# Understanding Mediterranean and Black Sea Level Variations, 1993-2004.

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**The TOPEX/Poseidon and Jason-1 altimetric satellite missions have precisely monitored the Mediterranean and Black Sea levels, showing a complex but very interesting behavior both in spatial pattern and in time evolution. In this work we report the main results of two studies that we conducted for a deeper understanding of the geophysical causes underlying the observed sea level variations in the Mediterranean and the Black Seas during 1993-2004.**

## The long-term Sea Level Anomaly (SLA) variations in the Mediterranean and the Back Seas

### *DATA ANALYSIS AND RESULTS:*

The altimetry data used in this study are monthly SLA maps (Courtesy of CLS Aviso Project), on a 1º by 1º grid, solved from the ocean radar altimetry data from satellite missions of T/P, Jason-1, ERS-1/2 and ENVISAT for an ~11-year period of 01/1993 – 11/2003. Several corrections have been applied to the data: orbit error reduction of ERS and ENVISAT via the precise orbit of T/P and Jason-1, geophysical (dry and wet troposphere, ionosphere and inverse barometer effect), sea state bias, and tides (ocean and load tides, solid earth tide and pole tide).

The Sea Surface Temoerature (SST) anomaly data set is provided by NOAA. We use the National Center for Environmental Prediction (NCEP) Optimally Interpolated (OI) SST version 2 data set which is produced monthly on a 1º by 1º grid for the same period of time as for SLA above. The analysis uses SST from the Advanced Very High Resolution Radiometer (AVHRR) on board of NOAA satellites, and in situ SST collected from buoys and ships.

To corroborate the altimetry results, we analyze the monthly tide gauge (TG) data available from the Permanent Service for Mean Sea Level (PSMSL). In PSMSL, there are 42 TGs in the Mediterranean and 7 in the Black Sea with data spanning the altimetry period (01/1993 – 11/2003). However, only few of those TG's have a time span suitable to study the change of linear trend in 1999 they are located in Figure 2.

### *a. Linear trends in Mean Sea Level (MSL) :*

In this part we only concentrate on the (non-seasonal) SLA and SST , figure 1 shows the temporal variation of the spatially-averaged mean while in the rest we examine their spatial variation

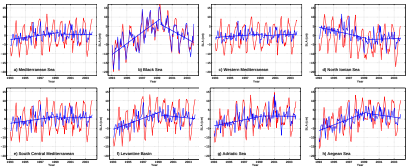

Figure 1. A kink in the linear rate-of-change in MSL between Periods I and II. Each time series corresponds to a different region. In all cases is shown the non-seasonal signal (blue curve) and with seasonal signal (red curve).

Figures 1 (a) and (b) confirms for Mediterranean and Black Seas earlier finding of SSH rise during 1992-98, with a peak around 1996. However, a dominant reverse of the trend took place around 1999, which is even more prominent in the Black Sea. From the cue provided by the 2nd EOF pattern for SLA (Figure 5.b), we conduct a break-down of the Mediterranean into 6 regions (Figure 2) in order to study the individual temporal variation.

Figure 1 (c) to (d) shows the interannual variability for the six regions and its linear trend that in all cases present a "kink" around 1999. Most interesting is that in all cases this means a reversal of the SLA trend, except the western Mediterranean, where a small general drop is shadowed by a rise in the Tyrrenian after 1999.

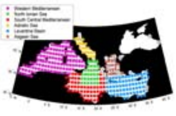

Figure 2 Regionalization of Mediterranean Sea and TG locations

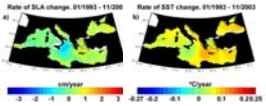

Figure 3. Linear rate-of-change map for the whole period: (a) SLA (cm year-1), (b) SST (ºC year-1)

Figure 3 shows the rate-of-change of SLA and SST for the whole period. We can observe a moderate, general sea level rise in the Mediterranean and Black Seas at a rate of less than +0.5 mm/year, with the exception of the north Ionian Sea which dropped at a rate up to -1 mm/year. At the same time, SST exhibited a general rise in the whole Mediterranean and Black Seas with values up to 0.1 ºC/year. Based on Figure 1, it is of high interest to examine the linear rate-of-change maps separately for periods before and after 1999, as in Figure 4.

We see a quite dramatic reversal between Figures 4a and 4b before 1999 (rising on the east -dropping on Ionian - steady on the west – strong rising in the Black Sea) and after 1999. The results confirm this inversion on the trend following the regional pattern described above. The spatial correlation between the rate-of-change maps of SLA and SST is obviousn for period I: 0.5 in the Mediterranean and as high as 0.99 in the Black Sea (Table 2) , this correlation implies that the interannual linear trend of SLA has been largely driven by thermo-steric changes in the Mediterranean and Black Seas.

In contrast, as seen in Figures 4b and 4d, after mid-1999 this SLA-SST correlation became greatly reduced (Table 2). Evidently some unidentified oceanographic dynamics is at work here.

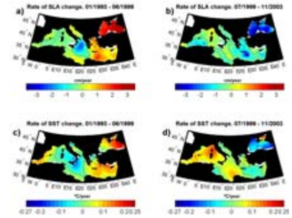

Figure 4. Linear rate-of-change map of: (a) SLA for the period 01/93-06/99 (cm year-1); (b) SLA for the period 07/99-11/03 (cm year-1); (c) SST for the period 01/93-06/99 (ºC year-1); (d) SST for the period 07/99-11/03 (ºC year-1).

| | Linear rate of change (cm/year) of MSL | | |
|---|---|---|---|
| **Region** | **01/93-06/99** | **07/99–06/02** | **07/99–11/03** |
| **a) Mediterranean Sea** | **+0.6** | **+0.0** | **-0.1** |
| **b) Black Sea** | **+3.0** | **-3.0** | **-2.3** |
| **c) W. Mediterranean** | **+0.3** | **+0.3** | **+0.2** |
| **d) North Ionian Sea** | **-1.0** | **+0.8** | **+0.1** |
| **e) S. cen. Mediterranean** | **+0.6** | **-0.1** | **0.0** |
| **f) Levantine basin** | **+1.5** | **-0.4** | **-0.4** |
| **g) Adriatic Sea** | **+0.8** | **-0.2** | **0.0** |
| **h) Aegean Sea** | **+1.6** | **-0.6** | **-0.6** |

Table 1. Linear rate of change for MSL, for the different regions and periods.

| **Time Period** | **01/93-11/03** | **01/93-06/99** | **07/99-06/02** | **07/99-11/03** |
|---|---|---|---|---|
| **Mediterranean Sea** | **0.51** | **0.72** | **0.15** | **0.17** |
| **Black Sea** | **0.99** | **0.93** | **-0.20** | **0.72** |

Table 2. Spatial correlation coefficient for linear rate-of-change of SLA vs SST.

### *b. EOF/PC spatial-temporal variations*

Figure 5 (a) and (b) show the first and second EOF/PC for the (non-seasonal) SLA in Mediterranean. The first mode probably reflects the circulation patterns in Mediterranean, an oscillating mode with very little long term variability, while the second mode reflects the strong long-term trends. From this second EOF we identify the spatial pattern of the inversion of the SLA around 1999. For example, SLA drops in the Ionian from 1992 till 1998 (with a peak in 1996) and rises from 1999 and onward, while the Levantine basin does the opposite.

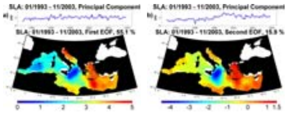

Figure 5. EOF/PC modes of SLA in the Mediterranean for the period 01/1993 – 11/2003: (a) First mode explains 55% of the variance of the data, (b) Second mode explains 16%.

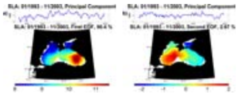

Figure 6. EOF/PC mode of SLA in the Black Sea for the period 01/1993 – 11/2003: (a) First mode explains 90% of the variance of the data, (b) Second mode explains 2%.

Figure 6 (a) and (b) show those for the Black Sea. Here the first EOF explains 90% of the signal power and reflects the strong long term trends with the 1999 reversal. The second EOF is a dipole, but only accounts for 2% of power.

### *c. Tide gauge (TG) data analysis*

Overall most of the available TG data show a change of trend in 1999, corroborating the results from altimetry. One of course recognizes that in general the TG measures the local sea level which is largely influenced by local conditions. For example, vertical crustal motions in the TG site may produce spurious sea level variations. It should also be noted that all TGs do not span the same period of time, hence introducing extra discrepancies in these estimates.

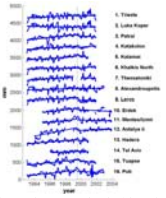

Figure 7. The non-seasonal sea level time series from the TGs. Separate linear regression is applied for periods before and after 1999.

### *CONCLUSIONS*

From altimetry data we found that: (i) A significant, but enigmatic, abrupt change in the trend of SLA in Mediterranean and Black Seas took place in mid-1999. This change was non-uniform in the Mediterranean Sea, and has been corroborated by independent tide gauge data. (ii) No corresponding change was present in the sea surface temperature, implying that prior to 1999 the steric effect was a major factor in interannual variability in the Mediterranean and Black Seas SLA, but after 1999 the steric effects became less important as a forcing factor. Although it is premature to draw conclusions about the physical processes involved based on the data sets we study, it appears that the Mediterranean Sea might be seeing a restoration of Adriatic as the main source of deep water in the eastern basin, while Black Sea level has been largely controlled by an interannual or interdecadal steric effect.

[I. Vigo, D. García, B. F. Chao, *Change of Sea Level Trend in Mediterranean and Black Seas,* Journal of Marine Research, 63 No.6, 1085-1100 , 2005]

## Annual Sea Level Variations (SLV) in the Mediterranean Sea

We examine the closure of the seasonal SLV budget and estimate the relative importance of the steric and mass contributions in the Mediterranean Sea as a function of time.

### *DATA ANALYSIS AND RESULTS*

The total SLV is estimated from altimetry data (from TOPEX/Poseidon, Jason-1, ERS and ENVISAT missions) same format as above, with all standard corrections applied, , including the inverted barometer effect to reduce aliasing errors, although it may introduce slight errors of its own by violating water mass conservation in the semi-enclosed sea. The time span is 01/1993-07/2004.

To estimate the steric SLV, the temperature *T* and salinity *S* fields from the *JPL-adjoint-smoothed wind driven* (ECCO ocean model products, http://www.ecco-group.org) are used . Data profiles are from surface to the (non-uniform) sea bottom at each point on a 1º x 1º regular grid, and the time span used is 1997-2004 with a time step of ten days.

The mass induced SLV is estimated from GRACE time variable gravity (TVG) data. We use the 22 monthly sets of normalized spherical harmonic Stokes coefficients provided by the GRACE Project (http://podaac.jpl.nasa.gov/grace) for the period 04/2002 - 07/2004. The GRACE TVG data have been corrected forfor the following: the atmospheric effect according to the ECMWF GCM output, the short-period oceanic effect based on a barotropic ocean GCM, the solid Earth tides (including solid pole tide), ocean tides (including the ocean pole tide as a consequence of the solid pole tide via an equilibrium response, but not including the effects of loading and self-gravitation of the ocean pole tide), as well as the routine satellite orbit perturbations of secular polar motion, N-body and general relativistic effects.

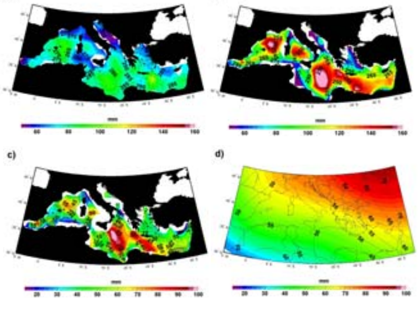

Figure 1. Annual amplitude (color scale in mm) and phase (contour lines in degrees) from equation xx for different datasets: (a) *SLV* from altimetry; (b) *steric* $SLV_c$ from ECCO model; (c) mass induced $SLV_s$ = (a) – (b); (d) mass induced *SLV* from GRACE data.

*Total SLV* and steric *SLV* do not properly match each other (Figures 1 a and b). Not only steric *SLV* has greater amplitude on average, but its phase also leads that of total *SLV* by around 30º. Their difference, which is an indirect estimate of mass induced *SLV*, is clearly non-vanishing, as shown in Figure 1c. Its annual amplitude is 30-60 mm, with two localized regions showing more than 90 mm, and its annual phase is between 10º and 55º (mid January and late February), except for a localized region in the Western Basin with a phase of 330º (or -30º). When comparing it with Figure 1d,which shows the mass induced *SLV* estimated from GRACE. Its annual amplitude is ~50 mm and its phase range from 45º to 65º (second half of February), which propagates north-eastward in the Levantine Basin and is quite homogeneous in the Western Basin.

Aside from the much lower spatial resolution of the GRACE map, which does not allow the detection of the small features observed in figure 1c, the agreement between both approaches is reasonably good in general (or more precisely in average), considering that (i) they are completely independent data types with uncorrelated noises; and (ii) Figure 1c is a residual signal between two large varying fields. Particularly notable is the large phase difference of the mass induced *SLV* with the total *SLV* or the steric *SLV*.

Figure 2. The time series represent the monthly mean values over the Mediterranean Sea for several datasets. Red curve: SLVmass from GRACE data; green curve: SLVtotal from altimetry data; yellow curve: SLVsteric from ECCO assimilation model; blue curve: SLVmass estimated according to equation 1, SLVmass = SLVtotal - SLVsteric.

Figure 2 and Table 1 show the same agreement between the total SLV and steric SLV observed in Figure 1 in both annual amplitude and phase. We notice (i) the amplitude of the total SLV is ~10 mm lower and peaks ~23 days later than the steric SLV; (ii) the mass induced SLV estimated from GRACE shows an annual amplitude of 55 mm and a phase of 52º (mid February) which are noticeably different from those of the total and the steric SLV; (iii) the estimation of the mass SLV as total SLV minus steric SLV from Equation (1) agrees very well with GRACE-observed mass SLV. Thus, the annual mass SLV in the Mediterranean is ~230º (8 months) ahead or ~130º (4 months) lagging with respect to the total SLV. The similitude of the steric and total SLV curves in Figure 2 indicates clearly that Mediterranean sea level is mainly driven by the steric changes, while the mass SLV amounts to about one third of the total SLV but having a quite different phase.

| | Period (month/year) | Amplitud (mm) | Phase |
|---|---|---|---|
| GRACE | 04/02 – 07/04 | 55 ± 15 | 52º ± 15º |
| Alt – ECCO steric | 04/02 – 07/04 | 38 ± 16 | 16º ± 27º |
| Altimetry | 04/02 – 07/04 | 83 ± 13 | 281º ± 10º |
| ECCO steric | 04/02 – 07/04 | 94 ± 5 | 258º ± 3º |
| P-E (NCEP) | 04/02 – 07/04 | 31 ± 8 /month | 7º ± 17º |
| F (Eq. 5) | 09/02 – 07/04 | 17 ± 16 /month | 263º ±76º |

Table 1. Annual amplitude and phase of the different spatially averaged monthly time series and the period covered by the datasets. The uncertainty indicates 95% formal error.

Besides the above indirect scheme of determine the mass induced *SLV,* alternatively it can be observed the net barotropic flow through the Strait of Gibraltar from *in situ* sensors and compare it with the $P - E$ estimates in the area. It can be deduced this mass signal arising as the balance between the "horizontal" water mass flux $F$ and the vertical flux $P - E$, taking the form

$$\delta(SLV\text{mass}) = F + (P - E)$$

where δ indicates the month-to-month incremental change which is calculated from GRACE data.

Figure 3 depics the estimate of the water mass flux $F$ estimated this way. $F$ comes primarily from the flux through the Gibraltar Strait, while the river run-off and the exchange with the Black Sea are negligible in comparison. Its estimated annual signals are $A$ = 17 mm/month and = 263º (late September). The yearly mean value of $F$ cannot be readily estimated using GRACE data because there are only 18 months of δ(*SLV*mass). Nevertheless, as long as the interannual variability and trends are insignificant, the Mediterranean mean mass content does not vary much from year to year and the mean $F$ should be completely offset by $P - E$ flux.

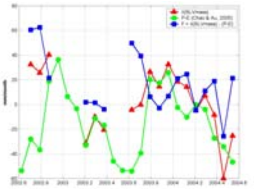

Figure 3. The time series represent the monthly mean values over the Mediterranean Sea for several datasets. Red curve: δ(*SLV*mass) from GRACE data; green curve: $P - E$ field from *Chao and Au* [2005]; blue curve: water mass flux $F$ from the difference between the above two curves according to Equation (6).

### *CONCLUSIONS*

We found that the annual cycle of total SLV from altimetry data (T/P, Jason-1, ERS and ENVISAT missions) in the Mediterranean is mainly driven by its steric component (computed from the ECCO ocean model) but moderately offset by the change of mass (computed from GRACE data). The agreement between the seasonal change of mass estimations from the difference between the total SLV and the steric SLV and from GRACE is quite remarkable; the annual cycle reaches the maximum value in mid-February, almost half a cycle later than the total SLV or the steric SLV, which peak by mid-October and mid-September, respectively. Thus, when sea level is rising (falling), the Mediterranean Sea is actually losing (gaining) mass. Furthermore, as the change of mass is balanced by vertical (precipitation minus evaporation, P–E) and horizontal (exchange of water with the Atlantic, Black Sea and rivers runoff) mass fluxes, we have compared it with the P–E determined from meteorological data estimating the annual cycle of the horizontal flux.

[ García, D., Chao, B.F, Del Rio , J., Vigo, I. And García-Lafuente, J. *On the steric and mass-induced contributions to the annual sea level variations in the Mediterranean Sea,* JGR-Ocenas (In press,2005) ]