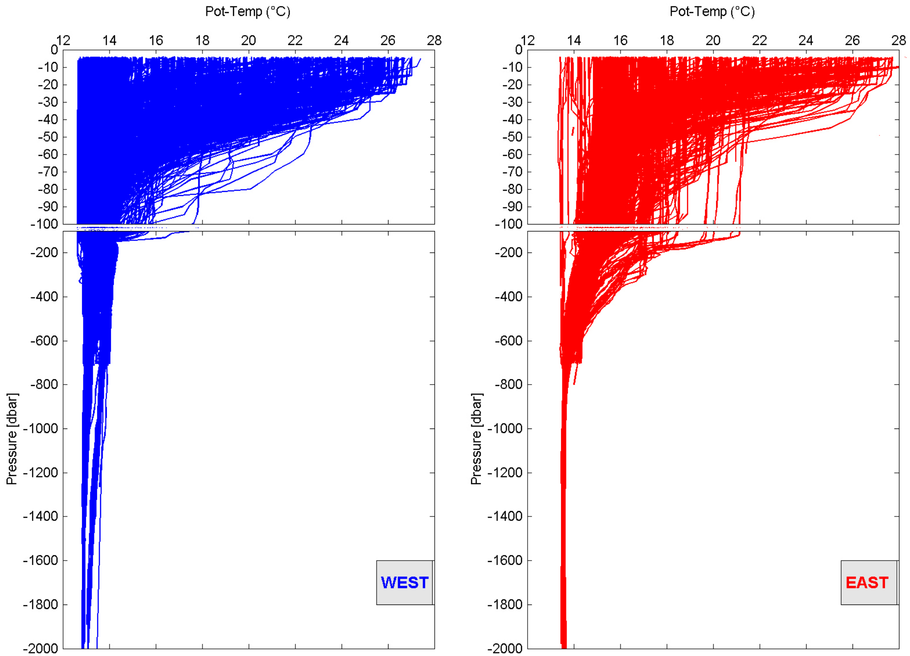

Fig. 7a. Potential temperature profiles obtained from the MEDARGO profilers between July 2004 and March 2006 for the Western and Eastern Mediterranean basins.

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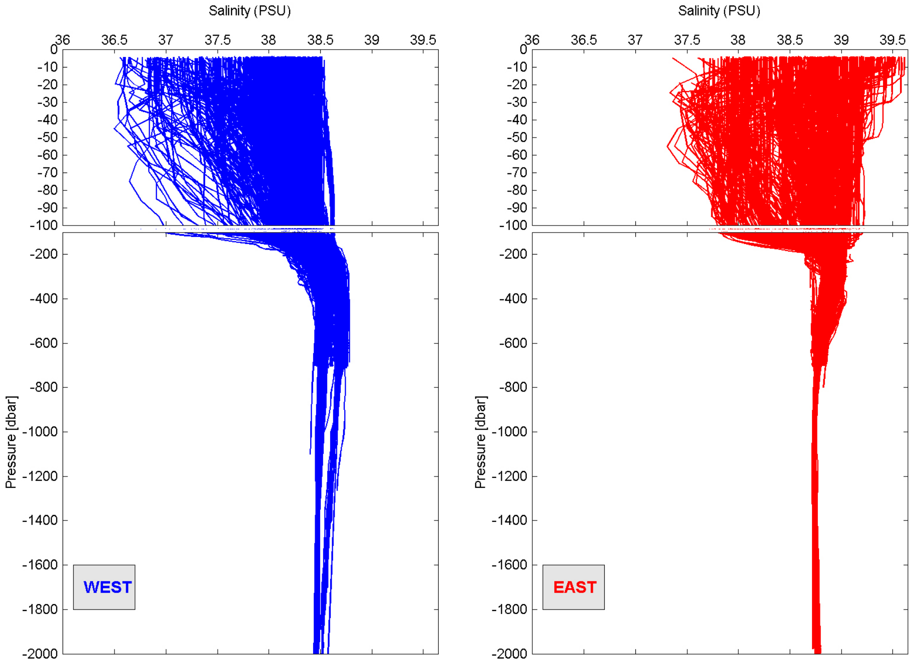

Fig. 7b. Same as Fig. 7a but for salinity.

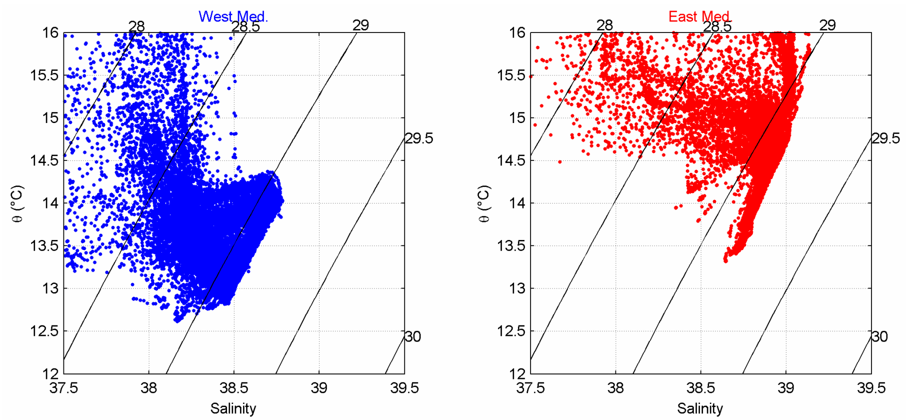

Fig. 7c. θ/S diagram obtained from the MEDARGO data between July 2004 and March 2006 for the western and eastern basins (excluding near-surface values which vary seasonally). Isopycnals (sigma-θ) are overlaid.

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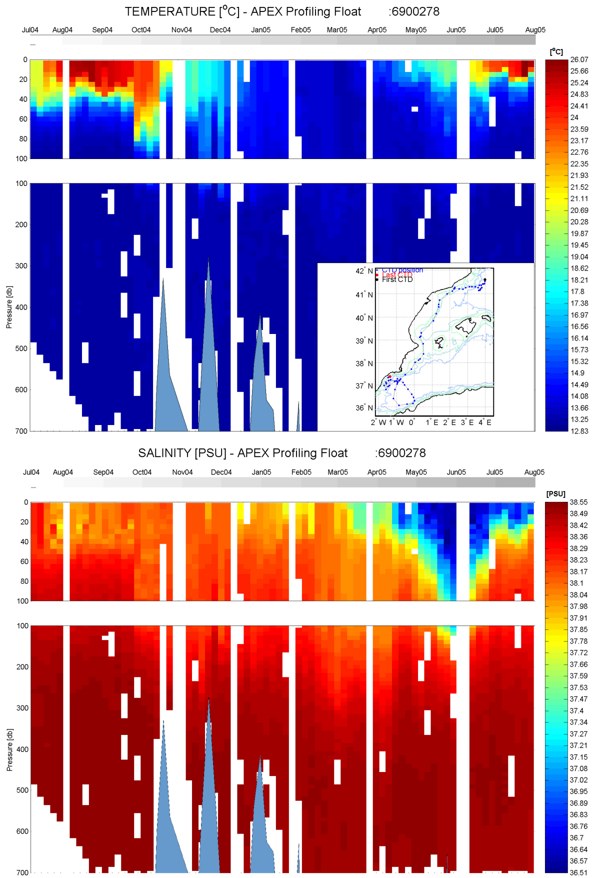

Fig. 8. Contour plot of the potential temperature (top panel) and salinity (bottom panel) following profiler WMO 6900278 between 30 June 2004 and 30 July 2005 in the Western Mediterranean basin. The positions and track of the instrument are overlaid in the temperature panel. White areas correspond to missing data.

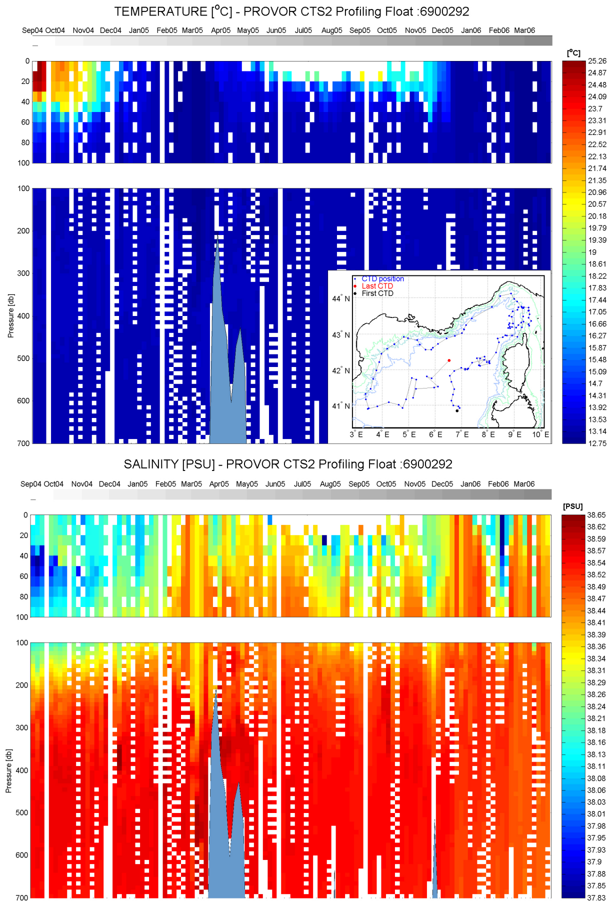

Fig. 9. Same as Fig. 8 but for profiler WMO 6900292 between 7 September 2004 and 29 March 2006 in the northwestern part of the western Mediterranean basin.

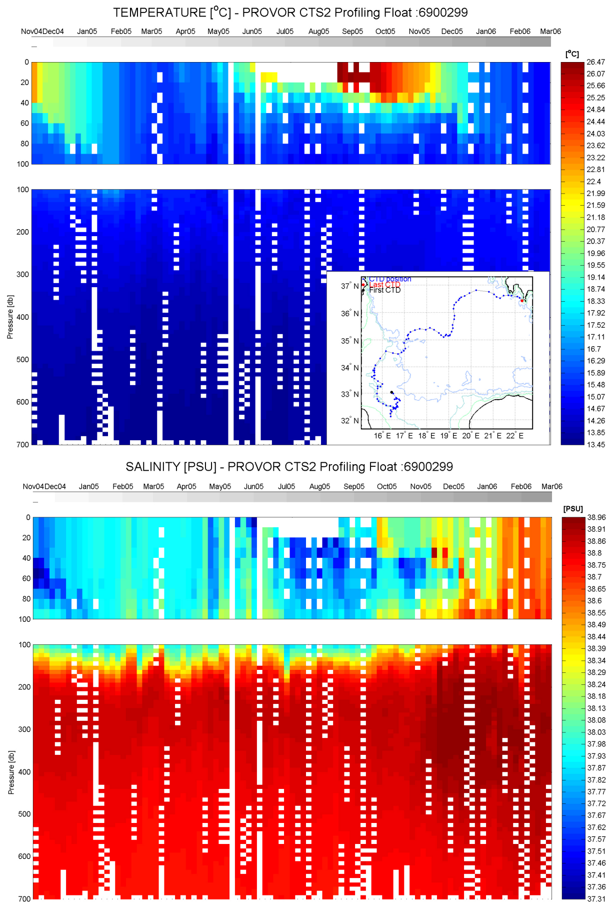

Fig. 10. Same as Fig. 8 but for profiler WMO 6900299 between 12 November 2004 and 4 March 2006 in the Ionian.

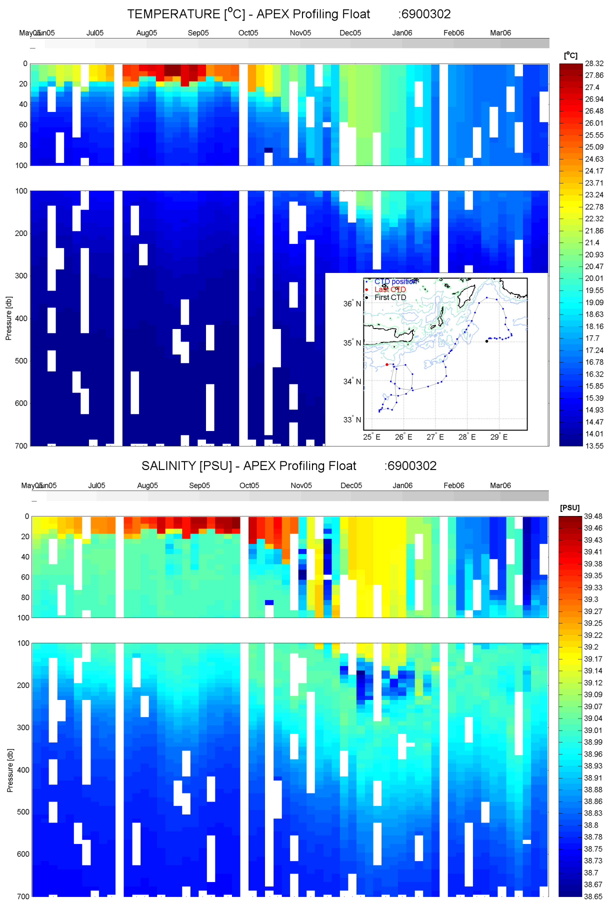

Fig. 11. Same as Fig. 8 but for profiler WMO 6900302 between 21 May 2005 and 27 March 2006 in the Levantine subbasin.

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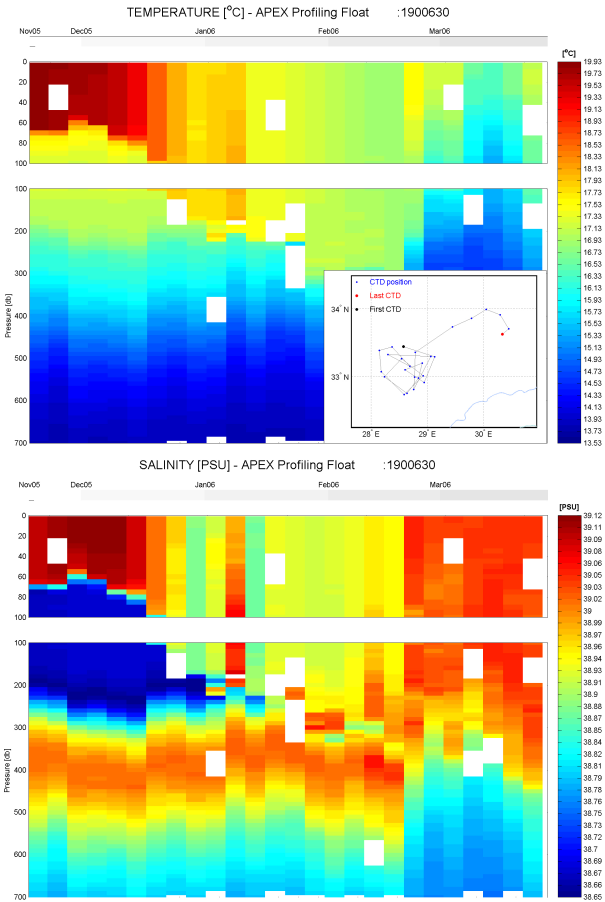

Fig. 12. Same as Fig. 8 but for profiler WMO 1900630 between 16 November 2005 and 31 March 2006 in the Levantine subbasin.