Assessment of the Argo sampling in the Mediterranean and Black Seas (part II)

by

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Director, Department of Oceanography

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1. Introduction

Since 2000, numerous Argo floats have been deployed in the Mediterranean and Black Seas under various programs and by different institutions/countries. Different cycling and sampling characteristics have been chosen to monitor these marginal seas, including cycles of 5 to 10 days, parking depths between 350 and 650 m for the Mediterranean and between 200 and 1550 m for the Black Sea, and maximum profiling depths between 700 and 2000 m. These parameters are different from the standards defined by the global Argo program. It is therefore important to assess the adequacy of these parameters for monitoring the thermohaline variability of the Mediterranean and Black Seas using the existing float data and numerical simulations. This report contains the final assessment results obtained using the historical and simulated Argo data in the Mediterranean Sea (section 2) and the Argo data in the Black Sea (section 3). Conclusions and recommendations for the continuation of the Argo program in the Mediterranean and Black Seas are included in section 4.

2. Argo sampling strategy in the Mediterranean Sea

2.1. Assessment using historical Argo data

In total, 90 Argo floats have been operated in the Mediterranean Sea between December 2000 and June 2009, out of which 28 correspond to the MFSTEP project (Poulain et al. 2007). Most of the MFSTEP floats were programmed to cycle every 5 days, to drift at a parking depth of 350 m and to profile down to 700 m (to 2000 m every 10 cycles). Subsequent floats operated by Spain and France were programmed with the same cycling/sampling characteristics, referred to, in this report, as the MedArgo parameters.

2.1.1.Vertical and horizontal coverage

Using the data of 33 floats with the MedArgo characteristics, Poulain and Solari (2009) found that:

- If all the profiles of these floats were programmed to sample as deep as 2000 m, only 22% of the Mediterranean water column is not sampled.
- Using bins of 2°x2°, only 25% of the entire Mediterranean was covered in March 2006. For the deep sea (> 1900 m) this percentage increases to 45%.
- Using bins of 3°x3°, only 25% of the entire Mediterranean was covered in March 2006. For the deep sea (> 1900 m) this percentage increases to 45%. In general the bins sampled by the floats are oversampled (more than one float per bin).
- In general the bins effectively sampled by the floats are over-sampled (more than one float per bin).

2.1.2. Robustness of the statistical results for sub-basins

The variability of the temperature (T) and salinity (S) in most Mediterranean sub-basins was described by Notarstefano and Poulain (2009) using monthly statistics and calculating the decorrelation scales of the water properties at selected depths following the floats.

We now discuss the issue of sampling, with a limited number of floats, the thermohaline properties in selected sub-basins given the natural variability observed with the historical Argo data. The main goal is not to sample all the sub-basin and mesoscale variability with floats, but to obtain unbiased robust estimates of, let us say, monthly and sub-basin averaged properties to successfully monitor the evolution of the Mediterranean over the years.

2.1.2.1. Levantine sub-basin

For the Levantine sub-basin where Argo data are most abundant, there is continuous sampling between June 2001 and June 2009, and the maximal float population reached 10 floats during several months in 2005 and 2006. The number of CTD profiles vary between 5 and 55 per month. If we focus on the thermohaline properties near 600 m, the maximal variability around mean values occur between March 2007 and April 2008, with standard deviations of about 0.29°C in potential temperature (Fig. 1) and 0.06 in salinity (Fig. 2). This is mainly the deep impact of ubiquitous and recurrent eddies prevailing in the basin, such as the IeraPetra and Mersa Matruh structures.

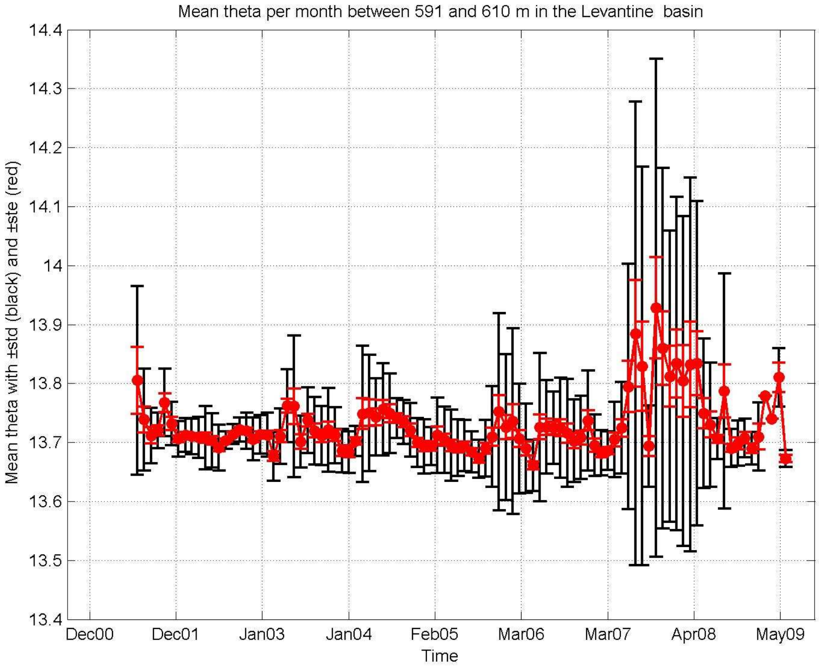

Figure 1. Monthly mean of θ near 600 m in the Levantine sub-basin between December 2000 and June 2009 (from Notarstefano and Poulain, 2009).

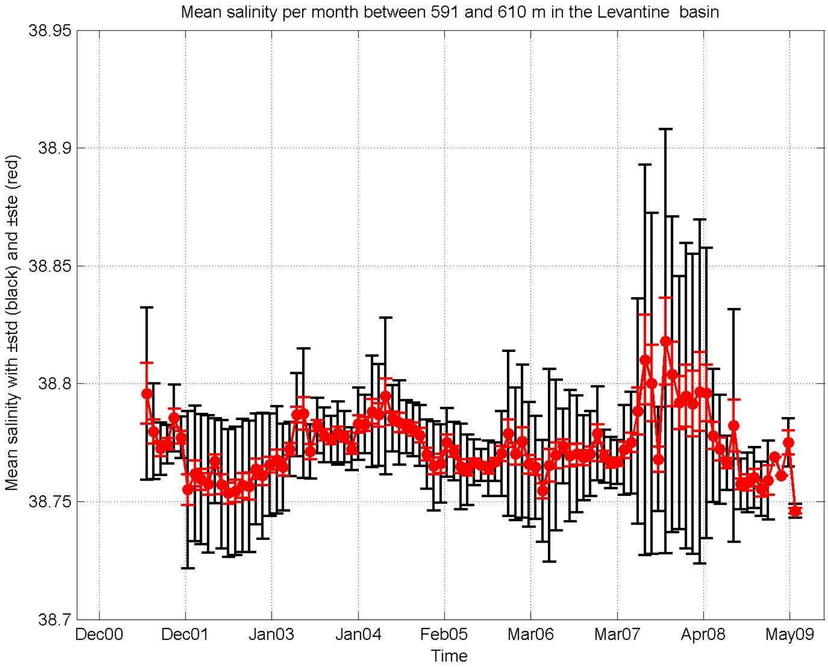

Figure 2. Monthly mean of S near 600 m in the Levantine sub-basin between December 2000 and June 2009 (from Notarstefano and Poulain, 2009).

2.1.2.2. Ionian sub-basin

In the Ionian Sea, there is continuous sampling between October 2001 and May 2009, and the maximum float population reached 7 floats in December 2005. The number of CTD profiles vary between 5 and 35 per month. At 600 m, the maximal variability around mean values can be as large as 0.31°C in potential temperature (Fig. 3) and 0.06 in salinity (Fig. 4). In 2003, the relatively large values of θ and S are due to a single float (6900087) drifting in the southeastern Ionian.

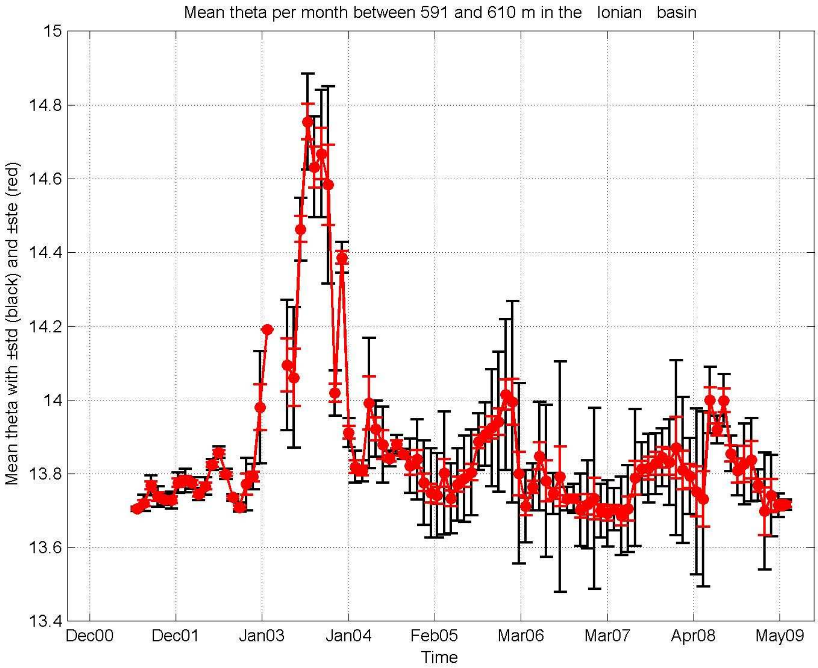

Figure 3. Monthly mean of θ near 600 m in the Ionian sub-basin between December 2000 and June 2009 (from Notarstefano and Poulain, 2009).

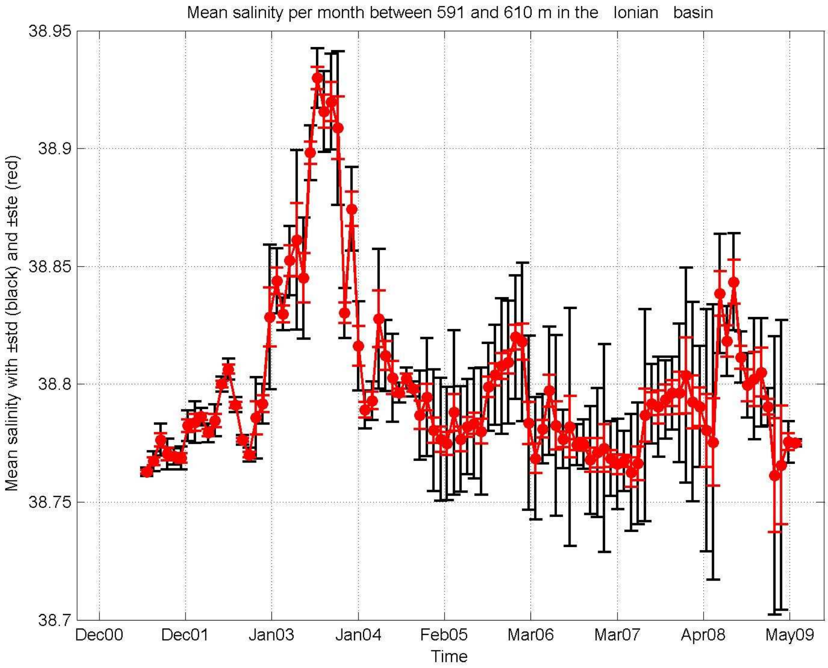

Figure 4. Monthly mean of S near 600 m in the Ionian sub-basin between December 2000 and June 2009 (from Notarstefano and Poulain, 2009).

2.1.2.3. Tyrrhenian sub-basin

In the Tyrrhenian Sea, Argo floats were deployed starting in August 2004. The maximum float population reached 4 floats in May 2006. The number of CTD profiles per month can be as large as 18. At 600 m, the maximal variability around mean values can be as large as 0.25°C in potential temperature (Fig. 5) and 0.07 in salinity (Fig. 6). The monthly and basin averaged temperatures and salinities show significant variations. For instance, S at 600 m appears to decrease significantly over the year. By looking at the positions of the CTD profiles, it turns out that this trend was produced by one float (6900281) located between the southeastern tip of Sardinia and the northwestern tip of Sicily. As a result, the trend of decreasing S is just an artifact (biased statistics) resulting from the non-uniform spatial coverage of the observations.

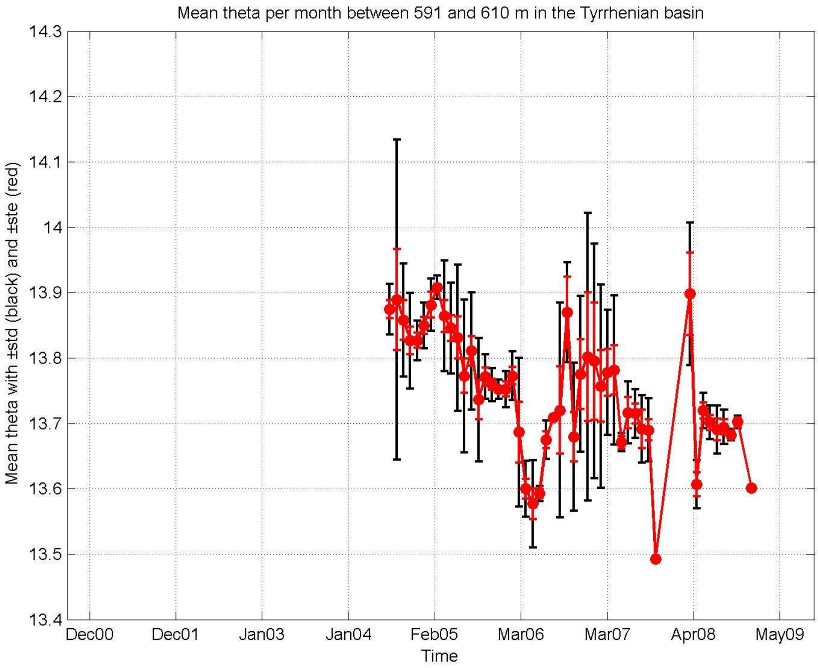

Figure 5. Monthly mean of θ near 600 m in the Tyrrhenian sub-basin between December 2000 and June 2009 (from Notarstefano and Poulain, 2009)..

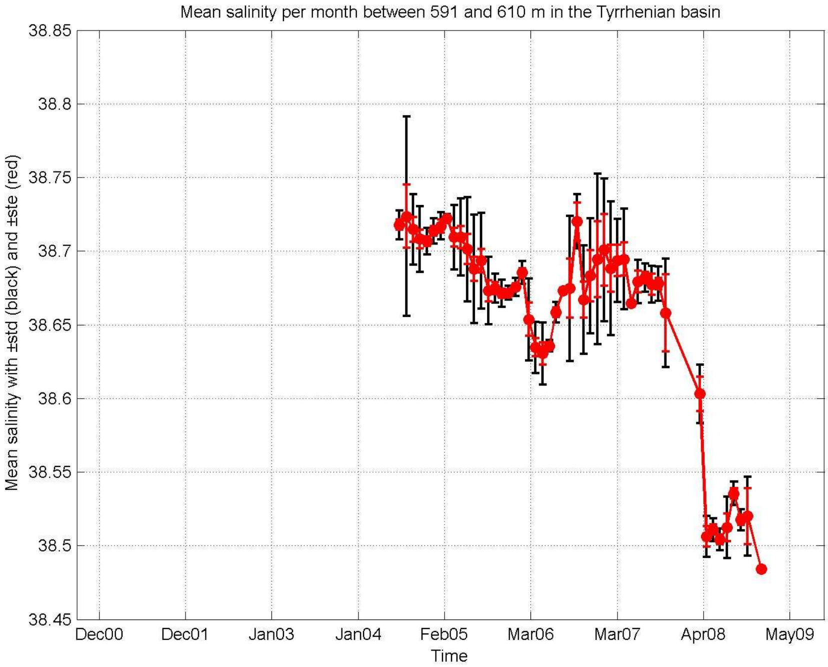

Figure 6. Monthly mean of S near 600 m in the Tyrrhenian sub-basin between December 2000 and June 2009 (from Notarstefano and Poulain, 2009).

2.1.3. Decorrelation time scales following the floats

It is interesting to discuss the Argo sampling in terms of the decorrelation time scales calculated by Notarstefano and Poulain (2009). At mid-depth (600 m) where most floats have collected data and where the seasonal deterministic signal is reduced, the correlation coefficients for the potential temperature decreases to 0.84 after 5 days, and to 0.75 after 10 days. The zero-crossing occurs after about 140 days, whereas the integral time scale is about 60 days. The results are similar for S at 600 m.

These results indicate that sampling CTD profiles every 5 days might be excessive since in general the temperature and salinity data are still highly correlated even after 10 days.

2.2. Assessment using numerically simulated Argo data

Numerical simulations of Argo profilers were performed in order to optimize both deployment strategy and cycling characteristics of Argo profilers in the Mediterranean Sea. Eulerian velocity fields of the Mediterranean model of the Mediterranean Forecasting System (1/16° x 1/16 °, 71 levels, http://bo.ingv.it/mfstep) were used to simulate Argo floats. Several experiments were made to study the dependence of the Argo population characteristics on the cycle parameters (maximum profiling depth 500, 700, 1000, 2000 m, and cycle length, 5 and 10 days) and the initial density of the Argo float regular array (0.5° x 0.5°, 1° x 1° and 2° x 2°). In total, 32 numerical simulations were performed considering for each experiment 9 ensembles of initial conditions, resulting in a total of 288 2-year-long simulations (years 2004-2005 and 2006-2007). Detailed information about the experiments and results are available at (http://clima.casaccia.enea.it/staff/rupolo/euroargo/wp4-4.pdf); here we synthesize the main results.

2.2.1 Assessment of MedArgo Parameters

As reported in the Introduction, most of the Argo floats deployed in the Mediterranean Sea were programmed with cycling parameters different from the standard defined for the global Argo program. The ensemble of numerical simulations are used to study the dependence of the Mediterranean Argo Array characteristics using parameters that may be directly measured from real Argo floats.

The main parameter that influences the results is the cycle length T_{cyc}, while weaker or no dependence was found on the other parameters of the experimental setting. Considering the different experiments with $T_{cyc} = 5$ and 10 days, we found that the smaller T_{cyc} (5 days) ensures:

- a better Argo population (larger than about 10%, the population is defined with regard to the initial density of the initial condition) of the Mediterranean area;
- a smaller redundancy of profiles (less than about 10%, the redundancy is defined as the number of obtained profiles divided by the number of cycles for each month and the number of populated bin);
- a better estimate of the root mean square of the velocity at the parking depth (underestimate larger than about 15%).

In contrast, the larger T_{cyc} (10 days) ensures:

- a larger percentage of independent successive vertical profiles (percentage larger than about 20%,);
- a better estimate of the velocity at the parking depth (the error is less than about 30%).

Weak or no dependence was observed on the other parameters (e.g., on the values for the maximum profiling depth).

It was found that the dependence of the spatial coverage of the Mediterranean Sea on the resolution of the initial conditions is approximately linear, i.e. degrading the initial array by a factor 4 (from

0.5° x 0.5° to 2° x 2 °) decreases the coverage by about a factor 4. It was also observed that the cycles with $T_{cyc} = 5$ days ensures a slightly better coverage of the Mediterranean Sea. But perhaps the main information we obtained is that with a “realistic” number of floats (about 40 floats for the 2 ° x 2 ° array of initial condition) the coverage of the Mediterranean Sea is rather poor (about 20 % of the entire area). This has greater consequences on the capabilities of monitoring the water mass properties of the Mediterranean considering the high degree of variability due to the small dynamical scales.

2.2.2. Model and “reconstructed” variability of the 3D T/S fields

2.2.2.1. Variability of the modeled Eulerian velocity fields

To evaluate the spatial variability, as it is reproduced by the model, we compare the original 1/16° x 1/16° T/S fields with ‘degraded’ fields obtained averaging on coarser meshes composed of horizontal boxes of 1°x1° and 2°x2°. In each box of the coarser meshes, we compute the mean and standard deviation (hereafter variability) of the modeled T and S, and then we compute the spatial mean and standard deviation of this variability (see examples in Figs. 7 and 8). Obviously the variability on the 2°x2° is larger. For both T and S, the mean values are smaller than the root mean square and the vertical profiles show clear seasonally-varying peaks in the subsurface layers. Both T and S display a definitely smaller variability at depth greater than 300 m

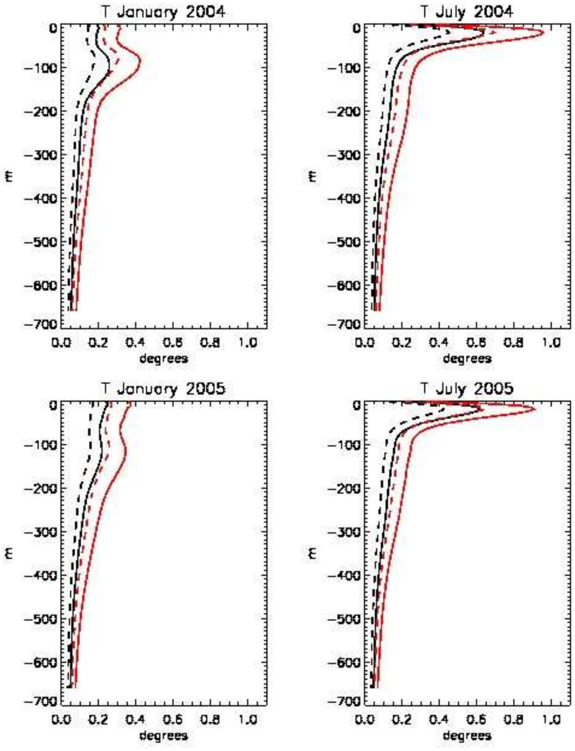

Fig. 8: Mean (dashed) and standard deviation (continuous) over the entire Mediterranean of the variability of T versus depth for the model fields degraded on 1°x1° (black) and 2°x2° (red) coarse meshes for January (left panels) and July (right panels) 2004 and 2005.

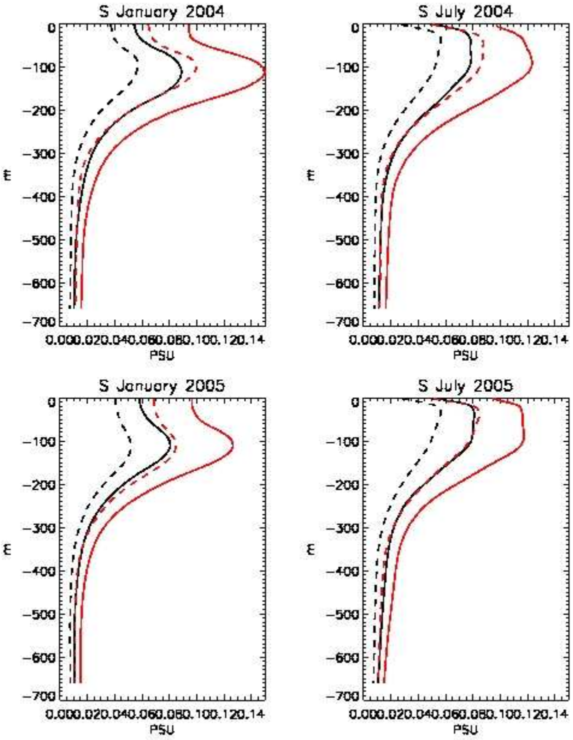

Fig.9: Same as Fig.8 but for S.

Examples of the spatial pattern of such high subsurface variability are shown in Figs. 10 and 11, where the T and S variability is mapped inside the degraded meshes for January and July. We note that the values of variability observed in summer (not shown here) near the surface (20 m) are high in the regions characterized by the presence of preponderance of mesoscale features or gyres, such as in the Alboran Sea, the NW Mediterranean, the northern Tyrrhenian Sea east of the Bonifacio Strait, the northeastern Ionian Sea, the area South of Crete and the eastern Levantine. The maximum values of the winter variability at 120 m (Fig. 10) seem to be more linked with the Atlantic Water (AW) dynamics even if all the eastern Levantine it is characterized by high values of variability. It is interesting to note the high variability observed in 2004 South of Crete. Variability of salinity, both in summer and winter (e.g. Fig. 11) is clearly linked to the eastward path of the AW, with high values of variability observed north of the Algerian Current probably related to the eddies created from the instability of this current. However other structures are observed, as for example the high variability observed during 2004, in the North Tyrrhenian east of the Bonifacio Strait, between Corsica and Sardinia.

These results highlight the large variability simulated by the Eulerian model of the Mediterranean Sea at surface and subsurface, which is also affected by some inter-annual variability. The spatial variability is due both to the presence of meandering current systems (e.g. related to the eastward flow of AW) characterized by peculiar values of T/S fields and the presence of mesoscale and sub-mesoscale transient coherent structures of small length scale. This precludes, even in the more optimistic scenario (a float for each bin of 1°, which means about 200 floats in total) the possibility of detecting long term trend in the subsurface layers, say in the upper 200-300 m, with an Argo float array.

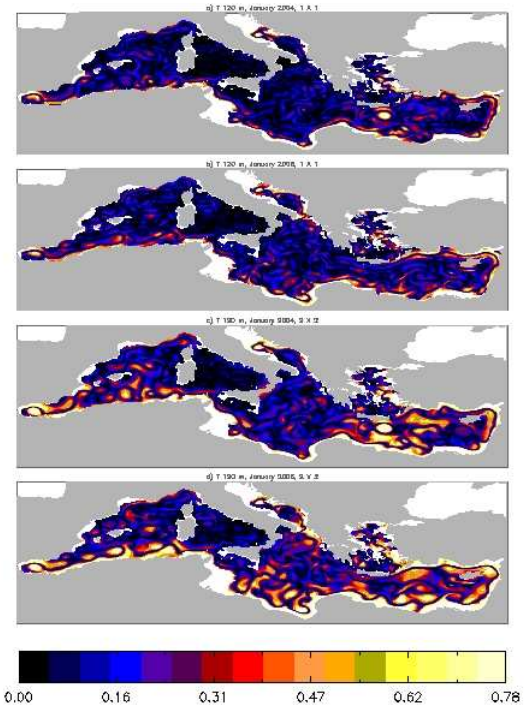

Fig. 10: Map of mean variability of T at 120 m (depth of the winter maximum of variability) for January 2004 and 2006 on 1°x1° (panels a and b, first two panels from top) and 2°x2° (panels c and d, last two panels toward bottom).

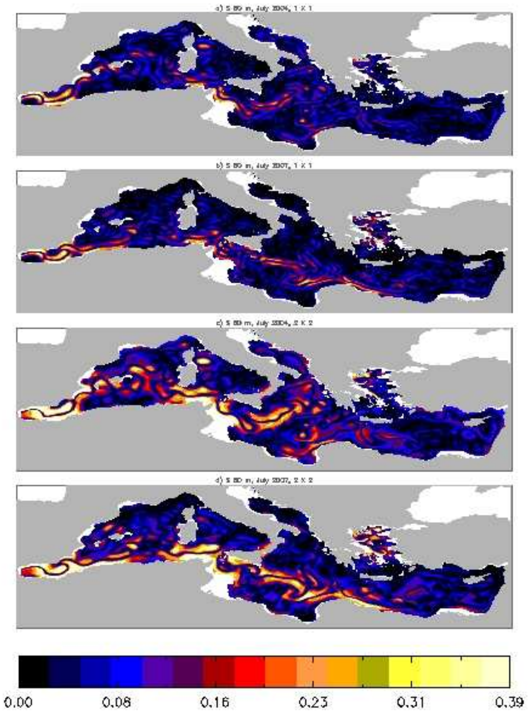

Fig. 11: Map of mean variability of S at 80 m (depth of the summer maximum of variability) for July 2004 and 2007 on 1°x1° (panels a and b, first two panels from top) and 2°x2° (panels c and d, last two panels toward bottom).

2.2.2.2. Reconstructing the 3D T/S fields with the simulated floats

We now estimate the error done in reconstructing the 3D fields of T and S, averaging the vertical profiles of numerical Argo floats in 1°x1° and 2°x2° meshes. In Fig. 12 we show, as a function of the initial condition density, an example of the reconstructed field of temperature near 365 m, the drifting depth of the floats, compared to the ‘real’ field given by the model. The progressive degradation of the reconstructed field for experiments with lower initial condition density is obvious. In the more realistic case (initial density of 2°x2°, approximately 40 floats) it is evident that all the small scales features of the Mediterranean Sea circulation are lost, even at a mid depth.

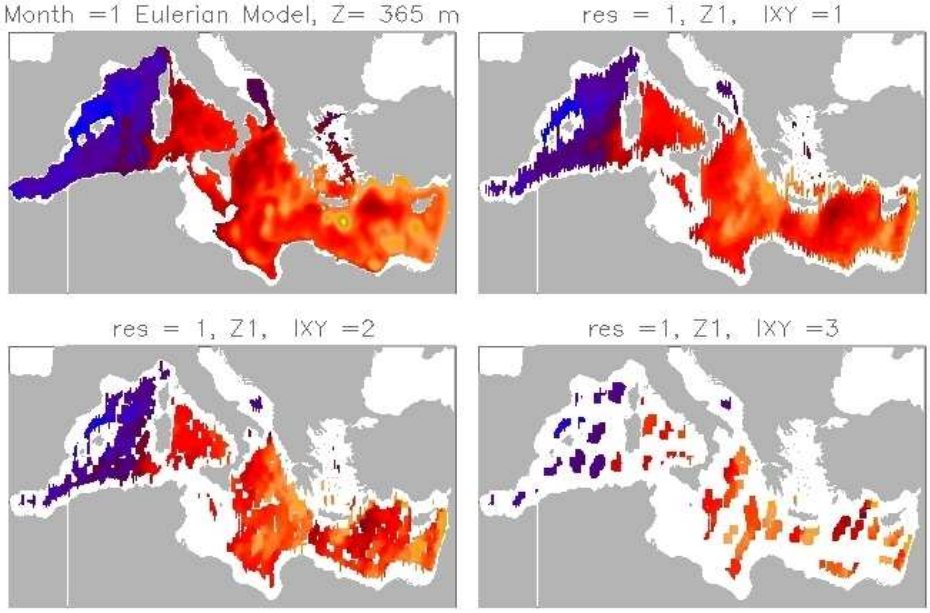

Fig 12: Mission 700/2000: mean monthly T for January 2004 at 365 m from the Eulerian model (upper left panel) and reconstructed in a regular grid of 1°x1° for the three sets of initial condition with density of one float for bin of 0.5°x0.5°, 1°x1° and 2°x2°.

A more quantitative view of the error may be obtained computing, for each bin where it is available, a reconstructed monthly mean T/S value from the numerical Argo profiles, and the root mean square of the difference between the reconstructed and real mean values (hereafter called bias). In Figs. 13 and 14 we plot, for T and S, the vertical profiles of the mean and root mean square, computed over the entire basin, of the bias between the real and reconstructed values.

Even in this case, mean values are smaller than the root mean square and the vertical profiles show the same qualitative behavior of the vertical profiles of the variability of the Eulerian model (see Figs. 8 and 9). Bias errors are slightly larger than the variability shown in Figs. 8 and 9 due to the difference between the T/S field reconstructed from the Argo profiles and the 'real' mean values. The reconstructed T fields show larger errors in the top layer down to 100-150 m, with an high degree of seasonality. In particular, the error on the mixed layer temperature goes from about 0.5-0.9 °C in winter to about 2.2-2.5 °C in summer at ~120 m. The reconstructed salinity fields display seasonal variability and show a maximum error at about 100 m that probably corresponds to the mean depth of the lower interface of the AW. Finally, it is interesting to note that even an obvious dependence is found on the 'density' of the initial conditions (different colors), the huge variability of the Eulerian model largely dominates the errors on the reconstructed fields, specially in the subsurface layer since only a small improvement is observed going from the densest (0.5°x0.5°) to the coarser (2°x2°) data set of initial condition.

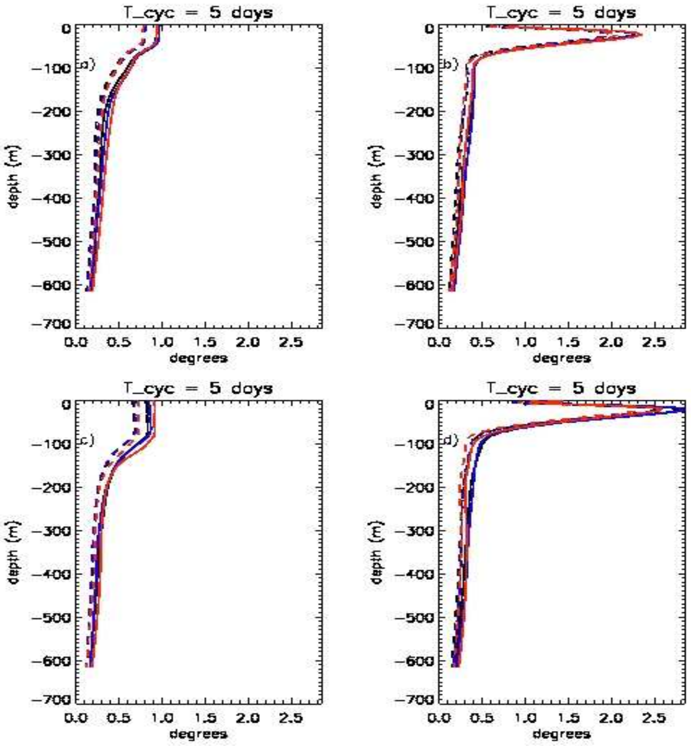

Fig. 13: Monthly mean and rms profiles (over the entire Mediterranean, dashed and continuous lines, respectively) of the 1°x1° bin rms between the reconstructed T and the model "real" values. Black, blue and red curves correspond to the three sets of initial conditions with density of one float for bin of 0.5°x0.5°, 1°x1° and 2°x2°, respectively. Panels a) to d) are relative to reconstructed fields after 1,7,13 and 20 months from 1-1-2004, respectively.

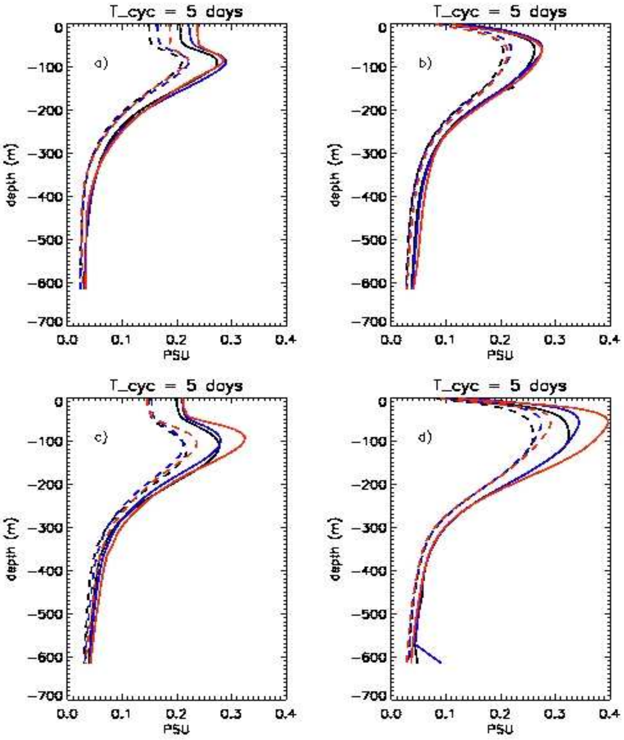

Fig. 14: As in Fig.13 but for S.

2.2.2.3. Reconstructing temporal trends of T/S in Mediterranean sub-basins

A further confirmation of the large T/S variability and of the consequent difficulty of detecting trend in the Mediterranean sub-basins using Argo floats is illustrated in Figs. 15 and 16 for the Tyrrhenian Sea. The spatial mean (over the sub-basin) and the extreme values of T and S at 615 m reconstructed by 6 numerical Argo floats are plotted together with the mean values directly computed from the Eulerian model. The maximal variability around mean values sampled by the numerical Argo floats is about 0.5°C and 0.15, for T and S respectively. In such situation, and even at the intermediate depth of 615 m, the sparse sampling from Argo floats may show oscillations or apparent trend (see e.g. Fig. 15 for temperature) that are not present when averaging all the model values. The same exercise was performed using only 3 numerical floats in the Tyrrhenian Sea (not shown). It was found that errors, oscillations and trends are as large as in the case with 6 floats.

In Figs. 17 and 18 we plot the spatial mean T and S at 615 m obtained using 9 Argos floating in the Ionian Sea, along with the extreme values “observed” by the floats and the mean obtained using all the model values. It appears that in this case the agreement between the Argo observations and the “real” fields is better (smaller difference, no significant false trend). Using 5 floats instead of 9 gives similar results.

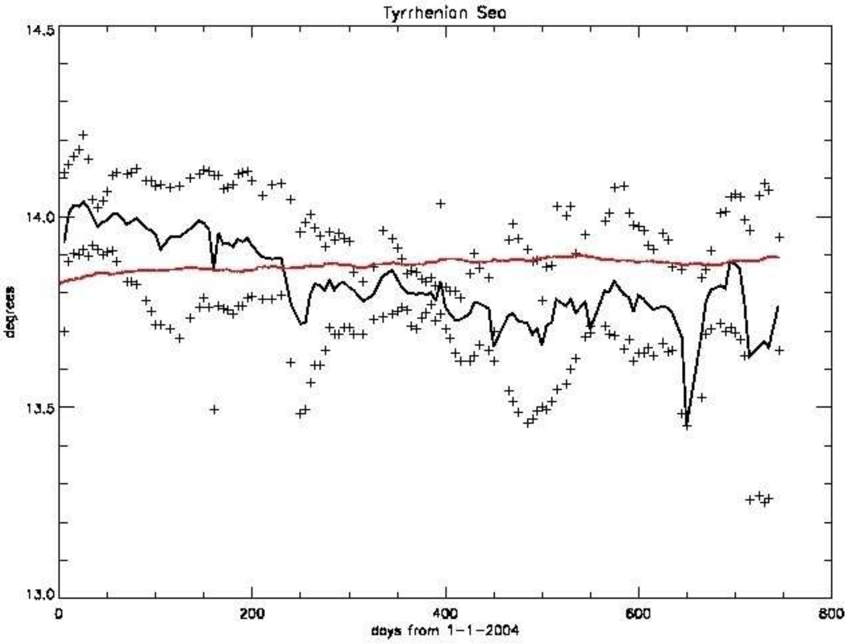

Fig. 15: Mean T values reconstructed by 6 Argo numerical floats in the Tyrrhenian Sea at 615 m (black curve) with minimal and maximal values sampled (crosses). The red curve indicates the mean value computed at the same depth from the Eulerian model (all data).

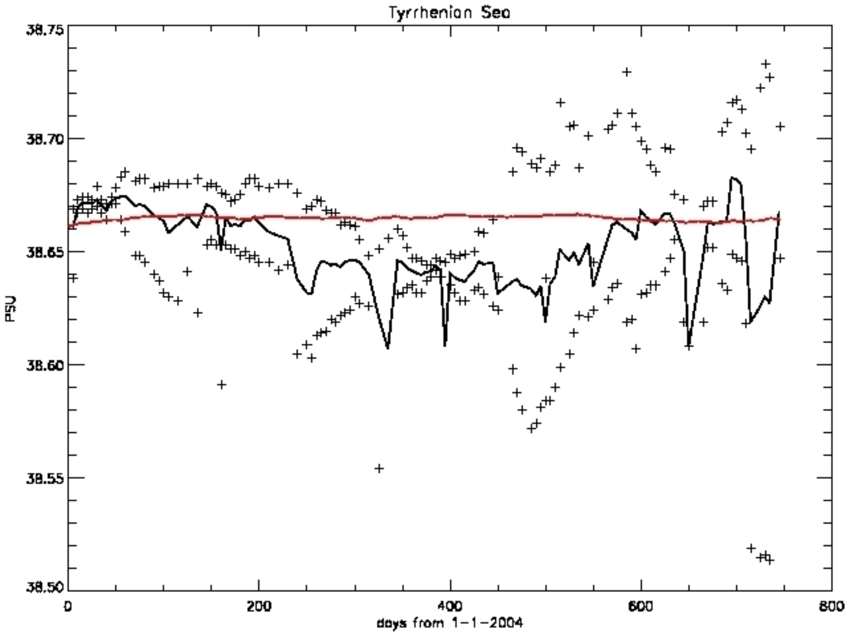

Fig. 16: Same as Fig.15 but for S.

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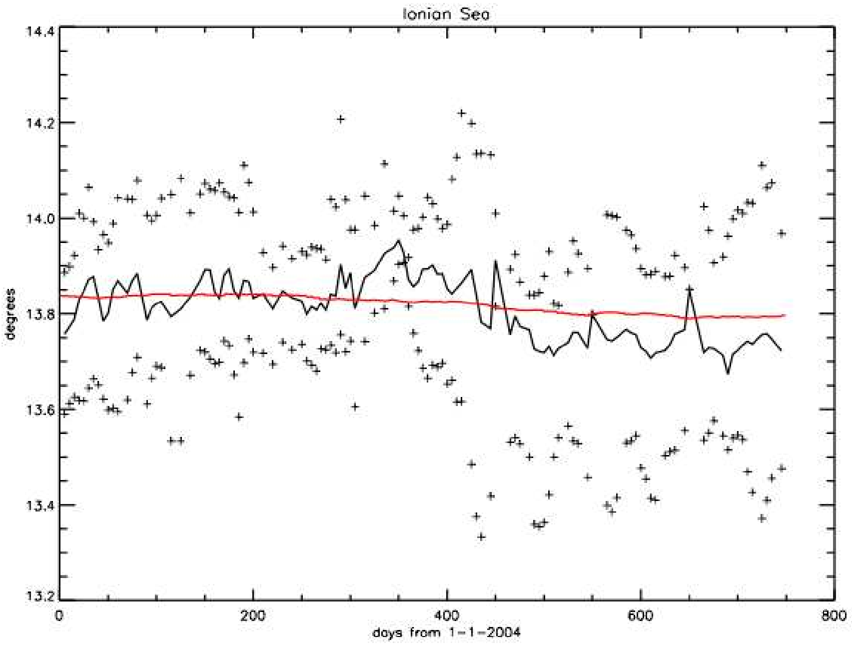

Fig. 17: Mean T values reconstructed by 9 Argo numerical floats in the Ionian Sea at 615 m of depth (black curve) with minimal and maximal values sampled (crosses). The red curve indicates the mean value computed at the same depth from the Eulerian model (all data).

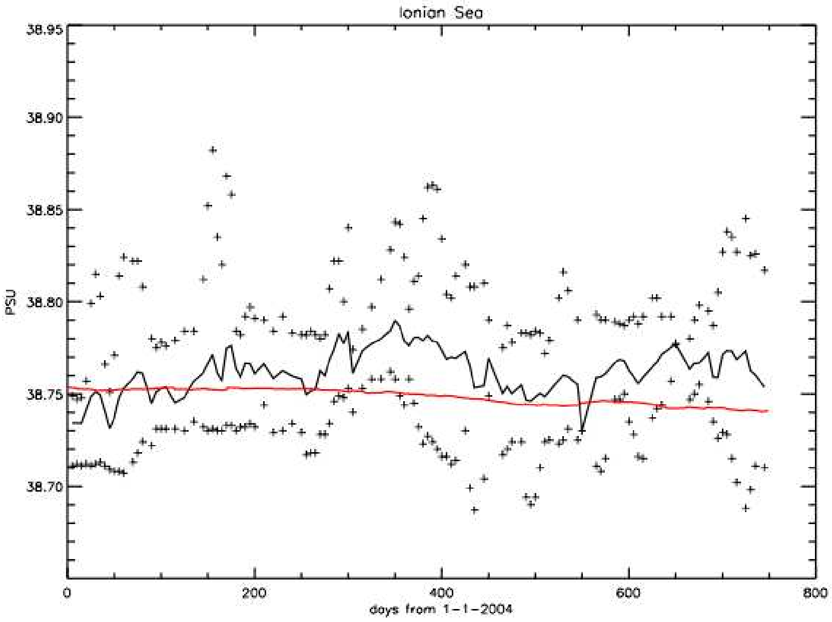

Fig. 18: Same as Fig. 17 but for S.

Finally, as a last example of the dependence of reconstructed basin mean values from Argo floats on the number and trajectories of floats we show in Figs. 19 and 20 the time series of the mean T and S at 615 m obtained with two different sets of 5 numerical floats, with a set of 9 numerical floats and of the "real" mean computed from all the data of the Eulerian model. Differences can be as large as about 0.5 °C and 0.07 for T and S, respectively.

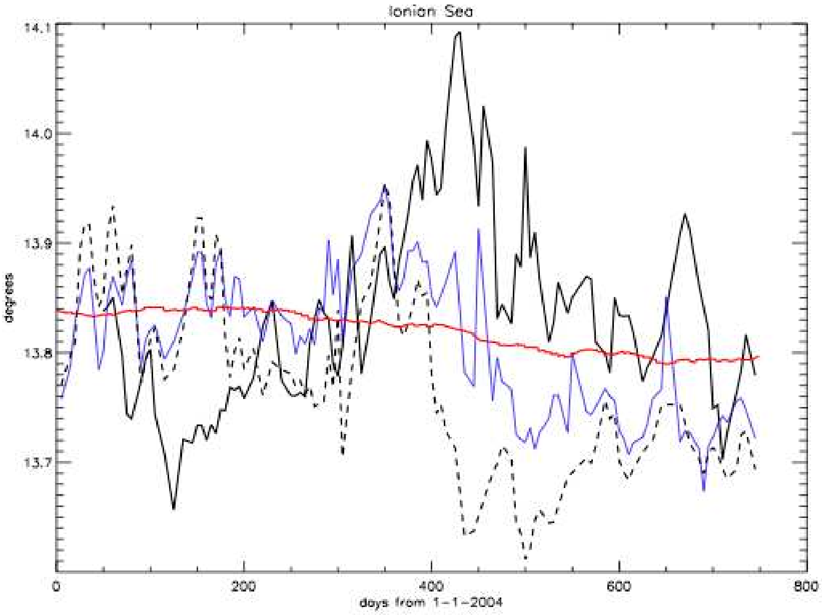

Fig. 19: Mean T at 615 m in the Ionian Sea from two different sets of 5 Argos (continuous and dashed black lines), a set of 9 Argos (blue line) and from the numerical Eulerian model (red line)

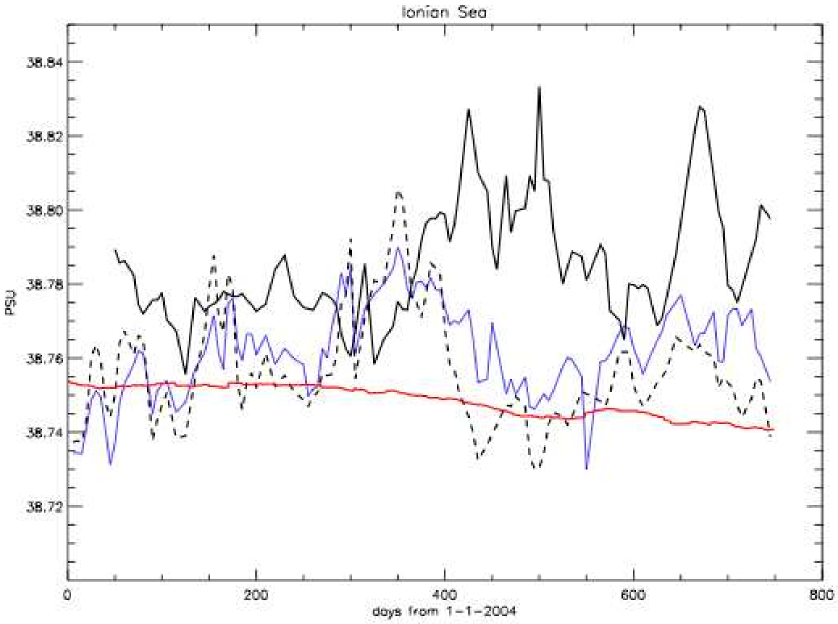

Fig. 20: Same as Fig.23 but for S.

3. Argo sampling strategy in the Black Sea

A total of 7 Argo floats have been operated in the Mediterranean Sea between 2002 and 2008 and have provided more than 900 CTD profiles. These floats had a cycle length of 7 days and a parking depth between 200 and 1550 m. The maximum density of floats was obtained in 2008 with 4 floats running simultaneously.

3.1. Vertical and horizontal coverage

Using the data of the 7 floats in the Black Sea, Poulain and Solari (2009) found that:

- If all the profiles of these floats were programmed to sample as deep as 2000 m, only 4% of the Black Sea water column is not sampled.
- Using bins of 2°x2°, a maximum of 50% of the entire Black Sea was covered in April 2008. In general the bins sampled by the floats are over-sampled (more than one float per bin).

3.2. Robustness of the basin-wide statistical results

The variability of the temperature and salinity in the Black Sea was described by Notarstefano and Poulain (2009) using monthly statistics. If we focus on the thermohaline properties near 200 m, the maximal variability around mean values occur between March 2008, with standard deviations of about 0.16°C in potential temperature (Fig. 21) and 0.42 in salinity (Fig. 22). This is mainly the impact of sub-basin and mesoscale structures barely sampled by 3 or 4 floats.

3.3. Decorrelation time scales following the floats

It is also interesting to discuss the Argo sampling in terms of the decorrelation time scales calculated by Notarstefano and Poulain (2009). Near the depth of 200 m, where most floats have collected data and where the seasonal deterministic signal is reduced, the correlation coefficients for the potential temperature decreases to 0.84 after 7 days, and to 0.74 after 14 days. The zero-crossing occurs after about 170 days, whereas the integral time scale is about 45 days. The results are similar for the salinity at 200 m.

These results indicate that sampling CTD profiles every 7 days might be excessive since in general the temperature and salinity data are still highly correlated even after 14 days.

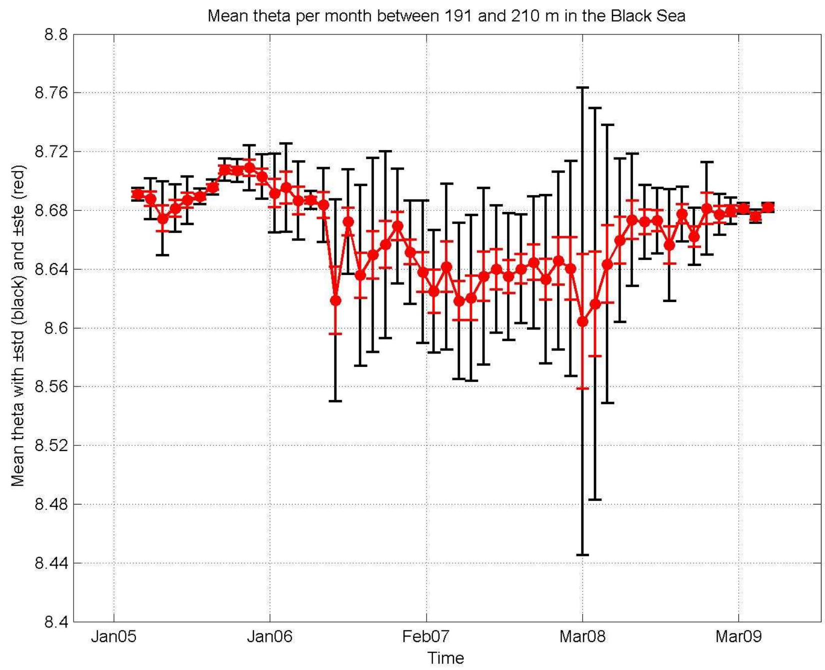

Figure 21. Monthly mean of θ near 200 m in the Black Sea between March 2005 and June 2009 (from Notarstefano and Poulain, 2009).

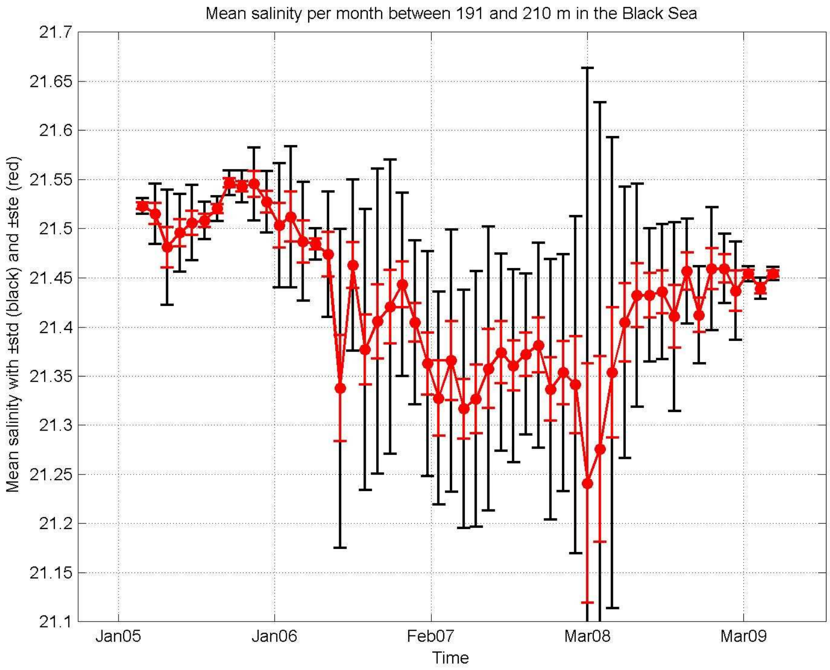

Figure 22. Monthly mean of S near 200 m in the Black Sea between March 2005 and June 2009 (from Notarstefano and Poulain, 2009).

4. Conclusions and recommendations

Based on the above-described studies using historical and simulated Argo float data in the Mediterranean and Black Seas, we can conclude that robust statistics of temperature and salinity can only be obtained with a large number of float dispersed quasi-uniformly in all the areas. The main reason is that these seas are characterized by significant variability (in space and time) of the thermohaline fields, mainly at surface and mid-depth levels. We have shown that using limited numbers (less than 10) of real and simulated floats in selected sub-basins, we can obtain biased unrealistic basic statistics such as false long-term trends in the spatially averaged temperature and salinity, even at intermediate depth. It is also obvious that monitoring the Mediterranean and Black Seas with hundreds of floats is not practically possible due to logistical and economical reasons. In contrast, the observed trends in the deep layers of the Mediterranean characterized by less spatial variability, suggest the opportunity to increase the observations at great depths with the Argo network. Despite this problem of under-sampling, we recommend the following for the continuation of the Argo program in the Mediterranean Sea:

- Maximum profiling depth of 2000 m at every cycle or every two cycles, with a short 700 m profiles in between;

- Deployment in deep waters (depth > 2000 m);

- Cycles of 5 days: this is a good compromise to capture more variability of the sub-surface velocity field and to obtain a robust estimate of the mean velocity at parking depth. Note that from historical data, displacements of floats near 350 m during ~5 days have been as large as 100 km (Solari, 2008b). In addition, a cycle length closer to the decorrelation time of the velocities is also an advantage for the assimilation of float displacements into numerical forecasting models. Numerical simulation reveal that floats with cycles of 5 days tend to cover better the Mediterranean when compared to those with cycles of 10 days;

- Parking depth between 300 and 400 m to track the LIW throughout the Mediterranean;

- Use Argos-3 or Iridium telemetry to reduce surfacing time (from about 6 h to less than one hour) and probability of hazards (stranding, theft by seafarers, etc.);

- Maintain a minimum population of 30/50 floats in the Mediterranean. If we use the decay rate of the historical Argo fleet in the Mediterranean (mean life time of 563 days; Solari, 2008a) there is a reduction of ~30% after a year. This means that every year 10/15 floats have to be deployed to maintain an initial population of 30/50 units. If Argos-3 or Iridium telemetry is used, the “mortality” of the floats should be reduced and reseeding of 5/10 floats might be sufficient.

- Deploy the floats inside and outside the significant circulation structures (with sub-basin scale of about 100 km) such as the instability eddies of the Algerian and Lybio-Egyptian Currents, in order to obtain unbiased statistics.

Using the very limited historical Argo float dataset in the Black Sea, we can recommend that:

- A minimum population of 5 floats;

- Since floats operated in the Black Sea indicate a possible longer operating life with respect to the Mediterranean (with a half mean file near 1000 days, Solari, 2008a), redeploying one or two floats per year might be enough to maintain the fleet of 5 operating units.

To conclude, we propose the deployment strategy depicted in Fig. 23 for the continuation of the Argo program in the Mediterranean and Black seas. This is a conservative proposal corresponding more or less to the worldwide 3° x 3° resolution of the Argo project. Floats should be deployed as uniformly as possible in the different sub-basins and plans should be made to deploy 10/15 units in areas deprived of observations on a yearly basis.

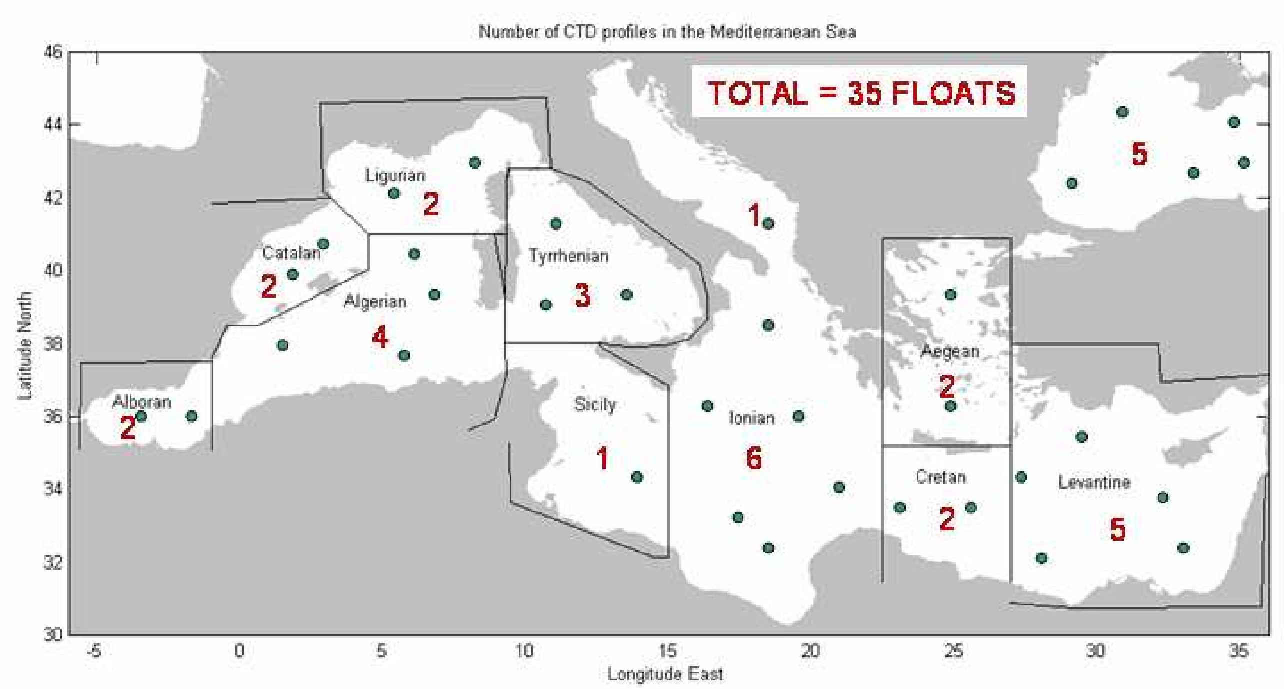

Figure 23. Proposed minimum distribution of the float array in the Mediterranean and Black Seas for the continuation of the Argo project. Numbers indicate the quantity of proposed floats in the sub-basins.

5. References

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