Comparison of Mediterranean Sea levels fields for the period 1961-2000 as given by a data reconstruction and a 3D model.

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Abstract. Two Mediterranean Sea level distributions spanning the last decades are examined. The first one is a reconstruction of sea level obtained by a reduced-space optimal interpolation applied to tide gauge and altimetry data. The second distribution is obtained from a 3D (baroclinic) regional circulation model. None of the two representations includes the mechanical atmospheric forcing. Results are presented for two different periods: 1993-2000 (for which altimetry data are available) and 1961-2000 (the longest period common to both distributions).

The first period is examined as a test period for the model, since the reconstruction is very similar to altimetry observations. The modelled sea level is in fair agreement with the reconstruction in the Western Mediterranean and in the Aegean Sea (except in the early nineties), but in the Ionian Sea the model departs from observations. For the whole period 1961-2000 the main feature is a marked positive trend in the Ionian Sea (up to 1.8 mm yr^{-1}), observed both in the reconstruction and in the model. Also the distribution of positive trends in the Western Mediterranean (mean value of 1.1 mm yr^{-1}) and the smaller trends in the Aegean Sea (0.5 mm yr^{-1}) are similar in the reconstruction and in the model, despite the first implicitly accounts for sea level variations due to remote sources such as ice melting and the second does not. The interannual sea level variability associated with key regional events such as the Eastern Mediterranean Transient is apparently captured by the reconstruction but not by the model (at least in its present configuration). Hence, the reconstruction can be envisaged as a useful tool to validate further long-term numerical simulations in the region.

1. Introduction

The study of long-term sea level variability is usually undertaken either from available observations (collected by tide gauges and satellite altimeters) or from hindcasts of the last decades. Observations are obviously more accurate than models, but they are handicapped by their spatial and temporal distribution: tide gauge records can span several decades, but the need of a land mark reference makes that all them are located at coastal sites; conversely, satellite altimetry allows a complete spatial coverage of the open sea, but it only spans a short time period (from the early nineties).

The partial pictures of the actual time-space sea level variability given by observations can be improved when tide gauge records and satellite altimetry data are combined to reconstruct sea level fields. In the Mediterranean the only reconstruction available at present has been obtained by Calafat and Gomis (2009). Sea level fields spanning the period 1945-2000 were reconstructed by using a reduced-space optimal interpolation method similar to the one used by Church et al. (2004) to reconstruct global sea level.

Regarding long-term sea level hindcasts, they are usually obtained from the output of global or regional baroclinic circulation models. In the Mediterranean Sea, global models are handicapped by their low resolution, which usually prevents an accurate representation of key processes such as deep water formation or the water exchange through Gibraltar. [An exception is the hindcast carried out by Barnier (1998), which has proven to be rather accurate within the Mediterranean basin.] On the other hand, regional hindcasts such as the 1961-2000 run carried out by Somot et al. (2006) with OPAMED8 (a Mediterranean version of the OPA model), have enough resolution; the drawback of regional models is that sea level variations inside the Mediterranean basin depend on the boundary conditions imposed at the Strait of Gibraltar and/or in the Atlantic boundary of the domain.

An advantage of the hindcasts over sea level reconstructions is that they give a much more complete information on the physical processes driving sea level variability. Hence, changes in the mass content of a semi-enclosed basin such as the Mediterranean Sea could in principle be evaluated from the evaporation-precipitation-river runoff (E-P-R) budget and the mass exchanges through Gibraltar. The steric component, resulting from changes in the volume of the water column, can be computed from temperature and salinity distributions. [The mass and the steric components are not fully independent, since salinity changes are obviously related to the freshwater budget.]

The objective of this work is to compare the 1945-2000 reconstruction of Mediterranean sea level carried out by Calafat and Gomis (2009) with the 1961-2000 3D hindcast simulation carried out with OPAMED8 by Somot et al. (2006). The two representations are fully independent and based on different hypotheses. On one hand, the reconstruction entirely relies on sea level observations; basic hypotheses are that the dominant (usually large-scale) spatial modes inferred from the altimetric period are almost stationary in time (i.e., that they are valid for the whole reconstructed period) and that at least the overall pattern of these modes can be reconstructed from the discrete tide gauge spatial sampling. The validation of these hypotheses is presented in Calafat and Gomis (2009) altogether with other sensitivity tests. On the other hand, the hindcast is forced by a downscaled meteorological analysis and does not assimilate any oceanographic observation; the basic hypotheses are that the heat, fresh water and momentum forcings are accurate and that the model equations can account for the most important processes driving the dynamics of the Mediterranean Sea. The characteristics of the simulation performed by Somot et al. (2006) will be detailed in section 2.3, but it is worth advancing here that the Atlantic boundary of the domain is set to match a monthly climatology and therefore the observed warming of Atlantic waters or the eventual mass increase and water freshening derived from ice-melting are not accounted for by the model. This implies that the mass exchanges through Gibraltar and hence the Mediterranean sea level variability will not be affected by remote influences.

The comparison between the reconstruction and the hindcast is performed for two different periods: 1993-2000 (for which altimetry data are available) and 1961-2000 (the longest period common to both distributions). For the first period the reconstruction has already been validated against altimetry data by Calafat and Gomis (2009). Before that period the reconstruction has only been validated locally, against a few, independent tide gauges that were not included in the reconstruction process (Calafat and Gomis, 2009). It is therefore of great interest to compare both sea level representations and to determine their strengths and weaknesses for the pre-altimetric period. The ultimate aim is to end up with a reliable representation of the spatial and temporal variability of Mediterranean sea level spanning the last decades.

Key magnitudes that can be derived from sea level variability are basin mean and regional trends, not only for total sea level but also (in the case of the hindcast) for the steric component. At global scale, total sea level trends have been estimated by different authors. Widely accepted values are the 1.8 mm yr^{-1} given by Church et al. (2004) for the period 1950-2000 and the 1.7 mm yr^{-1} given by Church et al. (2006) for the whole 20^{th} century, both obtained from reconstructions based on altimetry and tide gauge records. More recently, Domingues et al. (2008) have considered the bias affecting part of the historical observations and have given an updated value of 1.5±0.4 mm yr^{-1} for the period 1961-2003. The rate of the thermosteric component of global sea level rise has usually been evaluated from gridded ocean temperature data sets (Levitus et al., 2000; Levitus et al., 2005; Ishii et al., 2003); the values given by different authors (e.g., Antonov et al., 2005; Cabanes et al., 2001; Ishii et al., 2006) typically range between

0.3 and 0.5 mm yr^{-1}. However, the new estimates given by Domingues et al. (2008) increase the thermosteric sea level trend up to 0.6-0.9 mm yr^{-1} for the period 1961-2003. Estimations of the global halosteric component are much sparser; Ishii et al. (2006) gave a rate of 0.04 mm $yr^{-1}$for the period 1955-2003. At global scale, the differences between total sea level rise and the steric component must be attributed to other contributions such as the ocean mass increase derived from the melting of continental ice, but also to errors in the estimated trends.

At regional scale sea level shows a high spatial variability even at subbasin scale. In the Mediterranean Sea, Bethoux et al. (1990) and Rixen et al. (2005) showed that the temperature and salinity of deep waters are not constant, and therefore long-term sea level changes derived from changes in the temperature, salinity and circulation are expected. Moreover, transient events can strongly modify the internannual sea level variability. As an example, the Mediterranean Sea is believed to have the Adriatic Sea as the major source of deep waters during most of the last century. However, between 1987 and 1995 the location of the Eastern Mediterranean Deep Water Formation changed and the Aegean became the major source of deep water formation (Roether et al. 1996; Theocharis et al., 1999). This changed, referred to as the Eastern Mediterranean Transient (EMT), was due to anomalous meteorological conditions over the Aegean Sea and also in the region of the Adriatic (Josey, 2003), with very cold winters in 1992 and 1993. After 1995 the situation returned back to normal: the Aegean Sea returned to pre-EMT conditions, exporting small amounts of dense water that do not reach the bottom of the Ionian and the Levantine basins (Theocaris et al., 2002) while the Adriatic Sea became again the main contributor to the dense waters of the Eastern Mediterranean (Klein et al., 2000; Manca et al., 2006). The marked sea level dropping observed in the altimetry maps of the Ionian Sea during the nineties (Cazenave et al., 2001; Fenoglio-Marc, 2002; Criado-Aldeanueva et al., 2008) are now thought to be a consequence of the EMT. Other regional trends have been estimated by Calafat and Gomis (2009) from the 1945-2000 reconstruction used in this work. When averaged over the whole Mediterranean basin, sea level rise has been estimated in 0.7 ± 0.2 mm yr^{-1} for the period 1945-2000.

The paper is organized as follows. All the data sets used in this work are presented in section 2. Section 3 is devoted to present the results of the comparison between the reconstruction and the hindcast; that section is divided in two different periods: the altimetric period (1993-2000) and the total period 1961-2000. The regional distribution of sea level trends and the time variability of selected regionally-averaged sea level are shown for both periods. All results are discussed and summarized in section 4.

2. The datasets

2.1 Reconstructed sea level fields

The reconstruction obtained by Calafat and Gomis (2009) consists of monthly 1/4º x 1/4º gridded total sea level fields covering the Mediterranean Sea during the period 1945-2000. Empirical orthogonal functions (EOFs) obtained from altimetry data were combined with long tide gauge records in a reduced-space optimal interpolation scheme. This technique was also used by Kaplan et al. (2000) to recover sea level pressure and by Church et al. (2004) to reconstruct global sea level fields. The approach used to recover sea level assumes that EOFs are stationary in time, so that the dominant modes computed for the altimetric period are also the dominant modes of the whole reconstructed period 1945-2000. The covariance pattern was estimated using 13 years of satellite altimeter data, which should give a reasonably accurate estimate of covariance patterns but do not truly ensure the stationarity of the EOFs. Calafat and

Gomis (2009) carried out an empirical test consisting of the computation of EOFs for different subperiods of the altimetric period and comparing the reconstructions resulting from each EOF set. No significant difference was found between them.

The sensitivity of the reconstruction to the distribution of tide gauges was also checked by Calafat and Gomis (2009). Optimal interpolation naturally accounts for irregular distribution, giving less relative weights to redundant stations (in mathematical terms, to stations that are highly correlated among them). On the other hand, the method will hardly be able to recover the signal in regions where sea level is not correlated with any available tide gauge record (e.g., in the Algerian basin).

2.2 The atmospheric contribution

At regional scale, sea level variability is not only due to the steric and mass components. The mechanical atmospheric forcing (atmospheric pressure and wind) can also play a key role. In the Mediterranean Sea, for instance, the increase of the atmospheric pressure observed in the region during the last decades of the 20th century has counteracted the positive thermosteric trend, yielding negligible or even negative sea level rise (Tsimplis et al., 2005; Gomis et al., 2008).

The reconstruction undertaken from sea level observations has all the components in it, while the hindcast described in the next section is not forced by atmospheric pressure. Hence, the atmospheric component of sea level has to be estimated in an independent way and subtracted from the reconstruction (it could also be added to the hindcast) before comparing the two sea level representations.

The atmospheric component was produced in the framework of the HIPOCAS (Hindcast of Dynamic Processes of the Ocean and Coastal Areas of Europe) project (Guedes et al., 2002). The sea level simulation was obtained from a barotropic run of the HAMburg Shelf Circulation Model (HAMSOM) forced by surface atmospheric pressure and 10-m wind and performed with the same set-up used in the operational Spanish Sea Level Forecasting System. All the details of the simulation are given in Álvarez-Fanjul et al. (1997), Alvarez-Fanjul et al. (2001) and Sotillo et al. (2005). The skill of the model for the complete set of hindcasted oceanographic parameters is fully evaluated in Ratsimandresy et al. (2008). Several examples of the good agreement between modelled and actual sea level are given in Gomis et al. (2006). For the purpose of this work monthly time series were constructed for each grid point.

2.3 The 3D hindcast model

The high resolution Mediterranean Sea model used by Somot et al. (2006) is a regional version (OPAMED8) of the OPA model (Madec et al., 1998). It was used in a hindcast mode with a resolution of 1/8° x 1/8°cos(*latitude*) in the horizontal and 43 non-uniform Z-levels in the vertical. The 40-year simulation (1961-2000) will be hereinafter referred to as the OM8 simulation.

The forcing was based on an ERA-40 dynamical downscaling excluding atmospheric pressure. The downscaling technique (described in Herrmann and Somot, 2008) was carried out with a regional version of the ARPEGE-Climate model (Déqué and Piedelievre, 1995) that uses a stretched and tilted grid resulting in a horizontal resolution of about 50 km over the Mediterranean Sea. When the ARPEGE model is used in a “climate mode” it does not follow the real time chronology, but for the present application it was used in a “hindcast mode”, which allowed a high-resolution dynamical downscaling of the ERA40 reanalysis (Simmons and Gibson, 2000). The hindcast simulation covers the ERA40 period 1961-2001; air-sea fluxes (heat, water and momentum) were extracted from the atmospheric simulation at a daily time scale and used to force the OPAMED8 model leading to the OM8 simulation. The Mediterranean Sea simulation is then driven by air-sea fluxes which (1) have a high resolution (50 km),

(2) are homogeneous over a long period of time (no change in the model configuration), (3) follow the real synoptic chronology and (4) have a realistic interannual variability. A first validation of the air-sea flux dataset has been done in Herrmann and Somot (2008) for the case study of the 1986-87 winter.

Additional forcings of the OM8 simulation are climatological values (with an annual cycle) for the river runoff fluxes, the Black Sea inflow and the Atlantic boundary conditions; the latter consist of a 3D relaxation for θ and S applied in a buffer zone extending beyond the western limits of the Iberian Peninsula (11ºW). Hence, eventual sea level trends derived for instance from ice-melting occurring beyond the Atlantic boundary of the domain are not taken into account. Moreover, because the model is a rigid lid model, volume is conserved within the Mediterranean basin. Evaporation/ precipitation are accounted for by adding/taking out salt at the sea surface. On the other hand, the zero volume exchange through Gibraltar implies a net salt outflow, since the salt content of the outflowing Mediterranean water is higher than the salt content of the same volume of incoming Atlantic water. This altogether means that the model cannot reproduce actual mass variations. On the other hand, the fact that no sea surface salinity (SSS) relaxation is applied in OM8 means that the interannual variability of the SSS is free, what represents a significant improvement compared to state-of-the-art Mediterranean Sea models.

In a rigid lid model, total sea level change (ΔZ) must be computed from changes in the surface pressure. The steric component of sea level change (ΔZs) can be computed for each grid point as the vertical integration (from surface to bottom) of changes in the specific volume anomaly ($\Delta\alpha$) caused by changes in temperature and salinity:

$$\Delta Zs = -\frac{1}{g}\int_{Pb}^{Po} \Delta\alpha \cdot dp \qquad (1)$$

where P_o(=0) and P_b are the surface and bottom pressures.

2.4 The altimetry dataset

Altimetry data are used in this work as a reference when comparing the reconstruction and the hindcast simulation. 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 adjusted according to the most recent geophysical corrections.

3. Results

3.1 Sea level trends for the period 1993-2000

The reconstruction has already been compared with altimetry data in Calafat and Gomis (2009); the spatial distribution of trends (Fig. 1a-b) are shown here for the sake of completeness and because they differ from those shown in Calafat and Gomis (2009) in that those include the atmospheric forcing. Figures 1c-d show the trends for total sea level and the steric component derived from the model. In the Western Mediterranean the model shows a pattern that includes both negative (−5 mm yr^{-1}) and markedly positive (10 mm yr^{-1}) values and that does not match the pattern obtained from altimetry and the reconstruction. The positive trends obtained in the Eastern Mediterranean are more similar, but the values are smaller with respect to altimetry and the reconstruction. Slightly negative trends (−2 mm yr^{-1}) are obtained in the Ionian Sea, but they are much weaker than the observed trends and only cover a reduced sector to the south of the Ionian basin (Fig. 1c). The steric trends (Fig. 1d) show a spatial pattern similar to total sea level trends, but with small positive trends in the Ionian Sea and slightly larger positive trends in the Levantine basin.

The temporal sea level variability has been examined for the whole Mediterranean basin and for regions showing distinct features. Yearly time series of observed and reconstructed sea level averaged over the entire basin together with averaged total and steric sea level from the 3D model are plotted in Fig. 2. The interannual variability of the reconstruction is in good agreement with altimetry; the model (both total sea level and the steric component) shows an overall similar behaviour, but the interannual variability departs from observations. The trends computed for the four curves of Fig. 2 are given in Table 1. It must be stressed that for such a short period, trends undergo significant variations just by adding or taking out one year from the computations (e.g., Criado-Aldeanueva et al. (2008) give altimetric trends of 6.3±0.8 mm yr^{-1} for the period 1993-2001, in front of the 3.3±0.4 mm yr^{-1} given in Table 1 for the period 1993-2000).

Figure 3 shows yearly sea level time series averaged over the Aegean Sea, the Ionian Sea, the central Western Mediterranean (excluding the Alborán Sea and the Tyrrhenian Sea) and the whole Eastern Mediterranean basin. The limits of the averaged domains are shown in Fig. 1, while the derived linear trends are listed in Table 1. Note that the limits of the domain averaged in the Ionian Sea are different for the reconstruction (Fig. 1a) and the model (Fig. 1c). The reason is that in the model the negative trends appear displaced to the south (with respect to the reconstruction and altimetry) and the aim of the average was to reflect the time evolution of the main features observed in the trend distribution.

The Aegean Sea (Fig. 3a) is the region showing the closer behaviour to the basin mean sea level (Fig. 2) and also the region for which all estimations are closer to each other. All signals show a marked sea levl rise up to 1999, when sea level starts to decrese. The model clearly departs from altimetry only between 1994 and 1996, but these two years are enough to yield significantly different trends (Table 1). In the Ionian Sea (Fig. 3b) the model reflects some of the major features of the altimetric interannual variability, but it fails to reproduce the marked sea level decrease observed between 1998 and 2000. The reconstruction follows the altimetric variability much more closely.

The changes observed in the Aegen and Ionian Sea have been related to changes in the regional circulation associated with the Eastern Mediterranean Transient (EMT). Vigo et al. (2005) already found this sort of time-space oscillation between the Ionian Sea and the Levantine basin in which before 1999 a sea level rise and drop is observed in the Levantine basin and the Ionian Sea, respectively, while after 1999 the behaviour seems to be the opposite. This description is however handicapped by the short coverage of the altimetric period, which starts about eight years after the onset of the EMT. The described features will be re-visited when examining the whole 1960-2000 period.

The Western Mediterranean (Fig. 3c) is the only region where the model follows the observed interannual variability, sometimes even more closely than the reconstruction (in 1993-1998 for instance). The reconstruction and model trends are both in agreement with the altimetric trend (within the statistical uncertainty; see Table 1). Regarding the Eastern Mediterranean (Fig. 3d), the reconstruction follows the altimetric variability much more closely than the model; however, the reconstructed and the steric trends for this regions are very similar and in good agreement with altimetric trends (Table 1). Trends associated with total model sea level are much higher than the observed trends.

3.2 Sea level trends for the period 1961-2000

The regional distributions of sea level trends for the period 1961-2000 estimated from the reconstruction and the model (total sea level and the steric component) are shown in Fig. 4. The distribution estimated from the reconstructed fields (Fig. 4a) shows positive trends everywhere, but larger in the Western Mediterranean (up to 1.2 mm yr^{-1}) than in the Eastern Mediterranean (up to 0.6 mm yr^{-1}). A prominent feature is the relative maximum in the Ionian Sea (up to 1.8 mm yr^{-1}), while almost zero trends are observed in the Levantine basin. The trend distribution obtained from the OM8 simulation (Fig. 4b) is also positive everywhere; the overall differences with respect to the reconstruction are that trends are less homogeneous and values are slightly higher than in the reconstruction (up to 1.5 mm yr^{-1} in the Western Mediterranean and larger than 0.5 mm yr^{-1} in the Eastern basin). The OM8 simulation also reproduces the positive peak in the Ionian Sea, though it covers a smaller area and it appears surrounded by other mesoscale structures.

The distribution of trends derived from the model steric contribution (Fig. 4c) resembles model total sea level trends except in that values are significantly larger in the Western Mediterranean (above 2 mm yr^{-1} everywhere) and also, though to a lesser extent, in the Eastern basin (up to 1.5 mm yr^{-1}). The positive peak in the Ionian Sea is similar to the one obtained for total sea level (up to 2 mm yr^{-1}). Higher values of steric and total sea level trends in the model are obtained in the Alboran Sea.

It is worth noting that the steric trend distribution appears to follow the most prominent bathymetric changes. This is due to the fact that steric changes are integrated over the whole water column (see expression (1)) and therefore they depend on depth. This does not mean that, in the case of a hypothetical homogeneous warming, sea level would remain much higher where the water column is deeper (i.e., over larger depths); as the water would warm up and start to be higher over larger depths, it would flow over shallower depths, where sea level would be lower. This mass redistribution (associated with changes in the circulation) is usually referred to as the dynamical component.

The temporal sea level variability of the whole period 1961-2000 has also been examined for the whole Mediterranean basin and for regions showing distinct features. Yearly time series of reconstructed sea level averaged over the entire basin together with averaged total and steric sea level from the 3D model are plotted in Fig. 5. Like for the altimetric period, the reconstructed and modelled mean sea level show a similar overall behaviour, though some details of the interannual variability are rather different (see for instance the disagreement in 1970 and in 1982-1985); the correlation between the two series is 0.8 (quoted correlations are always significant at the 95% confidence level, unless otherwise stated). The rate of mean sea level rise for the reconstruction and for the total sea level derived from the model are very similar (around 1 mm yr^{-1}, see

Table 2). The evolution of the steric contribution closely follows the modelled total sea level, though the linear trend is slightly larger (Table 2).

The overall comments pointed out for the comparison of reconstructed and modelled basin mean sea level can be extended to the time evolution of the Aegean Sea, the Ionian Sea, the Western Mediterranean and the Eastern Mediterranean (Fig. 6). In the Aegean Sea (Fig. 6a), the evolution of the reconstructed sea level can be broken into three different periods: negligible trends for the period 1961-1987, a marked sea level lowering for the period 1987-1995 (the EMT) and a pronounced rebound for the period 1995-2000. The modelled sea level reproduces the first period and the 1995-2000 sea level rebound, but fails to reproduce the sea level fall associated with the EMT (the correlation between the two series is 0.6). The trends estimated in the Aegean Sea for the reconstruction are weaker than for the total OM8 sea level fields (Table 2). The difference is mainly due to the departure between both signals during the EMT period (1987-1995). The steric component closely follows the total modelled sea level and hence the associated trend is also similar (Table 2).

Also the Ionian sea level evolution can be split into three distinct periods attending to the reconstruction: a smooth sea level increase from 1961 to 1987, values much higher than normal during the EMT years (1987-1995) and values lower than normal after the EMT (Fig. 6b). For the first period the reconstructed and modelled sea level are rather similar, though with some localized departure (e.g. in 1969). Consequently the trends are similar for this period (1.6 ± 0.2 mm yr^{-1} for the reconstruction and 1.4 ± 0.2 mm yr^{-1} for the OM8 simulation). The behaviour of both representations diverges after 1987. While the reconstruction shows a sudden sea level increase during the EMT years (peaking in 1991) followed by a fall down to values that are several cm smaller than pre-EMT values, the OM8 simulation does not show significant variations, neither during the EMT nor for the post-EMT years. The correlation between the reconstructed and total OM8 mean sea level in the Ionian Sea is 0.5 and the trends for the whole period 1961-2000 are shown in Table 2. The steric sea level resembles total sea level for the whole period 1961-2000, with only a few localized disagreements.

In the western Mediterranean (Fig. 6c) the reconstructed and the total OM8 sea level fields show similar positive trends (Table 2). However, the agreement between the two series is only fair at the interannual scale (the correlation between the two series is 0.7). A distinct feature with respect to the Aegean and the Ionian Sea is that here the steric sea level departs more significantly from the modelled total sea level. The steric component is smaller than total sea level in the 60s and larger in the 90s, which results in a larger trend (2.5 mm yr^{-1} for the whole period 1961-2000). The correlation between the reconstruction and the steric sea level in the western Mediterranean is 0.8.

Finally, in the Eastern Mediterranean the variability of the period 1961-2000 (Fig. 6d) resembles the variability found in the Aegean Sea (Fig. 6a), though the variations during the EMT and post-EMT periods are obviously smoothed. Another difference is that the variability of the reconstruction and the model (for both total sea level and the steric component) are more similar, which translates in more similar trends (Table 2).

4. Discussion and conclusions

We have compared the reconstruction of Mediterranean sea level fields carried out by Calafat and Gomis (2009) with the sea level fields obtained from the output of a regional 3D baroclinic model. The comparison covers the four decades common to both sea level representations (1961-2000) and has been divided in two periods: the period for which altimetry data are available (1993-2000) and the whole period 1961-2000.

The fact that the overall trends of mean sea level given by the reconstruction and the model are similar must not hide the significant differences between the two representations. First of all it must be recalled that the model uses a (monthly) climatology at the boundary of the Atlantic sector covered by the domain. It is clear that by using such condition the model cannot account for mass increments derived from continental ice melting, mass redistribution in the Atlantic Ocean or any other remote source of sea level changes. On the other hand, the reconstruction bases on the interpolation of actual sea level data and therefore it implicitly accounts for the eventual impact of such remote sources. Hence, unless the mass increase in the nearby Atlantic region has a negligible impact on Mediterranean sea level, the trends derived from the reconstruction should be larger than the trends derived from the model.

The crucial question is which of the two representations gives the best approach to actual sea level fields. For the altimetric period the reconstruction is clearly superior, but this was an expected result, since altimetry data are used to build up the reconstruction. For the whole period the only available sea level observations are tide gauge records. In order to be compared with the model and the reconstruction, the atmospheric contribution can be estimated at tide gauge stations from the output of the barotropic model described in section 2.2 (taking the closest HAMSOM gridpoint) and subtracted from tide gauge records. The result for the longest tide gauge records available in the Mediterranean Sea is shown in Fig. 7 (shown in Tsimplis et al., 2005 and reproduced here for the sake of completeness). The comparison between Figs. 5 and 7 reveals that the time evolution of mean sea level as given by the reconstruction is much more similar to tide gauge records than the mean sea level computed from the model. Prominent features common to most tide gauges such as the relative maxima recorded around 1960 and 1970 or the minima recorded in the middle 60s and the middle 70s are well recovered by the reconstruction, but not by the model.

There are also evidences that the reconstruction does a better job at regional scale. During the EMT (1987-1995) sea level dropped in the Aegean Sea and rose in the Ionian Sea, following the shift in the location of the main source of deep water formation from the Adriatic to the Aegean Sea (Roether et al. 1996; Theocharis et al., 1999). A first explanation for the impact of the described physical processes on regional sea level would be that the onset of deep water formation in the Aegean Sea implies densities higher than normal and, consequently lower sea level (sometimes linked to cyclonic circulation, depending on bathymetric constraints). Conversely, in the Ionian Sea, a transit basin for deep waters formed in the Adriatic, the stop of deep water formation would imply a lowering of isopycnals, with the consequent sea level rise and the triggering of anticyclonic circulation. The minimum/maximum values in the Aegean/Ionian Sea were achieved in 1991-1992, getting back to ‘normal’ values by 1995 (when the EMT was over, according to Klein et al., 2000, and Manca et al., 2006). In terms of sea level, however, after 1995 both the Aegean Sea and the Ionian Sea show a clear positive/negative rebound that affected the whole Eastern basin and that apparently ended in 1999 (Vigo et al., 2005). The physical processes underlying the observed rebounds would need of a carefully interpretation of the hydrographic data available in the region during the post-EMT years.

All these features are well reproduced by the reconstruction (Figs. 6a-b) but not by the model. It is worth noting that the period 1987-1992 is not covered by altimetry, so that the recovery of sea level fields for that period must be attributed to the successful methodology used for the reconstruction and not to the advantage of using contemporary altimetry data.

There may be several reasons why the model does not properly reproduce some of the major sea level features observed in the Mediterranean Sea during the last decades. Using climatological boundary conditions beyond the Atlantic sector might not only exclude the influence of remote features; it could also affect the water exchange through Gibraltar (which depends on the pressure gradients at the Strait) and hence influence Mediterranean mean sea level. A second model feature that might constrain the long-term evolution of hydrographic variables within the basin is the condition of zero net volume flux through Gibraltar (a consequence of using a rigid-lid model). The large trends of the steric component found in the western Mediterranean could actually be attributed to a spurious warming of deep waters (S. Somot, personal communication), but the ultimate cause of the warming has not yet been explained. Simple (box) models could help to investigate the effects of model constraints on the mean temperature and salinity of the basin and find out whether they may be causing spurious trends as a response to changes in the heat and freshwater budgets within the basin.

At regional scale, the difficulties of the model to reproduce sea level changes derived for instance from the EMT are more likely due to the heat and freshwater forcing. Beuvier et al. (2008) have recently shown that considering the interannual variability of the river runoff and the Black Sea outflow (instead of considering just an annual cycle) has a significant impact on the EMT. In particular, the Black Sea runoff impacts the Aegean convection during the years preceding the EMT, though the timing of the EMT seems more related to the atmospheric forcing.

Regarding the reconstruction, it is worth recalling that the atmospheric contribution was subtracted from the original values shown in Calafat and Gomis (2009) in order to be compared with the model. The trend associated with the atmospheric contribution has a basin mean value of -0.7 ± 0.2 mm yr^{-1}, which implies that the total sea level trend for the period 1961-2000 would be 0.3±0.1 mm yr^{-1}. Figure 8 shows the reconstructed mean sea level with and without the atmospheric contribution, as well as the atmospheric contribution itself. It shows that the negative trend of the atmospheric contribution lasted until 1990, when it started to recover.

The sea level reconstruction is surely submitted to significant uncertainties. However, the fact that not only the inferred basin mean sea level follows the behaviour of tide gauge records, but also key regional sea level features such as those associated with the EMT are reproduced, suggests that the reconstruction can be used to check further improvements in the output of regional models. This is particularly important for regions and periods for which historical hydrographic data are sparse.

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FIGURE CAPTIONS

Figure 1. The distribution of sea level trends for the period 1993-2000 estimated from (a) altimetry data: (b) reconstructed sea level fields; (c) sea level derived from the OM8 simulation; and (d) the steric component of sea level derived from the OM8 simulation. The contour interval is 5 mm yr^{-1}. Note the different scale ranges. The enclosed regions in figures (a) and (c) denote the averaged domains used in Figs. 3 and 6: the Western Mediterranean, the Aegean Sea and the Ionian Sea (note that for the latter the averaged domain is different for the reconstruction (a) and for the model (c)). The Eastern Mediterranean domain has not been enclosed since it includes the whole basin to the east of the strait of Sicily.

Figure 2. Yearly Mediterranean mean sea level for the period 1993-2000 estimated from altimetry data, reconstructed sea level fields, total OM8 sea level and the steric component of OM8 sea level.

Figure 3. Yearly regional-averaged sea level for the period 1993-2000 estimated from altimetry data, reconstructed sea level fields, total OM8 sea level and the steric component of OM8 sea level for: (a) the Aegean Sea; (b) the Ionian Sea; (c) the Western Mediterranean and (d) the Eastern Mediterranean. The domains of the averages are shown in Fig. 1.

Figure 4. The distribution of sea level trends for the period 1961-2000 as estimated from (a) reconstructed sea level fields; (b) sea level derived from the OM8 simulation; and (c) the steric component of sea level derived from the OM8 simulation. The contour interval is 0.3 mm yr^{-1} in (a) and 0.5 mm yr^{-1} in (b) and (c).

Figure 5. Yearly Mediterranean mean sea level for the period 1961-2000 estimated from reconstructed sea level fields, total OM8 sea level and the steric component of OM8 sea level.

Figure 6. Yearly regional-averaged sea level for the period 1961-2000 estimated from reconstructed sea level fields, total OM8 sea level and the steric component of OM8 sea level for: (a) the Aegean Sea; (b) the Ionian Sea; (c) the Western Mediterranean and (d) the Eastern Mediterranean. The domains of the averages are shown in Fig. 1.

Figure 7. The longest tide gauge records in the Mediterranean Sea after removal of the atmospheric contribution (from Tsimplis et al., 2005).

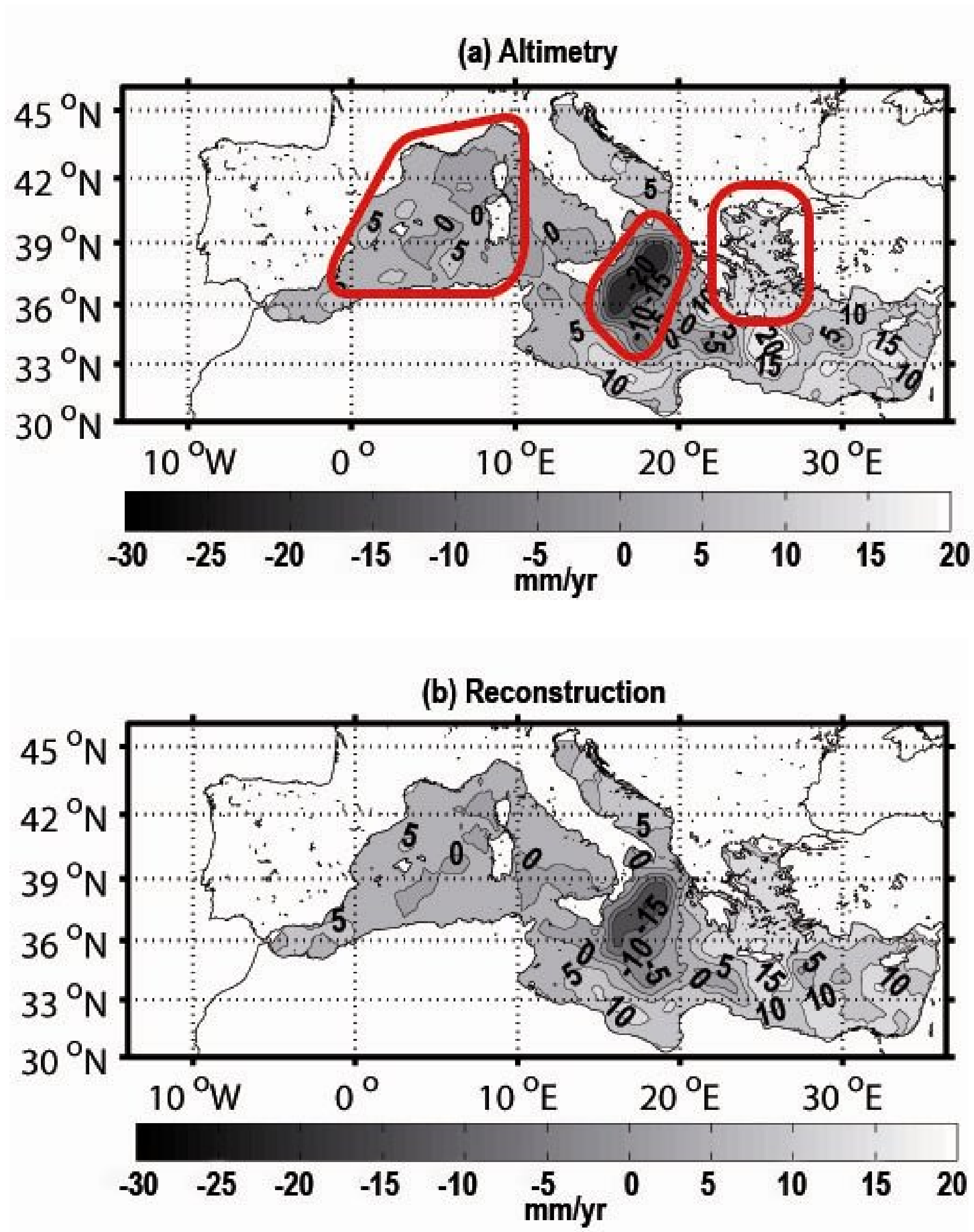
Figure 8. Total Mediterranean mean sea level obtained from the reconstruction with and without the atmospheric contribution. The latter is plotted with a zero mean value.

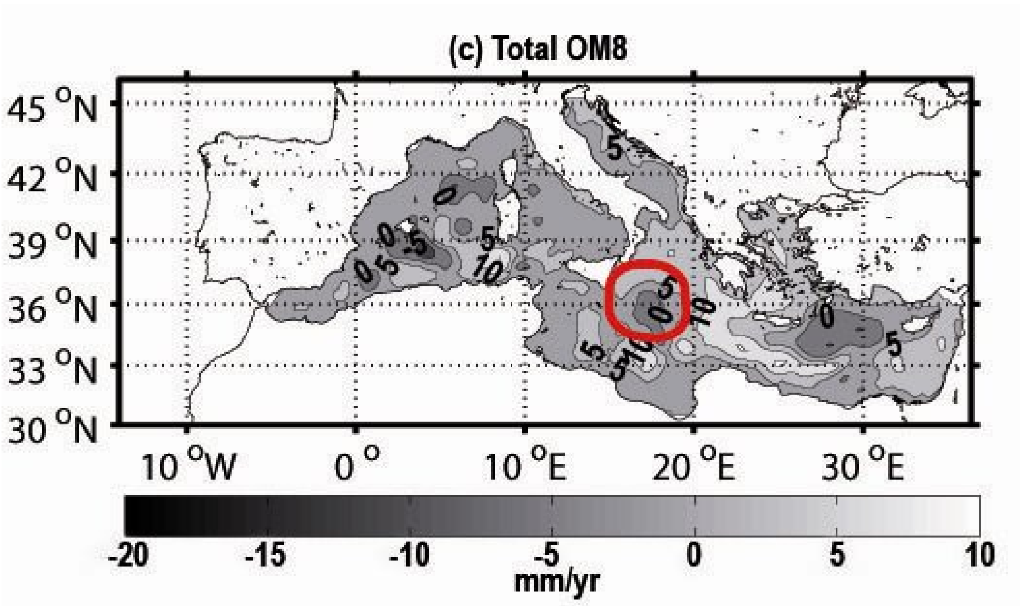
Table 1. Sea level trends for the period 1993-2000 estimated from altimetry data, reconstructed sea level fields, total OM8 sea level and the steric component of OM8. Trends are given for the whole Mediterranean, the Aegean Sea, the Ionian Sea the Western Mediterranean and the Eastern Mediterranean.

Sea level trends 1993-2000 (mm yr^{-1})	**Mediterranean basin**	**Aegean Sea**	**Ionian Sea**	**Western Mediterranean**	**Eastern Mediterranean**
Altimetry data	3.3 $\pm$ 0.4	11.8 $\pm$ 1.0	-13.0 $\pm$ 1.0	1.8 $\pm$ 0.4	4.1 $\pm$ 0.4
Reconstruction	3.5 $\pm$ 0.5	11.6 $\pm$ 1.0	-9.7 $\pm$ 1.0	1.8 $\pm$ 0.4	4.5 $\pm$ 0.5
Total OM8	4.1 $\pm$ 0.4	6.5 $\pm$ 0.8	-1.9 $\pm$ 0.6	2.2 $\pm$ 0.4	4.9 $\pm$ 0.6
Steric OM8	4.6 $\pm$ 0.5	9.1 $\pm$ 1.0	0.3 $\pm$ 0.2	2.1 $\pm$ 0.4	6.1 $\pm$ 0.5

Table 2. Sea level trends for the period 1961-2000 estimated from reconstructed sea level fields, total OM8 sea level and the steric component of OM8. Trends are given for the whole Mediterranean, the Aegean Sea, the Ionian Sea, the Western Mediterranean and the Eastern Mediterranean.

Sea level trends 1961-2000 (mm yr^{-1})	**Mediterranean basin**	**Aegean Sea**	**Ionian Sea**	**Western Mediterranean**	**Eastern Mediterranean**
Reconstruction	1.0 $\pm$ 0.2	0.5 $\pm$ 0.1	1.7 $\pm$ 0.2	1.1 $\pm$ 0.2	0.8 $\pm$ 0.2
Total OM8	1.1 $\pm$ 0.2	1.1 $\pm$ 0.2	1.5 $\pm$ 0.2	1.4 $\pm$ 0.2	1.1 $\pm$ 0.2
Steric OM8	1.3 $\pm$ 0.2	1.0 $\pm$ 0.2	1.8 $\pm$ 0.2	2.5 $\pm$ 0.3	1.1 $\pm$ 0.2


(a) Altimetry
45 °N
42 °N
39 °N
36 °N
33 °N
30 °N
10 °W
0 °
10 °E
20 °E
30 °E
-30 -25 -20 -15 -10 -5 0 5 10 15 20
mm/yr
(b) Reconstruction
45 °N
42 °N
39 °N
36 °N
33 °N
30 °N
10 °W
0 °
10 °E
20 °E
30 °E
-30 -25 -20 -15 -10 -5 0 5 10 15 20
mm/yr



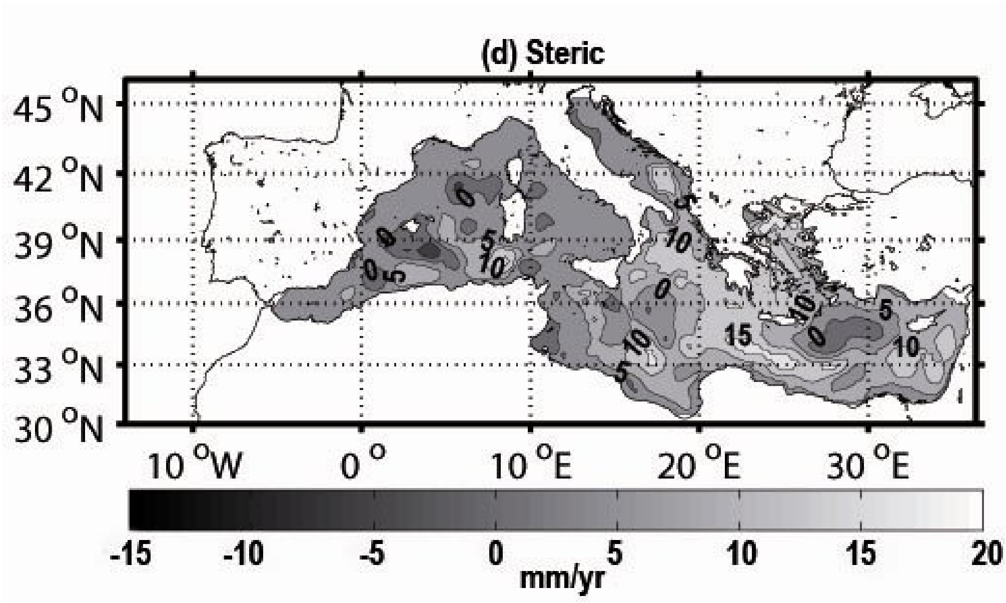


Figure 1. The distribution of sea level trends for the period 1993-2000 estimated from (a) altimetry data: (b) reconstructed sea level fields; (c) sea level derived from the OM8 simulation; and (d) the steric component of sea level derived from the OM8 simulation. The contour interval is 5 mm yr^{-1}. Note the different scale ranges. The enclosed regions in figures (a) and (c) denote the averaged domains used in Figs. 3 and 6: the Western Mediterranean, the Aegean Sea and the Ionian Sea (note that for the latter the averaged domain is different for the reconstruction (a) and for the model (c)). The Eastern Mediterranean domain has not been enclosed since it includes the whole basin to the east of the strait of Sicily.

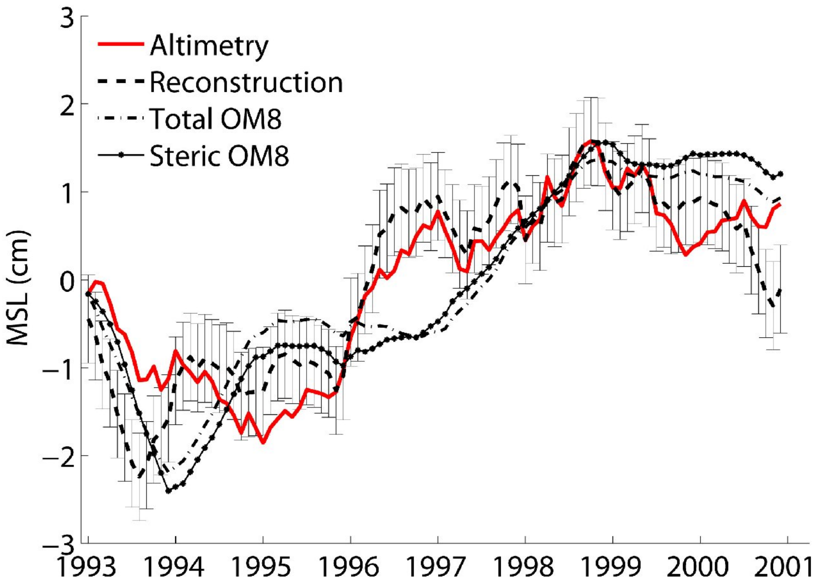
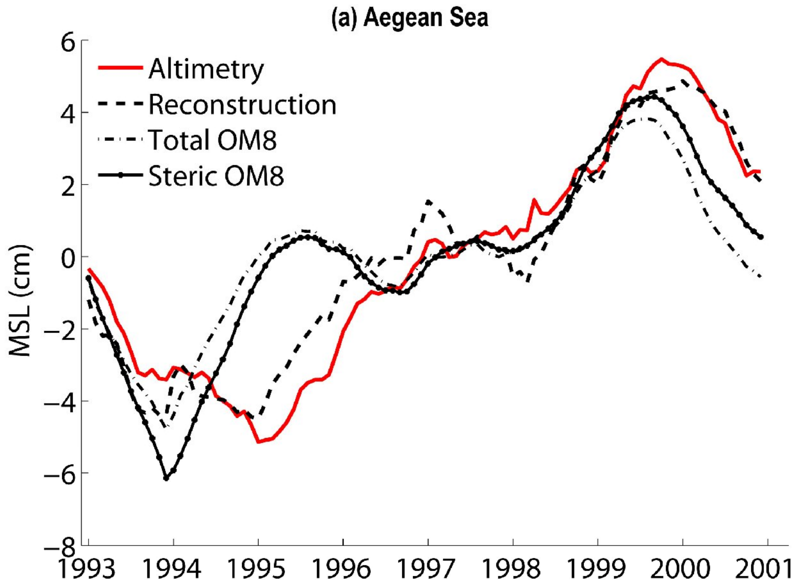
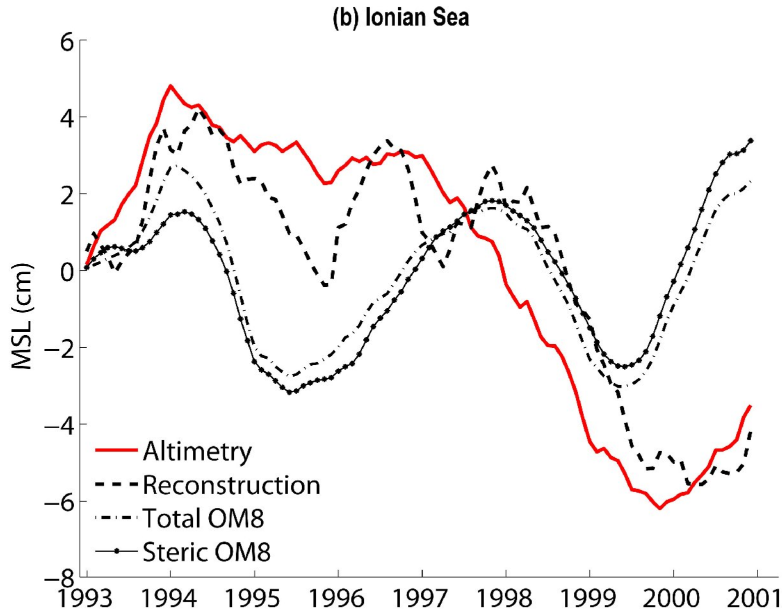
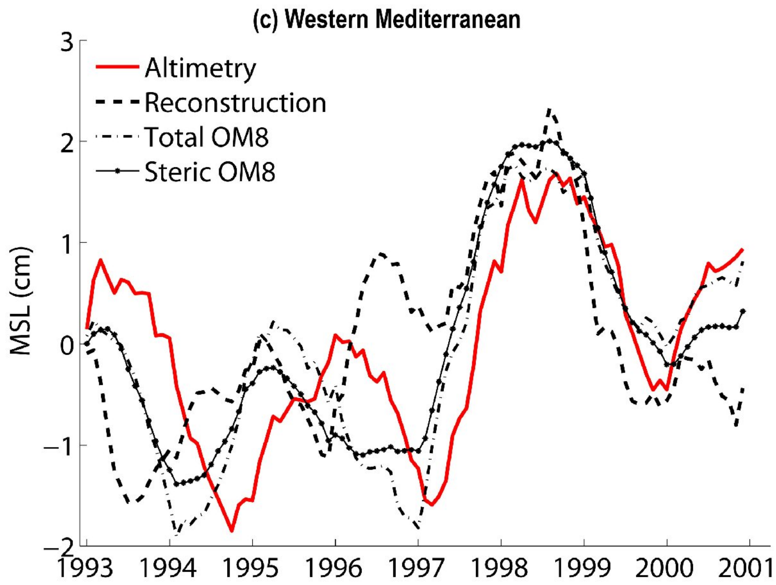


Figure 2. Yearly Mediterranean mean sea level for the period 1993-2000 estimated from altimetry data, reconstructed sea level fields (with error bars), total OM8 sea level and the steric component of OM8 sea level.


(a) Aegean Sea
Altimetry
Reconstruction
Total OM8
Steric OM8
MSL (cm)
6
4
2
0
−2
−4
−6
−8
1993
1994
1995
1996
1997
1998
1999
2000
2001


(b) Ionian Sea
Altimetry
Reconstruction
Total OM8
Steric OM8
MSL (cm)
6
4
2
0
−2
−4
−6
−8
1993
1994
1995
1996
1997
1998
1999
2000
2001



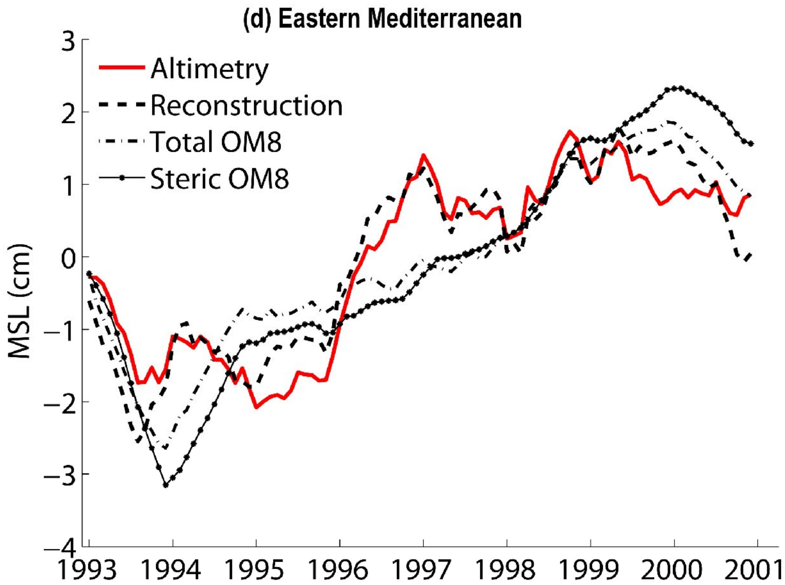
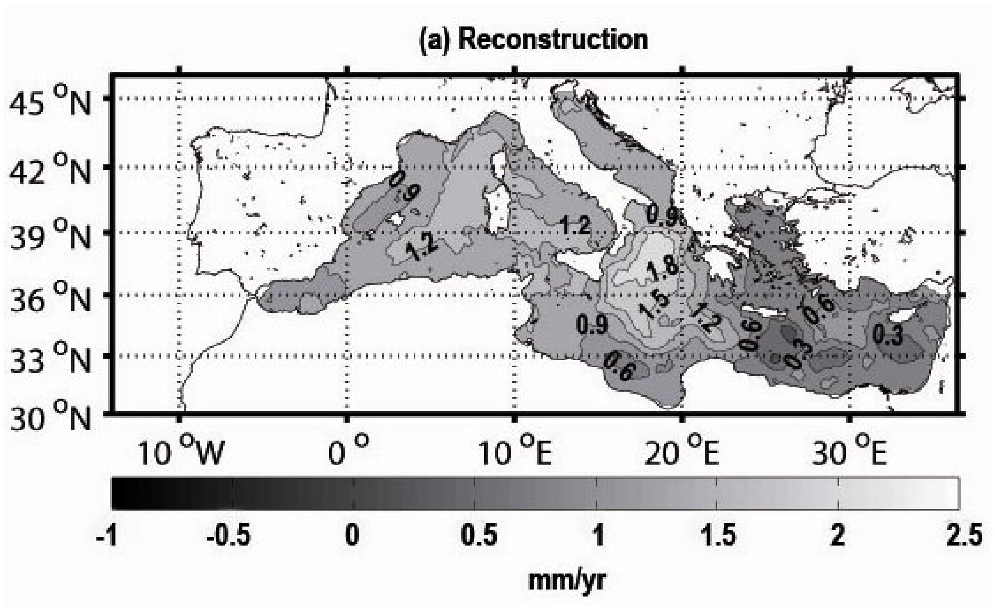
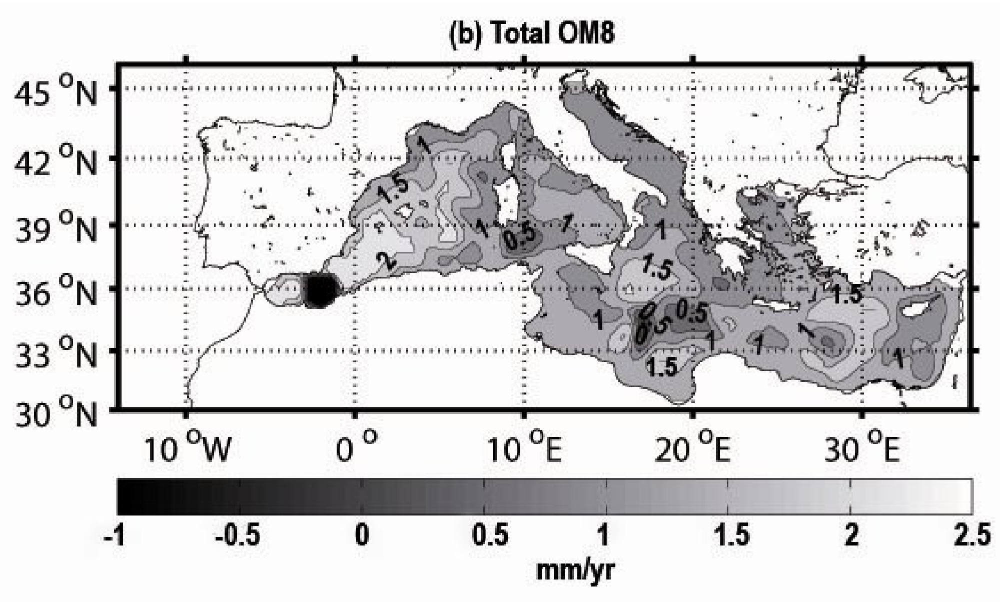


Figure 3. Yearly regional-averaged sea level for the period 1993-2000 estimated from altimetry data, reconstructed sea level fields, total OM8 sea level and the steric component of OM8 sea level for: (a) the Aegean Sea; (b) the Ionian Sea; (c) the Western Mediterranean and (d) the Eastern Mediterranean. The domains of the averages are shown in Fig. 1.


(a) Reconstruction
45 °N
42 °N
39 °N
36 °N
33 °N
30 °N
10 °W
0 °
10 °E
20 °E
30 °E
-1
-0.5
0
0.5
1
1.5
2
2.5
mm/yr


(b) Total OM8
45 °N
42 °N
39 °N
36 °N
33 °N
30 °N
10 °W
0 °
10 °E
20 °E
30 °E
-1
-0.5
0
0.5
1
1.5
2
2.5
mm/yr

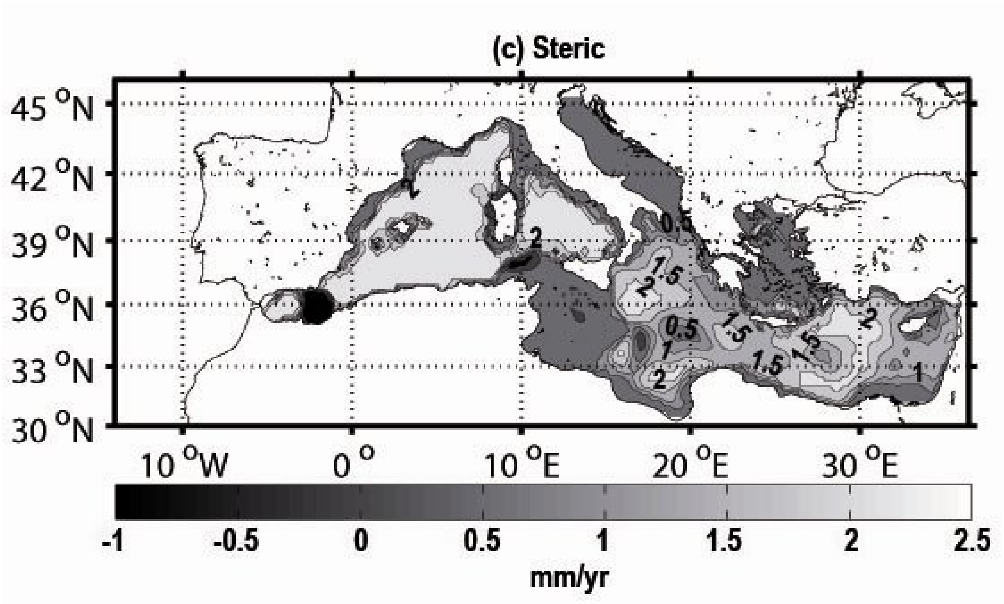


Figure 4. The distribution of sea level trends for the period 1961-2000 as estimated from (a) reconstructed sea level fields; (b) sea level derived from the OM8 simulation; and (c) the steric component of sea level derived from the OM8 simulation. The contour interval is 0.3 mm yr^{-1} in (a) and 0.5 mm yr^{-1} in (b) and (c).

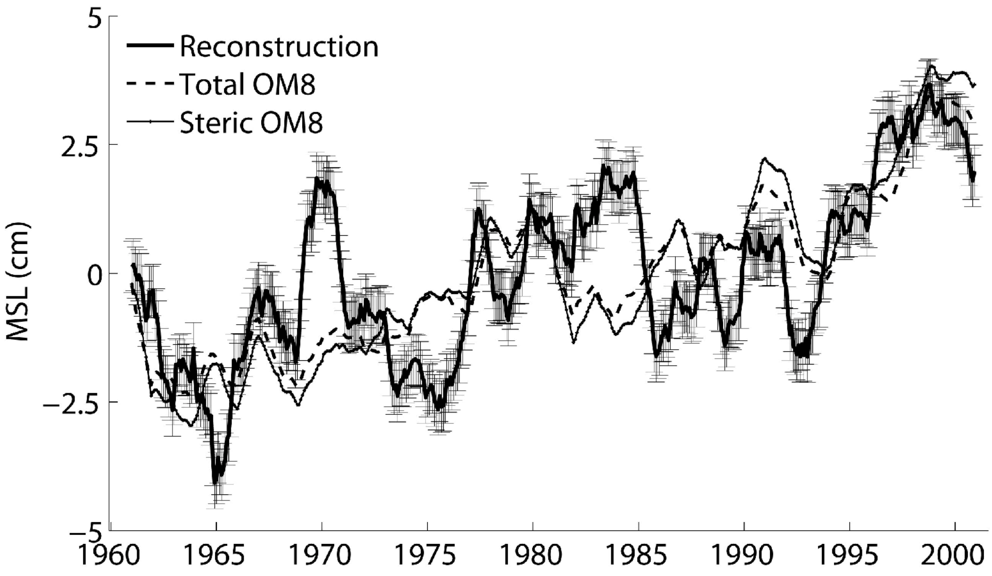
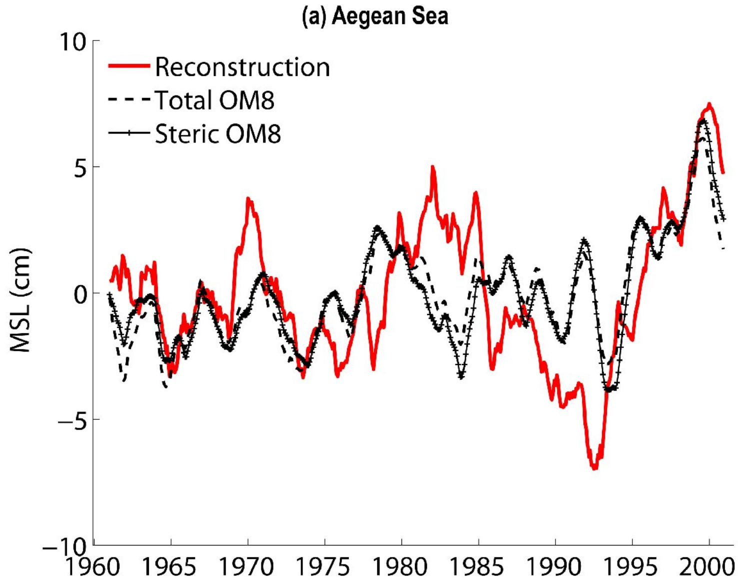
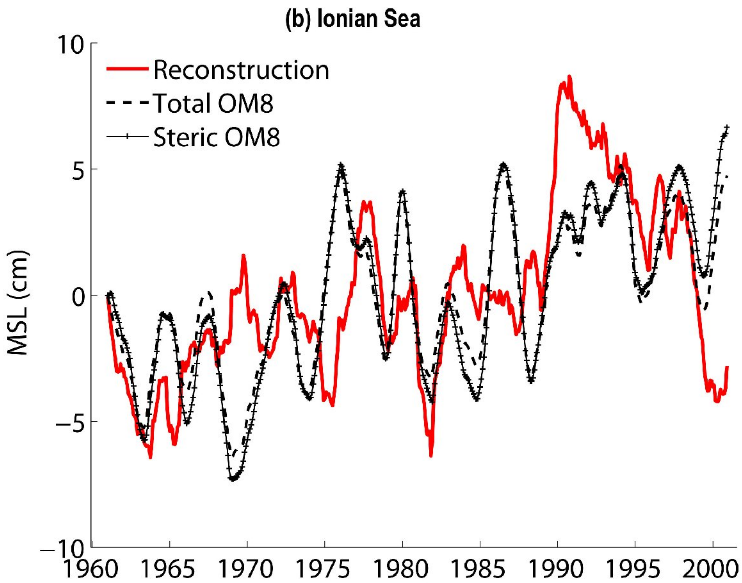
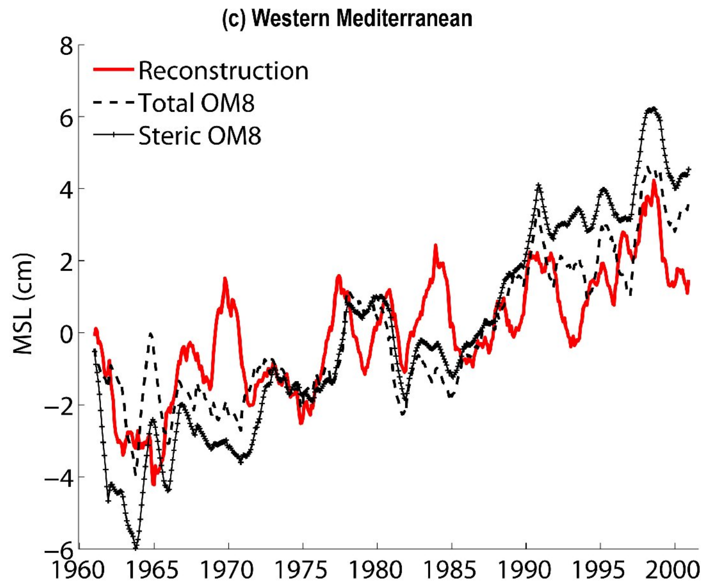
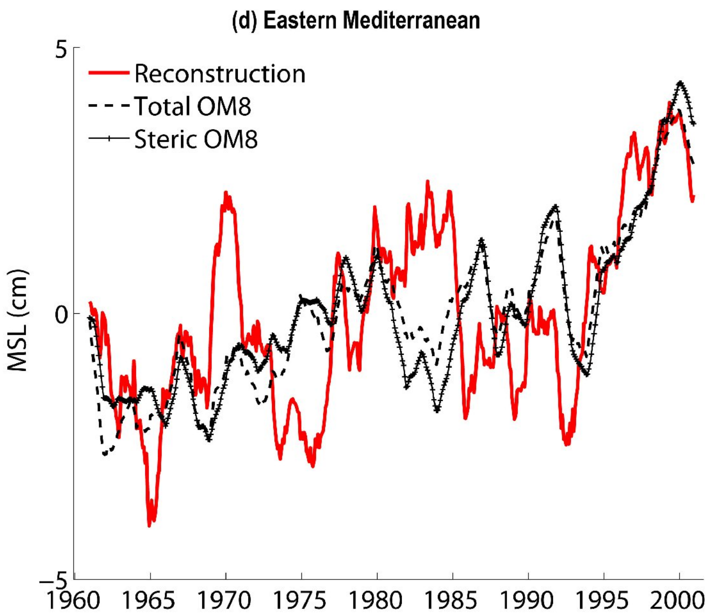


Figure 5. Yearly Mediterranean mean sea level for the period 1961-2000 estimated from reconstructed sea level fields, total OM8 sea level and the steric component of OM8 sea level.


(a) Aegean Sea
Reconstruction
Total OM8
Steric OM8
MSL (cm)
10
5
0
−5
−10
1960
1965
1970
1975
1980
1985
1990
1995
2000


(b) Ionian Sea
Reconstruction
Total OM8
Steric OM8
MSL (cm)
10
5
0
−5
−10
1960
1965
1970
1975
1980
1985
1990
1995
2000





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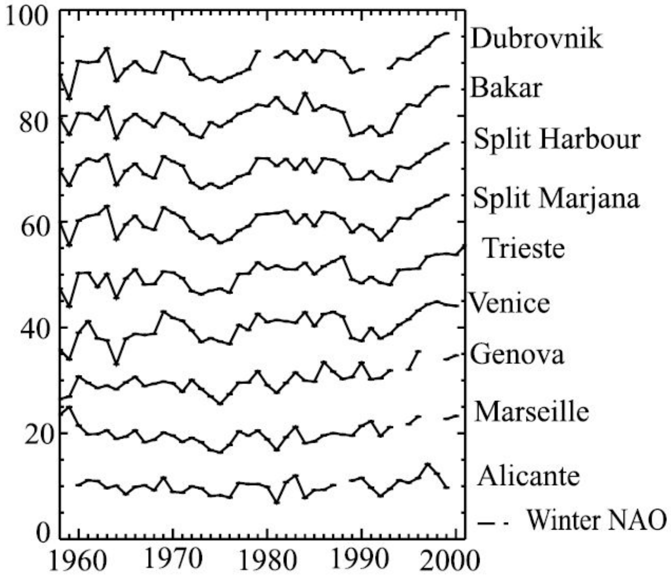

Figure 7. The longest tide gauge records in the Mediterranean Sea after removal of the atmospheric contribution (from Tsimplis et al., 2005).

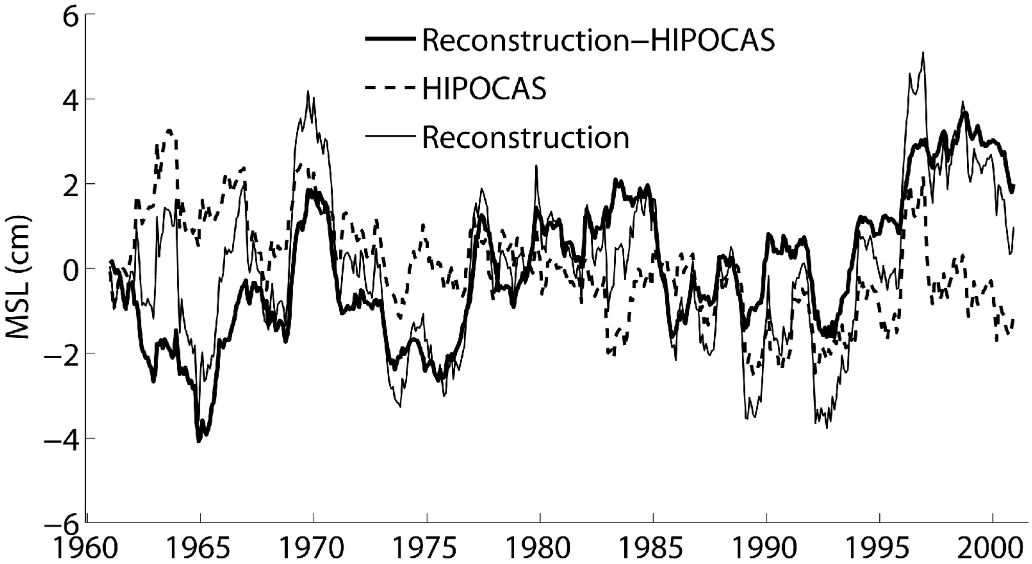

Figure 8. Total Mediterranean mean sea level obtained from the reconstruction with and without the atmospheric contribution. The latter has been obtained from a barotropic model and is plotted with a zero mean value.