STERIC AND MASS-INDUCED MEDITERRANEAN SEA LEVEL TRENDS FROM 14 YEARS OF ALTIMETRY DATA

Francisco Criado-Aldeanueva[1], Jorge Del Río Vera[2] and Jesús García-Lafuente[1]

[1] *Departamento de Física Aplicada II, Universidad de Málaga, Málaga, Spain.*

[2] *Mission Planning and User Services Office ESRIN/European Space Agency, Rome, Italy*

Corresponding author:

Francisco Criado Aldeanueva

Dpto. Física Aplicada II, Universidad de Málaga

29071 Málaga, Spain

Tel.: +34 952 132849, Fax: +34 952 131355

fcaldeanueva@ctima.uma.es

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ABSTRACT

Long-term series of almost 14 years of altimetry data (1992-2005) have been analysed along with Sea Surface Temperature (SST) and temperature and salinity profiles to investigate sea level trends over the Mediterranean Sea. Although sea level variations are mainly driven by the steric contribution, the mass-induced component plays some role in modulating its oscillation. A spatially averaged positive trend of 2.1±0.6 mm/year has been observed, but a change in sign in 2001 seems to appear. Steric effects (mainly on thermal origin) account for ~55% of sea level trend. Although Mediterranean Sea is a semi-enclosed basin, this value is comparable to that reported for the global ocean. Sea level rise is particularly important in the Levantine basin south of Crete with values up to 10±1 mm/year. Other areas of sea level rise are localised throughout the Levantine basin and in the Adriatic and Alboran Seas, with more moderate values. Sea level drop areas are localised in the Algerian basin, between the Balearic Islands and the African coasts and, particularly, in the Ionian basin. In this area, negative trends as high as -10±0.8 mm/year are detected mainly due to the mass-induced contribution, which suggests decadal changes of surface circulation. The inferred sea level trends have been correlated with North Atlantic Oscillation (NAO) indices and a low but significant correlation has been detected between sea level in the Levantine and Balearic basins and NAO index.

KEYWORDS

Sea Level, Sea Surface Temperature, trends, satellite altimetry, Mediterranean Sea.

1.- INTRODUCTION

The Mediterranean Sea (Figure 1), a semi-enclosed basin that extends over 3000 km in longitude and over 1500 km in latitude, communicates with the Atlantic Ocean through the Strait of Gibraltar and with the Black Sea through the Turkish Bosphorus and Dardanelles Straits. The Strait of Sicily separates the western and eastern Mediterranean basins. Due to the prevailing dry northwestly winds and frequent sunny days, there is a yearly average excess (about 100 cm/year) of evaporation over precipitation (Bethoux and Gentili, 1999; Cazenave et al., 2002), with higher values over the eastern basin. An Atlantic inflow through the Strait of Gibraltar contributes to balance the volume and salt budgets and becomes saltier and denser while spreading into the western and eastern basins under the influence of intense air-sea interactions. Most of this flow returns to the Atlantic Ocean as Levantine Intermediate Water (LIW), formed during winter convection in the Levantine basin, while other part is transformed into western Mediterranean Deep Water (WMDW) in the Gulf of Lyon, which may eventually comprise the Gibraltar outflow (Bryden and Stommel, 1982; Larnicol et al., 1995; Astraldi et al., 2002). This makes all water masses closely related and any significant modification involving a single water mass may propagate its effect to the others.

Over the past few decades, a series of important changes such as the increase in the temperature and salinity of the WMDW (Rohling and Bryden, 1992; Bethoux and Gentili, 1999), the appearance of a deep water formation site in the southern Aegean Sea (Roether et al., 1996) and some changes in the LIW characteristics both in the eastern and western basins (Hetch, 1992, 1995) have been taking place. Tsimplis and Josey (2001) suggest that all the changes may be linked with changes in the large-scale meteorological forcing, particularly with the North Atlantic Oscillation (NAO). The signature of these changes in the total sea level and Sea Surface Temperature (SST) is nowadays a topic of interest as it can be used for predicting correlated changes and diagnosing climatic trends.

Santoleri et al. (1999), using a nine-year (1982-1990) dataset of SST satellite images depict the interannual variability of the SST field in the western Mediterranean and report a positive trend of 0.15ºC/year, which is similar to that presented by Marullo et al. (1999) for the eastern basin. Moron (2003), using the Global Ocean Sea Temperature Atlas data from 1856 to 2000, analyses the long term variability of the SST over the Mediterranean Sea and reports a weak positive trend of 0.1ºC per century superposed to an irregular oscillation of 60-70 years period (maxima around 1875, 1940 and 2000 and minima near 1860, 1905 and 1980).

The estimation of total sea level was primarily achieved by means of tide gauge stations located in coast worldwide. Trends vary considerably with location, although the accepted global range is 1-2 mm/year (Church et al., 2001) with lower values, about 0.5 mm/year (Cazenave et al., 2002) for the Mediterranean Sea over the last decades. The launch in 1991 of ERS-1 and TOPEX/POSEIDON (T/P) satellites started the altimetry missions, which provide open ocean sea level data shedding new possibilities to sea level studies. Larnicol et al. (1995), using 2 years of T/P altimetry data, first studied the mean sea level and surface circulation variability of the Mediterranean Sea. More recently, using 6-year long time series, Larnicol et al. (2002) refined their pioneer study and detailed major changes in the Mediterranean surface circulation at basin and sub-basin scales. Cazenave et al. (2002), merging 6 years (1993-1998) of T/P data with

ERS-1 data (October 1992 to June 1996), have reported a mean sea level rise of approximately 7±1.5 mm/year in the Mediterranean Sea, although its spatial distribution is not uniform: while the Levantine basin is rising at a rate of 25-30 mm/year, the Ionian Sea is falling 15-20 mm/year. In the western basin, sea level trends are significantly lower, some regions rising and others falling. Using longer data series -9 years of T/P, ERS-1 and ERS-2 merged data-, Fenoglio-Marc (2002) found more moderate trends: 2.2 mm/year for the entire Mediterranean, with lower values in the western basin (about 0.4 mm/year), higher in the eastern (some 9.3 mm/year) and, again, a sharp decrease of 11.9 mm/year in the Ionian Sea. The high correlation observed between the total sea level and SST points to a thermal origin for the sea level change. Using almost 15 years of altimetry data, Vigo et al. (2005) have reported a significant change in the sea level trend from mid-1999 in certain regions of the Mediterranean that claims for further research.

The volume of water that determines the mean sea level in an oceanic basin (ξ_T) is the combination of two effects: steric, ξ_S and mass-induced, ξ_M. The first one accounts for the volumetric expansion or contraction induced by variations in temperature and salinity in the water while the mass-induced contribution is the result of addition (precipitation, river runoff, melting of glacier ice,…) or subtraction (evaporation, dam impoundment on land,…) water to or from the sea.

$$\xi_T = \xi_S + \xi_M + \text{noise} \qquad (1)$$

These two contributions are difficult to separate out. The use of global circulation models and assimilation techniques along with new satellite missions such as Gravity

Recovery And Climate Experiment (GRACE) provide new tools to achieve independent estimations of each contribution. Recently, García et al. (2006) and Fenoglio-Marc et al. (2006) have accomplished such separation in the Mediterranean Sea for the annual cycle and have shown a remarkable agreement between the seasonal ξ_M estimated as $\xi_T - \xi_S$ from (1) and the direct estimation from GRACE data. The knowledge of the spatial and temporal relative importance of these contributions in sea level trends will lead to valuable understanding of the ocean dynamics and global climate change. This paper addresses this issue for the Mediterranean Sea.

The work is organised as follows: section 2 describes the data and methodology; in sections 3 and 4 the main results are presented: first a basin-scale analysis over the Mediterranean is considered and then spatial patters in trends are analysed. Finally, section 5 discusses and summarises the conclusions.

2.- DATA AND METHODOLOGY

Different sources of data have been used in this study: the total sea level has been determined from altimetry data from diverse satellite/missions (T/P, ERS-1/2, GFO, ENVISAT and JASON 1) collected through the merged AVISO (Archiving Validation and Interpretation of Satellite Oceanographic data) products, freely available on www.aviso.oceanobs.com. The data consist of sea level anomalies referred to a 7-year average and combine information from different missions, which significantly improves the estimation of mesoscale signals (Le Traon and Dibarboure, 1999; Le Traon et al., 2001). The AVISO regional solution for the Mediterranean Sea for the period 1992-2005, with 1/8 x 1/8 degrees spatial resolution and weekly time resolution has been used. All standard geophysical and environmental corrections including ionospheric, dry and wet tropospheric corrections, solid Earth and ocean tides, ocean tide loading, pole tide, electromagnetic bias, instrumental corrections, orbit error reduction and inverse barometer have been applied by AVISO processing algorithms (AVISO, 1996). The inverse barometer correction has arguable validity for semi-enclosed seas because the sea level response is noticeably influenced by topographic constrictions of the flow in the straits (Le Traon and Gauzelin, 1997). However, these authors also show that departure from the isostatic response is significant at periods shorter than 200-300 days. As far as this work deals with trends over a 15 year-period, the inverse barometer correction is applicable.

In order to estimate the steric contribution ξ_S, temperature and salinity profiles from the Jet Propulsion Laboratory ECCO (Estimating the Circulation and Climate of the Ocean) model have been collected. The data have 1x1 degree spatial resolution, 46 depth levels with 10 meter interval for the first 150 meters and a temporal resolution of 10 days. The simulation uses the NCEP (National Centers for Environmental Prediction)/COADS (Comprehensive Ocean-Atmosphere Data Sets) reanalyses as forcing (see Lee and Fukumori, 2003 for details). Changes in the steric contribution (ξ_S) of total sea level (ξ_T) represent the effect of expansion and contraction of water column due to changes in density (ρ) and are computed according to:

$$\xi_S = -\frac{1}{\rho_0}\int_{-H}^{0}\frac{\partial\rho}{\partial T}\cdot T'(z)dz + \frac{1}{\rho_0}\int_{-H}^{0}\frac{\partial\rho}{\partial S}\cdot S'(z)dz \qquad (2)$$

where $T'(z)$ and $S'(z)$ are temperature and salinity anomalies referred to their climatic mean value; ρ_0 represents a reference density and H is the bottom depth. Increases (decreases) of temperature and/or decreases (increases) of salinity lead to positive (negative) ξ_S anomaly.

Other datasets used in this study are the NOAA optimum interpolated SST data version 2 (NOAA_OI_SST_V2, see www.cdc.noaa.gov), with a spatial resolution of 1x1 degree and weekly sampling covering the period from 1990 to 2005 and monthly North Atlantic Oscillation (NAO) indices computed using the normalised sea level pressures in Gibraltar and in Southwest Iceland during the period 1992-2005 (Jones et al., 1997).

Data were spatially and in-time interpolated by means of cubic splines in order to have all variables defined at the same grid points (1/8 x 1/8 degrees) and with the same time interval (7 days). Although the distributions are rather insensitive to moderate changes of the interpolating splines, a low degree is desirable to avoid spurious oscillations associated with higher degrees and cubic interpolation has turned out to be one of the most adequate both for its simplicity and accuracy (Sokolov and Rintoul, 1999). Additionally, ξ_T has been filtered with a lowpass butterworth filter (cut-off frequency of 60 days^{-1}) in order to remove high-frequency variability and achieve similar frequency content in ξ_T and NAO series.

3.- BASIN SCALE ANALYSIS

3.1.- Thermohaline fields

SST averaged over the Mediterranean Sea (Figure 2a) describes a clear seasonal cycle with maxima around 26ºC and minima around 15ºC. Higher values were observed in

1994 (up to 27ºC) and 2003 (almost 28ºC) due to the exceptional heat wave in Europe during that summertime. Minimum values (slightly above 14ºC) correspond to 1992 and 1993 years. SST seasonal oscillation reaches maxima at the end of August and minima at the end of February.

The 3-D spatially averaged temperature and salinity of the whole Mediterranean are displayed in Figure 2b. To evaluate the seasonal cycle and diagnose trends, the signal has been least squares fitted to the following function:

$$y = a_0 + a_1 t + A_1 \cos(\omega_1 t - \varphi_1) + A_2 \cos(\omega_2 t - \varphi_2) \qquad (3)$$

that includes annual (ω_1) and semi-annual (ω_2) frequencies. The semi-annual amplitude turned out to be an order of magnitude smaller than the annual amplitude and results do not vary significantly when considering only the annual oscillation.

Superposed to the clear annual oscillation, temperature signal exhibits a positive trend of 0.015±0.003 ºC/year (95% confidence interval) for the whole period 1992-2005. There is, however, the possibility that the trend has changed sign in year 2001. Salinity shows more irregular oscillations without a defined trend. It diminishes from 1992 to 1995, but from 1995 onwards a positive trend of 0.0011±0.0001 year^{-1} is observed. The evolution of temperature and salinity of the different water masses cannot be resolved from this spatial mean and it is not possible to detect either the reported positive temperature and salinity trend of deep waters (Rohling and Bryden, 1992; Bethoux and Gentili, 1999) or the trends mentioned by Painter and Tsimplis (2003) for the upper waters. However, Mediterranean averaged SST (Figure 2a) exhibits a positive trend of

0.061±0.02 ºC/year during 1992-2005, which means an increase of approximately 1ºC over 15 years. This value is less than half the trend reported by Marullo et al. (1999) and Santoleri et al. (1999) for the previous decade (about 0.15ºC/year for 1982-1990). The discrepancy may be due to the possibility mentioned by Moron (2003) that the SST trend had changed sign after reaching a relative maximum in year 2000, which would make the positive trend of period 1992-2005 be smaller than during 1992-1999. Notice, however, that the very hot year 2003 sheds doubts on the conclusion of Moron (2003) and future observations are necessary to check this result.

3.2.- Sea level

3.2.a.- Seasonal cycle

Figure 2c shows the spatially averaged steric contribution ξ_S during the analysed period computed from ECCO model. ξ_S describes a clear seasonal cycle with annual amplitude of 5.8±0.4 cm, maximum in early September and minimum in early March. The highest maximum is found in the hot year 2003 (above 8 cm), and the less pronounced minimum of -5.3 cm corresponds to 1998. The lowest maximum is in year 2002 (less than 5.5 cm), while the greatest minimum of -6.7 cm corresponds to year 2005. Comparison of Figures 2b and 2c reveals similarity between ξ_S and temperature oscillations, thus showing that ξ_S in Mediterranean Sea is mainly driven by the thermosteric effect and fairly independent of salinity (halosteric effect), in agreement with Tsimplis and Rixen (2002). The total sea level ξ_T computed from altimetry data also displays a seasonal oscillation (Figure 2c), whose maxima and minima are less neatly defined. Its amplitude is 8.1±0.5 cm, reaching maxima at mid-October and minima at mid-April, thus lagging by 50-60 days the SST oscillation. These results are in good agreement with those obtained by Fenoglio-Marc (2002), who observed maximum correlation between SST and ξ_T fields at the lag of two months and with those of Bouzinac et al. (2003) and García-Lafuente et al. (2004) for the western Mediterranean. Highest and lowest maxima (above 11 cm and about 5.5 cm, respectively) are observed in 1997 and 1994, respectively, whereas the more (< -11 cm) and less (~ -5 cm) pronounced minima occur in 1994 and 2002, respectively.

Figure 2c shows similar annual cycles of ξ_T and ξ_S, this indicating that the main contribution to ξ_T comes from the heat gain/loss of sea water during the year. However, ξ_S has lower amplitude and its phase leads that of ξ_T by around 40-45 days, which induces a non-negligible cycle of ξ_M (computed as ξ_T - ξ_S according to (1)) of 5.5±0.6 cm amplitude with maximum in early December and minimum in early June (figure 2c). These results compare reasonably well with the reports of Fenoglio-Marc et al. (2006) for the period 2002-2004, who obtained an annual amplitude of 5.2 cm and a phase of 327º (end-November) from direct gravity anomaly (GRACE) measurements.

Peaks of ξ_T and ξ_M are ~2-month out of phase leading to the rather unexpected result already mentioned by García et al. (2006) that, during a part of the rising phase of the sea level seasonal cycle, the Mediterranean is losing mass and vice-versa. We lack of a definite explanation for this behaviour although it can be linked to the annual production of deep water, particularly WMDW in the western Mediterranean basin. Recently, García-Lafuente et al. (2007), using up-going series of the Mediterranean outflow observed in the Strait of Gibraltar, have shown that the outflow increases in late winter / early spring, shortly after the deep convection processes. If this increased outflow is not compensated by a similar increase in the inflow or by net surface fluxes (precipitation, evaporation, river discharges), the Mediterranean Sea mass content will diminish during this part of the year. This reasoning, already mentioned by Ross et al. (2000), is rather speculative and needs of further observational evidences.

The cycle of ξ_M must be related to the net barotropic flow through the Strait of Gibraltar. The month-to-month incremental mass change $\delta(\xi_M)$ must be balanced by the horizontal water mass flow through the Strait of Gibraltar (F), river runoff (R) and the vertical flow (P-E) according to

$$\delta(\xi_M) = F + (P-E) + R \tag{4}$$

The LHS of (4) is estimated from the datasets by the month-to-month difference between observed sea level and steric sea level. Mariotti et al. (2002), using long-term Mediterranean Sea-averaged series of (P-E) from NCEP obtain annual amplitudes ranging from 24.25 mm/month to 30.25 mm/month, with maximum in May. Contribution of river runoff is much more reduced with annual amplitude of ~5.25 mm/month. Using (4), an annual amplitude of 37±6 mm/month is obtained for F. García et al. (2006) and Fenoglio-Marc et al. (2006) have also evaluated $\delta(\xi_M)$ during the period 2002-2004 calculated from GRACE data and compared it with the monthly (P-E) field averaged over the Mediterranean in the same period to estimate annual amplitudes of 18 mm/month and 60 mm/month, respectively. These values can be compared with historical results as reported by García-Lafuente et al. (2002) from in situ measurements between 10/95 and 05/98, who observe an annual amplitude of 78±44 mm/month. Both our results and that of the above authors are lower than the 1995-1998 observations, although phases are in good correspondence. Probably, the inter-annual variability is responsible of part of the discrepancies although the use of different datasets and procedures cannot be disregarded.

3.2.b.- Sea level trends

Equation (3) gives positive trend of 2.1±0.6 mm/yr for ξ_T during the period 1992-2005. These trends are not uniform over the Mediterranean (its spatial distribution is discussed in section 4.2). The above values are much lower than those reported by Cazenave et al. (2002) from satellite data for the period 1993-1998 (7±1.5 mm/year) although they are higher than the 0.5 mm/year obtained from long series of tide gauge data around the Mediterranean Sea (Cazenave et al., 2002). Better agreement is found with the results of Fenoglio-Marc (2002) who, based on satellite data for the period 1992-2000, reports a positive trend of 2.2 mm/year for the Mediterranean. Using data from 1993 to 2001, the computed ξ_T trend is 6.3±0.8 mm/year, a value much closer to that reported by Cazenave et al. (2002) that highlights the influence of the probable change in sea level trend observed from 2001-2002 (Figures 2b and 2c), which reduces to less than half the computed trend when the whole series (1992-2005) is analysed. The change, also shown by Vigo et al. (2005), could be related to long period oscillations of Mediterranean Sea level with decadal frequencies such as the irregular SST oscillation with 60-70 year period with maximum around 2000 described by Moron (2003).

Temperature and salinity profiles from ECCO model suggest that ~55% of total sea level trend (1.1±0.3 mm/year) is of steric (mainly thermosteric) origin, the remaining being accounted for the mass-induced component. The relative share of these two contributions depends on location and time. Middle and low latitudes often show a larger steric component, whereas at higher latitudes, where dynamic variability is strong, the mass-induced effect may become the major contribution. For the Atlantic ocean (40S-60N), the steric component accounts for more than 50% of total satellite-altimeter observed sea level, this contribution being higher (>60%) in the 30N-50N region (Cabanes et al., 2006). Global ocean spatial patterns of T/P and thermosteric sea level trends also agree rather accurately, the latter explaining above 50% of the former in average (Lombard et al., 2005; Chen et al., 2006). Although Mediterranean Sea is a semi-enclosed basin, the relative importance of the steric component is comparable with that of the open ocean, which is encouraging for the potential use of Mediterranean Sea to monitor climate change.

4.- SPATIAL PATTERNS

4.1.- Thermohaline trends

SST trend (Figure 3a) exhibits different behaviour in the eastern and western basins. Although positive trends are observed elsewhere, higher values concentrate in the Levantine basin, with values up to 0.1±0.02 ºC/year west of Crete and northwest of Cyprus, whereas lower values (~0.03±0.01 ºC/year) are located in the Alboran and Tyrrhenian basins and, especially, south of Sicily and Sardaigne. The above spatial pattern fits reasonably well with that reported by Fenoglio-Marc (2002) for the period 1992-2000, although values do not exactly coincide, probably because of the sensitiveness of trends to the length of the series analysed. Robustness of the results has been tested by computing the spatial distribution of the error associated with the estimated trends (Figure 3d). Low values (<0.02ºC/year) are obtained in most of the domain, this supporting the reliability of the results. The only exception is a small region north of the Adriatic, where uncertainty is higher.

Levantine basin exhibits a positive depth-averaged temperature trend of about 0.04±0.006 ºC/year and Balearic basin a negative trend of 0.02±0.003 ºC/year (Figure 3b). Salinity trends (Figure 3c) also show differences between eastern and western basins. Positive trends are detected over the easternmost basin and in the Gulf of Lyon with peaks up to 0.008±0.001 year^{-1} in the Levantine area, thus suggesting long-term changes in the haline properties of LIW, as mentioned by Roether et al. (1996), Klein et al. (1999) and Painter and Tsimplis (2003). In contrast, negative trends are in the Adriatic Sea and, particularly, in the south Algerian and Ionian basins off the African coasts, which coincide with the path of the Atlantic water coming from the Strait of Gibraltar. This might be suggesting some strengthen of this jet in the past decade which in turn would explain the positive trend deduced for ξ_M. Robustness of thermohaline trends has also been evaluated and low uncertainty values (<0.008 ºC/year for temperature and <0.001 year^{-1} for salinity) have been obtained.

4.2.- Local sea level trends

The relatively high spatial resolution of sea level data resolves mesoscale features (Figure 4). However, due to the inherent uncertainty of the detailed patterns, the discussion focuses on the large-scale structures, which are more likely related to physical features. The total sea level (ξ_T) map of Figure 4a shows that sea level rise is particularly important in the Levantine basin south of Crete with values up to 10±1 mm/year. Some other rising spots are localised throughout the Levantine basin as well as in the Adriatic and Alboran Seas with more moderate positive trends. Positive trends in the Alboran Sea could be related to variations in the water mass exchange through the Strait of Gibraltar in the last decade, as discussed in section 5. Negative trends mainly concentrate in the Algerian basin, between the Balearic Islands and the African coasts (some -5±0.8 mm/year decreasing rate) and, particularly, in the Ionian basin with negative trends of up to -10±0.8 mm/year. This spatial distribution of sea level trends (rising and falling regions) agrees reasonably well with that reported by Cazenave et al. (2002) for the period 1993-1998 although these authors found higher values (-20 mm/year in the Ionian basin and up to 25 mm/year south of Crete). The agreement with the results of Fenoglio-Marc (2002) for the period 1992-2000 (9.3 mm/year south of Crete and -11.9 in the Ionian Sea) is better. Obviously, trends are sensitive to the length of the series analysed and this becomes more evident when detailed patterns are considered. Robustness of the results has been tested again by computing the spatial distribution of the error associated with the estimated trends (Figure 4d), which shows low values (<0.6 mm/year) in most of the domain with the only exception of a small region south of Crete, where values up to 1.6 mm/year are reached.

Spatial distribution of ξ_S trend for the period 1992-2005 (Figure 4b) shows two well-defined regions: the Levantine basin, where ξ_S is rising at a rate of 4-6±0.5 mm/year with peaks of 8±0.7 mm/year south of Greece, and the Balearic and Algerian basins, with a negative trend of -4 to -6 ±0.4 mm/year and peaks of -8±0.6 mm/year north of the Balearic Islands. As ξ_S is mainly driven by thermal expansion or contraction of the water column, Figure 4b has great similitude with the spatial pattern of temperature (Figure 3b).

The good correspondence between ξ_T and ξ_S spatial patterns (Figures 4a and 4b) is broken in certain regions. The most noticeable is over the Ionian basin, where the ξ_T drop does not appear to be linked to the thermosteric contraction of the water column, but to the mass-induced component (ξ_M). Trends of ξ_M derived through equation (1) are shown in Figure 4c. Computation of ξ_M trend ignores noise in this equation and, therefore, it must be considered cautiously as noise may be non-negligible. In spite of this fact, the high negative mass-induced trend over the Ionian basin (up to -12±0.8 mm/year) suggests that it really corresponds to a physical feature. ξ_M rises north of Balearic Islands (~4±0.3 mm/year) and in some spots of the Levantine, Adriatic and Alboran basins. The error analysis shows again rather reduced values in the whole domain (<1 mm/year) for the steric and mass-induced components.

The negative trend over the Ionian basin is likely related to the Eastern Mediterranean climate Transient (EMT). A shift in the formation site of deep and bottom waters from the Adriatic to the Aegean Sea (Roether et al., 1996; Malanotte-Rizzoli et al., 1999; Theocharis et al., 1999) have altered both the deep and upper conveyor belts of the Eastern Mediterranean. Different hypothesis such as internal redistribution of salt (Klein et al., 1999), changes in the local atmospheric forcing combined with long term salinity change (Theocharis et al., 1999) or changes in circulation patterns (Malanotte-Rizzoli et al., 1999) have been proposed concerning possible causes of this unique event, although it is still an open issue whether some of them are rather consequences than causes of the EMT. In any case, noticeable changes in circulation patterns over the Ionian basin have been reported in the last decades: a shift in the surface circulation in the Ionian basin, which changed from cyclonic to anticyclonic, appeared around 1986-87 (Pinardi et al., 1997; Malanotte-Rizzoli et al., 1997, 1999). This circulation pattern was well established until about March 1998, when it returned to cyclonic (Banca, 2000). These changes forced variations in the path of the Atlantic Ionian Stream (AIS) along the Ionian basin (Banca, 2000) that has probably resulted in the mass-induced negative trend of ξ_M in this region.

5.- DISCUSSION AND CONCLUSIONS

Tsimplis and Josey (2001) suggest that changes in total sea level are linked with modifications in the large-scale meteorological forcing and, particularly, with the NAO. Positive NAO values mean positive pressure differences between Gibraltar and Iceland and are indicative of more and stronger winter storms crossing the Atlantic Ocean on a more northerly track, this resulting in warmer and wetter winters in Europe but colder and dryer winters over the Mediterranean (Hurrell, 1995) that increase the surface salinity. The higher state of NAO during recent decades (Hurrell, 1995) may also be cooperating to the positive water column average salinity trend. Some other concomitant factors such as the decrease in fresh water input as a result of human activities and decrease in precipitation since 1940 (Bethoux and Gentili, 1996, 1999) may be involved. Vignudelli et al. (1999) have demonstrated that NAO influences the circulation of the northwestern Mediterranean Sea through air-sea interactions. Thus, ultimately NAO might be responsible for the recent changes detected in the Mediterranean thermohaline circulation as well as for the sea level variations. To explore this possibility, correlation between NAO index and total sea level trend at each grid point for the period 1992-2005 has been computed (Figure 5). Positive (negative) NAO indices mean higher (lower) pressure over the Mediterranean and, in turn, lower (higher) sea level and hence, a negative correlation coefficient. Although the correlation is rather poor at basin scale (Figure 5), the high number of points involved in its computation (more than 650), gives some reliance on values over -0.3. In terms of this correlation, the Mediterranean Sea is divided into three regions: the Central basin, which is not reactive to NAO and the easternmost and westernmost areas (Levantine and Balearic basins), in which the highest values are reached and NAO influence on ξ_T might be more effective.

Another source of sea level variability, particularly in the western basin, could be the modifications of the hydraulic conditions in the Strait of Gibraltar. Ross et al. (2000) addressed this problem speculating with the possibility of a shift from maximal to submaximal exchange during the middle 90's. Maximal exchange needs an increased sea level difference between the Atlantic and Mediterranean sides of the Strait to accelerate the inflow which, in turn, increases the across-strait sea level difference by geostrophy. Ross et al. (2000) showed decreasing trends of the along and across-strait sea level slopes from 1994 to 1998 that they interpreted as a change from maximal to submaximal exchange (actually, to an increasing fraction of the year with submaximal regime), which reduced along-strait sea level slope (and, hence, the across-strait slope now forced by a slower inflow). This needs of a larger sea level rise rate in the Mediterranean respect to the Atlantic. Should this explanation be true, our data would suggest that the process went on until year 2001, when the change to negative trend would indicate a new shift towards maximal exchange (increased fraction of the year with maximal regime). Obviously, this explanation, though quite suggestive, is rather speculative and needs further confirmation.

The long series of almost 15 years (1992-2005) of altimetry data analysed in this work indicate a positive sea level trend of 2.1±0.6 mm/yr in the Mediterranean Sea. As previously showed by Vigo et al. (2005), a negative trend, more evident in the thermosteric component, from 2001 onwards is also detected. Mediterranean averaged SST exhibits a positive trend of 0.061±0.02 ºC/year (~1ºC over 15 years) during 1992-2005, with higher values in the eastern basin and lowers in the western. Even when this result is somewhat biased by the extremely hot 2003 year, it is less than half the trend reported for the previous decade (Marullo et al., 1999; Santoleri et al., 1999). Temperature and salinity profiles from ECCO model suggest that ~55% of total sea level trend (1.1±0.3 mm/year) is of steric (mainly thermosteric) origin, the remaining being accounted for the mass-induced component. Although Mediterranean Sea is a semi-enclosed basin, the relative importance of the steric component is comparable with that of the open ocean, which is encouraging for the potential use of Mediterranean Sea to monitor climate change.

Sea level rise is particularly important in the Levantine basin south of Crete with values up to 10±1 mm/year. Negative trends mainly concentrate in the Algerian basin, between the Balearic Islands and the African coasts (some -5±0.8 mm/year decreasing rate) and, particularly, in the Ionian basin southeast of Italy and Sicily, where the higher negative trends are reached (up to -10±0.8 mm/year). The mass-induced contribution is clearly dominant here, which strongly suggests an origin related to changes of the circulation pattern in this basin during the last decade linked to the Eastern Mediterranean Climate Transient (Pinardi et al., 1997; Malanotte-Rizzoli et al., 1997, 1999; Banca, 2000).

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Total sea level altimetry data have been collected through the merged AVISO products. JPL (Jet Propulsion Laboratory) simulation results of the ECCO model have been used for temperature and salinity profiles. Sea Surface Temperature (SST) data have been acquired from NOAA optimum interpolation dataset version 2 (NOAA_OI_SST_V2) provided by the NOAA/OAR/ESRL PSD. NAO index has been acquired from the Climatic Research Unit (CRU) database. All of them are acknowledged for free dissemination of data. Partial support from CTM2006-02326 Spanish-funded project is also acknowledged. We are grateful to two anonymous reviewers whose comments and suggestions helped to improve the manuscript.

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FIGURE CAPTIONS

Figure 1: Map of Mediterranean Sea, the region of study. The main basins and sub-basins are indicated.

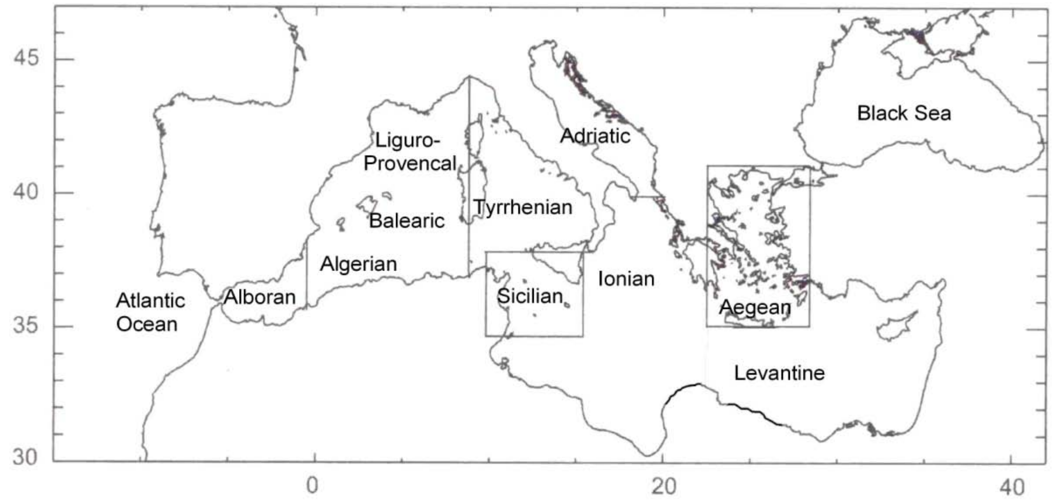
Figure 2: A) Sea Surface Temperature (SST) averaged over the Mediterranean Sea. Yearly mean values ± std have been marked. A positive trend of 0.061±0.02 ºC/year is observed. B) 3-D spatially averaged temperature (black line) and salinity (blue line) for the Mediterranean Sea. Yearly mean values ± std have been marked for temperature signal, where a positive trend of 0.015±0.003 ºC/year is observed. A negative trend from 2001 onwards is also suggested. C) Spatially averaged total sea level anomaly (ξ_T, black line) from altimetry data due to the steric (ξ_S, blue line) and mass-induced (ξ_M, red line) contributions. Yearly mean values ± std of ξ_T (marked at the mid-year) and ξ_S (marked at the end-year) have been plotted in their respective colour codes. Positive trends of 2.1±0.6 mm/yr and 1.1±0.3 mm/year have been found for ξ_T and ξ_S, respectively. Decreasing trend from 2001 onwards is also indicated.

Figure 3: Trends spatial patterns for SST (panel A) and water column averaged temperature (panel B) and salinity (panel C). The spatial distribution of the uncertainty (95% confidence interval) associated to the estimated SST trends is displayed in panel D.

Figure 4: Trends spatial patterns of total sea level (ξ_T, panel A) due to the steric (ξ_S, panel B) and mass-induced (ξ_M, panel C) contributions. The spatial distribution of the uncertainty (95% confidence interval) associated to the estimated ξ_T trends is displayed

in panel D. Sea level rise is particularly important in the Levantine basin (~10±1 mm/year), whereas sea level drop mainly concentrates in the Ionian basin (>10±0.8 mm/year), probably linked to ξ_M term.

Figure 5: Correlation between NAO index and total sea level ξ_T trends for the period 1992-2005. The easternmost and westernmost areas (Levantine and Balearic basins) are more sensitive to NAO influence.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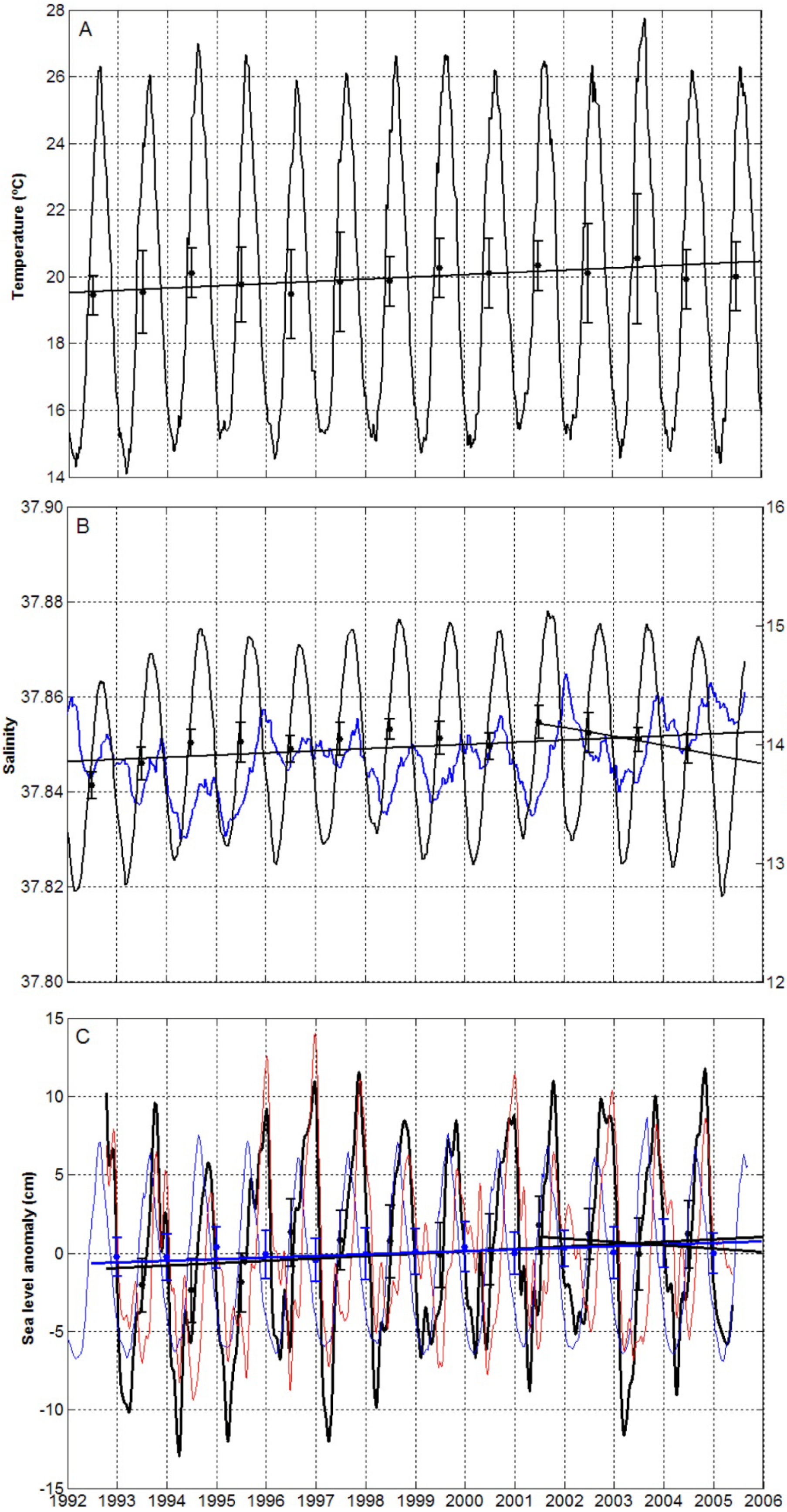
40
35
30
0
20
40
Black Sea
Adriatic
Liguro-
Provencal
Tyrrhenian
Balearic
Algerian
Ionian
Sicilian
Aegean
Atlantic
Ocean
Alboran
Levantine

Figure 1


A
Temperature (ºC)
28
26
24
22
20
18
16
14
B
Salinity
37.90
37.88
37.86
37.84
37.82
37.80
Temperature (ºC)
16
15
14
13
12
C
Sea level anomaly (cm)
15
10
5
0
-5
-10
-15
1992
1993
1994
1995
1996
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2002
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2006

Figure 2

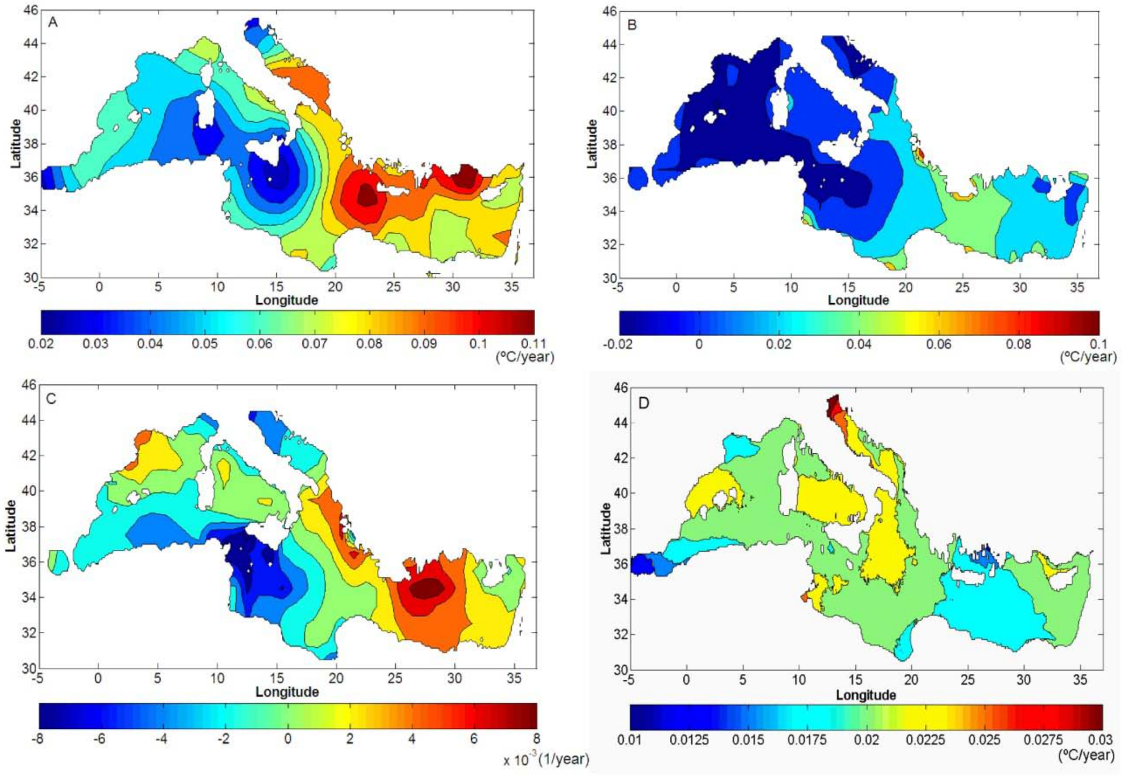


Figure 3

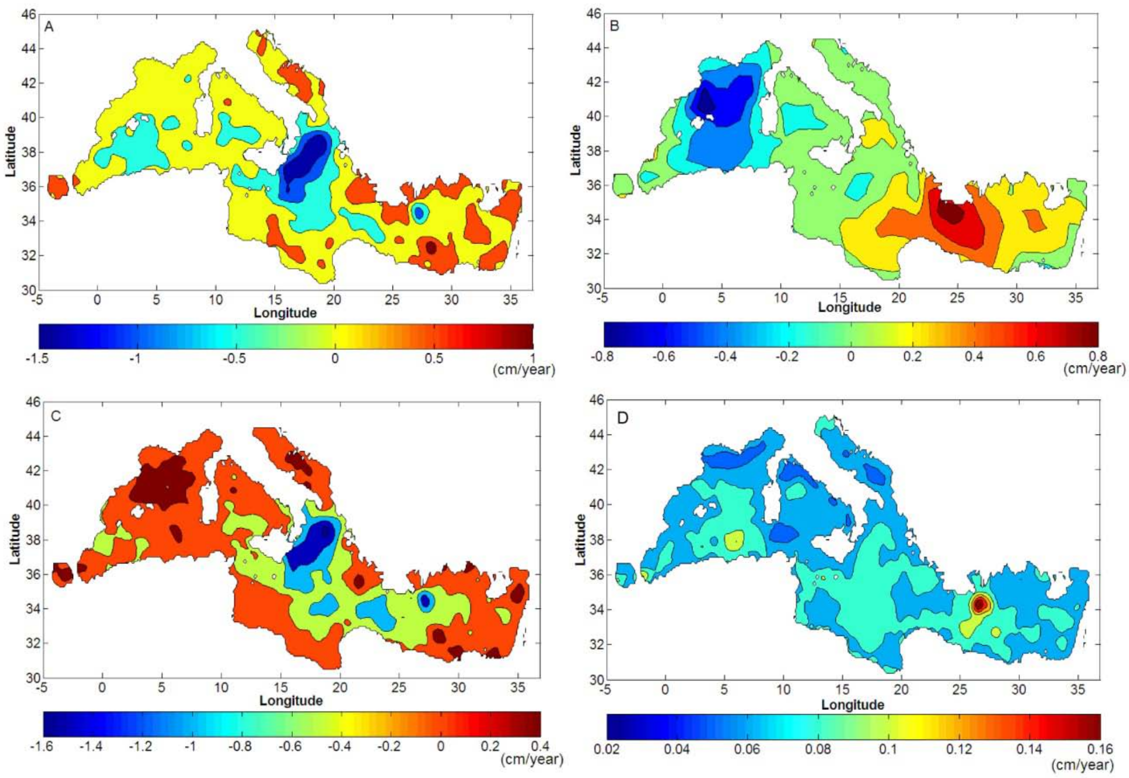
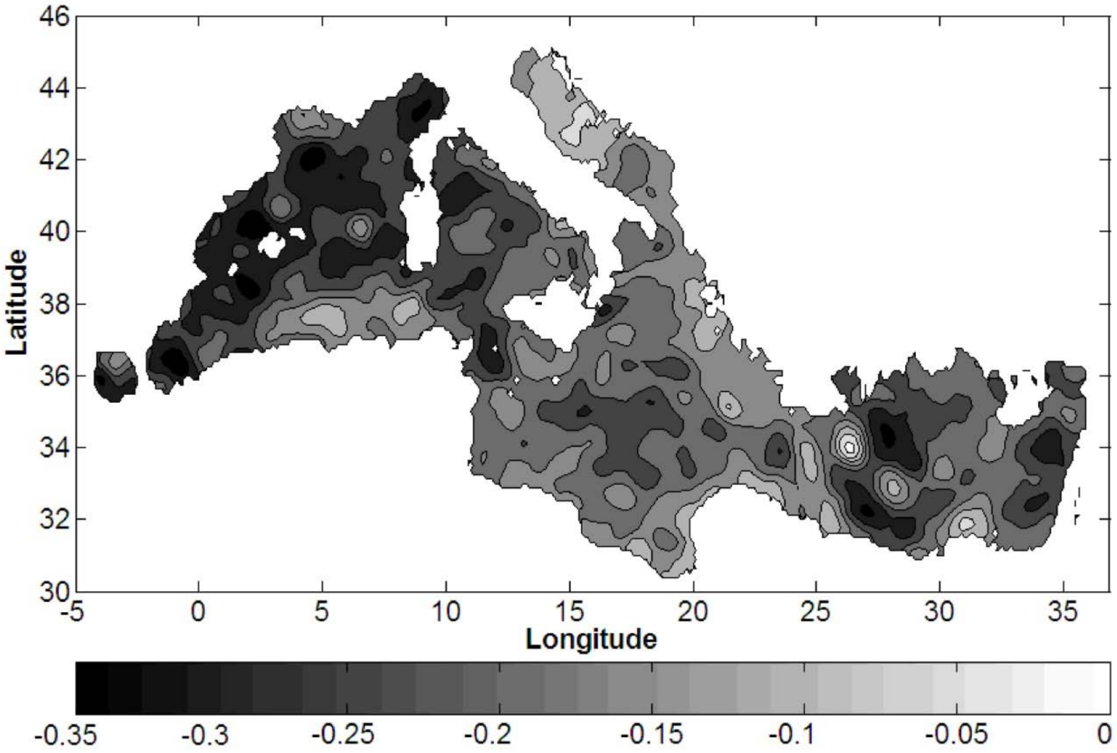


Figure 4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44
42
40
38
36
34
32
30
Latitude
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0
5
10
15
20
25
30
35
Longitude
-0.35
-0.3
-0.25
-0.2
-0.15
-0.1
-0.05
0

Figure 5