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Steric sea level variations in the central-eastern Mediterranean Sea from Argo observations

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ABSTRACT Temporal variations of the sea level have been assessed by means of satellite altimetry for many years. While the total sea level change is determined by altimetry very precisely, at the level of a few millimeters, knowledge of the effects of mass-related and volume-related contributions is comparatively poor. Here, we report on the effect of volume changes of sea water in the central-eastern Mediterranean Sea. The study is performed on the basis of in-situ data collected by the floats of the Mediterranean and Black Sea Argo Centre (MedArgo) established in 2003. On a grid of 1°×1° the total steric sea level variations as well as the individual contributions of thermal and haline expansion are computed. The study reveals a strong volume-related, sea level change at a rate of about 18 mm/year between 2004 and the end of 2008 in the Ionian Sea that is clearly dominated by thermal expansion. In contrast, thermal and haline contributions show opposite trends in the eastern Mediterranean Sea where both effects tend to counteract each other on inter-annual time scales. Steric sea level changes from Argo and the total sea level change from the altimetry satellite mission Jason-1 agree very well in the Ionian Sea, suggesting that most of the observed sea level rise is caused by thermal expansion in this region. However, the comparison of Jason-1 with the steric sea level change computed from Argo data between 2004 and the end of 2007 indicates an unexplained mass loss at a rate of -20 mm/year in the region around Crete.

1. Introduction

In recent years there has been a lot of concern about sea level rise as a consequence of global climate change. Precise observations of the sea level by means of satellite altimetry indicate an annual rise of more than 3 mm since the last decade of the 20th century (Cazenave and Llovel, 2009). Whereas this number represents a global average, large regional discrepancies were observed. Church *et al*. (2004) estimated regional sea level trends of up to 25 mm/year between 1993 and 2000 from TOPEX/Poseidon satellite altimeter data. At present, the increase of ocean water mass, mainly as a consequence of land ice ablation, is assumed to account for about 50% of the observed global sea level rise (Bindoff *et al*., 2007; Criado-Aldeanueva *et al*., 2008), but may become much more important in the future in a scenario of further global warming (Alley *et al*., 2005). Another large fraction of the observed sea level change can be explained by the volume change of sea water due to the variation of ocean temperature and (to a minor extent) ocean salinity, the so-called thermosteric expansion/contraction.

While observations of the total sea level change by means of satellite altimetry are very accurate, knowledge of individual contributions from volume and mass effect are less well known. Until a few years ago, respective estimates were based on numerical models and a very sparse in-situ archive of temperature and salinity observations. The first direct measurements of oceanic mass variation through the gravity field mission GRACE (Tapley *et al*., 2004; Lombard *et al*., 2007) (launched in 2002) and the steadily improving coverage of in-situ observations of temperature and salinity performed by the global array of profiling Argo floats (Roemmich and Owens, 2000) (since 2000) significantly enhanced the data basis. Since the introduction of these techniques the analyses of volume and mass effect became much more effective. In particular, the improved in-situ data of the Argo floats opened the possibility for advanced regional studies.

In our study, we focus on the Mediterranean Sea which is a peculiar part of the global ocean that is open to the global circulation only through the Strait of Gibraltar. Previous studies revealed a strong regional variability of the Mediterranean Sea level change from satellite altimetry (e.g., Criado-Aldeanueva *et al*., 2008; Fenoglio-Marc, 2002). A more precise understanding of the observed sea level change and its dynamics (that also provides the basis for its prediction in the future) is especially important for this region due to the densely populated coast. Our analysis concentrates on the thermosteric and halosteric contributions computed from data collected by the floats of the Mediterranean and Black Sea Argo Centre (MedArgo) (Poulain *et al*., 2007). These instruments provide valuable data as basis for a regional assessment of ocean volume variations since 2003. More detailed background information on the Argo project is given in Section 2. Section 3 provides the theoretical and computational foundations for the conversion of the raw Argo temperature and salinity measurements into volume-related changes in sea level. Numerical results of our study as well as comparisons with external studies and with the total sea level change observed by satellite altimetry are provided and discussed in Section 4.

2. The Argo project

The Argo project is one of the most important multi-national endeavours ever undergone for the in-situ observation of physical properties of the oceans. It consists of an array of instruments that freely float in the global ocean. Each float transmits a record of temperature and salinity observations over a vertical profile of a few hundred to 2000 meters depth every 10 days. Deployment started in the year 2000. Meanwhile, the mission, whereby 23 countries have contributed floats, has achieved its goal of more than 3000 globally distributed instruments active at the same time. Since every float has an average life time of about 4 years, 750 new floats are deployed each year in order to keep the global network at a more or less constant level. The most important goals of the Argo project are:

- improvement of the knowledge of ocean dynamics: the Argo observations contribute significantly to an improved understanding of regional and large-scale ocean circulation, its variability and heat and freshwater transport processes;
- improvement of ocean models: Argo data sets serve as a reference for the validation of ocean models and allow for the computation of state variables for their initialisation. Furthermore Argo provides a valuable resource of observations to be applied in assimilation procedures;
- reach a synergy with satellite altimetry: the combination of profiling floats and altimetry

enables the physical interpretation of observed sea level variations. Since satellite observations alone do not allow for the assessment of vertical profiles of density variations, in-situ measurements are indispensable for the investigation of subsurface processes and the quantification of volume-related sea-level change.

The Argo mission overcame the limitations of previous in-situ observations of temperature and salinity that were confined to stationary instruments (in most cases close to the coast) or to occasional observations along shipping routes. Now continuous, in-situ measurements are also available in regions that were poorly covered before, for example in the Southern Hemisphere, where the lack of in-situ data involved serious uncertainties regarding the conclusions (Ishii *et al*., 2006).

Argo is lead-managed by the international Argo Steering Team that was formed within the World Climate Research Project's Climate Variability and Predictability Experiment (CLIVAR) and the Global Ocean Data Assimilation Experiment (GODAE). The array of floats is an important component of the Global Climate Observing System (GCOS) as well as of the Global Ocean Observing System (GOOS) (Roemmich and Owens, 2000). For the Mediterranean Sea, the deployment of the profilers and the distribution of Argo data is coordinated by MedArgo (Poulain *et al*., 2007). Since 2003, a total of about 100 profilers has been deployed. MedArgo's deployment strategy proposes to keep a constant fleet of 30 simultaneously operating and homogeneously distributed floats, measuring between 50-90 profiles per month. The collected data are freely available from the Coriolis Data Centre which is the official Argo data disseminator (http://www.coriolis.eu.org).

3. Theory

3.1. Parameters of the analysis

We perform a regional study on steric sea level anomalies (SLA), i.e., the variations of the sea level with respect to a long-term mean in the central-eastern Mediterranean Sea for a time frame of five years from the beginning of 2004 to the end of 2008 using Argo observations. The analysis covers the area between 30°-44° N and 12°-36° E on a grid of 1°×1°. In addition to the analyses performed for the entire area, separate studies on steric sea level variations are performed for two smaller zones within the region, namely the Ionian Sea (32°-38° N, 16°-20° E) and the Levantine Sea (32°-36° N, 28°-34° E).

In general, Argo data are released in near-real time together with a quality flag. The largest fraction of the observations collected worldwide undergoes a subsequent validation process in which the so-called delayed mode data is generated. However, no Argo data in delayed mode was available for the Mediterranean Sea at the time of our study. The real-time data applied in the following were entirely flagged by the quality control. For the analyses, only floats with flags 1 (good data), 2 (probably good data), 5 (edited value), and 8 (interpolated value) were considered; for details regarding the quality classes see Wong *et al*. (2009). Nevertheless, real-time data may partly be affected by biases in reported pressure values. According to a note on the Argo web site (http://www.argo.ucsd.edu) from April 7, 2010, these biases are usually less than 5 dbar, but occasionally can be larger (> 20 dbar). At present, the bias errors are being steadily removed in the reprocessing of older Argo data.

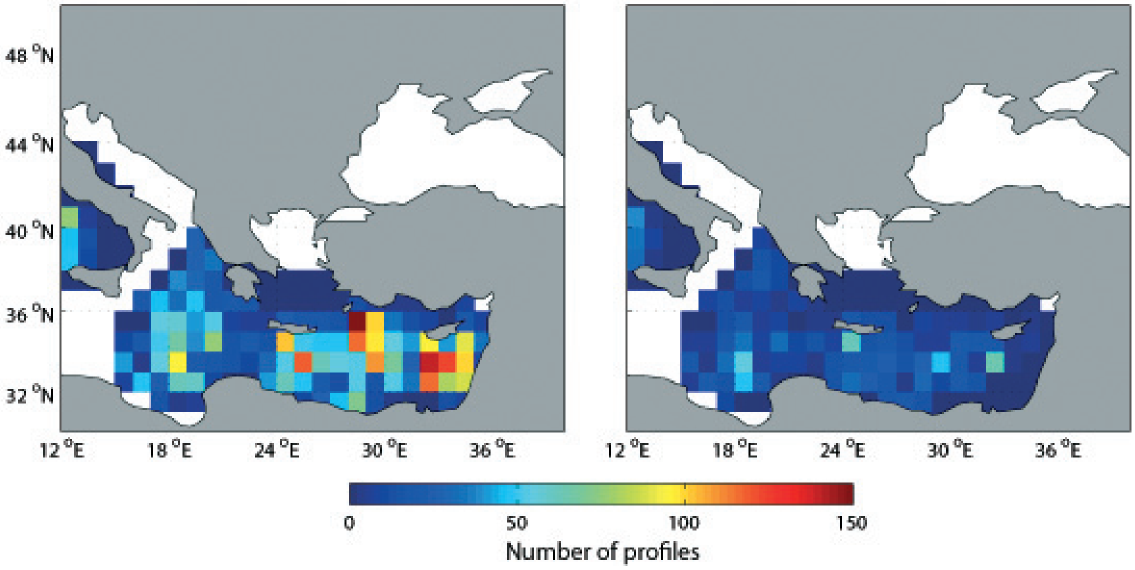

Fig. 1 - Available valid Argo profiles at different maximum depths on the 1°×1° grid of our analysis. Left: number of profiles reaching down to 400 m; right: number of profiles reaching down to 700 m.

Temperature and salinity profiles from Argo down to 400 m are taken into account. Though previous studies also used deeper measurements (down to 900 m) (e.g., Cazenave *et al*., 2009), we aimed at a compromise between data coverage and maximum sampled depth. In fact, only data of two single floats would be available to estimate the volume change below 400 m in our region during the time span of interest. Therefore, the extension of the grid to larger depths would obstruct a reasonable in-situ analysis in this area. Fig. 1 shows the amount of Argo profiles in the Mediterranean Sea depending on the maximum depth. A significant lack of data at deeper levels is obvious: although all Argo cycles reach down to at least 700 m as a matter of principle, the majority of the profiles do not contain any usable data records below 400-500 m. While 4655 valid records of temperature and salinity are available above 400 m within our region, only one third of the measurements is available for deeper layers. Besides the problems with the deeper layers, Fig. 1 also shows the rather non-uniform horizontal distribution of the profiles over the area of interest. The reason for this adverse pattern is the tendency of the Argo profilers to keep floating within the same basin over long time spans after several cycles (Poulain *et al*., 2007).

3.2. From Argo profiles of temperature and salinity to steric sea level variations

Applying the equation of state, defined by the Joint Panel on Oceanographic Tables and Standards published by UNESCO in 1981 and described by Gill (1982), a density profile at each sampled location is derived from the Argo records of temperature and salinity.

Following the general vertical sampling rate of the Argo floats, density values at depth are computed with an interval of 10 dbar (equivalent to 10 kPa), resulting in a total of 40 depth levels per profile. Since the measurements are not taken at exact 10 dbar intervals, the observations are linearly interpolated from the actual pressure levels to the 10 dbar grid spacing.

The assessment of the steric sea level anomalies from the density profiles is based on the integral method, also followed by previous studies and described in detail by Tomczak and Godfrey (1994). The steric height η_{st} is a measure of the vertical thickness by which a water column expands or contracts when its specific volume changes. Steric height and ocean density are related by:

$$\begin{aligned}\eta_{st}(\lambda,\phi,z_1,z_2,t) &= \int_{z_1}^{z_2}\left(\frac{1}{\rho(\lambda,\phi,z,t)}-\frac{1}{\rho_0(z)}\right)\rho_0(z)\ \mathrm{d}z \\ &\approx -\int_{z_1}^{z_2}\frac{\rho(\lambda,\phi,z,t)-\rho_0(z)}{\rho_0(z)}\ \mathrm{d}z\end{aligned} \tag{1}$$

for $\frac{|\rho(\lambda,\phi,z,t)-\rho_0(z)|}{\rho_0(z)} \ll 1$ (Jayne *et al.*, 2003; Lombard *et al.*, 2005). Here $\rho_0(z)$ is a constant standard reference density (usually at temperature T_0 = 0° C and salinity S_0=35) and $\rho(\lambda, \phi, z, t)$ is the density as a function of geographical position, depth and time. The limits of the integration, z_1 and z_2, are the depths of two pressure levels P_1 and P_2 with $z_1=z(P_1)$ and $z_2=z(P_2)$ respectively.

Following Jayne *et al.* (2003), a time-variable fraction η'_{st} can be separated from the mean steric sea level change over the entire time span $\overline{\eta}_{st}$ by

$$\begin{aligned}\eta'_{st} = \eta_{st}-\overline{\eta}_{st} &= -\int_{z_1}^{z_2}\frac{\rho(\lambda,\phi,z,t)-\rho_0(z)}{\rho_0(z)}\ \mathrm{d}z + \int_{z_1}^{z_2}\frac{\overline{\rho}(\lambda,\phi,z)-\rho_0(z)}{\rho_0(z)}\ \mathrm{d}z \\ &= -\int_{z_1}^{z_2}\frac{\rho(\lambda,\phi,z,t)-\overline{\rho}(\lambda,\phi,z)}{\rho_0(z)}\ \mathrm{d}z\ .\end{aligned} \tag{2}$$

The mean density $\overline{\rho}(\lambda, \phi, z)$ is obtained by averaging the observations at all pressure levels for every grid square. The separate assessment of the thermosteric and the halosteric contribution to the total steric SLA is not possible without approximation. Since the equation of state is non-linear, terms that are solely dependent on temperature or on salinity cannot be isolated.

In a previous study, Ivchenko *et al.* (2007) used climatological data from the World Ocean Atlas (WOA) 2001 (Boyer *et al.*, 2002; Stephens *et al.*, 2002) in order to separate the thermosteric and the halosteric effects: for the estimation of the thermosteric contribution to the total steric SLA, the annually averaged salinity values from the WOA climatology were introduced into the equation of state; vice versa, the temperature field was taken from the climatology when the halosteric contribution was computed. In our study, we used, exclusively, the Argo profiles within the five year time window: depending on the case, one of the two variables temperature or salinity is varied only in depth but is kept constant in time (i.e., each pressure level corresponds to a time-averaged salinity or temperature value respectively). It has to be emphasized, that both procedures for the computation of the thermosteric and halosteric contribution mean approximations of the non-linear equation. Therefore, even in theory, the sum of both contributions cannot be expected to equal the total steric SLA from Argo. However, as will be shown below, the approximation is quite accurate.

3.3. Space and time interpolation

Our region of interest is divided into a grid of 1°×1° as stated above. By means of inverse distance weighting, a value for the steric sea level change is computed for every grid point.

Since the Argo floats take the measurements at different points in time, and since the observed profiles are unevenly distributed over the area, two parameters have to be set: first, a time window has to be defined that determines for how long a measurement shall be representative or, in other words, for how long measurements can be related to each other in the course of the interpolation procedure. Second, a distance up to which measurements shall influence the interpolation for a certain grid point has to be defined.

Since our study is performed in a comparably narrow latitudinal zone, we choose a constant distance for the delimitation of observations surrounding a grid cell (on a grid that spans longitudinal, a variable distance might be advised). The distance is empirically set at 300 km which means a compromise between sufficient data coverage and spatial representativeness of individual point measurements. More critical, however, is the choice of the time window: while in the case of altimeter satellites, like e.g., Jason-1, the data are already divided in time by the half-cycles of the satellite, the Argo floats are independent one from the other and the tracks are not repeated. Here the compromise between a sufficient number of measurements on the one hand and the requirement that measurements should be as close in time as possible on the other hand leads us to the choice of 10 days which corresponds to two cycles of a float.

For the interpolation of the steric sea level anomaly at each point of the grid the following equation is applied:

$$\eta'_{st}(\lambda,\phi,t)=\frac{\dfrac{\eta'_{st}(\lambda_1,\phi_1,t_1)}{R_1}+\dfrac{\eta'_{st}(\lambda_2,\phi_2,t_2)}{R_2}+\ldots+\dfrac{\eta'_{st}(\lambda_N,\phi_N,t_N)}{R_N}}{\dfrac{1}{R_1}+\dfrac{1}{R_2}+\ldots+\dfrac{1}{R_N}} \tag{3}$$

where the coordinates (λ_i, ϕ_i, t_i) (i=1, ..., N) are the reported positions of all available observations of η'_{st} collected within 10 days around t at distances $0<R_i<300$ km between the location of the observation and the grid point (λ, ϕ) for which the steric height change is interpolated.

Given the amount of measurements available, we set the temporal resolution of our steric estimates to one month. This means that an eventual annual periodic variation should be clearly visible. Monthly values are computed as an average of all measurements obtained within the respective month inside a grid cell. Nevertheless, some gaps remain in the time series of individual cells. For each grid cell the annual variability of the SLA is computed by estimating the amplitudes of its sine and cosine components with frequency 1/365.25 days via least-squares adjustment. In addition, a linear trend of each grid cell's time series is determined. Presented uncertainties of the trend are calculated from the formal error of the linear fit. It should be kept

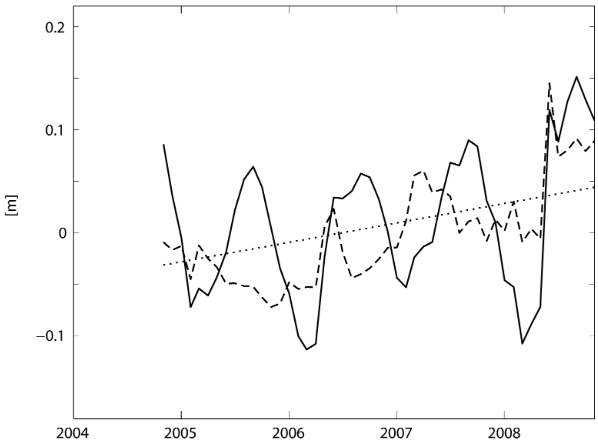

Fig. 2 - Steric sea level change in the Ionian Sea between 2004 and the end of 2008 (solid: total steric effect; dashed: after reduction of annual component). Linear trend (dotted): 17.9 ± 2.6 mm/year.

in mind that formal errors must be viewed as lower error bounds. For rescaling formal errors into realistic errors of sea level trends several widely unknown effects (e.g., systematic measurement and model errors) need to be assessed (Ablain *et al*., 2009).

Inverse distance weighting and time interpolation have also been applied in order to grid the trend of the total sea level change from Jason-1 in the central-eastern Mediterranean Sea [for details on the Jason-1 mission see, e.g., Ménard *et al*. (2003)]. This way, the altimetrically observed sea level change, that represents the sum of steric and eustatic sea level effects, can later be used for comparisons with the steric sea level change from Argo. According to the parameters of our space interpolation procedure all points within a radius of 300 km that belong to the same half-cycle of the satellite track are considered by the weighting function.

At the time our study was performed, Jason-1 data after January 2008 had not yet been cross-calibrated. Therefore the year 2008 is not considered for the computation of the sea level trend. Jason-1 data applied in this study has been processed at DGFI (Deutsches Geodätisches Forschungsinstitut), Munich, Germany, according to the GDR-B standard corrections. Instead of the inverted barometer correction the dynamic atmospheric corrections as produced by CLS Space Oceanography Division using the Mog2D model from Legos (see http://www.legos.obs-mip.fr for details) and distributed by Aviso with support from CNES was used. The radial error component was corrected by means of multi-mission-crossover analysis (Bosch and Savcenko, 2007), and ocean and loading tides were corrected by means of EOT08 ocean tide model (Savcenko and Bosch, 2008).

4. Results

4.1. Ionian Sea

The steric sea level change in the Ionian Sea is characterised by strong annual variations (amplitude: 5.9 cm) and a positive trend of 17.9 ± 2.6 mm/year between 2004 and the end of 2008 as shown in Fig. 2.

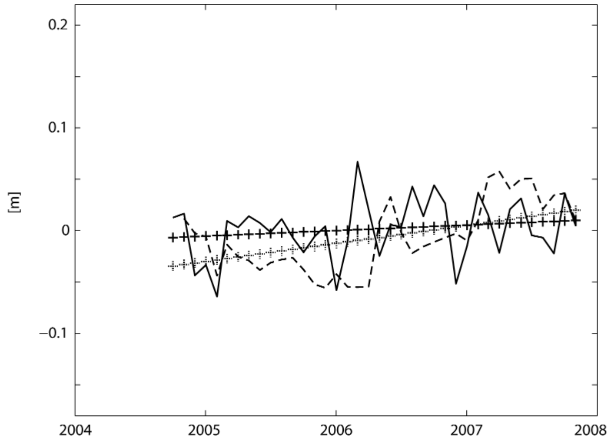

Fig. 3 - Total steric (solid), thermosteric (dashed) and halosteric (dotted) contributions to sea level change in the Ionian Sea between 2004 and the end of 2008.

Splitting the total steric signal into thermosteric and halosteric components (Fig. 3) reveals the clear dominance of the thermosteric effect. The volume change due to temperature fluctuations features primarily a strong annual cycle. On the contrary, the halosteric effect is comparatively small and characterised by mainly inter-annual variations. In mid-2008 conspicuous opposite directed spikes are present in the thermosteric and the halosteric time series as well as in the sum of both (see Fig. 2). Since the spikes are only present for a single month (June 2008) after which the time series return to a normal level, it can be assumed that this feature is due to erroneous real time Argo data and should not be interpreted.

Fig. 4 compares the steric SLA from Argo with the total SLA from Jason-1 for the same region within the time span between 2004 and the end of 2007 (see above). Annual components are removed from both series. With 7.3 cm the annual amplitude of the total SLA is somewhat larger than the annual amplitude of the steric SLA (5.9 cm). In both cases the trends are positive, but

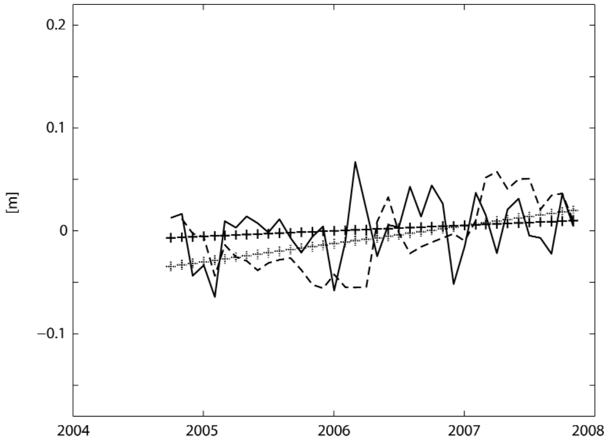

Fig. 4 - Steric sea level change from Argo (dashed, linear trend: 15.5 ± 2.6 mm/year) and total sea level change from Jason-1 (solid, linear trend: 11.0 ± 1.6 mm/year) in the Ionian Sea for the period 2004-2007. Annual components have been removed.

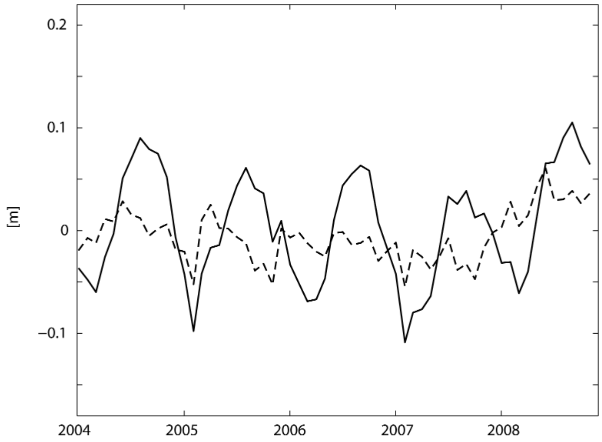

Fig. 5 - Steric sea level change in the Levantine Sea between 2004 and the end of 2008 (solid: total steric effect; dashed: after reduction of annual component).

the rate of the steric sea level change from Argo is larger (15.5 ± 2.6 mm/year) than that of the total sea level from Jason-1 (11.0 ± 1.6 mm/year) during that period. This difference suggests a slight decrease of water mass, i.e., a negative eustatic effect on the sea level. But, of course, it should be emphasized that trends computed over such a short period must be interpreted with caution. The altimetrically determined curve features stronger oscillations, which lets us conclude that the steric sea level variations contain less short-period oscillations.

4.2. Levantine Sea

In contrast to the Ionian Sea, the steric sea level change in the Levantine Sea does not show a clear trend between 2004 and the end of 2008. The amplitude of the annual signal decreases during the first four years of the analysis, and the signal features a negative tendency during this time. Between mid-2007 and the beginning of 2008 the signal increases strongly and the steric contribution to the Levantine sea level reaches its maximum towards the end of the analysed period (Fig. 5). A trend is not computed here since it would be clearly dominated by the large values in the last year of the analysis.

Like above, the thermosteric contribution is also dominant in the Levantine Sea (Fig. 6). This component features a clear annual signal that resembles the total steric sea level variation very well. The halosteric variations are much smaller and show a negative tendency. Like in the time series of Fig. 3 a clear spike is present in the time series of the halosteric fraction (April 2005). Again it is assumed that this peak is due to erroneous real-time Argo registrations. A strong increase of the thermosteric contribution in the year 2008 is accompanied by an opposite effect of the halosteric component. In order to understand if the increased thermal expansion after 2008 can be explained by exceptional air temperatures in the region, time series of surface temperature from the atmospheric reanalysis products of the National Centers of Environmental Prediction/National Center of Atmospheric Research (NCEP/NCAR) (Kalnay *et al*., 1996) are analyzed between 2004 and 2009. However, no obvious temperature anomalies are present in the atmosphere data around 2008. Therefore the reason for the increase of the thermal expansion towards the end of the time series remains unclear. Since we deal with real-time Argo data, the

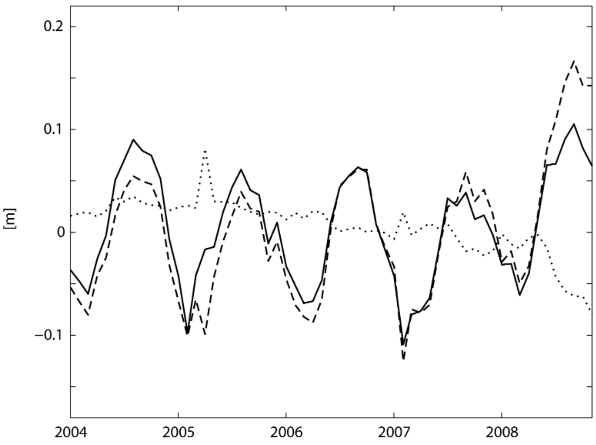

Fig. 6 - Total steric (solid), thermosteric (dashed) and halosteric (dotted) contributions to sea level change in the Levantine Sea between 2004 and the end of 2008.

signature might also be an artefact caused by undiscovered errors in the Argo data.

After reduction of the annual components from the steric sea level change from Argo and the total sea level variation from Jason-1 (Fig. 7) both curves are very similar. Like in the case of the Ionian Sea the amplitude of the annual signal of the steric SLA (5.2 cm) is somewhat smaller than the annual signal of the total SLA (6.6 cm). The residual time series feature comparable signal characteristics and a very similar negative trend (-3.8 ± 0.5 and -4.2 ± 0.6 mm/year, respectively) between 2004 and 2007 that can almost fully be explained by the halosteric contribution (see Fig. 6). Hence we conclude that the mass effect is even less pronounced here than in the Ionian Sea.

4.3. Central-eastern Mediterranean Sea

In the following, we present the steric sea level change in the central-eastern Mediterranean Sea in the form of maps of the entire study area on a 1°×1° grid. Considering the interpolation procedure discussed in Section 3.3, the analysis of the Argo observations for each individual

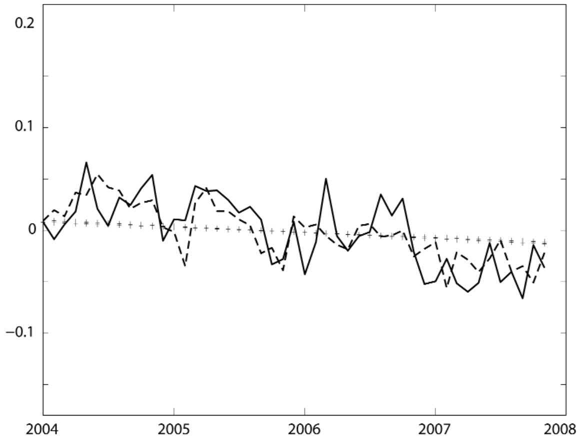

Fig. 7 - Steric sea level change from Argo (dashed, linear trend: -3.8 ± 0.5 mm/year) and total sea level change from Jason-1 (solid, linear trend: -4.2 ± 0.6 mm/year) in the Levantine Sea for the period 2004-2007. Annual components have been removed.

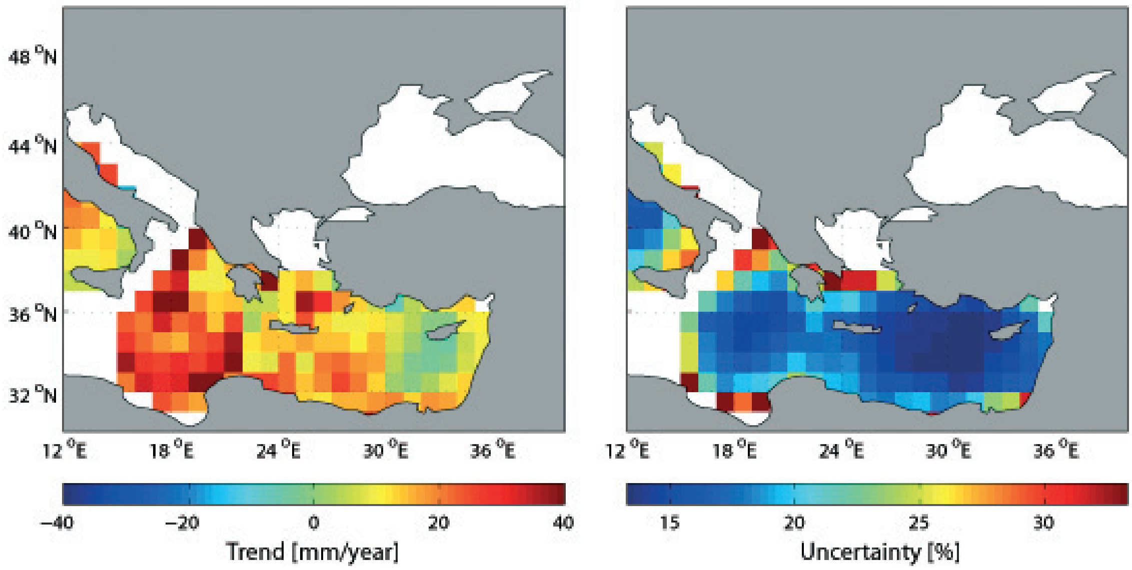

Fig. 8 - Left: steric sea level trend in mm/year in the central-eastern Mediterranean Sea from Argo observations (2004-2008) on a 1°×1° grid. Right: uncertainties of the trend in percent of the absolute value.

1°×1° grid cell results in the rates displayed in Fig. 8 (left) between 2004 and the end of 2008.

In almost all grid cells the rate of the steric sea level change is positive. However, there are significant regional discrepancies: very high rates over 25 mm/year are concentrated in the Ionian Sea, while the trends tend to get lower in an eastward direction and become even slightly negative in the region south of Cyprus. The right panel of Fig. 8 shows the uncertainties of the values in percent of the absolute value, calculated from the formal errors of the least-squares adjustment. Due to the higher number of valid measurements, results for the Levantine Sea are more precise than for the Ionian Sea (see Fig. 1).

Fig. 9 separates the contributions of thermal and salinity-related expansion and contraction. The rates of thermosteric sea level change are positive over the entire area. Reversely, the halosteric sea level trend is negative in most areas and thus attenuates the thermosteric sea level rise. The largest salinity-related sea level decline is observed in the eastern Mediterranean Sea.

A decreasing halosteric trend physically involves an increase of salinity. As the increase of salinity comes along with a high temperature-related expansion, rising temperatures and a related increase of evaporation are the likely hurriers of both effects. Fields of surface temperatures from NCEP/NCAR (see above) support this conclusion: air temperatures were generally higher in the east of our study area, featuring an increase of a few tenths of a degree between 2004 and the end of 2008.

Since the equation of state applied for the computation of the steric sea level change is non-linear, the separate computation of halosteric and thermosteric contribution is approximate (see Section 3). The validity of both fields is assessed by comparing their sum with the result of the joint computation of both effects. The difference between the total sea level change (Fig. 8; left) and the sum of thermosteric and halosteric sea level change (Fig. 9) is between -3 and 3 mm/year. Therefore the applied approximation using annually averaged values from climatology for the unconsidered

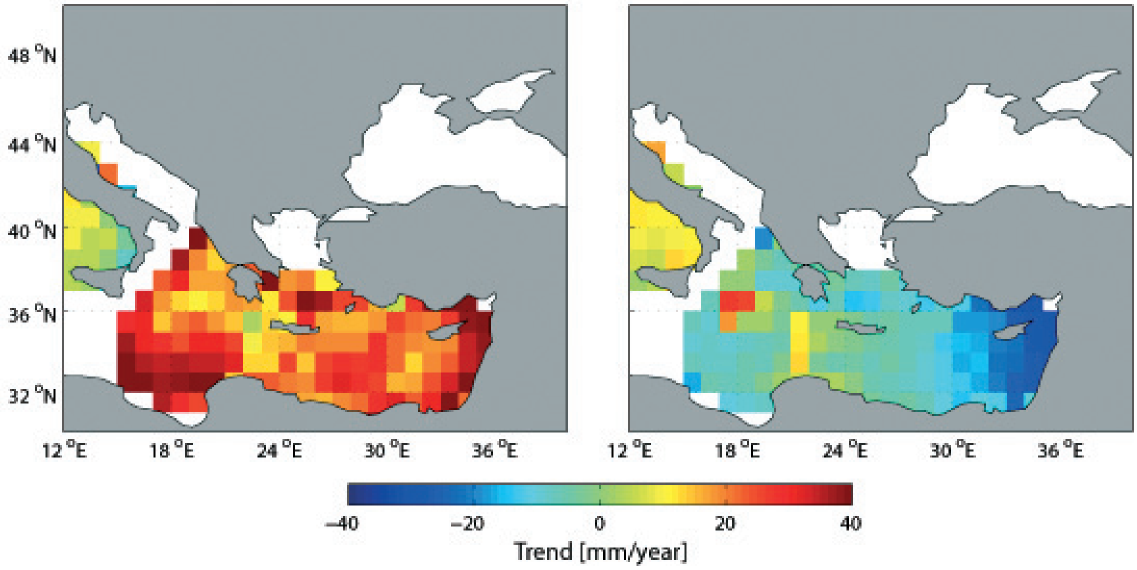

Fig. 9 - Thermosteric (left) and halosteric (right) sea level trend in mm/year in the central-eastern Mediterranean Sea from Argo observations (2004-2008) on a 1°×1° grid.

component turns out to be reasonable.

For validation, we compare our results with a global analysis of Argo observations performed by Cazenave *et al*. (2009). The general patterns of both studies match very well (Fig. 10). In principle, both investigations are based on the same Argo database; however, the analyses differ with respect to applied approaches and limits for spatial and temporal filtering. While Cazenave *et al*. (2009) considered globally distributed Argo profiles that reached down to a maximum depth of 900 m, our study in the Mediterranean Sea is limited to registering floats that reach down to a maximum depth of 400 m. Therefore slight differences of resulting steric sea level trends between the study of Cazenave *et al*. (2009) and our results may be due to the negligence of observations below 400 m as well as to differing analysis approaches. However, it can be assumed that the missing contributions are comparatively small. In a study on steric sea level variations in the Mediterranean Sea, Tsimplis and Rixen (2002) found that steric sea level variations are clearly dominated by temperature changes in the upper 400 m of the ocean. Fig. 11 separates the contributions of the depth layers between 0-200 m and between 200-400 m to the total steric effect: the first 200 m yield a clearly stronger contribution than the layer between 200 and 400 m, which also reflects the typical decay of the observed density profiles.

4.4. Comparison of the total sea level change from Jason-1 with the steric sea level change from Argo in the central-eastern Mediterranean Sea

The steric sea level trends for the central-eastern Mediterranean Sea from Argo observations described above are finally compared with corresponding total sea level trends from Jason-1. As above, the year 2008 is excluded in the Argo analysis due to the lack of cross-calibrated Jason-1 products. Fig. 12 shows a difference plot between the total sea level trend from Jason-1 and the steric

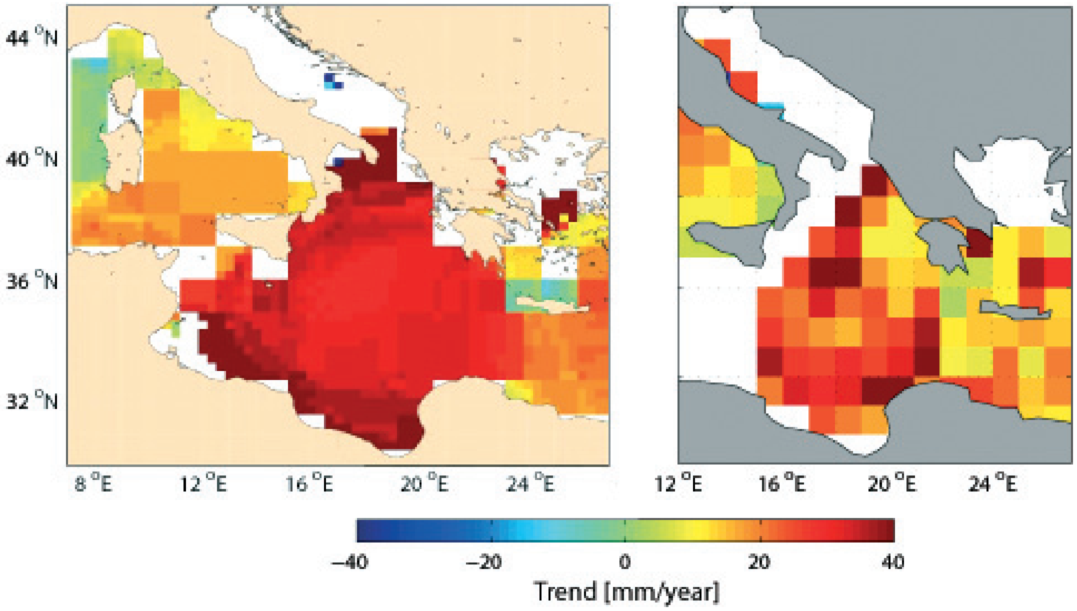

Fig. 10 - Comparison between the steric sea level trend in mm/year from Cazenave *et al*. (2009) (left; courtesy of S. Guinehut; private communication) and our study (right).

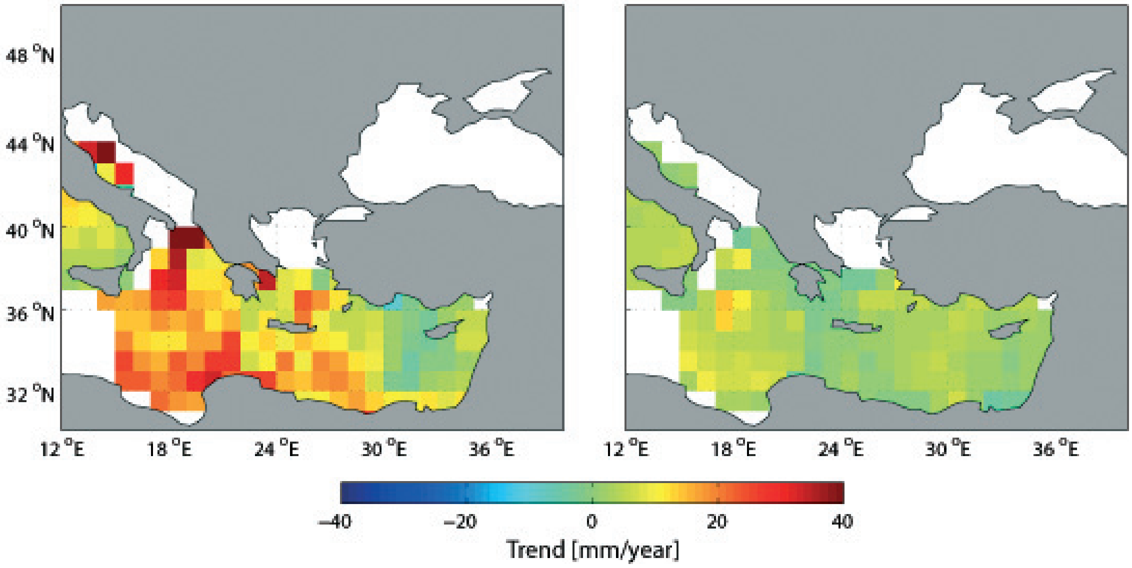

Fig. 11 - Steric sea level trend in mm/year: contributions of depth layers between 0-200 m (left) and 200-400 m (right).

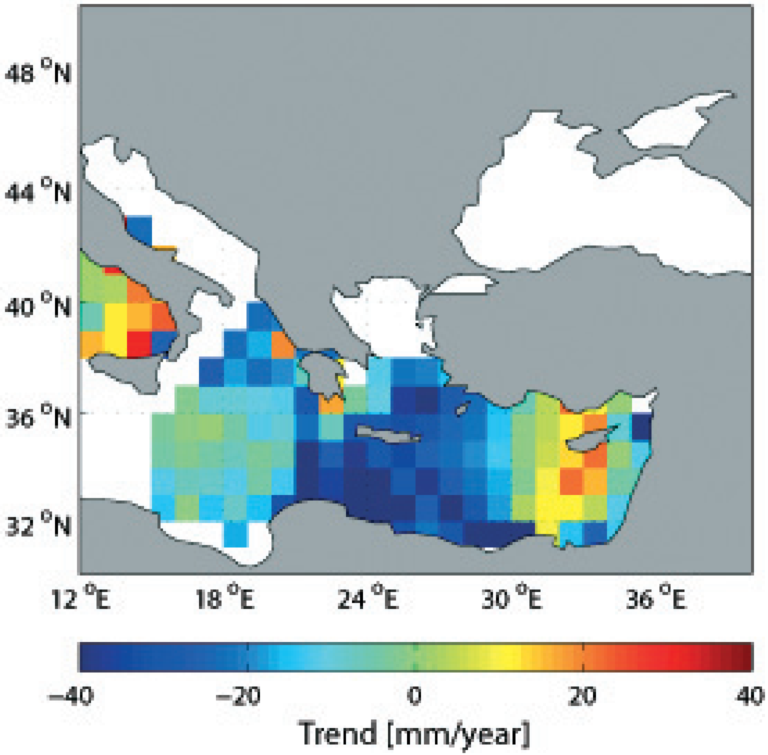

Fig. 12 - Difference between sea level trend from Jason-1 and steric sea level trend from Argo in the central-eastern Mediterranean Sea in mm/year (time window: 2004-2007; grid spacing: 1°).

sea level trend from Argo.

Maps of sea level trends from Jason-1 and steric sea level trends from Argo feature very similar patterns in the Ionian Sea and in the region west of Cyprus. For the Ionian Sea, the difference plot shows values around zero or marginally less which indicates a slight negative trend of a few mm/year for the mass component in this region (see Section 4.1). Over the entire geographical region of our previous analysis for the Levantine Sea (where the altimetrically observed negative sea level change between 2004 and 2007 is fully explained by steric compression; see Section 4.2) positive and negative mass signals cancel out. However, there are significant local differences, e.g., north and south of Cyprus (positive) and south of Crete (negative). Scarcely any change of the sea level was observed by altimetry in the latter region between 2004 and 2007. In contrast, a significant thermosteric sea level rise results from the Argo analyses south of Crete. Consequently a large negative signal exists in the difference plot in this region. The origin of this strong negative nonsteric sea level trend (larger than -20 mm/year) is hard to explain. Net water fluxes computed from atmospheric re-analysis products from NCEP/NCAR do not lead to the conclusion that significantly more water mass is lost here due to evaporation than in adjacent regions. This result, however, is in agreement with a recent study of Lombard *et al*. (2009) who compared regional patterns of net water fluxes with modelled ocean bottom pressure changes and found no evidence for a direct correlation. With respect to the Mediterranean Sea, Lombard *et al*. (2009) argue that a positive steric trend can be associated with a negative non-steric trend due to horizontal gradients that are induced by the steric effect and lead to a redistribution of water mass into adjacent areas.

5. Conclusions

At present, Argo floats are the most useful means for an in-situ analysis of the dynamics of the ocean and the analysis of steric contributions to sea level change at a comparatively high temporal and spatial resolution. By measuring vertical profiles of temperature and salinity, Argo also allows for the separation of the steric effect into a thermosteric and a halosteric fraction.

In our study, we analysed steric sea level changes in the central and eastern Mediterranean Sea computed from observations of floats within the MedArgo network with respect to seasonal variations and trends of steric sea level variations between 2004 and 2008. The analyses revealed a significant volume expansion of sea water in the central Mediterranean Sea between 2004 and 2008, even though the time window of Argo observations is still very short, making it impossible to interpret the expansion as a normal inter-annual variability or as an anomalous and alarming tendency.

It was shown that the expansion is clearly dominated by an increase of the water temperature. However, a contemporaneous increase of salinity tends to counteract the thermosteric effect by a negative volume change that is especially strong in the eastern Mediterranean Sea. In this region, the positive thermal effect (around 25 mm/year) and the negative salinity-related effect (around -20 mm/year) almost cancel each other out (see Figs. 8 and 9). It is not surprising that the halosteric effect has a significant influence on the sea level in closed basins at mid-latitudes, like the Mediterranean Sea, due to strong evaporation. This effect might become even more important in the future due to a strong decline in rainfall (and consequently in fresh water influx) in the eastern Mediterranean Sea that has been observed over the last decades (Sarris *et al*., 2007).

The results for the steric sea level change were compared with the total sea level variations as observed by satellite altimetry between 2004 and 2007. While the observed sea level rise in the Ionian Sea can be explained very well by steric (mainly thermosteric) volume expansion, there is an exceptionally large discrepancy between Argo and altimetry in the region south of Crete suggesting a very strong loss of water mass at a rate of about -20 mm/year. Even though Lombard *et al*. (2009) provide a possible explanation for the concurrence of positive steric and negative non-steric trends (see above), an independent validation of the mass-related component would be desirable. At present, however, the current spatial resolution of satellite gravity field missions, like e.g., GRACE, is too coarse for an analysis of such small-scale patterns.

The study showed the potential of Argo measurements for regional analyses, but it also revealed existing problems. A relatively sparse coverage of valid measurements due the limited number of simultaneously operating floats makes it difficult to analyse the data on dense grids. In contrast to satellite altimetry that is characterised by a high coherency of measurements along individual tracks and repeated passes within a period of a few days, the data collected by Argo are available at irregular times and positions, limiting in turn its interpretability. Another big problem is the loss of data from deeper pressure levels, so that the contributions of temperature and salinity changes in the deep Mediterranean Sea (i.e., below 400 m) could not be assessed in this study. Consequently, the future prospect of research based on in-situ measurements depends largely on the continuation of the Argo mission, its extension and improvement with respect to coverage and the solution of the related data loss problems. Since the end of 2009, all floats deployed in the Mediterranean Sea are programmed to make deep profiles (2000 m) at every cycle. Furthermore MedArgo aims at deploying 10 to 15 additional floats on a yearly basis in areas deprived of observations. These measurements are important towards the strengthening of the Argo network. The availability of denser and longer observation time series in the future will surely allow for more comprehensive and conclusive analyses than the relatively sparse and short data set that was available for our study.

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