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On the mesoscale monitoring capability of Argo floats in the Mediterranean Sea

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Abstract. In this work a simplified observing system simulation experiment (OSSE) approach is used to investigate which Argo design sampling in the Mediterranean Sea would be necessary to properly capture the mesoscale dynamics in this basin. The monitoring of the mesoscale features is not an initial objective of the Argo network. However, it is an interesting question from the perspective of future network extensions in order to improve the ocean state estimates. The true field used to conduct the OSSEs is provided by a specific altimetry-gridded merged product for the Mediterranean Sea. Synthetic observations were obtained by sub-sampling this "Nature Run" according to different configurations of the ARGO network. The observation errors required to perform the OSSEs were obtained through the comparison of sea level anomalies (SLAs) from altimetry and dynamic height anomalies (DHAs) computed from the real in situ Argo network. This analysis also contributes to validate satellite SLAs with an increased confidence. The simulation experiments show that a configuration similar to the current Argo array in the Mediterranean (with a spatial resolution of $2° \times 2°$) is only able to recover the large-scale signals of the basin. Increasing the spatial resolution to nearly 75 km × 75 km, allows the capture of most of the mesoscale signal in the basin and to retrieve the SLA field with a RMSE of 3 cm for spatial scales larger than 150 km, similar to those presently captured by the altimetry. This would represent a theoretical reduction of 40 % of the actual RMSE. Such a high-resolution Argo array composed of around 450 floats, cycling every 10 days, is expected to increase the actual network cost by approximately a factor of 6.

1 Introduction

The Mediterranean Sea is a semi-enclosed basin connected with the Atlantic Ocean through the Strait of Gibraltar. It also communicates with the Black Sea through the Turkish Bosphorus and Dardanelles straits. The Sicily Strait, with a depth of around 300–400 m, divides the Mediterranean Sea in two sub-basins: the western basin is influenced by the Gibraltar inflow, while the eastern basin is driven by winds and wind-induced formation of Levantine Intermediate Water (LIW). The basin-scale circulation of the Mediterranean interacts with sub-basin scale and mesoscale processes, then forms a highly variable general circulation. As a result, the Mediterranean Sea is a particularly interesting area since most of the ocean processes that occur in the world ocean also occur in this basin. The Mediterranean can be considered as a reduced-scale ocean laboratory, where processes can be characterized with smaller scales than in other ocean regions (Malanotte-Rizzoli et al., 2014). The internal Rossby radius of deformation in the basin is O (10–15 km), which is four times smaller than typical values for much of the world ocean according to Robinson et al. (2001). This fact highlights that in the Mediterranean Sea the spatial resolution of the Lagrangian profiling floats of the Argo programme, which consists of a global network of more than 3000 operating floats (Roemmich and the Argo Steering Team, 2009; Riser et al., 2016) drifting with less than 3° mean spacing, should be reduced four times compared to the open ocean.

The Argo programme is a major component of the global ocean observing system and aims to monitor the changing temperature and salinity fields in the upper part of the ocean (Riser et al., 2016). The majority of the profiling floats used in Argo are programmed to drift at a nominal depth (known as the parking depth) of 1000 m (Riser et al., 2016). They collect temperature and salinity data every 10 days from the upper 2000 m of the world oceans in order to observe the slow evolution of the large-scale ocean structure.

Argo data complement satellite altimetry. The combination of in situ Argo data with sea surface height (SSH) anomalies derived from satellites allows us to construct time series of the dynamical state of the ocean circulation (Riser et al., 2016). Altimetry resolves the mesoscale thanks to fine spatio-temporal sampling. Nevertheless, even though SSH estimates are becoming more precise, the uncertainty associated with altimeter measurements and the geophysical altimeter corrections applied in the SSH computation remains relatively high (Ablain et al., 2009; Couhert et al., 2015; Legeais et al., 2014; Rudenko et al., 2014). For this reason, some external and independent measurements provided by in situ observations and numerical models are required to calibrate and validate the altimeter sea level anomaly (SLA) data. These comparisons allow us to obtain the altimetry errors relative to the external measurements and provide an improved picture of SSH that can be used for global and regional studies.

At present, Argo data are systematically used together with altimeter data to describe and forecast the 3-D ocean state, for ocean and climate research and for sea level rise studies (see e.g. Guinehut et al., 2012; Le Traon, 2013). This fact demonstrates the very strong and unique complementarities of the two observing systems (Le Traon, 2013).

The Argo network in the Mediterranean Sea presently consists of around 80 operating floats deployed in the frame of the MedArgo program (http://nettuno.ogs.trieste.it/sire/medargo/active/index.php). The specific semi-enclosed morphology with a large fraction of coastal areas, shallow bathymetry and circulation structures of the basin make profilers programmed with the Argo standard global parking depth of 1000 m inappropriate for this program (Poulain et al., 2007). This is why a parking depth of 350 m was chosen for the Mediterranean basin. The objective was to track the intermediate waters throughout the Mediterranean which are mostly composed by LIW. This water mass is formed during winter convection in the northern Levantine sub-basin, being a crucial component of the Mediterranean thermohaline "conveyor belt" circulation (Poulain et al., 2007). According to the small radius of deformation of the Mediterranean compared with the open ocean at the same latitude, the current number of operating floats in the basin (equivalent to an average spatial resolution of around 2°) is higher than the global coverage of the Argo network. Nonetheless, it is not enough to properly capture the significant mesoscale circulation features of the basin.

The aim of this paper is to investigate which Argo design sampling in the Mediterranean Sea is necessary to recover the mesoscale signal as seen by altimetry. The monitoring of the mesoscale structures is not an initial target of the Argo network (Riser et al., 2016). However, this is an interesting question in the perspective of future network extensions in order to improve ocean state estimates. Actually, the Argo Steering Team has recently provided a road map for how the Argo mission might expand in the near future (Riser et al., 2016). According to these authors, one of the proposed projects is to support an increase in the spatial sampling resolution in particular areas of the world ocean. The objective is the improvement of our view of the complex structure of oceanic variability at spatial scales lesser than the climate scale.

To accomplish the proposed aim, we conduct several observing system simulation experiments (OSSEs) in the basin. OSSEs provide a methodology to evaluate and design optimum sampling strategies in ocean observing systems (OOS) (Alvarez and Mourre, 2012). Usually, the method consists of considering the outputs of an ocean model simulation of the area monitored by the OOS as "truth". Virtual observations from different ocean observing platforms in the OOS are then simulated from the model run and analysed in the same manner as real data (e.g. Alvarez and Mourre, 2012). OSSEs have been used in oceanography to analyse the impact of different components of the global OOS for ocean analysis and forecasting (see, for example, Oke and Schiller, 2007; Guinehut et al., 2012; Alvarez and Mourre, 2012; Ninove et al., 2016; Oke et al., 2015a, b). Here a slightly different approach will be followed, with the "truth" being provided by a specific altimetry-gridded merged product for the Mediterranean Sea and not by an ocean model simulation. This approach is similar to the one followed by Pascual et al. (2009). These authors evaluated the quality of global real-time altimetric products by comparing them with independent in situ tide gauges and drifter data. Moreover, our procedure does not include the validation of the outcomes of the OSSEs against a reference observing system experiment (OSE) using real data (Hoffmann and Atlas, 2016). Thus, our approach can be qualified as a simplified OSSE. This study will assess the scales covered by altimetry which are larger than 100 km (Pujol and Larnicol, 2005). Notice that the scales mentioned in this paper allude to a definition based on the diameter of individual structures, usually referred to as "feature scales".

The paper is organised as follows: the datasets are described in Sect. 2. Section 3 details both the processing sequence developed to compare the altimeter data with Argo in situ measurements and the quantification of the differences between Argo and SLA. These differences are needed to conduct the OSSEs. Thus, a quality assessment of the performances of the altimeter product in the Mediterranean Sea is performed in the first part of this study. The method used here to evaluate the altimeter data is based on the comparison of SLAs from altimetry and dynamic height anomalies (DHAs) computed from the in situ Argo network. Section 4 is devoted to the experiments conducted to recover the SLA fields in the basin from the different configurations of the simulated Argo arrays. Finally, discussion and suggestions to the Argo community regarding future prospects of the in situ network in the Mediterranean Sea are given in Sect. 5.

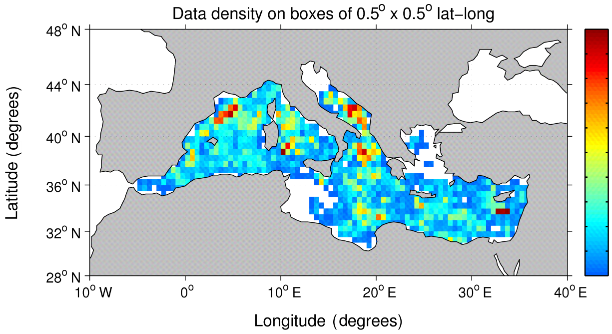

Figure 1. Number of Argo profiles on boxes of 0.5° × 0.5° of latitude–longitude, performed between 2003 and 2015 in the Mediterranean Sea and used to compute Argo DHs. Only profiles with a position quality flag of 1 (good data) have been considered.

2 Datasets

2.1 ARGO dataset

We use delayed mode quality-controlled temperature and salinity (T–S) profiles from 2003 to middle 2015 as obtained from the Coriolis Global Data Assembly Centre (http://www.coriolis.eu.org, ARGO GDAC global distribution database) in the Mediterranean Sea (Fig. 1). Dynamic height (DH) was computed at 5 m depth as an integration of the pressure, temperature and salinity vertical profiles through the water column, using a reference level at 400 and 900 dbar (close to 400 and 900 m, respectively). The choice of these reference levels is conditioned by the availability of the climatology used to compute DH anomalies. This issue will be addressed later. An additional quality control criterion relative to both the profile's position and the pressure, temperature and salinity measurements was applied: only profiles with a quality position flag of 1 (good data) were employed. Moreover, data exhibiting temperature and/or salinity flags different from 1 were removed before the DH computation. As a result of this additional quality check, 194 Argo floats and about 17000 T–S profiles distributed over almost the whole Mediterranean basin are available to compute DH. Their deployment's temporal evolution is shown in Fig. 2. More than 90 floats and almost 9000 profiles have been deployed in the last three years of the period investigated. They represent more than 50 % of the Mediterranean Argo network. Actually, the number of both floats and profiles has been systematically increasing from 2008 until 2015, reaching its maximum value in 2014 (36 floats deployed and nearly 4000 profiles carried out).

To calculate a consistent DHA with the altimeter SLAs, we use a mean DH as a reference computed through a synthetic climatology approach (Guinehut et al., 2006). The method to compute the synthetic climatology described in Guinehut et al. (2006) consists of the combination of altimeter SLA with simultaneous in situ DH in order to compute a mean DH, which is referred to the time period spanning from January 2003 to December 2011. This climatology presents a global coverage and it has been recently used by Legeais et al. (2016) to analyse global altimetry errors by using Argo and GRACE data. In this paper we will test the mean DH computed in the Mediterranean Sea at 400 and 900 dbar to estimate DHAs.

2.2 Altimeter measurements

Radar altimeters provide SSH measurements that are not directly comparable with in situ measurements. Therefore, they must be first referenced and corrected from geophysical signals in order to determine SLAs. In this work, we use SLAs obtained from the SSALTO/DUACS multi-mission (Saral, Cryosat-2, Jason-1, Jason-2, T/P, Envisat, GFO, ERS-1, ERS-2 and Geosat) specific reprocessed gridded merged product (level 4) for the Mediterranean Sea. This product is available in the Mean Sea Level Anomaly (MSLA) section of the Archiving, Validation and Interpretation of Satellite Oceanographic website (AVISO, http://www.aviso.altimetry.fr). It has been computed with respect to a 20-year mean referred to the period 1993–2012. A comprehensive description of SSALTO/DUACS is given in Pujol et al. (2013, 2016). The spatial resolution of the dataset is $1/8° \times 1/8°$ and the time period used in this work spans from January 1993 to December 2014. The quality of this product can be estimated among others by comparison with in situ Argo data. Notice that the availability of altimetry and Argo data does not match. Therefore, a common period spanning the period from January 2003 (beginning of the Argo dataset) to December 2014 (ending of the altimetric data analysed in this study) has been used in both datasets. Moreover, to perform this comparison, it is critical that altimetry and Argo data have the same interannual temporal reference (Legeais et al., 2016). We estimate DHAs from Argo data through a synthetic mean Argo DH referred to the time period between 2003 and 2011. Thus, the temporal reference of the altimeter SLA must be adapted to this time period. To do that, we subtract the mean of altimetric SSALTO/DUACS maps over 2003–2011 from the original SLA time series (Valladeau et al., 2012). On the other hand, the physical content captured by altimetry and Argo profiles is not precisely the same (Dhomps et al., 2011) because the barotropic and the deep steric (deeper than the reference level of the Argo DHA) contributions are missing from the Argo measurements. Therefore, the comparison of altimeter SLA and in situ Argo DHA is used to detect relative anomalies in altimeter data and not absolute bias (Valladeau et al., 2012). This comparison allows us to obtain a total error estimate including both the instrument and the representation errors which are needed to perform the OSSEs. Representation er-

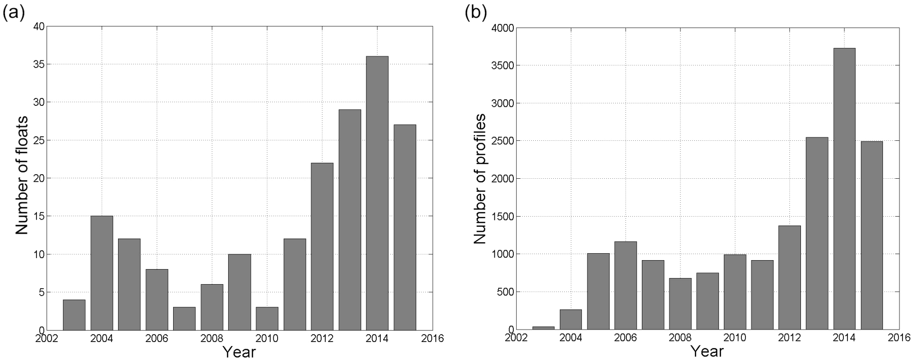

Figure 2. Temporal evolution of Argo floats **(a)** and Argo profiles **(b)** with a position quality flag of 1 deployed in the Mediterranean Sea since 2003 until the middle of 2015.

ror can be defined as the component of observation error due to unresolved scales and processes (Oke and Sakov, 2008).

3 Error estimates from comparison of Argo dynamic heights and altimetry sea level anomalies

This section focuses on the comparison of altimetry data with Argo DH in order to estimate the differences between Argo DHA and altimeter SLA needed to specify observation errors in our OSSEs. In addition, this analysis can contribute to the validation of satellite SLAs with an increased confidence. A sensitivity analysis of the method of comparison of both datasets is provided. This analysis mainly focuses on the impact of the reference depth selected in the computation of the Argo DH on the comparison with specific altimetric SLA gridded merged product for the Mediterranean Sea.

3.1 Method for comparing altimetry and in situ Argo data

The comparison method of altimetry with Argo data consists of co-locating both types of datasets since spatial and temporal sampling of altimetry and Argo data are different (Valladeau et al., 2012). Altimeter grids and synthetic climatologies were spatially and temporally interpolated at the position and time of each in situ Argo profile, which are considered as reference, by using a mapping method based on an optimal interpolation scheme. This considerably reduces errors due to different sampling characteristics of altimeter and in situ data. As mentioned before, the period investigated extends from January 2003 to December 2014. Then, statistical analyses are performed between both datasets. Co-located altimeter and Argo DH differences are analysed in terms of the standard deviation (SD) for the two reference levels used to compute DHAs from the Argo profiles (namely 400 and 900 dbar). In addition, the robustness of the results was investigated by computing means of a bootstrap method with 10^3 random samples taken from the original SLA–DHA series (see details of the method in Efron and Tibshirani, 1993). The studies conducted include the following: (i) the assessment of the method of comparison between altimetry and Argo data in the Mediterranean Sea; and (ii) the evaluation of the impact of the reference depth selected in the computation of the Argo DH.

3.2 Sensitivity to the reference depth for the integration of the Argo dynamic height

The integration of the Argo T–S profiles for the computation of the in situ DHs requires a reference level (pressure) where null horizontal velocities are assumed (Legeais et al., 2016). As a rule, the deeper the reference level, the more information from the T–S profiles is considered. This implies a deep sampling of the steric signal through the water column. However, a lower number of vertical profiles (those that reach the reference level) are used in the computation. On the contrary, shallower reference levels allow us to use more floats, although the vertical steric signal will be less sampled. Thus, we aim at determining the impacts of a given reference depth of integration on the Argo spatial sampling and on the comparison with altimeter data in the Mediterranean basin.

As mentioned before, the choice of a deep reference level for Argo DHAs provides a better estimation of the baroclinic signal. This is more in agreement with the observed signal by altimetry (Legeais et al., 2016). Therefore, we conduct the analysis on DH comparison computed from Argo data referred to the deeper available reference depth of 900 dbar (nearly 900 m) and the specific altimetry product for the Mediterranean Sea. Results are reported in Table 1. The number of T–S Argo profiles used to compute DH (those that reach at least 900 m depth) was 416, corresponding to 23 floats. The SD of the differences between DH from altimetry and Argo (SLA minus DHA) for the common period investigated (from January 2003 to December 2014) was 5.31 cm. It is equivalent to more than 95 % of SLA signal variance. The correlation between both datasets was 0.80.

In order to study the impact of the reference level, we repeated the analysis using the shallower reference level

Table 1. Comparison of correlation and standard deviation (cm) of the differences between the new AVISO product for the Mediterranean Sea and Argo data referred to both 400 and 900 dbar (sub-columns on the left). Sub-columns on the right display the results of the robustness experiments in terms of standard deviations (see text for details). DHA referred to 400 dbar has been computed for all valid Argo profiles and those reaching 900 m depth for comparison purposes. The number of Argo platforms and vertical profiles used are also shown.

	All valid profiles (DHA ref. 900 dbar)		Profiles reaching 900 m (DHA ref. 400 dbar)		All valid profiles (DHA ref. 400 dbar)	
Argo floats	23		24		41	
Argo profiles	416		479		2258	
SD (SLA–DHA, cm)	5.31	0.20	5.04	0.17	4.92	0.07
R (SLA–DHA)	0.80	0.02	0.82	0.02	0.76	0.01

of 400 dbar (almost 400 m) for the Argo anomalies but using the same array of Argo profiles reaching 900 m. Now, 24 floats and 479 profiles are available to compare with altimetry due to the synthetic climatology used to compute DHA referred to 900 dbar (see Table 1). Nonetheless, we kept the same number of floats and profiles than in the previous computation in order to make both results comparable. The SD of the differences between SLA and DHA referred to 400 dbar computed from profiles spanning until 900 m depth was 5.04 cm (see Table 1). It represents an improvement of nearly 10 % in terms of signal variance with respect to the SD difference computed from Argo DHA referred to 900 dbar (5.31 cm). Moreover, the correlation coefficient increased from 0.80 to 0.82. This is an unexpected outcome since the larger thickness of the water column integrated in the former should promote a lower value of SD. A possible explanation will be given in Sect. 5.

These results (also confirmed from the bootstrap analyses) show that in the Mediterranean basin, it will be advisable to compare SLA from altimetry with DHA from in situ Argo data referred to 400 dbar. Consequently, DHA referred to 400 dbar was recomputed but using all the available profiles reaching 400 m depth. Now, the number of T–S Argo profiles used to compute DH increased to 2258, thus corresponding to 41 Argo floats. Notice that this more comprehensive number of Argo profiles is almost 6 times larger than the profiles used to compute DHAs referred to 900 dbar. The SD of the differences of SLA–DHA was 4.92 cm while the correlation between both datasets decreased to 0.76. In the framework of our OSSE, this SD value can be considered as an error estimate of the Argo DHA with respect to altimeter SLA in the Mediterranean Sea for the time period investigated. Furthermore, this result represents an improvement of 14 % in terms of signal variance with respect to the one obtained from the differences between SLA and DHA referred to 900 dbar.

4 Impact of the number of Argo floats on the reconstructed SLA fields

In this section we aim to investigate which configuration in terms of spatial sampling of the Argo array in the Mediterranean Sea will properly reproduce the mesoscale dynamics in this basin, which is comprehensively captured by new standards of specific altimeter products for this region. To do that, several OSSEs have been conducted to simulate the Argo observing system in the Mediterranean, assuming altimetry data computed from specific reprocessed gridded merged product for the basin as the "true" field. As with most of the ocean OSSEs conducted to date, OSSEs performed here do not follow the comprehensive design criteria and validation methodology developed for the atmosphere (Halliwell Jr. et al., 2014). Rigorous OSSE procedure includes the validation against a corresponding OSE to guarantee the reliability of the outcomes of the OSSEs (Hoffmann and Atlas, 2016). As a consequence, our approach can be qualified as simplified OSSE. Further validation will be needed in the future implementation of a comprehensive OSSE system.

4.1 Experiments design

This section describes the different elements of the OSSEs conducted in the Mediterranean Sea. A flow chart of the methodology developed is provided in Fig. 3. The specific altimetry-gridded merged product for the Mediterranean Sea, described in Sect. 2.2, has been used as the nature run (NR) component of the OSSEs. Namely, we use daily SLA maps throughout 2014. The region considered covers the entire Mediterranean basin. The original altimetry dataset has a spatial resolution of $1/8° \times 1/8°$ and presents 17 283 grid points (see Table 2). We obtain synthetic observations from the nature fields by sub-sampling the NR with the different spatial resolutions displayed in Table 2. The aim is to reproduce some possible configurations of the Argo array network in the Mediterranean Sea. The stations (grid points) associated with each sub-sampled field (figures not shown) will simulate the positions of the Argo floats over a regular grid.

In addition, the synthetic observations (re-gridded daily SLA maps) were perturbed, simulating realistic observation

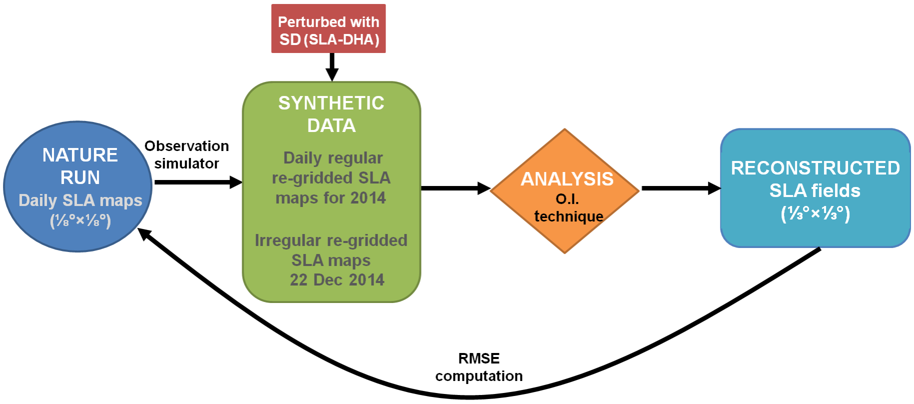

Figure 3. Flow chart showing the elements of the OSSEs conducted for the Mediterranean Sea. Datasets used in each component are also indicated.

Table 2. Spatial resolution (degrees) and associated number of stations of the different sub-sampled fields used to reconstruct the SLA in the Mediterranean. The lower row displays the spatial resolution and stations of the original altimetry maps. The filtering scale (km) used to compute the recovered SLA fields in the different reconstructions have been also included.

Spatial resolution (degrees)	Number of stations	Filtering scale (km)
2° × 2°	69	445
1.5° × 1.5°	121	333
1° × 1°	273	225
0.75° × 0.75°	482	167
0.5° × 0.5°	1082	111
0.4° × 0.4°	1458	95
0.3° × 0.3°	1915	82
0.125° × 0.125°	17 283	–

errors. The differences between altimeter SLA and real Argo DHA directly provide the observation errors in our particular OSSE experiment where Argo DHAs are the observations and altimeter SLA is the true field.

A random noise generated from a normal distribution function, representing the errors characterized in Sect. 3 but limited to the year 2014, is added to the values of the synthetic observations. The SD difference for the year 2014 is 4.79 cm. Seven experiments were conducted to reconstruct the 2-D SLA fields (sub-sampled daily SLA fields) in the Mediterranean throughout 2014 with a spatial resolution of $1/3° \times 1/3°$ by applying the optimal interpolation (OI) technique. The parameters used for the computation of the reconstructed fields were the following: (i) the first guess used to obtain the statistically null-mean residuals was computed by fitting a polynomial of degree 1. This first guess will be subsequently added after the computation to recover the total daily field; (ii) the filtering scale was set to be twice the spatial distance between stations (according to the box size used in each experiment). Table 2 summarises the filtering scale used to compute the recovered SLA fields in the different reconstructions; (iii) the spatial scale of correlation between stations was determined from a Gaussian correlation curve computed as follows:

$$W = e^{\frac{-d^2}{2\cdot S^2}}, \qquad (1)$$

where d is the mean distance between stations and S the spatial scale of correlation. In order to determine the more suitable spatial scale of correlation for the Mediterranean basin, we computed the correlation curve W for spatial scales varying from 15 to 50 km. The mean distance between stations ranged between 0 and 100 km. Then we compared these correlation curves with the one obtained for altimetric data computed for the same distances between stations as follows:

$$\mathrm{COR}(x) = \left[1 + ar + \frac{1}{6}(ar)^2 - \frac{1}{6}(ar)^3\right] e^{-ar}, \qquad (2)$$

where $r = x/L$, $a = 3.337$, x is the spatial coordinate of the studied point, and L is the zonal correlation scale (km) of the Mediterranean basin (100 km). The reader is referred to Pujol and Larnicol (2005) for a more detailed description of this computation. Figure 4 shows the correlation curve computed for the altimetric data from Eq. (2) and the best-fitting curve obtained from Eq. (1), which corresponds to a spatial correlation scale of 40 km. Therefore, the S parameter was set to 40 km in all the experiments. (iv) The last parameter to include in the experiments is the noise-to-signal variance ratio (γ), defined as the ratio between the Argo error and the altimetry variance. The former can be established as the variance of the differences between SLA and DHA in the Mediterranean. This parameter is estimated from the SD of SLA–DHA differences (4.79 cm) computed for 2014. As a result, we obtain $\gamma = 0.85$ as the true value for the datasets used here (see further details about this parameter in Gomis et al., 2001).

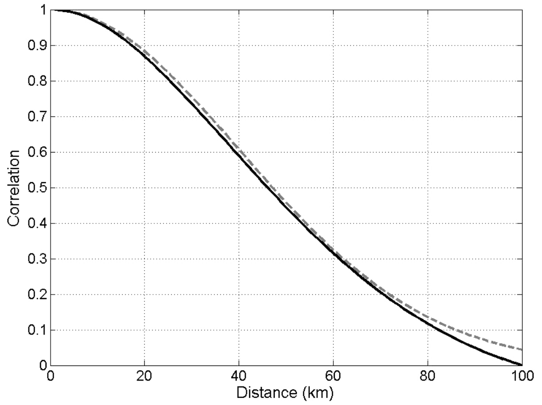

Figure 4. Correlation curve computed for altimetric data (black solid line) for a typical zonal scale of correlation for the Mediterranean region of 100 km. The grey dashed line shows the best-fitting correlation curve obtained for the reconstruction experiments. It corresponds to a spatial scale of correlation of 40 km.

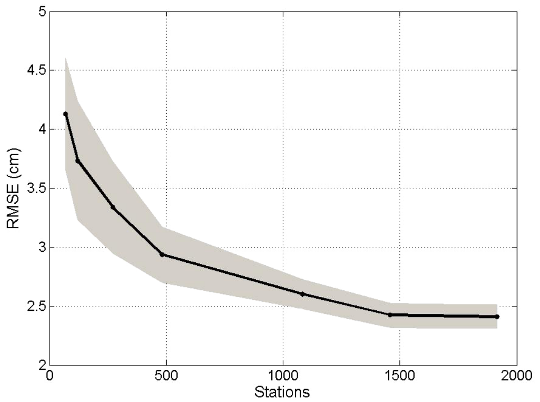

Figure 5. Root mean square errors (cm) associated with the altimetry maps recovered throughout 2014 from the different regular sub-sampled fields mentioned in the text. The black line represents the yearly mean value and the grey patch stands for the annual variability.

Finally, the retrieved daily SLA maps for 2014 were compared to the NR (also interpolated to a spatial resolution of 1/3° × 1/3°) in order to compute the RMSEs associated with the recovered maps from the sub-sampled fields. This procedure will let us establish the spatial resolution that better captures the mesoscale dynamics in the Mediterranean with a feasible number of stations simulating the locations of Argo floats.

4.2 Impact of the grid box size on analysed SLA fields

In this section we will discuss the impact of the spatial resolution of the synthetic observations (sub-sampled SLA fields) on the retrieval of mesoscale signals in the Mediterranean basin. As a previous step, the RMSE obtained for the seven experiments will be analysed. The 2014 yearly mean values of the RMSE associated with the altimetry maps recovered from the different sub-sampled fields and their annual variability are displayed in Fig. 5. Maximum mean RMSEs larger than 4 cm (equivalent to 79 % of SLA signal variance) are obtained for the maps recovered from the sub-sampled field reproducing the current spatial resolution of the Argo array in the Mediterranean (2° × 2°). Therefore, this spatial configuration only retrieves 21 % of SLA signal variance due to a poorer capture of the mesoscale features. These maps also exhibit the larger annual variability. This is an expected result that can be explained by both the challenge of reconstructing the same scale signals with only 69 stations (grid points) and the larger filtering scale (around 450 km) used in the experiment (see Table 2). The mean RMSE of the recovered maps exponentially decays as the box size of the sub-sampled altimetry fields diminishes and therefore, the number of stations enhances. As a result, the mean RMSE reaches an asymptotic value of 2.4 cm (equivalent to 28.7 % of SLA signal variance) for the SLA maps retrieved from the sub-sampled fields with a box size of 0.4° × 0.4°. This configuration is equivalent to 1458 stations and captures 71.3 % of SLA signal variance. The SD of the RMSE follows the same pattern, exhibiting a minimum annual variability for this spatial resolution.

Figure 6 shows an example of the altimetry maps recovered from the sub-sampled SLA fields on 22 December 2014. The original SLA field for that day, interpolated to a spatial resolution of 1/3° × 1/3°, is displayed in the uppermost panel for comparison purposes. Notice that the coarse spatial resolution of the 2° × 2° sub-sampled grid (upper-left panel in Fig. 6) prevents us from retrieving the mesoscale features observed in the original map, and only the large-scale signals are properly captured. As a consequence, the RMSE associated with this reconstruction, which simulates the present Argo array in the Mediterranean, is around 4.6 cm. On the contrary, the sub-sampled grids with box sizes of 0.4° × 0.4° and lower (map not shown) are able to retrieve most of the mesoscale structures of the basin with a RMSE of around 2.6 cm. Nonetheless, the high number of stations required to reconstruct the SLA maps (respectively 1458 and 1915, see Table 2) makes this option unviable. Therefore, it is imperative to reach a compromise between the stations used and the extent of the reconstruction performed. In this case, a reasonable solution would be to reconstruct the SLA field from a sub-sampled grid with a box size of 0.75° × 0.75°. This spatial resolution agrees with the theoretical one for the Argo array in the Mediterranean extracted from the internal Rossby radius of deformation computed for the Mediterranean basin. Also, it allows us to retrieve the most representative mesoscale patterns of the basin, for spatial scales larger than 150 km, with a feasible number of Argo floats (450 stations). Moreover, the spatial scales resolved by this configuration simulate the spatial scales captured by the altimetry.

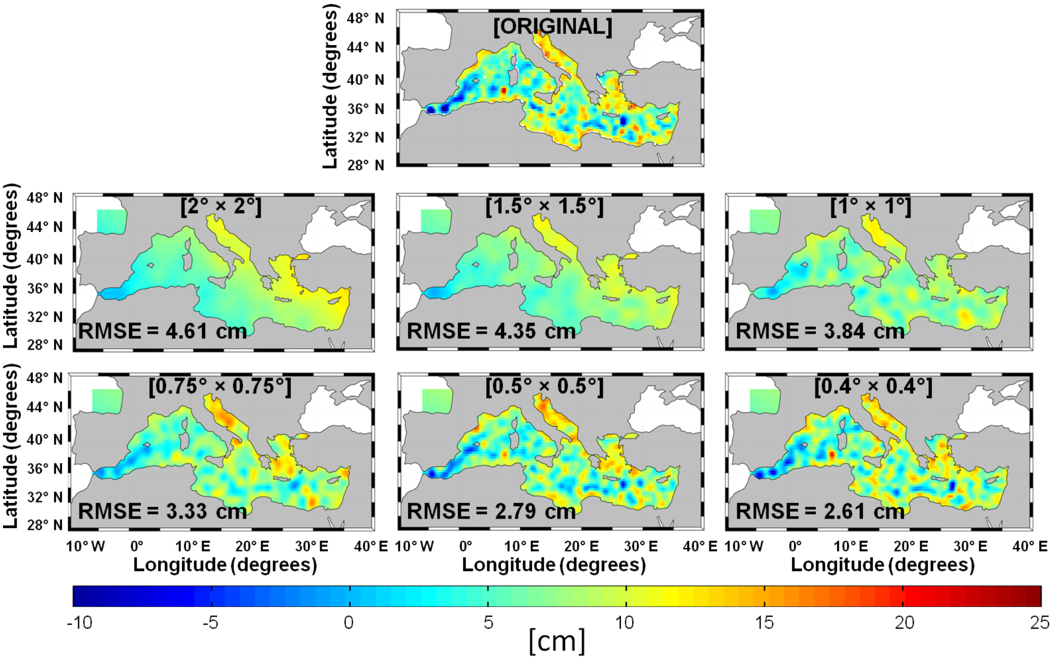

Figure 6. Altimetry maps recovered from the different sub-sampled SLA fields (cm) on 22 December 2014. The spatial resolution of the different regular grids and the RMSEs associated with each reconstruction for that day are also indicated. Moreover, the original SLA field of that day, interpolated to a spatial resolution of $1/3° \times 1/3°$, is displayed in the uppermost panel for comparison purposes.

4.3 Sensitivity to the irregular sampling

The experiments conducted above let us recover SLA maps computed from theoretical regular-gridded configurations of the Argo array in the Mediterranean. In this section we aim at retrieving altimetry maps from a realistic configuration of the Argo network by using the actual uneven positions of the Argo floats in the basin. Figure 7a displays the real positions of the 58 Argo floats operating in the Mediterranean Sea on 22 December 2014. SLA at each single Argo float position was extracted from the original altimetry map of that day (figure not shown). Then, the SLA field for the whole basin was retrieved by following the procedure applied to the regular-gridded sub-sampled fields.

On the other hand, and since the mean number of Argo floats in the Mediterranean is set to around 80, random virtual floats were added to the actual Argo array of that day. The aim was to reach the mean number of platforms normally operating on the basin. The virtual floats were added by using a normal distribution function computed from the mean and SD of the positions of the Argo Array in the Mediterranean. Then, the SLA data was obtained at the locations of both the actual and virtual floats (see Fig. 7b). We kept on adding random virtual floats until an Argo array of 150, 250 and 450 stations was reached. Their locations and the corresponding SLA data extracted at each position are respectively displayed in Fig. 7c–e. The SLA field for the whole basin was then recovered for each configuration of the Argo array according to the procedure described above. Reconstructed SLA fields were compared with the original altimetry map of that day. Figure 8 summarises the results obtained from both the uneven and regular-gridded experiments conducted on 22 December 2014. The errors associated with the SLA maps recovered from the different configurations of the Argo array (grey triangles) present a maximum RMSE of nearly 5 cm when only the 58 Argo floats operating that day are used to reconstruct the SLA field. As expected, RMSEs decay as the number of Argo floats increases (notice that here an Argo array configuration with 750 floats has been also included in order to have a better overview of their general pattern). This decrease follows the same pattern that the RMSEs obtained from the regular-gridded experiments (black line) although larger values are observed here. This fact is related to the uneven spatial distribution of the Argo platforms in the basin.

5 Discussion

The Argo network in the Mediterranean Sea presently consists of around 80 operating floats drifting with less than 2° mean spacing. Even though this array improves the global coverage of the Argo network, it only captures the large-scale circulation features of the basin. In this work, we have investigated which configuration in terms of the spatial sampling of the Argo array in the Mediterranean would be necessary to recover the mesoscale dynamics in the basin as seen by altimetry. The monitoring of the mesoscale features is not an

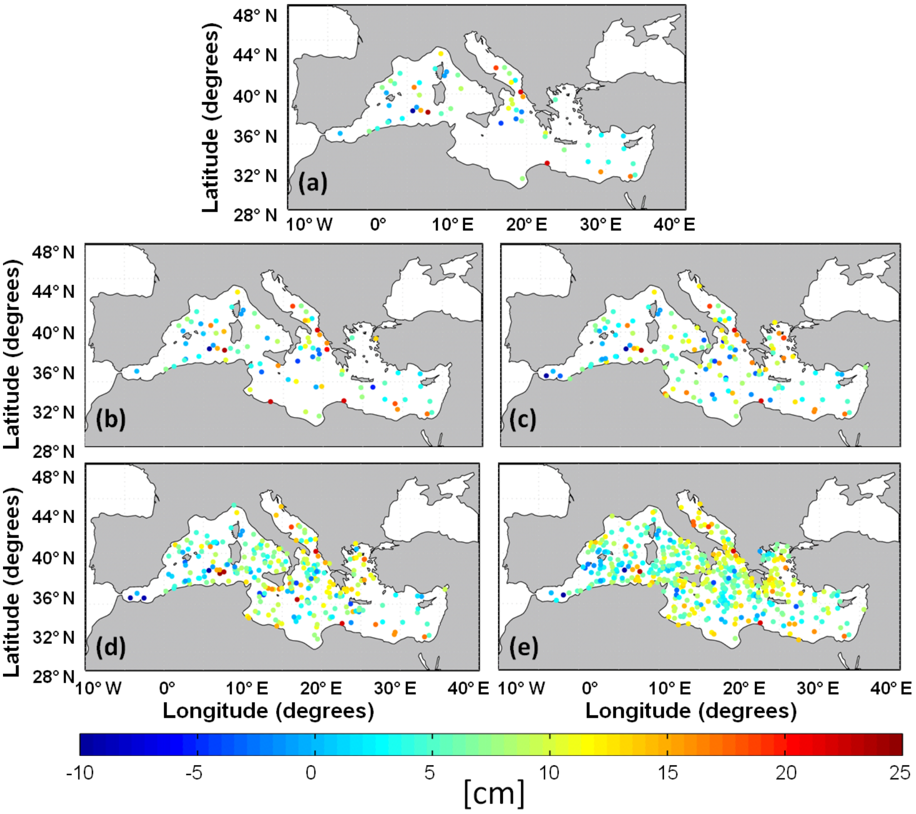

Figure 7. **(a)** Actual positions of the Argo array operating in the Mediterranean basin on 22 December 2014 (58 floats). Colours indicate the SLA (cm) extracted at those locations from the original altimetry map of that day. The panels **(b)**–**(e)** display the original Argo array enlarged with random virtual floats in order to simulate an Argo array configuration of 84, 150, 250 and 450 floats, respectively.

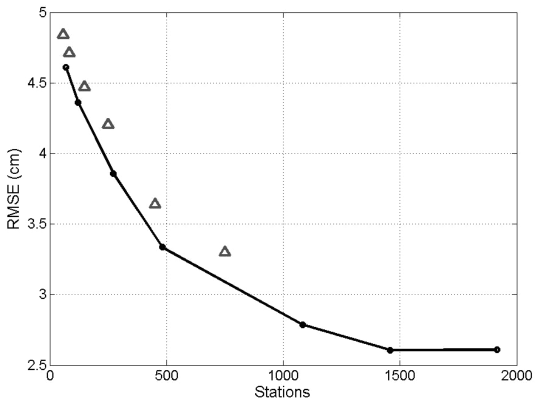

Figure 8. Root mean square errors (cm) associated with the altimetry maps recovered on 22 December 2014 from the different regular sub-sampled fields mentioned in the text (black line). Triangles stand for the errors associated with the SLA fields retrieved for that day from the different configurations of the Argo array in the Mediterranean Sea (see Fig. 6). Notice that an Argo array configuration with 750 floats has been also included for comparison purposes.

Argo program target. However, this issue is of concern since it can help the current ocean state estimates.

To do that, we have conducted several observing system simulated experiments (OSSEs) in the basin. We have followed a simplified OSSE approach by contrast to the comprehensive approach, including an equivalent observing system experiment. Consequently, our results represent a first look that could be further validated in the future with a comprehensive OSSE system. The true field, provided by gridded altimetry maps in this OSSE, was subsampled according to different configurations of the Argo network. The observation errors required to perform the OSSEs were obtained through the comparison of SLAs from altimetry and DHAs computed from the real in situ Argo network. The comparisons have been focused on the sensitivity to the reference level (400 or 900 dbar) used in the computation of the Argo DH. We found that the number of Argo profiles reaching 900 m used to compute DHA is almost 6 times smaller than those reaching 400 m. Therefore, the choice of the reference depth has repercussions in the number of valid Argo profiles and thus in their temporal sampling and the coverage of the Argo network used to compare with altimeter data. In addition, the computation of the differences between altimetry and Argo data referred to both 400 and 900 dbar revealed a SD of SLA–DHA differences 1.67 cm lower (in terms of variance) when computing DHA referred to 400 dbar. This fact, together with both a higher correlation coefficient between both datasets and the larger number of available profiles, suggests that it is preferable to consider the 400 dbar level as the reference level to compute DHA from Argo data in the Mediterranean basin. This leads to a SD of the differences between both datasets of 4.92 cm (equivalent to 90 % of SLA signal variance). Conversely, one would expect better results when using 900 dbar as a reference level because the physical content (variance) of a larger fraction of the water column is considered when computing Argo DH. However, the more comprehensive number of available Argo profiles when using 400 dbar as reference level, and thus the larger coverage of the Argo network, seem to play a more critical role in the comparisons with altimeter data in the Mediterranean basin than the deep sampling of the steric signal. On the other hand, the climatology used here to compute DHA could be not as accurate at 900 m due the lower number of historical data available at that depth, then resulting in larger SDs of the differences between both datasets. Nonetheless, the evaluation of this climatology is out of the scope of this paper and it will be addressed in further investigations.

Another interpretation of the results obtained here could be done in terms of the dynamics of the water masses residing in the Mediterranean Sea. Due to the excess of evaporation over precipitation and river run-off, an Atlantic inflow through the Strait of Gibraltar is required to balance the salt and freshwater budgets of the basin. As the Atlantic water spreads into the Mediterranean, it becomes saltier and denser under the influence of intense air–sea interactions (Criado-Aldeanueva et al., 2012). Most of this flow will return to the Atlantic Ocean as Levantine Intermediate Water (LIW), formed during winter convection in the Levantine sub-basin, while another part will be transformed into deep waters along the basin (Criado-Aldeanueva et al., 2012). The LIW spreads over different fractions of the water column along its path towards the Atlantic Ocean: in the eastern basin it is located between 100 and 400 m depth while it spreads between approximately 200 and 700 m in the western basin (Zavatarelli and Mellor, 1995). Therefore, in the eastern Mediterranean the reference level of 400 dbar (near 400 m depth) will be close to the interface between this water mass and those residing at deeper levels, which usually have different pathways. As a consequence, velocities around 400 m depth would be significantly reduced as a result of friction, while they could be enhanced as we move towards deeper levels fed by the Mediterranean deep water masses. As a result, velocities at 900 m depth could not be close to zero, as we assume in the DHA computation, then promoting coarser results when comparing altimetry with Argo data referred to 900 dbar. In order to check this hypothesis, we recomputed the SLA–DHA differences for the eastern and western basins (see Tables S1 and S2 in the Supplement). In the first step, the Argo profiles available to compute DH in the whole Mediterranean were sorted according to their location. We found that 44 % of them are deployed in the western Mediterranean while the remaining 56 % are located in the eastern basin. Then, DHA referred to 400 and 900 dbar was computed and compared with SLA from Altimetry according to the procedure described in Sect. 3. In the eastern Mediterranean, the computation of the differences between altimetry and Argo data referred to both 400 and 900 dbar revealed a SD of SLA–DHA differences 1.88 cm lower (in terms of variance) when computing DHA referred to 400 dbar. This pressure level is located nearby the bounds of the LIW in this region, where velocities close to zero are expected. By contrast, in the western basin we obtained a SD of SLA–DHA differences 1.26 cm lower when computing DHA referred to 900 dbar. This result is consistent with the vertical distribution of the LIW in the western Mediterranean. Furthermore, the depth of the LIW core in most of the Mediterranean basin is also the reason for choosing 350 m as the parking depth for the Argo floats in the Mediterranean (Poulain et al., 2007).

Results reported from the regular-gridded experiments have shown that the reconstructed SLA maps from a configuration similar to the current Argo array in the Mediterranean (spatial resolution of 2° × 2°) are not able to capture the mesoscale features of the basin. As a consequence, these maps only retrieve 21 % of SLA signal variance. This is an expected result because the initial target of the Argo program is to monitor the large-scale ocean variability. Increasing the resolution, reconstructed SLA fields from a 0.75° × 0.75° grid box of SLA observations retrieve 66 % of SLA signal variance. This reconstruction captures the large-scale signal and most of the mesoscale features of SLA fields in the basin, exhibiting a mean RMSE lower than 3 cm (equivalent to 34 % of SLA signal variance). In addition, this spatial resolution agrees with the theoretical one extracted from the internal Rossby radius of deformation computed for the Mediterranean basin. The same outcomes were also obtained from the experiments conducted by using the actual positions of the Argo array in the basin. Here, larger values for the RMSEs of the recovered SLA maps were systematically obtained due to the uneven spatial distribution of the Argo platforms in the basin. However, we must be cautious about these results because the test has been conducted only along one Argo cycle (10 days). Anyway, similar results to the ones obtained here are expected to emerge from longer experiments according to the results obtained from the analysis of 2014 yearly RMSEs associated with the altimetry maps recovered from the different regular-gridded sub-sampled fields.

To summarise, and in light of a hypothetical future expansion of the Argo network, this OSSE experiment provides indications that a spatial resolution of nearly 75 km × 75 km would be enough to retrieve the SLA field with an RMSE of 3 cm for spatial scales higher than 150 km, similar to those presently captured by the altimetry. This would represent a theoretical reduction of 40 % of the actual RMSE. Such a high-resolution Argo array, composed of around 450 floats and cycling every 10 days, is expected to increase the actual network cost by approximately a factor of 6. This investment would in turn certainly have significant and positive repercussions on the realism of numerical models that assimilate Argo profiles.

Data availability. Argo data are collected and made freely available by the International Argo Program and the national programs that contribute to it (http://argo.ucsd.edu/ and http://www.jcommops.org/argo). Altimetry data are generated, processed and freely distributed by CMEMS (http://marine.copernicus.eu/).

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