Recovery of sea level fields in the Mediterranean Sea for the period 1945-2000

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Abstract. The distribution of sea level in the Mediterranean Sea is recovered for the period 1945-2000 by using a reduced space optimal interpolation analysis. The method involves estimating empirical orthogonal functions from satellite altimeter data spanning the period 1993-2005 that are then combined with tide gauge data to recover sea level fields over the period 1945-2000. The reconstruction technique is discussed and its robustness is checked through different tests. For the altimetric period (1993-2000) the prediction skill is quantified over the whole domain by comparing the reconstructed fields with satellite altimeter observations. For past times the skill can only be tested locally, by validating the reconstruction against independent tide gauge records. The reconstructed distribution of sea level trends for the period 1945-2000 shows a positive peak in the Ionian Sea (up to 1.5 mm yr^{-1}) and a negative peak of -0.5 mm yr^{-1} in a small area to the south-east of Crete. Positive trends are found nearly everywhere, being larger in the western Mediterranean (between 0.5 and 1 mm yr^{-1}) than in the eastern Mediterranean (between 0 and 0.5 mm yr^{-1}). The estimated rate of mean sea level rise for the period 1945-2000 is 0.7 ± 0.2 mm yr^{-1}. These overall results do not appear to be very sensitive to the distribution of tide gauges. The poorest results are obtained in open-sea regions with intense mesoscale variability not correlated with any tide gauge station, such as the Algerian Basin.

Keywords: sea level rise; altimetry; empirical orthogonal functions; tide gauge; Mediterranean Sea

1. Introduction

The study of low-frequency (interannual and interdecadal) sea-level variability is a major issue in the framework of climate change. In order to predict sea level evolution for the next decades, considerable efforts are devoted to understand the driving mechanisms. Global low-frequency sea-level trends are dominated by the steric component and the ocean mass increase (Meier, 1984; Levitus et al., 2000, Domingues et al., 2008). However, at regional scale the atmospheric pressure and wind can also play a key role (see for instance Tsimplis et al., 2005; Marcos and Tsimplis, 2007a; Gomis et al., 2008 for the Mediterranean region).

The study of sea-level variability is usually undertaken from hindcasts of the last decades (e.g., Barnier, 1998; Somot et al., 2006) and from available data sets (collected by tide gauge records and satellite altimeters). Observations are obviously more accurate than models, but they are handicapped by their spatial and temporal distribution. Tide gauges are limited by the need for a fixed platform and thus they are installed at coastal stations, where they can be referenced to some land mark. An important consequence is that tide gauges can only measure coastal and island sea level. Conversely, satellite altimetry allows a complete coverage of sea-level, though with some handicaps. When dealing with long-term sea level variability, the crucial limitation is the short period covered by altimetry, since the first satellite measurements date back to the early nineties. These partial pictures of the actual time-space sea-level variability given by raw observations can lead to incomplete or biased results on crucial issues such as the diagnosis of sea level rise due to global warming. Obtaining an accurate reconstruction of sea level fields is therefore of key importance to improve the present knowledge on long term sea-level variability and in particular to obtain more accurate sea level trends.

Several attempts to reconstruct sea level variability over the twentieth century have been carried out, both globally and regionally. The methodologies used for the reconstruction range from simple regional averaging of selected tide gauge records (e.g. Holgate and Woodworth, 2004) to more optimal interpolation methods (e.g. Church et al., 2004). These methodologies have yielded estimates of the linear rate of global-averaged sea level rise for different periods, such as the 1.8 ± 0.3 mm yr^{-1} given by Church et al. (2004) for the period 1950-2000. More recently, Jevrejeva et al. (2006) have used a method based on Monte Carlo Singular Spectrum Analysis to determine nonlinear long-term trends for 12 large ocean regions.

In the Mediterranean Sea there have also been some attempts of reconstructing the sea-level fields of the last decades. A first attempt was carried out in 2004 in the framework of the ESEAS (European SEA-level Service) project, but some doubts on the stationarity of the computed EOFs made that work to remain unpublished. Later on, Tsimplis et al. (2008) have carried out an EOF analysis of Mediterranean tide gauge records and altimetry data and compared the time amplitudes of the respective leading modes. They also give some examples of tide gauges reconstructed through a very simple technique, but no basin-wide reconstruction has been produced.

Hence, all long-term sea level trends reported in the Mediterranean have been estimated from individual tide gauge records, not from a basin-wide sea level reconstruction. As an example, Tsimplis et al. (2005) evaluated sea level trends of between 0.4 – 0.8 mm yr^{-1} for the period 1958-2001. They identified two periods with marked positive trends (before 1960 and after 1994) and an intermediate period for which most tide gauges show clearly negative trends. Tsimplis et al. (2005) and Gomis et al. (2008) pointed to the atmospheric pressure as responsible for the negative trends: its contribution has been evaluated in -0.6 mm yr^{-1} for the period 1958-2001 and in -1.0 mm yr^{-1} for the 1960-1994 period.

The objective of this work is to reconstruct the monthly distribution of sea level in the Mediterranean Sea for the period between January 1945 and December 2000. As an application, the spatial distribution of sea level trends will be computed for the first time over the whole Mediterranean basin. When dealing with reconstructions such as the one attempted here, having an estimate of the analysis errors is almost as important as the fields themselves. Therefore, the method selected to obtain the reconstruction is the reduced space optimal interpolation analysis proposed by Kaplan et al. (1997, 1998, 2000) and used by Church et al. (2004) to recover global scale sea level fields. The method intends to combine in an optimal way the benefits of the available long tide gauge series with the complete spatial coverage offered by satellite altimetry.

The structure of the work is as follows. We first select and process the data used to carry out the reconstruction (section 2). The method used for reconstructing sea level fields is described in section 3; a second, simpler method used to compare with the main one is also described. Section 4 is devoted to check the impact of two crucial features: the assumption that EOFs are stationary in time and the effect of the distribution of tide gauges within the domain. In section 5 we present the spatial distribution of sea level trends and the evolution of mean sea level for the period 1993-2000. These results are validated against satellite altimeter data (even though it is not a totally independent test, because satellite altimeter data are used to compute the EOFs). The spatial distribution of sea level trends and the evolution of mean sea level for the period 1945-2000 are shown in section 6; before the altimetric period results can only be validated locally, by comparing independent tide gauge records with the reconstruction evaluated at the closest grid point. All results are summarized and conclusions are outlined in section 7.

2. Data processing

2.1 The tide gauge data set

The tide gauge dataset used to carry out the reconstruction consists of monthly mean sea level series obtained from the data archive of the Permanent Service for Mean Sea Level (PSMSL) (Woodworth and Player, 2003). All data used in this work are Revised Local Reference (RLR) data. The RLR data have arbitrary biases applied at each site of the order of 7000 mm in order to avoid negative number. This bias should be removed for all tide gauges before computing the amplitudes used in the reconstruction if we were solving for sea levels, however, since we solve for changes in sea level between subsequent time steps it is not necessary to remove such a bias.

A different issue is that tide gauges measure sea level relative to land marks, and therefore significant land movements can contaminate the trends. The trends computed from both, recent CGPS series (Wöppelmann et al, 2007) and from altimetry and tide gauge series (García et al., 2007) suggest that most Mediterranean shores would be slightly subducting; however, CGPS series are too short to be reliable and do not cover all tide gauge sites. On the other hand, according to the ICE-4G VM2 model developed by Peltier (2001), the land movement due to the post-glacial rebound (or Glacial Isostatic Adjustment, GIA) is rather small in the Mediterranean: a maximum rising of 0.3 mm/yr is reported in the Adriatic shores. Since GIA is the only correction available for all sites, all tide gauge series were corrected using the GIA values obtained from the PSMSL data archive.

The period of the reconstruction was determined as a trade-off between the length of the period and the number of tide gauges spanning it. A reasonable choice was the period from January 1945 to December 2000. Tide gauge records with large gaps were discarded and also the tide gauge located in Malaga was discarded because of its unrealistically large trend (8 mm/yr over the period 1965-2000). All nearby stations have correlation larger than 0.7 and trend differences smaller than 1 mm yr^{-1}. We broke the period of the reconstruction 1945-2000 into 6 smaller periods and selected tide gauges with useful data for each period. This left a total of 3 tide gauges for the period 1945-1954, 6 for the period 1955-1964, 8 for the period 1965-1974, 10 for the period 1975-1984, 11 for the period 1985-1994 and 12 for the last 6 years. Gaps of 1-2 months were filled by using splines; gaps larger than 2 months were filled by means of a multiple linear regression using nearby records. The distribution of tide gauges over the selected domain is not uniform: in the Mediterranean Sea, most of them are located at the northern shores, whereas we barely find a single tide gauge along the African Coast (Fig. 1). This can be a serious handicap to resolve local events taking place close to the southern shores of the Mediterranean Sea.

Prior to any computation the mean seasonal cycle was removed from tide gauge records by means of a harmonic analysis. Because the annual cycle is not constant in time (see Marcos and Tsimplis, 2007b) a common period (1975-2000) was selected to compute the annual cycle of most tide gauge records. The time variability of the annual amplitude of each tide gauge record has been computed by Marcos et al. (2007b) and range from 0.26 to 0.69 cm (for amplitudes ranging from 3.15 to 8.90 cm).

Finally, since the reconstruction method minimizes for changes in sea level, the reference frame of tide gauge data is not relevant. However, when recovering sea level, changes are integrated backward in time and then a reference frame is to be defined for the reconstruction. We set the reconstruction to be in the same reference frame as the altimeter data.

2.2 The altimetry dataset

Gridded Sea Level Anomaly (SLA) fields were obtained at CLS (Collecte Localisation Satellites, http://www.cls.fr) by combining several altimeter missions, namely: Topex/Poseidon (T/P) data spanning the 1993-2001 period, Jason-1 (from June 2002 onwards), ERS1/2 data (spanning from January 1993 to June 2003 with a lack of ERS1 data from January 1994 to March 1995) and ENVISAT data (from June 2003 onwards). In space, the resolution of altimetry fields is 1/4º, resulting in a total of 5022 grid points covering the Mediterranean basin.

The methodology used in AVISO (Ssalto/Duacs system, http://www.aviso.oceanobs.com/) to build up the homogeneous and inter-calibrated data set is based on a global crossover adjustment, using T/P as the reference mission (Le Traon and Ogor, 1998). Then, these data are geophysically corrected (tides, wet/dry troposphere, ionosphere). The atmospheric correction is also applied in order to minimize aliasing effects (Volkov et al., 2007). In the new dataset provided by AVISO, the classical Inverted Barometer correction has been replaced by the MOG2D barotropic model correction (Carrere and Lyard, 2003) which improves the representation of high frequency atmospheric forcing as it takes into account both pressure and wind effects. Then, along-track data are resampled every 7 km using cubic splines and SLA is computed by removing a 7-year mean corresponding to the 1993–1999 period. Measurement noise is reduced by applying Lanczos (cut-off and median) filters. The mapping method to produce gridded SLA fields from along-track data is described in Le Traon et al. (2003). The long-wavelength error parameters are presently adjusted according to the new geophysical corrections (Carrère et al, 2007, submitted manuscript).

In order to recover the total sea level signal, we added back the atmospheric component of sea level (the MOG2D outputs) to SLA gridded fields. This may seem equivalent to not applying the atmospheric correction to along-track data, but it is not: the objective of correcting along-track data prior to the interpolation is to avoid the aliasing of atmospherically generated small-scale structures (not well resolved by the track sampling) onto the large scale pattern. When adding back the atmospheric signal to gridded fields no aliasing is expected, since the output grid is dense enough to resolve the atmospheric scales.

The mean seasonal cycle was removed from satellite altimeter data by means of a harmonic analysis. A regional-averaged sea level trend was also removed, not because it is spurious or unreliable, but in order to make the EOF representation more effective and unbiased (see Kaplan et al., 2007). Obviously this does not prevent the reconstruction from having a trend: the EOFs only give the dominant spatial pattern of sea level variability; the time variability will be obtained when projecting the tide gauge records onto the spatial EOFs, so that if those records have a trend this will be projected onto the reconstruction.

2.3 Comparison between both data sets

A key assumption of the methodology is that altimetry and tide gauge data are different spatial samplings of the same field. Before starting with the analysis we wanted to compare tide gauge records with the altimetry time series at the closest grid point. For the tide gauges located in Dubrovnik and Split, for instance, the distances to the nearest altimetry point are 47 and 13 km, respectively. The correlation and relative RMSE (RMS differences divided by the standard deviation of the series) between tide gauge records and the corresponding altimetry series are 0.81 and 0.61 for Dubrovnik and 0.89 and 0.47 for Split. Therefore, although altimetry and tide gauges measure in principle the same signal, there are some differences. These figures must be kept in mind when evaluating the skill of the reconstructing technique.

3. Methodology

3.1 Optimal interpolation

When working with climate datasets it is often necessary to develop methods to extract the signal from noisy observations. Among the methods aimed to characterize a lower-dimensional structure in large multivariate datasets, perhaps the most well known is the Principal Component Analysis (PCA, Preisendorfer, 1988). PCA is designed to obtain the modes that explain most of the field variance. In our case the modes will be constituted by spatial Empirical Orthogonal Functions (EOFs) and temporal amplitudes. An interesting property of PCA is that the lower-order modes contain the largest spatial structures, and therefore it can be used to filter small spatial structures that are significantly affected by noise and that can hardly be resolved with the tide gauge distribution. This can be achieved by truncating the number of modes to a smaller number which captures most of the signal.

For the reconstruction we use the reduced space optimal interpolation described by Kaplan et al. (1997, 1998, 2000) and used by Church et al. (2004) to recover global sea level. This method combines feature extraction and least squares optimal estimation, and provides theoretical error estimates for analyzed values. As in Church et al. (2004), we minimize for changes in sea level between subsequent time steps and then integrate over time to obtain sea level, in order to avoid the problem of locating all stations in a single, consistent vertical reference frame. This approach is an extension of the technique used by Smith et al. (1998) and Chambers et al. (2002).

The first step of the method (feature extraction) involves computing the spatial EOFs from satellite altimeter data. Following the procedure of Church et al. (2004), the spatial mean sea level is computed for each time step and removed prior to the EOF computation. The advantage of this procedure is that it avoids pouring spatially uniform sea level changes into different EOFs. The disadvantage is that a spatially-constant EOF (named as EOF0 in Church et al., 2004) has to be added to those obtained from the EOF analysis, in order to account for spatially uniform sea level changes. A test carried out without removing the spatial mean (and hence without adding the EOF0) resulted in a different modal distribution of the variability, but in practically the same reconstruction.

The longer the period used to estimate covariance patterns the more faithful the reconstruction will be. Hence, we use the longest altimetry dataset presently available: 13 years spanning from January 1993 to December 2005. In order to obtain the EOFs we construct an *m*x*n* matrix *Z* containing the satellite altimeter data, where *m* is the number of spatial grid points (5022) and *n* is the number of months (156). The matrix Z can be separated into three matrices by using a singular value decomposition (SVD):

$$Z = ULV^{T} \tag{1}$$

where "^{T}" denotes matrix transposition, *U* is an *m*x*n* matrix whose columns are the EOFs, *V* is an *n*x*n* matrix whose columns are the orthogonal time series (the amplitudes) of the modes, and *L* is an *n*x*n* diagonal matrix whose elements are the square root of the eigenvalues of the spatial covariance matrix. This is, the columns of *U* are functions of space only and the amplitudes of *V* are functions of time only.

The EOF expansion of the dataset can be truncated to a smaller subset by including only the lowest *M* EOFs:

$$Z_M(x,y,t) = U_M(x,y) \cdot L_M \cdot V_M^T(t) \tag{2}$$

where subindex "*M*" indicates matrices that only contain the lowest *M* modes. Expression (2) can be rewritten as:

$$Z_M(x,y,t) = U_M(x,y)\cdot\alpha(t) \tag{3}$$

where $\alpha(t) = L_M \cdot V_M^T(t)$ is an Mxn matrix whose rows are the time series of the amplitudes of the lowest M EOFs.

The second step of the method is the optimal interpolation described by Kaplan et al. (2000). The reduced space optimal interpolation solution for $\alpha(t)$ is the one minimizing (for each time step) the cost function

$$S(\alpha) = \left(HU_M\alpha - Z^o\right)^T R^{-1}\left(HU_M\alpha - Z^o\right) + \alpha^T\Lambda^{-1}\alpha \tag{4}$$

where Z^o is a matrix of available tide gauge observations, H is a sampling operator equal to 1 where and when tide gauge data are available and 0 otherwise, and Λ is a diagonal matrix which contains the M largest eigenvalues of the covariance matrix.

R is the error covariance matrix and consists of two terms:

$$R = \Sigma + HU'\Lambda'U'^T H^T \tag{5}$$

The term Σ is the data error covariance matrix accounting for the instrumental error. We assumed spatially uncorrelated errors of the order of 20 mm. This implies that $\Sigma = \sigma$ I, where I is the identity matrix and σ is the observational error variance. The second term in R contains the covariance of the truncated modes; it accounts for the errors introduced by ignoring higher-order EOFs in the reconstruction (the prime indicates matrices of the omitted EOFs and eigenvalues).

The second term on the right-hand side of the cost function (4) is a constraint on the EOF spectrum of the solution. It prevents the solution from giving too much energy to the features described by higher modes: the higher the mode, the smaller is the associated eigenvalue and therefore more severe is the punishment for deviations of its amplitude from zero. If this term is not used, the reconstruction can bring too much variance to grid points with no nearby observations, particularly when a large number of EOFs are used. In our case, a reconstruction obtained without using this term showed exaggerated variance in areas with no tide gauge data, a feature that was corrected when adding the term. In the simpler approach used by Smith et al. (1998) and by Chambers (2002) this term is omitted and matrix R is simply the identity matrix.

Since tide gauge measurements are all made relative to their own local datum, we will solve for changes in sea level between adjacent time steps. Following Church et al. (2004), for adjacent times t_n and t_{n+1}, (3) can be written as

$$\Delta Z_M = U_M(x,y)\left(\alpha(t_{n+1}) - \alpha(t_n)\right) = U_M(x,y)\Delta\alpha(tn) \tag{6}$$

The change in the amplitudes of the leading EOFs between each time step can be estimated by minimizing the cost function (4). The solution is

$$\Delta\alpha = PU_M^T H^T R^{-1} \Delta Z^o \tag{7}$$

where $\Delta Z^o = Z^o(x,y,t_{n+1}) - Z^o(x,y,t_n)$, and $P = \left(U_M^T H^T R^{-1} H U_M + \Lambda^{-1}\right)^{-1}$ is a theoretical estimate for the error covariance of the solution.

Once the change in the amplitudes has been obtained for each time step, the amplitudes themselves can be recovered by integrating backward in time. To do so, the average amplitude of each EOF is set equal to the average amplitude of the corresponding EOF of the altimeter data over the period between January 1993 and December 2000. Since matrix Z^o contains the tide gauge observations of the period 1945-2000, the amplitudes obtained by minimizing the cost function (4) will also span this period. Finally, the whole reconstruction of sea level is obtained by substituting the estimated amplitudes $\alpha(t)$ in (3).

3.2 The substitution approach

As a subsequent test of the robustness of the reconstruction, we also use a different, simpler technique to obtain an alternative reconstruction. First, a principal component analysis is applied to tide gauge records and altimeter data in an independent way. Considering that for each time step tide gauge observations are a spatial subset of the whole sea level field measured by the altimeters, and assuming that the sampling is good enough to reproduce the leading spatial modes, then the leading tide gauge EOFs should be a spatial sampling of the leading altimetry EOFs and the time amplitudes should be similar for both data sets.

Results reveal that the correlation between the amplitudes of the leading mode (EOF1) is 0.81 (Fig. 2a), while it goes down to 0.45 for the amplitudes of EOF 2 (Fig. 2b). The correlation between the amplitudes of EOF 3 (not shown) is -0.5. These results indicate that a choice of 2 EOF would be the best option. The reconstruction can be then obtained using equation (3), where $U_M(x,y)$ contains the two leading spatial modes obtained from the altimetry data set and $\alpha(t)$ are the amplitudes of the two leading modes obtained from tide gauge records. We will refer to this approach as the 'substitution approach', since the basis of the method consists of substituting the short altimetry amplitudes of the leading modes by the corresponding longer tide gauge amplitudes.

3.3 Assumptions, error sources, and EOFs used in the analysis

The approach used to recover sea level fields assumes that EOFs are stationary in time, so that the dominant modes of the period 1993-2005 are also the dominant modes of the period 1945-2000. In this work the covariance pattern is estimated using 13 years of satellite altimeter data; that is slightly more than the 12 years of altimeter data used by

Church and White (2006) to estimate global sea level and the 12 years of SST data used by Smith et al. (1998) to estimate surface temperature variations in the tropical Pacific. The 13 years of satellite data should give a reasonably accurate estimate of covariance patterns, but do not truly ensure the stability of the EOFs. In section 4 we carry out an empirical test consisting of the computation of EOFs for different subperiods of the altimetric period and comparing the reconstructions that result for each EOF set. In any case it is worth stating that because the minimization of the cost function (4) constrains the solution to be close to observations, even if the EOFs are not stationary, the analysis could reconstruct sea level fields successfully at the expense of the amplitudes losing their physical meaning.

The distribution of tide gauges in the domain is envisaged as the major error source. Optimal interpolation naturally accounts for irregular distribution, giving less relative weights to redundant stations (in mathematical terms, stations that are highly correlated among them). However, the method will never be able to recover the signal in regions where sea level is not correlated with any tide gauge station. Both the effect of assuming the stationarity of EOFs and the impact of the tide gauge distribution are investigated in section 4.

Regarding the distribution of the field variance into the leading modes, the EOF0 (not shown) explains 58% of the variance. As stated above, it is constant over the whole domain and accounts for changes in mean sea level. EOF1 explains 10% of the variance. It has a dipole structure, changing sign between the western and eastern basins of the Mediterranean Sea; maximum (opposite) values are reached in the Ionian Sea and in the Aegean Sea (Fig. 3a). EOF2 explains 4% of the variance and has a more complex structure; the Ionian and Aegean Sea appear now in phase and in opposite phase to the Algerian basin (Fig. 3b). EOF 3 (not shown) only explains 2.5% of the variance.

Following Church et al. (2004), we test the effect of increasing the number of EOFs by quantifying the reduction of the residual variance in terms of the reduction in the degrees of freedom. First, only the lowest mode is considered; when adding a second mode, the reduction of the residual tide gauge variance is of 48 mm^2 per degree of freedom. When adding a third mode the reduction is of 20 mm^2 per degree of freedom, and when adding a fourth mode it is only 9 mm^2 per degree of freedom. Additionally, the distribution of sea level trends resulting from the use of 1, 2, 3, 4 and 5 EOFs have been compared with altimetry trends for a common period (1993-2000). All results suggest that for the application of the optimal interpolation method, using 3 EOFs is the best option, in order to avoid overfitting while reducing the residual variance.

4. Sensitivity study

In order to investigate the effect of assuming that EOF modes are stationary in time, we obtained two different reconstructions: one using EOFs computed from the period 1993-1998 and another one using EOFs computed for the period 1999-2005. The cut in 1999 coincides with a clear change in the Eastern Mediterranean dynamics and sea level trend (see Vigo et al., 2005), in an attempt to obtain EOFs corresponding to different regimes. Figure 4 shows the leading EOFs corresponding to each case; they are similar but not exactly the same. The correlations between the observed and reconstructed fields for the period 1993-2000 are similar for both reconstructions; average values of 0.73 and 0.72 are obtained when using EOFs from 1993-1998 and from 1999-2005, respectively. The rate of mean sea level rise for the period 1945-2000 is 0.6 ± 0.1 mm yr^{-1} for both reconstructions. We have also computed the distribution of sea level trends obtained from the two reconstructions for the period 1993-2000 (Figs. 5a,b): both are very similar to the distribution of sea level trends obtained from altimetry (Fig. 7a). These results suggest either that the assumption of stationarity is reasonable at least for the leading EOFs, or that the changes in time of the leading EOFs do not critically affect the reconstruction,

To test the effect of the distribution and the number of tide gauges entering the computations, reconstructions obtained using different distributions of tide gauges are compared. Namely, we reconstructed sea level fields using only tide gauges from the Adriatic Sea, using all tide gauges except the ones located in the Adriatic Sea and using all tide gauge records available (see section 2.1). The averaged correlation between satellite altimeter observations and the reconstructed fields for the 1993-2000 period is 0.70 when using only tide gauges from the Adriatic Sea, 0.72 when using all tide gauges except the ones from the Adriatic and 0.80 when using all tide gauges available. The rates of mean sea level rise obtained for the period 1945-2000 are 0.6 ± 0.2 mm yr^{-1}, 0.5 ± 0.2 mm yr^{-1} and 0.7 ± 0.2 mm yr^{-1}, respectively. Again, the results are similar and, therefore, the reconstruction does not appear to be very sensitive to the number or distribution of tide gauges used in terms of correlations and rate of mean sea level.

The above results do not imply that additional tide gauge records would not improve the reconstruction; the correlations shown in Fig. 6 (see next section) are clearly lower in the southern Mediterranean shores due to the absence of tide gauge records. What results suggest is that of the whole set of available tide gauges, a reasonable subset appears to do a similar job than using the whole set.

5. Reconstruction for the period 1993-2000

The only way to test the goodness of the reconstruction over the whole domain is to compare the observed and reconstructed fields for the period 1993-2000, since this is the period spanned by satellite altimeter data. Though it is not an independent test due to the fact that EOFs were estimated from satellite altimeter data, it will be useful to validate important aspects of the results. This test somehow complements the more independent validation carried out in section 4, where the altimeter data set was broken into 2 periods and the validation was carried out for the whole period.

The spatial distribution of the correlation between the observed and reconstructed fields (Fig. 6a) shows correlations close to 0.9 in the north-western region of the Mediterranean Sea, the Adriatic Sea and in the Gulfs of Gabes and Sirte. In the Ionian and Aegean Sea and near the coast of Morocco the correlation is smaller but still larger than 0.7 in most areas. The spatial mean of the correlation is 0.8. As expected, the reconstruction cannot recover the altimetric signal (the 'true' field in the test) in regions of high mesoscale activity such as the Algerian basin. Tsimplis et al. (2008) showed that Algerian mesoscale eddies are poorly correlated with sea level of nearby regions, which explains why their variability can hardly be reconstructed from discrete coastal data. A map of the percentage of variance explained (Fig. 6b) shows that the highest percentage is achieved in the same regions where correlation is high. The percentage of variance explained is above 60% in these region, and larger than 40% in all regions.

Also the distribution of sea level trends derived from the reconstruction can be compared with the trends estimated directly from satellite altimeter data (Fig. 7). The reconstructed and observed trends are very similar, showing positive values above 10 mm yr^{-1} in the eastern Mediterranean and smaller rates (less than 5 mm yr^{-1}) in the western Mediterranean. The reconstruction also reproduces the marked negative trend of more than -15 mm yr^{-1} observed in the Ionian Sea. This feature has already been reported by several authors (Cazenave et al., 2002; Fenoglio-Marc, 2002; Larnicol et al., 2002) and explained in terms of the sudden weakening of the anticyclonic circulation in the region during the Eastern Mediterranean Transient.

Also mean sea level (MSL) was computed for both, the reconstruction and altimetry values, obtaining very similar results (Fig. 8). The correlation between the reconstructed and observed MSL time series is 0.9 and the root mean square difference between the two series is 0.5 cm. The error bars of Fig. 8 are obtained from the error distribution produced by the optimal interpolation method. The method gives an estimate for the statistical error covariance matrix of the interpolated values; the diagonal of that matrix is the variance of interpolation errors at each point of the output grid. The error bars of MSL have been obtained simply as the average of the standard deviation of the interpolation errors at each grid point.

The MSL rise for the period 1993-2000 is 4.0 ± 0.7 mm yr^{-1} when computed from the reconstructed fields and 3.9 ± 0.6 mm yr^{-1} when derived from satellite altimeter data. The uncertainty of the trends is estimated by means of a bootstrap method. For a time series consisting of N data pairs (z,t), we randomly select one pair and return it to the series; we repeat the procedure until having N selected pairs (some of them will be repeated, and therefore some of the original pairs will not included in the new series). The trend of the resulting series is computed and the whole procedure is repeated for a large number of events. The result is a large number of trend values from which one can extract the mean and the values enclosing a given percentage of the distribution (in this work the uncertainty reported altogether with the trends is the standard deviation of the trend distribution). The described procedure accounts for the uncertainty derived from the statistical properties of the series (basically its length and variability), but it does not account for eventual errors in the values of the series. These errors can be taken into account by extracting not the original data pairs (z,t), but pairs (z*,t), where 'z*' is a random number in between [z−dz, z+dz] and 'dz' is the uncertainty associated to 'z'). The error bars of MSL (dz) are of the order of 1.1 cm (see Fig. 8), while for altimetry data we have considered dz=0. The uncertainties obtained for the trends (± 0.7 mm yr^{-1} for the reconstruction and ± 0.6 mm yr^{-1} for altimetry data) indicate that the impact of the errors in the reconstructed MSL is small compared with the uncertainty inherent to the series.

A last comparison is with the reconstruction obtained using the simple substitution approach described in section 3.2. When that approach is applied retaining the first 2 EOFs, the resulting rate of mean sea level rise is 3.6 ± 0.6 mm yr^{-1} (where the bootstrap method has been applied without considering the uncertainty of the series). The averaged correlation between this reconstruction and altimetry data is 0.75. Both results indicate that optimal interpolation is more accurate than the substitution approach.

6. Reconstruction for the period 1945-2000

The only way to validate the reconstruction beyond the period covered by satellite altimetry is checking it at tide gauge locations. To do it, we used tide gauge records that did not enter the computations because of their large amount of data voids and that can therefore be used as fully independent test sites. The tide gauges located at Rovinj and Alexandria, in the Adriatic Sea and the northern coast of Africa, respectively, were selected for the test. The time periods used for each record were 1974-1990, 1960-1976, respectively.

Figures 9a,b show the observed and reconstructed sea level at the two selected locations. Correlations are 0.85 and 0.70, respectively, and the percentages of variance explained by the reconstruction are 85% and 50%. The reason why the highest correlation and explained variance are obtained at Rovinj must be attributed to the fact that several tide gauges located in the Adriatic Sea were used for the reconstruction, while none was used in the southern shores of the Mediterranean Sea. These results are comparable to those obtained in section 5 for the altimetric period, which suggests that the reconstruction is fairly stable for the pre-altimetric period and hence that the open-sea correlations shown in Fig. 6 can be expected to be valid for the whole period.

The regional distribution of sea level trends for the period 1945-2000 is shown in Fig. 10. The main features are the maximum positive rate in the Ionian Sea (up to 1.2 mm yr^{-1}) and the nearly zero trends in the Aegean Sea, with a negative peak of -0.5 mm yr^{-1} to the south-east of Crete. In general we find small positive trends in the western Mediterranean (between 0.5 and 1 mm yr^{-1}) and even smaller trends in the Eastern Mediterranean, especially in the Aegean Sea (between 0 and 0.5 mm yr^{-1}).

The time evolution of mean sea level is presented in Fig. 11. It clearly shows the three different periods outlined by Tsimplis et al. (2005): marked positive trends before 1960 and after 1994 and an intermediate period with negligible or negative trends. For the whole period the mean sea level rise is 0.7 ± 0.2 mm yr^{-1}.

As for the altimetric period, we also reconstructed sea level fields by using the simpler, substitution approach. Results give a trend of 0.6 ± 0.2 mm yr^{-1} for mean sea level, that is, slightly lower than for the optimal approach. We also computed the rate of regional averaged sea level rise for different values of tide gauge errors but results showed little or no difference with respect to the values given above.

7. Summary and conclusions

The reduced space optimal interpolation approach described by Kaplan et al. (1997, 1998, 2000) and used by Church et al. (2004) to reconstruct global mean sea level has been successfully used to reconstruct the distribution of sea level in the Mediterranean Sea for the period 1945-2000. A different, much simpler technique referred to as 'the substitution approach' has also been used in order to compare results.

The robustness of the reconstruction has been checked by means of several tests. A crucial assumption is that EOFs are stationary over time; that is to say that EOFs computed for the period 1993-2005 are representative for the whole period 1945-2000. We have tested the validity of that assumption by computing EOFs for the periods 1993-1998 and 1999-2005 and then obtaining the reconstruction for both sets. Results are quite similar, though further tests should be carried out as soon as new altimetric data are available. The sensitivity of the reconstruction to the number and the distribution of tide gauges has also been tested. Results do not appear to be very sensitive to reasonable modifications in the tide gauge sites. However, in the regions where there are no tide gauges (i.e., Aegean Sea and southern Mediterranean) only the large scale structures can be expected to be recovered. Other complementary tests carried out, such as the sensitivity of the reconstruction to tide gauge errors, showed little impact on the results.

To quantify the goodness of the reconstruction over the whole domain we have compared the reconstructed fields with satellite altimeter observations for the period 1993-2000. For this period, reconstructed and observed results are remarkably similar. The spatially averaged correlation between the reconstructed and observed fields is 0.80 when using the optimal choice of parameters. The basin mean sea level rise for this period is 4.0 ± 0.7 mm yr^{-1}, which agrees with the rate of 3.9 ± 0.6 mm yr^{-1} obtained from altimetry fields. The distribution of sea level trends is also remarkably similar to altimetry trends except in regions with high mesoscale activity such as the Algerian basin. The substitution approach gives similar results for the basin mean sea level rise (3.6 ± 0.6 mm yr^{-1}), though the distribution of trends is less accurate.

The validation of the reconstruction for the period 1945-2000 is based on local comparisons with tide gauge records that were not used to obtain the reconstruction. The correlation between the reconstruction and these independent tide gauge records is higher than 0.7 for all cases. These values are comparable to those obtained for the altimetric period, which suggests that the accuracy of the reconstruction is fairly stable during the whole period.

Our best estimate for the Mediterranean mean sea level rise occurred during the period 1945-2000 is 0.7 ± 0.2 mm yr^{-1}. The uncertainty of the trend (± 0.2 mm yr^{-1}) is mostly due to the statistical properties of the series (length and variability), with a small impact of the errors associated with the interpolation process. The five Mediterranean tide gauge records that span most of the 20th century show positive trends between 1.2±0.1 and 1.5±0.1 mm/yr (Marcos and Tsimplis, 2008). When using the 21 longest records (>35 years) the obtained trends are smaller in the Mediterranean (–0.7±0.3 mm/yr to 0.3±0.4) than in the neighbouring Atlantic sites (1.6±0.5 to 1.9±0.5 mm/yr) for the period 1960-2000.

Our trends are therefore consistent with previous estimates. The progress beyond the state of the art is that the MSL trend derived in this work corresponds to a basin average, rather than to individual tide gauges. Moreover, the reconstruction also gives, for the first time in the Mediterranean, the spatial distribution of trends spanning more than five decades. A main feature of that distribution is the maximum positive trend obtained in the Ionian Sea (up to 1.2 mm yr^{-1}), precisely where maximum negative trends were observed for the altimetric period 1993-2000, Minimum values are obtained in the Aegean Sea, where trends are nearly zero; a negative peak of -0.5 mm yr^{-1} is obtained to the south-east of Crete. In general we find small positive trends in the western Mediterranean (between 0.5 and 1 mm yr^{-1}) and even smaller trends in the Eastern Mediterranean (between 0 and 0.5 mm yr^{-1}).

A more careful examination of the time evolution of the reconstructed sea level fields is expected to throw some light in the study of relevant features such as the Eastern Mediterranean Transient. However, this will be accomplished in a subsequent paper, since this first one is mainly devoted to ensure the robustness of the approach and to give overall numbers.

Finally, the continuation of altimeter measurements will make possible subsequent revisions of the reconstruction, as the empirical orthogonal functions estimated from altimeter data will be more and more representative of the actual spatial patterns. Other handicaps of the approach, such as the lack of tide gauges in the southern shores have more difficult solution.

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FIGURE CAPTIONS

Figure 1. The distribution of tide gauges for different periods of the reconstruction: (a) 1945-54, (b) 1955-64, (c) 1965-74, (d) 1975-84, (e) 1985-1994, and (f) 1995-2000.

Figure 2. The time amplitudes of the two leading EOFs estimated from altimetry (solid line) and tide gauges (dashed line): (a) amplitude 1, (b) amplitude 2.

Figure 3. The two leading EOFs of the altimetry data set (1993-2005) obtained after the removal of the seasonal cycle and a linear trend: (a) EOF 1, (b) EOF 2.

Figure 4. The two leading EOFs of satellite altimeter data obtained for two different subperiods: (a) EOF 1 for 1993-1998; (b) EOF 1 for 1999-2005; (c) EOF 2 for 1993-1998; and (d) EOF 2 for 1999-2005.

Figure 5. The distribution of sea level trends for the period 1993-2000 estimated from two different reconstructions: (a) from the EOFs obtained for the period 1993-1998; (b) from the EOFs obtained for the period 1999-2005. The contour interval is 5 mm yr^{-1}.

Figure 6. (a) Correlation between the reconstructed sea level fields and satellite altimeter observations over the period 1993-2000 (the contour interval is 0.2). (b) Percentage of the altimetry variance explained by the reconstruction over the same period (the contour interval is 20%).

Figure 7. The distribution of sea level trends for the period 1993-2000 as estimated from (a) satellite altimeter data; (b) the reconstructed fields, obtained using EOFs computed for the whole altimetric period (1993-2005). The contour interval is 5 mm yr^{-1}.

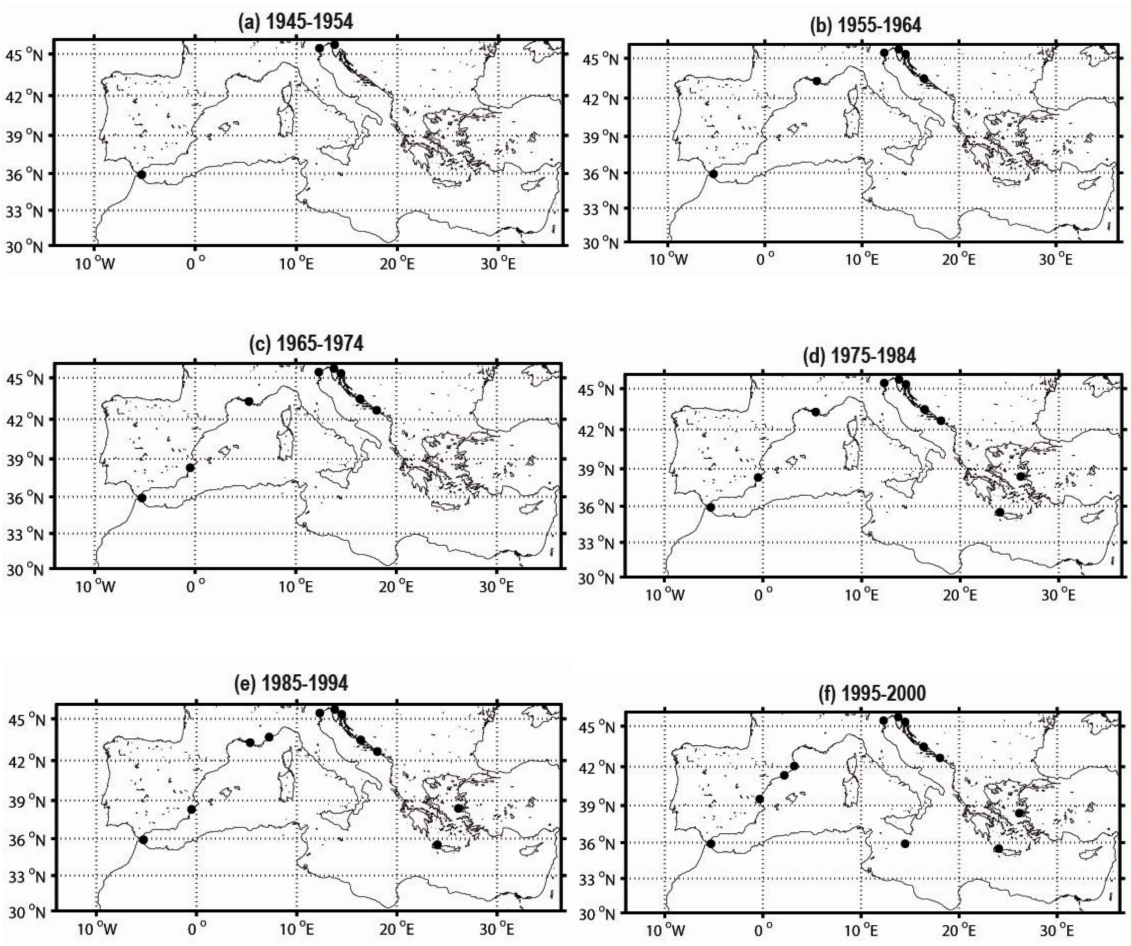
Figure 8. Mean sea level for the period 1993-2000 estimated from the reconstructed fields (dashed lines) and from satellite altimeter data (solid lines). Thin lines correspond to the original monthly data; thick lines are one year moving averages of the thin lines.

Figure 9. Comparison between reconstructed fields and tide gauge observations at (a) Rovinj; (b) Alexandria.

Figure 10. Distribution of sea level trends estimated for the whole reconstructed period 1945-2000. The contour interval is 0.3 mm yr^{-1}.

Figure 11. Mean sea level (MSL) for the whole reconstructed period 1945-2000. The thin line correspond to the original monthly data and the thick lines is a one year

moving average of the thin line. The red line corresponds to MSL computed from the altimeter data set for the period 1993-2000.



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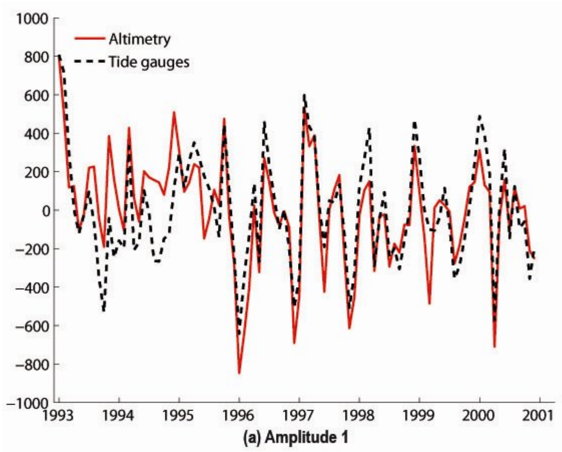

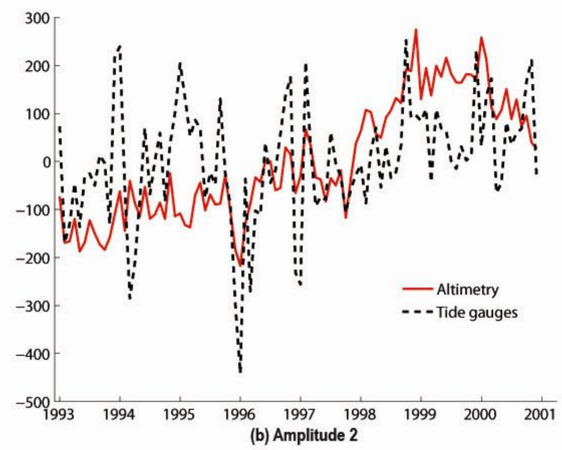

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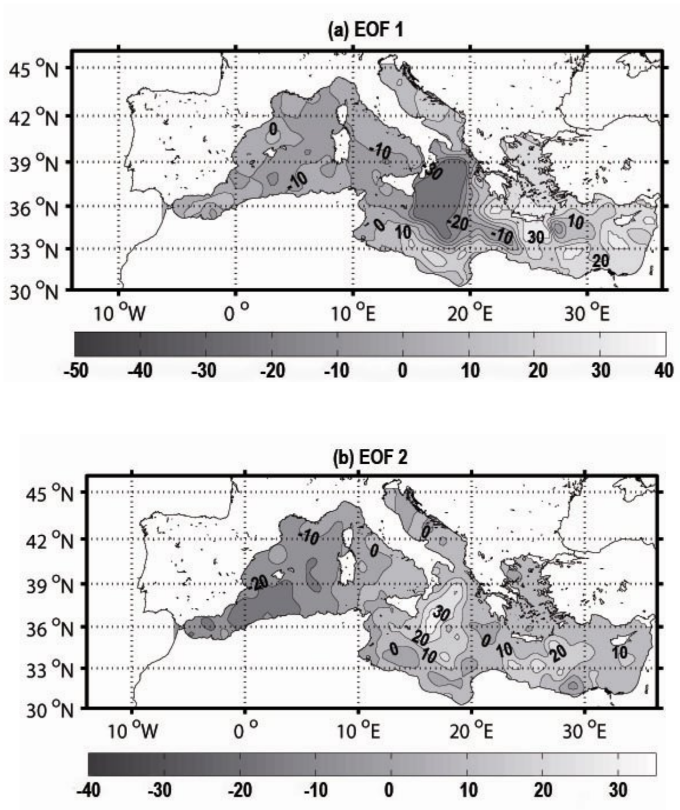

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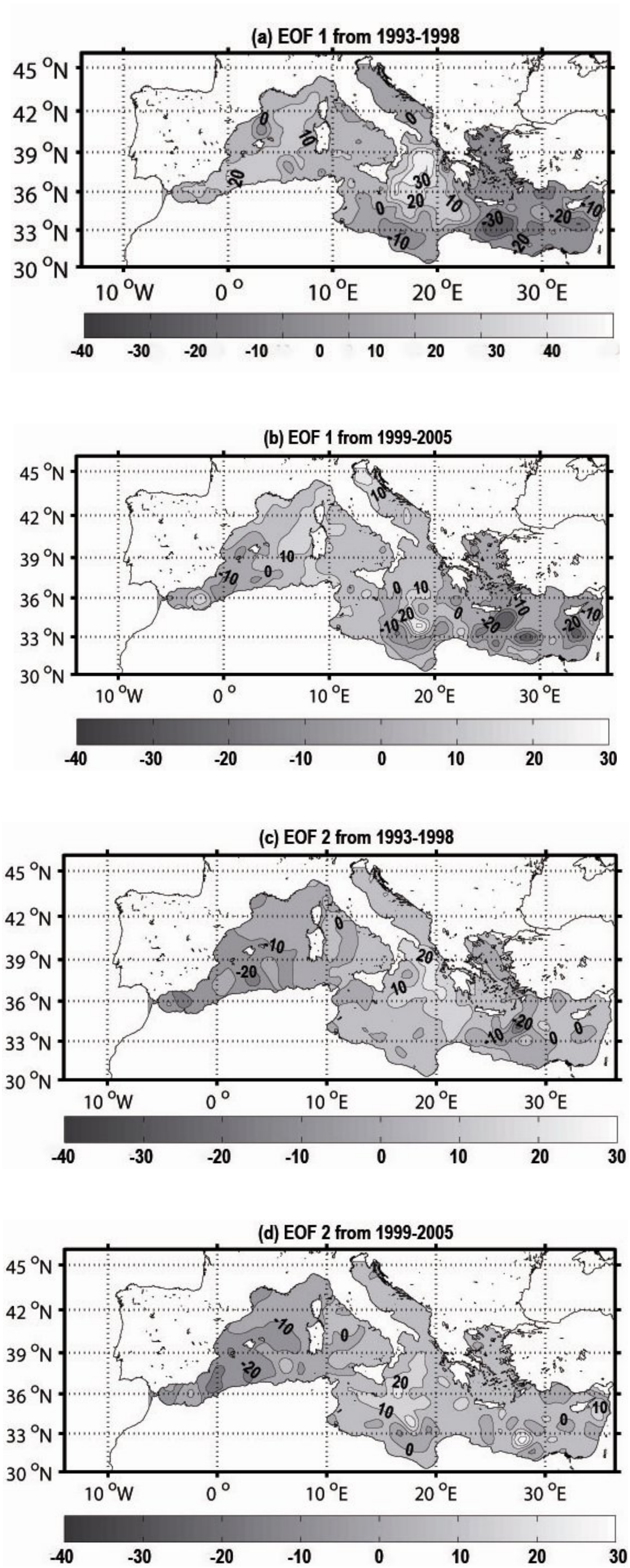

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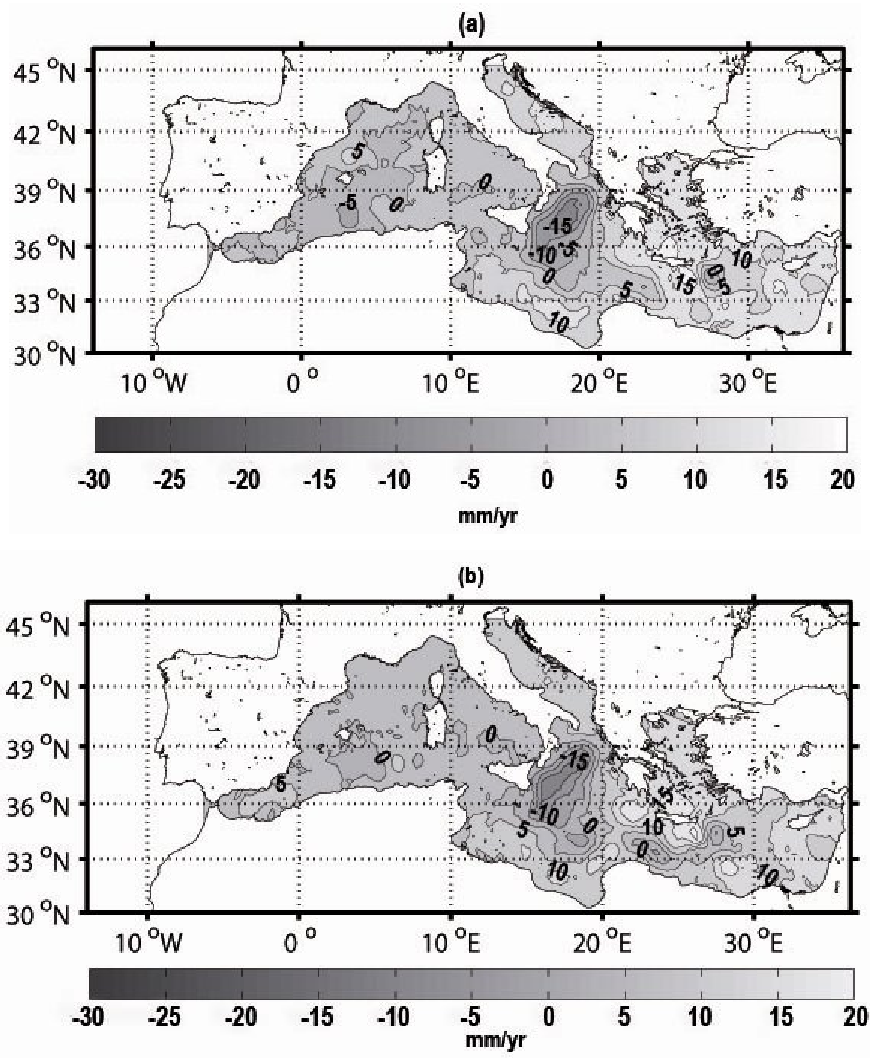

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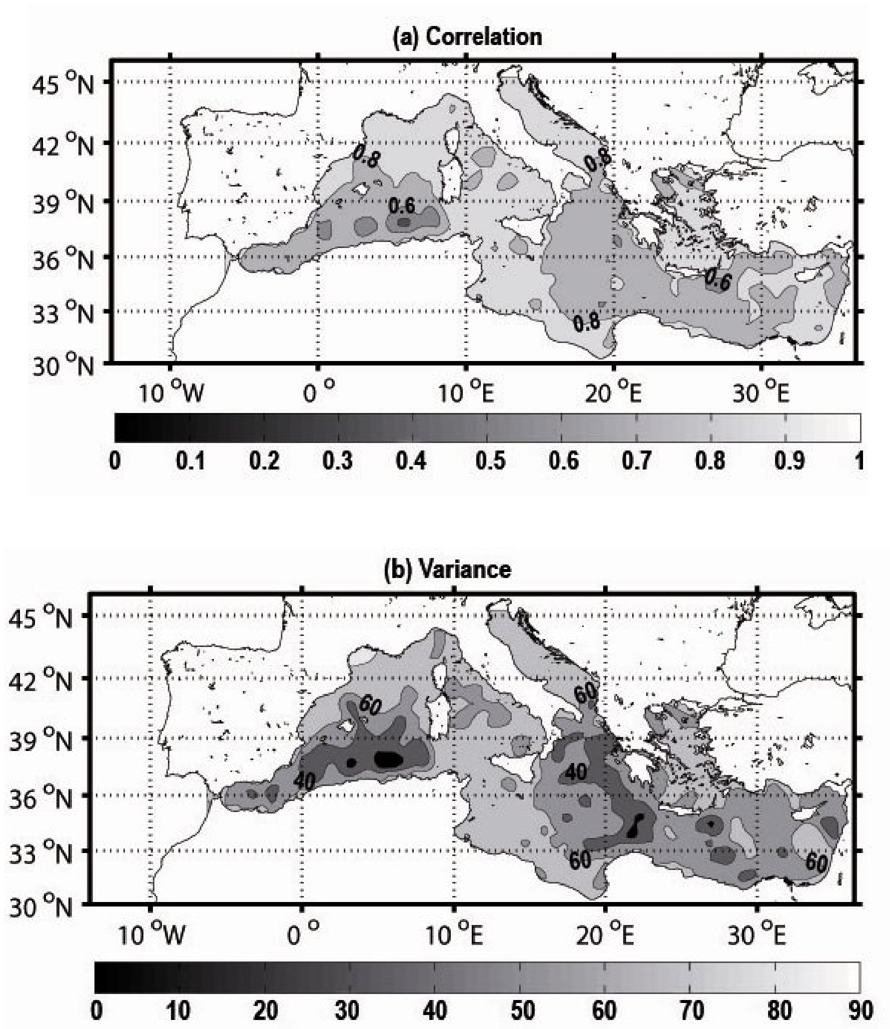

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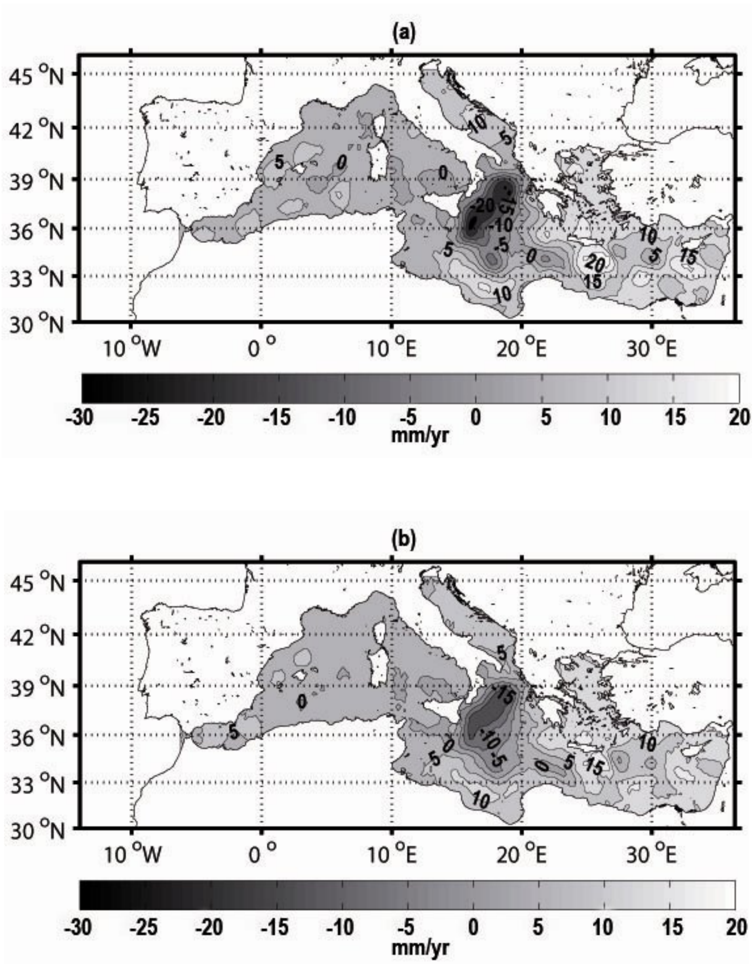

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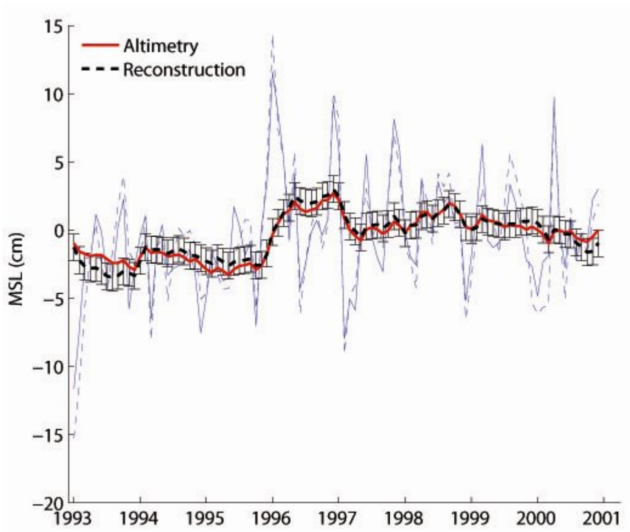

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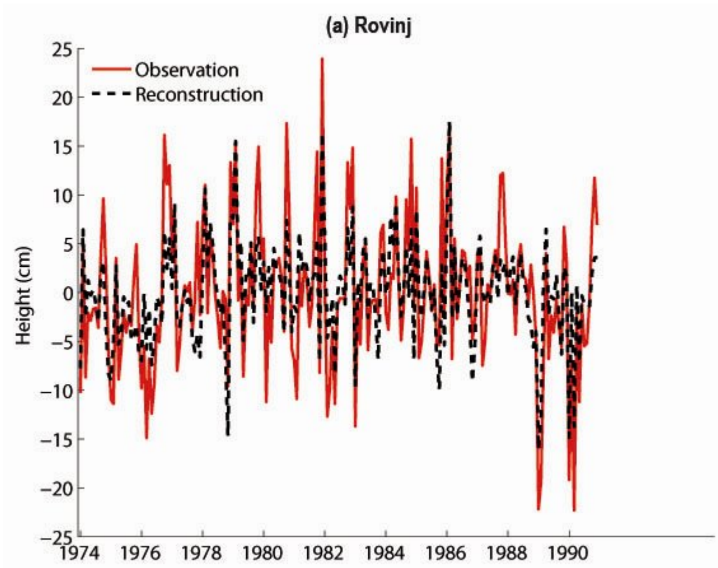

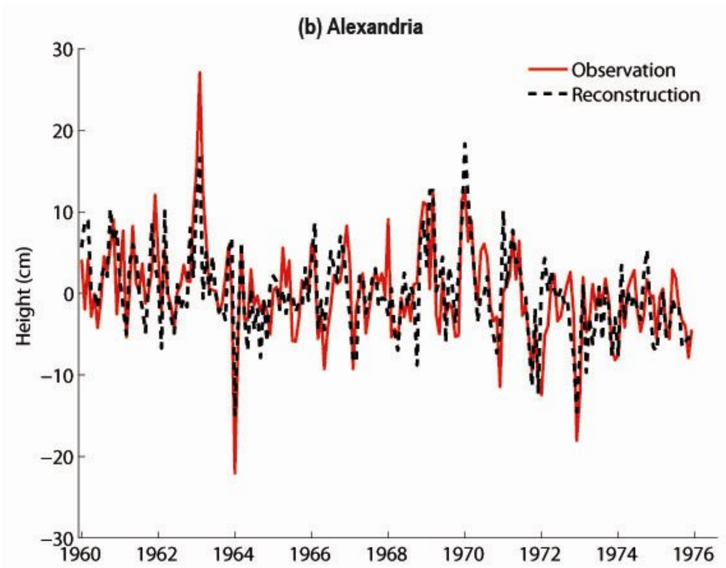

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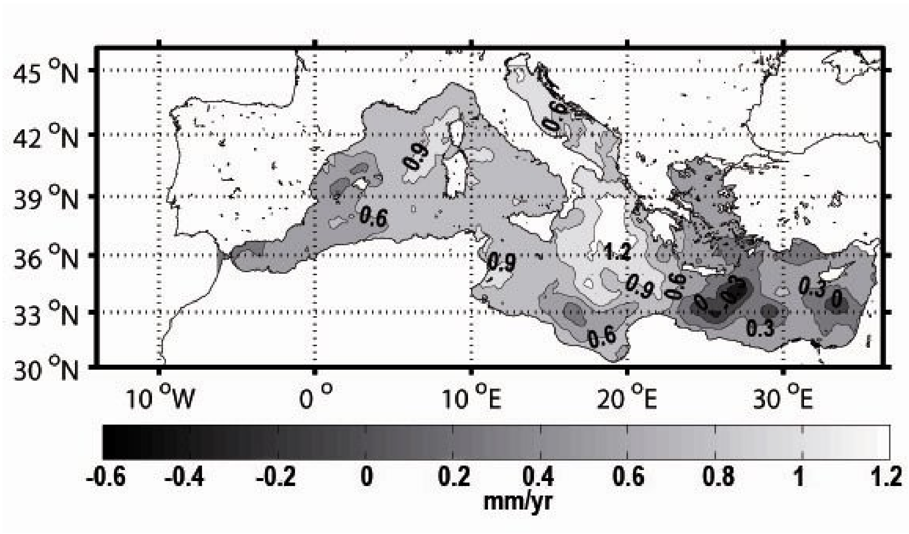

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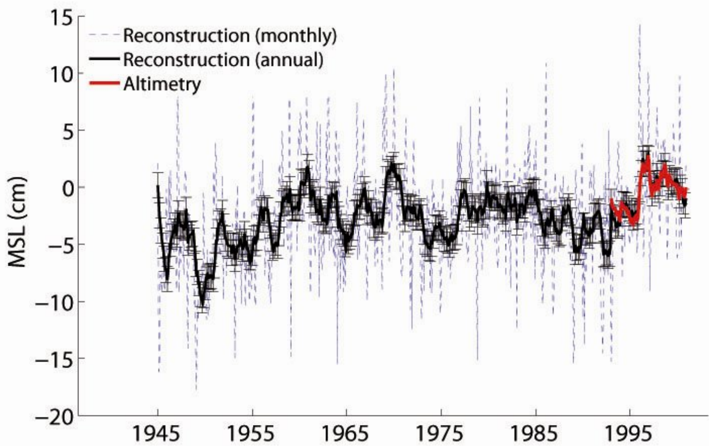

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