A NEW INSIGHT ON THE DECREASING SEA LEVEL TREND OVER THE IONIAN BASIN IN THE LAST DECADES

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ABSTRACT: Altimetry measurements over the Ionian region and tide gauge records along the southern Italian coasts have been combined to analyse the negative sea level trend over the Ionian basin in the last decades. The apparent decreasing trend should be better understood as an abrupt sea level drop in 1998 probably linked to changes in the surface circulation in the Ionian basin induced by the Eastern Mediterranean Transient, which changed from anticyclonic to cyclonic about March 1998. From then onwards, a rising rate of 7.9 ± 0.9 mm/year is observed over the basin.

Keywords: Sea level trends, altimetry and tide gauge records, Eastern Mediterranean Transient, Ionian Sea.

1.- PREFACE

The Mediterranean Sea, a semi-enclosed basin that extends over 3000 km in longitude and over 1500 km in latitude, is separated into the eastern and western basins by the Strait of Sicily (Figure 1). The average sea level trends estimated for the last years in the entire basin range from 7 ± 1.5 mm/year reported by Cazenave et al. (2002) from 6 years (1993-1998) of T/P and ERS-1 merged altimetry data to 2.2 mm/year and 2.1 ± 0.6 mm/year obtained by Fenoglio-Marc (2002) and Criado-Aldeanueva et al. (2008) from 8 years (09/1992-08/2000) and 13 years (1993-2005) of altimetry data, respectively. Trends considerably vary with location: sea level rise of thermosteric origin is particularly important in the Levantine basin south of Crete with values up to 10 ± 1 mm/year; in contrast, the Ionian basin has been identified as a falling sea level region. Cazenave et al. (2002) reported a decreasing trend of 15-20 mm/year over the area for the period 1993-1998. Using longer data series, Fenoglio-Marc (2002) and Criado-Aldeanueva et al. (2008) found more moderate values: -11.9 mm/year for 1992-2000 and -10 ± 0.8 mm/year for 1993-2005, respectively. Due to the relatively short time series, regional trends depend both on the length of the series and on the boundaries of the area selected to compute the regional mean sea level. The Ionian negative trend is more probably related to mass redistribution than to a thermosteric forcing, which suggests an origin related to changes of the circulation pattern in this basin during the last decade, probably linked to the Eastern Mediterranean Climate Transient (EMT, Pinardi et al., 1997; Malanotte-Rizzoli et al., 1997, 1999; Manca, 2000). In this paper, some features of this decreasing trend are revisited using altimetry and tide gauge records along the southern Italian coasts.

Approximate location of Figure 1

2.- DATA

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 (1993-1999) 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 1992–2007, with 1/8×1/8° spatial resolution and weekly time resolution has been used. To focus on seasonal variations, a low-pass Butterworth filter (cut-off frequency 60 days^{-1}) has been applied. 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).

Tide gauge sea level data recorded every hour by a SIAP ID0710 ultrasonic tide gauge (overall precision 0.1%) were obtained from the Italian Rete Mareografica Nazionale (RNM) in the locations of Catania (from 03/1992 to 09/2000), Reggio Calabria (from 02/1998 to 12/2004) and Crotone (from 03/1992 to 07/2000), all in the Ionian Sea coasts (see Figure 1). Only the period 1995-2002 is shown, where data is more reliable since two or more tide gauges often register simultaneously. Data from Reggio Calabria tide gauge between 12/1998 and 05/1999 were of suspicious quality and have been rejected. In order to remove high-frequency variability and match the altimetry data, a low-pass Butterworth filter (cut-off frequency 60 days^{-1}) has been applied to the averaged (taking data from the tide gauges available) series. For comparison with altimetry data, the atmospheric component has been removed from the tide gauge records using pressure values from the closest NCEP reanalysis grid point (17.5º W, 37.5º N).

3.- RESULTS AND DISCUSSION

Figure 1A displays the total spatially averaged sea level anomaly over the Ionian Sea (solid red rectangle) from altimetry data. More than 700 altimetry grid points have been extracted so the results are thought to be representative of the Ionian basin. To diagnose trends, the signal has been least squares fitted to the following function:

$$y = a_0 + a_1 t + A_1 \cos(\omega_1 t - \varphi_1) + A_2 \cos(\omega_2 t - \varphi_2) \qquad [1]$$

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. A total trend of -4.6 ± 0.7 mm/year (95% confidence interval) is computed for the entire period superposed to the seasonal oscillation. This value is lower than reported in the literature (Cazenave et al., 2002; Fenoglio-Marc, 2002; Criado-Aldeanueva et al., 2008) because sea level has positive trend in the last years (Figure 1A), thus reducing the overall trend. A remarkable feature is the presence of two well-differentiated periods before and after 1998. If the fitting process is performed separately, no significant trend and an annual amplitude of 9.1 cm is observed before 1998, whereas from 1998 onwards a positive trend of 7.9 ± 0.9 mm/year is observed superposed to an annual amplitude of 7.1 cm. In 1998, an abrupt sea level change occurred with a drop of 10-15 cm between maxima that appears to be responsible for the negative trend reported by different authors (Cazenave et al., 2002; Fenoglio-Marc, 2002; Criado-Aldeanueva et al., 2008) using time series spanning over this jump. Actually, the decreasing trend over the Ionian basin in the last decades is somewhat deceitful since from 1998 onwards, sea level is rising in the Ionian basin as well. This picture would explain the anomalously high negative trend of Cazenave et al. (2002), since the abrupt fall was at the end of the time series used in their analysis.

The altimetry measurements are now compared with tide gauge data in the locations of Catania (red line, Figure 2A), Crotone (blue line) and Reggio Calabria (black line). A good agreement between the different tide gauge records is observed and the abrupt sea level change of 1998 is clearly revealed, especially in the Crotone records, where sea level drops by more than 25 cm before and after 1998. This behaviour seems to be realistic since data from two or more tide gauge are available simultaneously until 2001. The steep change is more neatly observed in the low-passed series of the spatial mean of tide gauge data (Figure 2B), which helps to fill the gaps of the single series.

Approximate location of Figure 2

The question then arises as which could have been the physical forcing mechanism behind this sudden sea level drop. We propose that it was related to the 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 as possible causes of this unique event. At the same time, noticeable changes in circulation patterns over the Ionian basin have been reported in the last decades: a switch of the surface circulation in the Ionian basin from cyclonic to anticyclonic took place around 1986–87 (Pinardi et al., 1997; Malanotte-Rizzoli et al., 1997, 1999) and forced variations in the path of the Atlantic Ionian Stream (AIS) along the Ionian basin. This circulation pattern was well established until about March 1998, when it returned to cyclonic (Manca, 2000). The coincidence in time of the sea level drop and the switch of the circulation pattern over the Ionian basin suggests a cause-effect relationship between these two events. A rough estimation of the sea level drop associated to such change in the circulation pattern can be achieved by means of the geostrophic balance:

$$\Delta h = \frac{\Delta x}{g} \cdot fv \qquad [2]$$

where v is a reference velocity of the flow (~0.3 $m \cdot s^{-1}$ is representative for the mean velocity of the AIS in the Ionian Sea (Robinson et al., 1999)), Δx is a typical across-stream distance over which the velocity vanishes (~$5 \cdot 10^4$ m for the core of the AIS), f the Coriolis parameter (~$9 \cdot 10^{-5}$ s^{-1} for a latitude of 38 ºN) and g the gravity acceleration. With these values, equation [2] gives $\Delta h \sim 0.13$ m, which must be doubled to account for the change from anticyclonic to cyclonic circulation. Therefore, the computed drop is about 0.3 m, a value in good agreement (within the same order of magnitude) with the observed drop. This simple estimation supports the physical mechanism invoked.

The EMT did not only affect the Ionian Sea but the whole Eastern basin. Larnicol et al. (2002) suggested that the changes observed in the sea level during the period between 1995 and 1999 in the Levantine basin and between 1997 and 1999 in the Ionian Sea are related to variations in the deep and intermediate water masses distribution in the whole Eastern basin. Vigo et al. (2005) show a sort of time-space coupled oscillation between the Ionian Sea and the Levantine basin in which a sea level rise in the Levantine basin is connected to a sea level drop in the Ionian Sea before 1998, while after 1999 the behaviour seems to be the opposite. With longer time series available, we can now confirm and specify these findings. Figure 1B-C shows the low-passed sea level anomaly over the Aegean (panel B) and Levantine (panel C) basins. Different behaviours before and after 1998 are again revealed in both regions. Positive trends of 12 ± 2.5 mm/year and 14 ± 2.5 mm/year are obtained for the period 1993-1998 in the Aegean and Levantine basins that change into negative trends of -2.0 ± 0.8 mm/year and -2.9 ± 0.8 mm/years, respectively for the period 1998-2008, which strongly contrast with the Ionian sea level rise. Trends before 1998 are in good agreement with previous results of Vigo et al. (2005) but those for the period 1998-2008 are lower than reported by these authors from time series until 11/2003. An explanation for this could be that the rebound effect after the 1998 event extends during the 3-4 subsequent years (see, for instance the reduction of amplitude in the seasonal oscillations in Figures 1B-C), then recovering the usual behaviour. Although the change in trend has also been evidenced in the eastern basins, its magnitude was not as significant as in the Ionian basin (Figure 1A), this suggesting that this basin was more sensitive to the 1998 event, probably due to the changes of the path of the AIS flowing through the Ionian Sea.

4.- OPEN ISSUES AND CONCLUSIONS

In this work, two different sources of sea level data, i.e. altimetry and tide gauge data have been analysed to investigate an abrupt sea level drop in the Ionian basin by the late 90's. Both datasets have been processes similarly to make them comparable and a reasonably good agreement is found before 1998, although it becomes poorer after this year (Figure 2B). Vertical land motion (including glacial isostatic adjustment, GIA, volcanity and tectonic activity) may account for some discrepancies. Model of GIA by Peltier (2001) puts the vertical land motion at around ± 0.1-0.2 mm/year in the Mediterranean (up to 0.3 mm/year can be reached in the Adriatic). A detailed study of vertical land motions –out of the scope of this work- can be found in García et al. (2007) and Fenoglio-Marc et al. (2004). A second source of discrepancies could come from the corrections applied to the altimetry data, which were developed for the open ocean and raise problems when applied to near-shore areas. However, both datasets point to an abrupt sea level drop around 1998, greater in tide gauge data (~ 25 cm) than in altimetry records (~ 10 cm). There is not a clear explanation for such a high discrepancy in view of the good agreement that was obtained before. It might be that the interpolation of the altimetry data near the coast are influenced by observations in regions not affected by the event, thus underestimating its importance as suggested by Del Rio (2007). In fact, altimetry sea level computed for the coastal area (dashed red rectangle of Figure 1) is lower than that computed for the Ionian basin (solid red rectangle of Figure 1). Limitations of altimetry in near-shore areas may also be enhanced when complex dynamics, such as those related to the EMT, are involved.

A final cautionary remark is worth being mentioned since the altimetry data are anomalies referred to the 1993-1999 mean dynamic topography (7 years mean) and the abrupt sea level change in the Ionian Sea falls inside this period. For this reason, it would be more convenient to refer anomalies to the whole period of available altimetry data. Even with these weaknesses in mind, the data analysed in the present work shows that the historically reported sea level decreasing trend over the Ionian basin in the last decades stems from an abrupt sea level drop in 1998 rather than a continuous negative trend. Actually, the sharp drop was followed by a sea level rise from 1998 onwards. This unique event was probably linked to the EMT that induced noticeable changes in the surface circulation in the Ionian basin, which changed from anticyclonic to cyclonic about 1998.

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FIGURE CAPTIONS

Figure 1: Spatial distribution of sea level trend in the Mediterranean Sea from 1992-2007 altimetry data. Black stars indicate the locations of Catania, Crotone and Reggio Calabria tide gauges. The red rectangles limit the areas selected for the low-passed spatially averaged altimetry time series shown in panels A (Ionian basin), B (Aegean basin) and C (Levantine basin).

Figure 2: (A) Tide gauge sea level anomaly in Catania (red line), Crotone (blue line) and Reggio Calabria (black line). (B) Low-passed series of the averaged tide gauge (grey line) and altimetry sea level anomaly (black line) spatially averaged over the Italian coasts of the Ionian Sea closest to the tide gauge locations (dashed red rectangle of Figure 1).

FIGURES

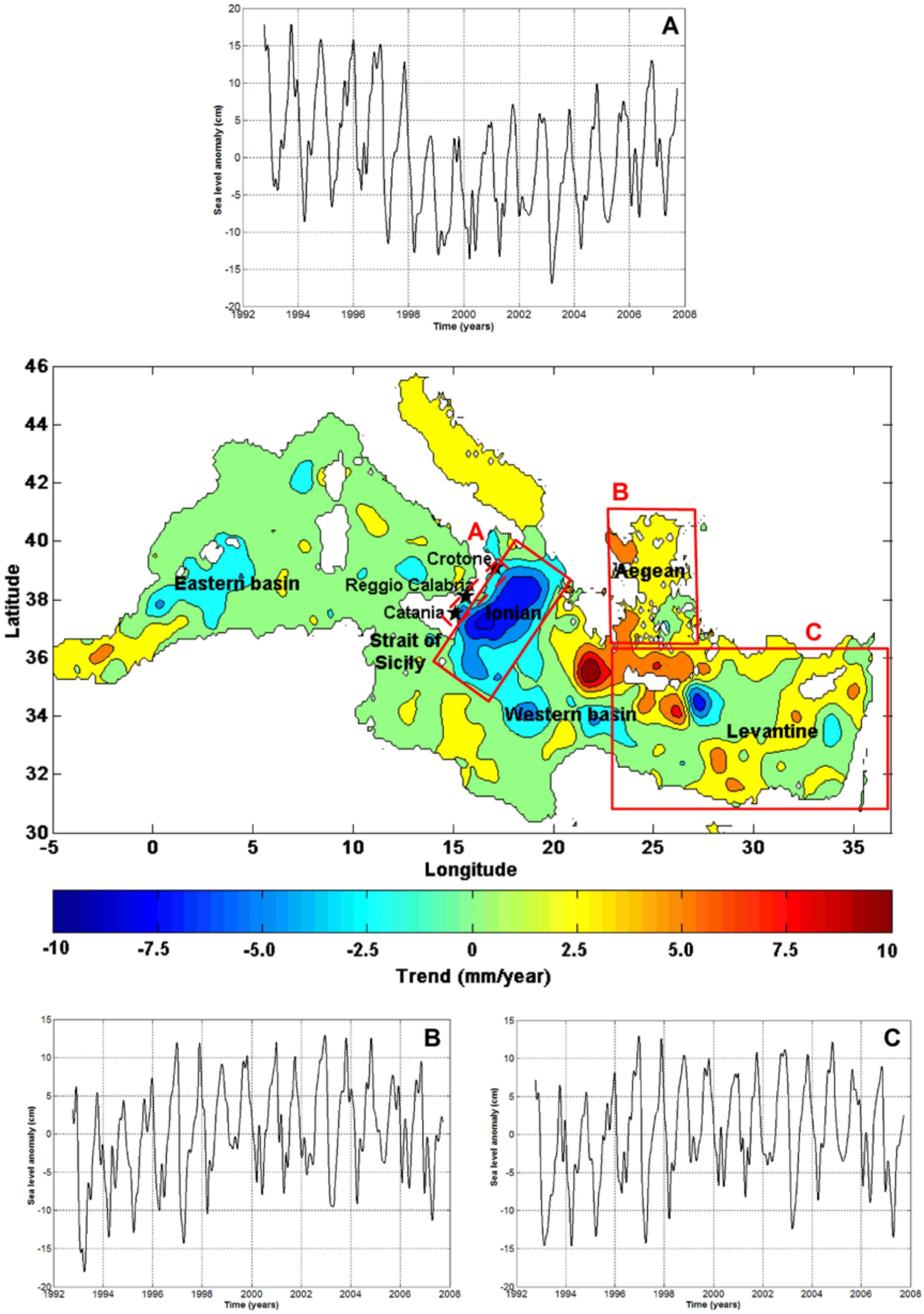

Figure 1

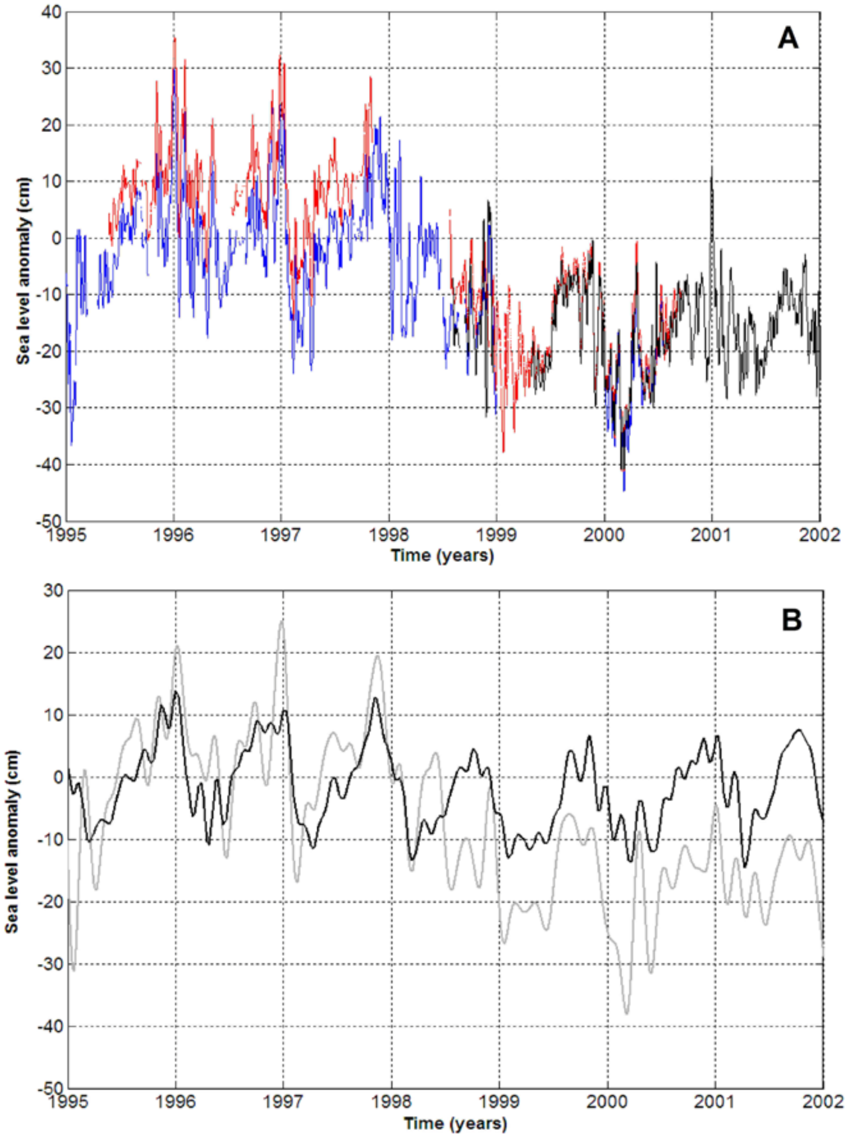
A
Sea level anomaly (cm)
40
30
20
10
0
-10
-20
-30
-40
-50
1995
1996
1997
1998
1999
2000
2001
2002
Time (years)
B
Sea level anomaly (cm)
30
20
10
0
-10
-20
-30
-40
-50
1995
1996
1997
1998
1999
2000
2001
2002
Time (years)

Figure 2