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Change of sea level trend in the Mediterranean and Black seas

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Abstract

Sea level anomaly (SLA) data in the Mediterranean and Black seas obtained by ocean radar altimetry missions (TOPEX/Poseidon, Jason, ERS-1/2 and ENVISAT) are studied in conjunction with corresponding sea-surface temperature (SST) data. The studied time span is 11 years long, 1993-2003. Besides confirming previously published results, we report a significant, but enigmatic, abrupt change in the SLA trend that took place in mid-1999 which has been corroborated by independent tide gauge data. Results obtained from an Empirical Orthogonal Function (EOF) analysis show that the change in 1999 is not uniform in the Mediterranean Sea, which can thus be divided into 6 sub-regions. This 1999 kink in the rate-of-change happened in four of these sub-regions as well as in the Black Sea. Upon splitting the time series at mid-1999, we see a good spatial correlation for the first period between SLA and SST trend maps in both the Mediterranean Sea and the Black Sea, while for the second period such correlation virtually disappeared in the Mediterranean and is greatly reduced in the Black Sea. It implies that prior to 1999 the steric effect was a major factor in interannual variability of sea level in the Mediterranean and Black seas, but after the time the SLA inverted its trend in mid-1999, this steric effects became less important as a forcing factor. It is premature to draw conclusions about the physical processes involved based on the data sets we study, but 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 the Black Sea level has been largely controlled by an interannual or interdecadal steric effect.

1. Introduction

Sea level varies as a function of location and time at all spatial and temporal scales for many reasons. In particular, a global sea level rise has been evident, at a rate of about 2 mm/year for the last century as determined from tide gauge records (e.g., Douglas, 1997), and somewhat higher rate for the last decade based on the TOPEX/Poseidon (T/P) satellite radar altimetry data (e.g., Nerem and Mitchum, 2001). Two factors contribute to the sea level variation (e.g., Fu and Cazenave, 2001): the steric effect due to thermal and salinity change in the water column and a net addition or subtraction of water mass.

In this paper we examine the sea level anomalies (SLA) in the Mediterranean and Black

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seas, as a function of space and time. Here we define SLA as the nontidal, nonseasonal signals relative to the "mean" state; our time scale of interest is longer than 1 month. Connected through the Dardanelles and Bosphorus straits, these two semi-enclosed basins exchange water with the open sea only through the narrow Strait of Gibraltar and with the land by the moderate runoff of rivers such as the Nile. If the fluxes through these waterways are closely monitored or modeled, then the only other water exchange is with the atmosphere in the form of P-E (precipitation minus evaporation), which can be modeled given sufficient meteorological data including temperature, humidity, wind and pressure fields (e.g., Au *et al*., 2005) from regional or global weather centers. Thus, on face values, the Mediterranean and Black Sea water budget can in principle be quite tractable.

However, the Mediterranean sea level variation has been enigmatic, and, as we will show, continues to be so. From historical records we know that around 1960 the mean sea level (MSL) of the Mediterranean underwent a change of average rate from a general rise of $+1.2 \sim 1.5$ mm/year to a drop at a rate of about -1.3 mm/year (Tsimplis and Baker, 2000). The MSL drop continued in the Mediterranean until the early 1990s. Less dramatic changes took place in the Atlantic where the rate changed from $+1.8$ mm/year to $+1.1$ mm/year around 1960, while that of the Black Sea stayed around $+2.2$ mm/year. The relation between the Mediterranean sea level and the North Atlantic Oscillation (NAO), in terms of the so-called NAO index, has been examined by, e.g., Tsimplis and Josey (2001) and Woolf *et al.* (2003). Using altimetry and tide gauge data during the last decade, positive correlation around northwest Europe and negative correlation around southern Europe and northeastern North America were found. This Mediterranean-NAO correlation pattern was also evident for the entire 20th century (Hurrell, 1995). NAO's influence on the Mediterranean sea level is largely uniform although stronger in the north Adriatic than in south Greece and the northern Levantine Basin. Furthermore, a change of NAO index from negative to positive states during 1960-1990 was connected with the aforementioned change in the Mediterranean MSL rate in 1960 (Tsimplis and Josey, 2001).

Cazenave *et al.* (2001, 2002) studied T/P altimetry data from 1993 to 1999 for the Mediterranean, reporting a general rise in the Mediterranean SLA except in the Ionian where a drop was observed. This new pattern in the Mediterranean SLA is very well correlated with that of the sea-surface temperature (SST) for that same time period. Tsimplis and Rixen (2002) indicated that the Ionian upper water was subject to strong heating in 1985-1990 and a subsequent cooling and that the Levantine basin was cooled after 1990 with a minimum in 1994. Thus it appears that the pattern is a return of a previous situation (Tsimplis and Rixen, 2002). This pattern has also been reported by other authors (Fenoglio-Marc, 2001, 2002).

Using this background knowledge, we will perform a comprehensive study of the Mediterranean and Black seas' SLA for the latest eleven years using multi-mission ocean radar altimetry data, primarily T/P's. Upon confirming the known pattern and correlation with SST for the earlier period of 1993-1998, we will report a reversal of this SLA pattern that occurred around mid-1999, after which the correlation with SST virtually disappeared in the Mediterranean. Corresponding, but significantly different, behavior is found for the Black Sea. We will examine these variabilities, and place them in the framework of thermohaline circulation changes in the eastern Mediterranean in 1999 and of interannual to decadal fluctuations in the Black Sea, which appear to be two separate and distinct dynamic systems.

2. Data analysis and results

The altimetry data used in this study are monthly SLA maps, on a 1° by 1° 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. Data are a combination of T/P+ERS, except for the period 01/1994 – 03/1995 (ERS-1 geodetic phase), up to August 2002, when Jason-1 replaced T/P. ERS-2 was also replaced by ENVISAT since 06/2003. SLA are given in units of cm, where a 7-year (01/1993 – 01/1999) T/P mean map representing the static geoid is removed from the altimeter data. There are about 310 grid points in the Mediterranean and about 61 grid points in the Black Sea. 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). For further details see AVISO (1996, 1998). Whether one should allow inverse barometer (IB) correction or not in this case is debatable as it was noted that IB is not prevalent for the Mediterranean Sea at relatively short periods (Le Traon and Gauzelin, 1997) nor for the Black Sea (Ducet *et al.*, 1999; Tsimplis *et al.*, 2004); we here use IB corrected data as we are interested in long-period variations, and mean atmospheric pressure has a small effect due to its small seasonal and interannual changes. In any case, we have also reproduced the study with T/P data for the period 10/1992 – 07/2002 without applying the IB correction (not shown) and the differences in the linear rates of change are small (as in previous studies, e.g., Ducet *et al.*, 1999) relative to the level of amplitudes that are of interest in the results we are presenting here. The only appreciable difference occurs in the Adriatic Sea, and it is due to the lower resolution of the T/P data versus the multimission data used in this study (multimission data have 9 extra points covering the northwest area where the negative linear trend is observed after 1999).

In our study, the data span 01/1993 – 11/2003 (~11 years) will be referred to as the "whole period." The whole period will be divided into two parts to accommodate for the abrupt change in the SLA behavior that took place around mid-1999: Period I = 01/1993 – 06/1999 (6.5 years) and Period II = 07/1999 – 11/2003 (4.5 years). The first part 07/1999 – 06/2002 (3 years) of Period II, called Period IIa, is sometimes further singled out for more detailed study.

The sea-surface temperature (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 1° by 1° 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 NOAA satellites, and *in situ* SST collected from buoys and ships. AVHRR measures emitted and reflected radiation from Earth in two visible channels and three infrared channels. Before the analysis is computed, the satellite data are adjusted for biases using the method of Reynolds (1988). The bias correction improves the large-scale accuracy of the OI. A description of the OI analysis can be found in Reynolds *et al.* (2002).

Both SLA and SST data series are dominated by strong seasonal signals, primarily annual and semi-annual. In this paper we are only interested in the nonseasonal, especially the interannual, anomalies. Thus, as the first step in processing the data, we least-squares fit the time series point by grid point, for the given time span as the case may be, with annual and semi-annual sinusoids. Then we remove the latter by simple subtraction from the data, forming a new, nonseasonal series of maps. The average annual amplitude of the SLA that we remove is about 7.5 cm for the Mediterranean Sea and 2.5 cm for the Black Sea; and for the semi-annual, it is 1.1 cm for the former and 1.7 cm for the latter. The seasonal signals will be studied in a separate paper together with new time-variable gravity data by Garcia *et al.* (2005).

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

a. Linear trends in mean sea level (MSL)

To obtain an overall idea of the long-term SLA variation in the Mediterranean and Black seas, we first study the time series for the MSL. The previously reported rise in MSL (as mentioned above) is confirmed for Period I, after which the MSL apparently starts dropping. In Figure 1b the overall MSL curve for the Black Sea dramatically shows this mid-1999 “kink” in the rate-of-change slope, or linear trend. The same MSL kink for the Mediterranean Sea clearly exists as well, although not as prominent; (see Fig. 1a).

Regional breakdown of the Mediterranean data, however, proves more revealing and more insightful regarding the behavior of the 1999 kink in the MSL rates of change. We divide the Mediterranean Sea into 6 regions as in Figure 2 for which Figure 1c-h examines the regional MSL variations in detail. This division is based upon the regional differences in the SLA variability as discussed in detail in the EOF analysis (see below). Similar divisions have been adopted for the Mediterranean in previous studies (e.g. Tsimplis and Rixen, 2002).

The Levantine Basin and the Aegean Sea (Figs. 1f and 1h) demonstrate a behavior similar to the Black Sea, albeit of a smaller magnitude, while the Ionian Sea (Fig. 1d) demonstrates a surprising, completely opposite behavior. This slope drop in the Ionian Sea relative to the pre-1999 rise in the rest of the Mediterranean has been reported from altimetry data (Cazenave *et al.*, 2001, 2002; Fenoglio-Marc, 2001, 2002); it has been

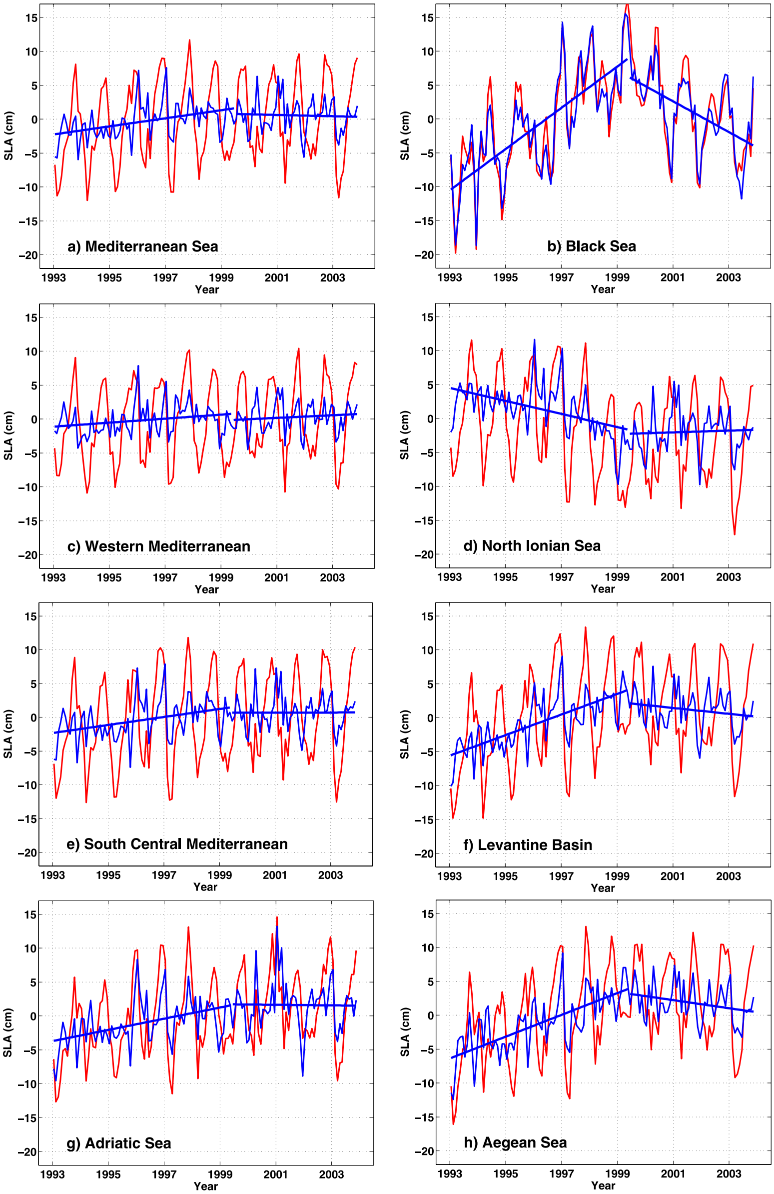

Figure 1. A kink in the linear rate of change in MSL between Periods I and II. Each time series corresponds to a different region. In all cases for MSL, the nonseasonal signal (blue curve) and the seasonal signal (red curve) are shown.

suggested by Tsimplis and Rixen (2002) that this is a manifestation of a return to the situation of the mid-1980s. In Figure 1 we also plot the data series with the seasonal signals just for comparison purposes. Here we can safely preclude the possibility that the 1999

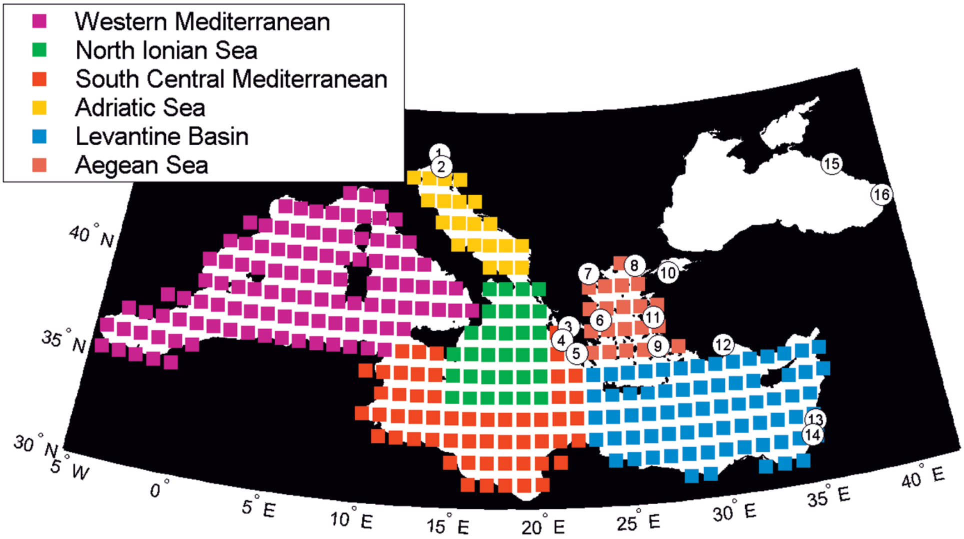

Figure 2. Regionalization in the Mediterranean Sea and TG locations used in this study.

kink is an artifact due to the switchover of the Side-A to Side-B altimeter on T/P that happened in early 1999 for the following reasons. First of all, the observed sea level changes are simply too large to be related to an instrument calibration error (B. Beckley, personal communication, 2005). Secondly, we note that in 1999 there are three different situations: (a) a change from dropping to rising sea level was observed in the Ionian Sea; (b) a change from rising to dropping was observed in the Levantine Basin, Adriatic, Aegean and Black seas; and (c) no change of trend was observed in the western Mediterranean. If the change of trend were related to the switchover of the altimeter, one would expect similar changes of trend for all cases.

The MSL rates of change of each region for Periods I, IIa, and II are given in Table 1. Comparing the values for the latter two periods, it can be seen that the behavior is similar between Periods II and IIa in all the regions except in the North Ionian and Black Sea. Generally, a decrease of the rate of change is observed for Period II as compared with Period IIa, indicating that the trending was stronger in the first three years after mid-1999. The slowing down in the rate of change when including the last 1.5 years of data does not appear to be related to the replacement of T/P by Jason-1because in that case, such a slow-down would have been perceptible in all the regions.

Next we examine the linear rate-of-change maps of SLA and SST for the Mediterranean and Black seas. The contours in Figure 3 and 4 depict the respective spatial pattern of the linear rate-of-change obtained by a least-squares fit of a linear slope at each grid point that makes up the maps.

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

Table 1. Linear rate of change for MSL for different regions in the Mediterranean and Black seas during three different periods.

	Linear rate of change (cm/year) of MSL		
Region	01/1993–06/199 (Period I)	07/1999–06/2002 (Period IIa)	07/1999–11/2003 (Period II)
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

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 entire Mediterranean and Black seas with values up to 0.1°C/year.

The spatial correlation between the rate-of-change maps of SLA and SST is obvious: 0.5 in the Mediterranean and as high as 0.99 (but see below) in the Black Sea (Table 2). As SST is an indicator of thermo-steric variations, this correlation implies that the interannual linear trend of SLA has been largely driven by thermo-steric changes in the Mediterranean and Black seas. Tsimplis *et al.* (2004) demonstrated that the long-term sea level rise in the Black Sea from mid-1950s to late-1990s was related to changes in P-E (precipitation - evaporation) instead of steric changes. Our result pertains to post-1993 on a shorter time scale and then it may be related to an interannual oscillation with no trend in the 40-year period studied by Tsimplis *et al.* (2004). This also manifests the strong dependence of the Mediterranean and Black seas' behavior on the time scale under consideration.

Based on Figure 1, it is important to examine the linear rate-of-change maps separately

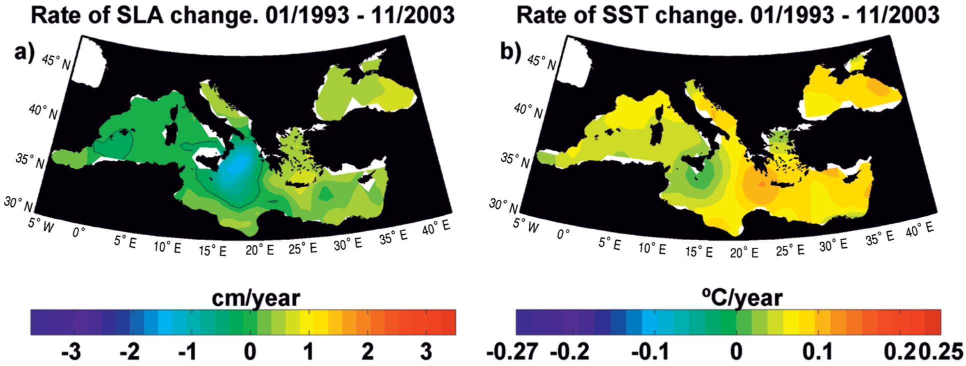

Figure 3. Linear rate-of-change map for the whole period: (a) SLA (cm year^{-1}), (b) SST (°C year^{-1}).

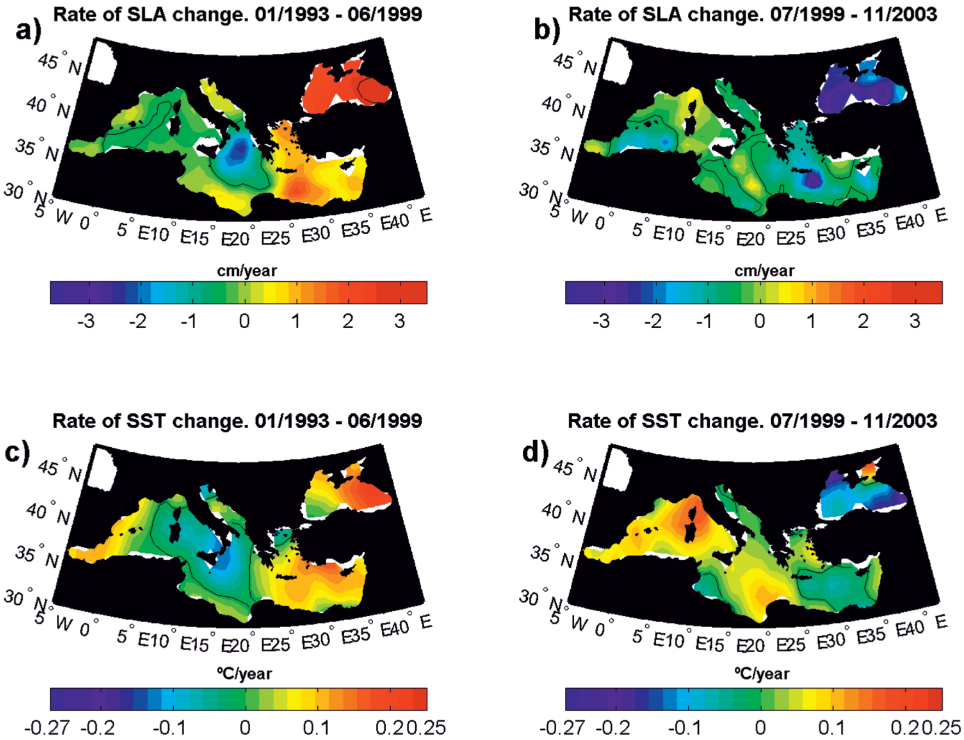

Figure 4. Linear rate-of-change map of: (a) SLA for Period I (cm year^{-1}); (b) SLA for Period II (cm year^{-1}); (c) SST for the Period I (°C year^{-1}); (d) SST for Period II (°C year^{-1}).

for Periods I and II before and after 1999, as in Figure 4. For Period I, one sees a general SLA rise in the Mediterranean Sea where the SST generally rose and a SLA drop in the Ionian Sea where the SST dropped (with the apparent exception of the western Mediterranean basin). The SST, and hence the steric effect, seems to be the major cause of the SLA trend, given its high correlation on the pattern (Figs. 4a and 4c; Table 2), as first reported by Cazenave *et al.* (2001). In contrast, as seen in Figures 4b and 4d, during Period II after mid-1999 this SLA-SST correlation became greatly reduced (Table 2) in the Mediterranean Sea, where an inversion of the pattern in SLA took place (Fig. 1). Similar phenomenon occurs in the Black Sea, although less severe. Table 2 also reports the spatial

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

Time Period	01/93–11/03 (whole period)	01/93–06/99 (Period I)	07/99–06/02 (Period IIa)	07/99–11/03 (Period II)
Mediterranean Sea	0.51	0.72	0.15	0.17
Black Sea	0.99	0.93	−0.20	0.72

SLA-SST correlations for Period IIa. In the Mediterranean Sea, a lower correlation between SLA and SST existed, with virtually no correlations except perhaps in the Levantine Basin and Aegean Sea (not shown).

We note that, since the value of the SLA or SST rate is hardly independent from point to point, the statistical degrees of freedom involved in evaluating the above spatial correlation coefficients are rather low relative to the number of the grid points in both the Mediterranean and Black seas' cases. Therefore the high correlation values for the Black Sea are actually not out of the ordinary, while the low values in Table 2 do mean weak or no correlation. Here, rather than trying to determine the effective degrees of freedom, the correlation coefficients in Table 2 should be judged in a quasi-quantitative and comparative manner.

In summary, the results above indicate that some oceanographic change took place in mid-1999, when certain factors seemingly related to changes in thermohaline circulation became more relevant for SLA in the Mediterranean Sea to the detriment of the steric effect. Similarly, a significantly lower SLA-SST correlation appeared for the Black Sea during Period IIa, presumably related to a 4-5 year periodicity in SST (e.g., Cazenave *et al.*, 2001) but absent in SLA. The 1999 kink in the rate of change in the Black Sea could be part of the interannual to decadal variability reported by Tsimplis *et al.* (2004).

We should emphasize that the above results only apply to the linear trends and the corresponding rate-of-change maps for SLA. While the SLA series see a clear kink in 1999 as above, the corresponding SST series (not shown, but see below) only exhibit general interannual fluctuations with little indication of such a kink.

b. EOF/PC spatial-temporal variations

To determine the spatial-temporal variations of SLA and SST in more detail, we conduct an Empirical Orthogonal Function (EOF) analysis with their associated time series (or the Principal Components PC) (e.g., Preisendorfer, 1988) done separately for the Mediterranean and Black seas. We shall normalize the EOF maps to unit variance, so that the PC time series has the unit of cm. Remember that the seasonal signals have already been removed, and the following describes the nonseasonal anomalies.

Let us examine the first two EOF/PC modes of SLA in the Mediterranean for the entire period of 01/1993 – 11/2003. The first EOF (Fig. 5a) explains 55% of the variance of the data and we see that every point has the same sign (here taken as positive), implying a "breathing" mode or an oscillation of the whole Mediterranean moving up or down in phase. The peak-to-peak amplitude of this mode is on the order of 2 cm. Conceivably this can be a manifestation of an in-phase heating or cooling of the whole Mediterranean, or simply an addition or loss of water mass that is distributed over the whole Mediterranean. Fukumori *et al.* (2003) suggest that this oscillation is associated with wind-driven mass transport across the Strait of Gibraltar. A wind-driven transport in the Strait should have a baroclinic compensation while this "breathing" mode actually implies a barotropic net exchange between the Mediterranean and the North Atlantic. Even though the SLA data

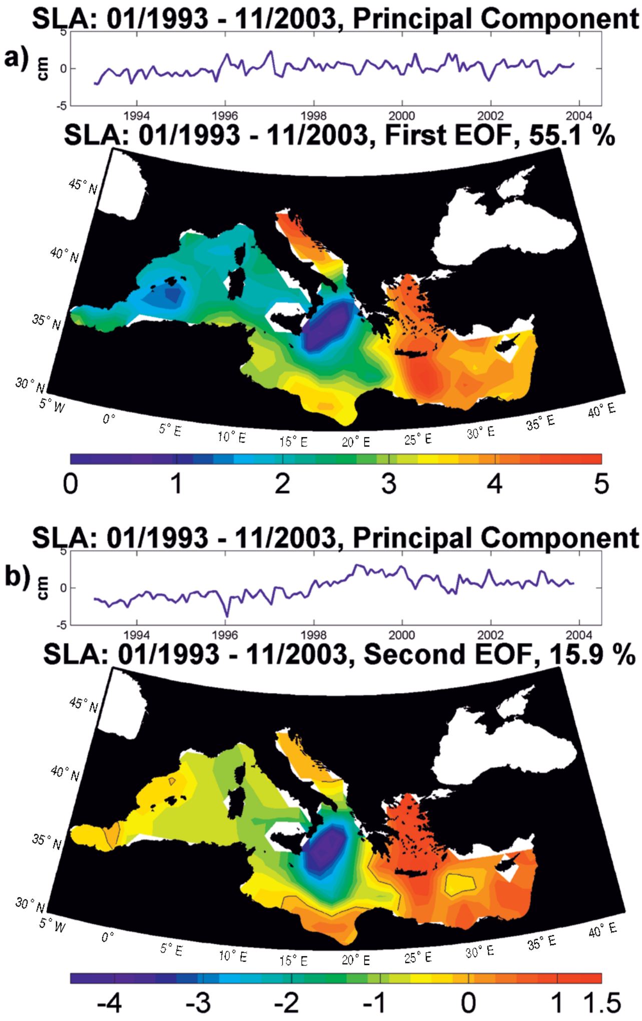

Figure 5. EOF/PC modes of SLA in the Mediterranean for the whole period of 01/1993 – 11/2003: (a) First mode explains 55% of the variance of the data, (b) Second mode explains 16%.

have been corrected for an IB effect, the oscillation implied by this mode could be mainly driven by the atmospheric pressure difference between the Mediterranean and the North Atlantic as the simple analytical model proposed by Candela *et al.* (1989) might suggest. The corresponding PC time series showing no significant trend implies that this mode has little to do with the 1999 kink in SLA.

On the other hand, the second EOF (Fig. 5b), which explains 16% of the variance, is nearly identical to the SLA rate-of-change map in the Mediterranean for the whole period (Fig. 3). This mode corroborates our findings above with respect to the change of behavior

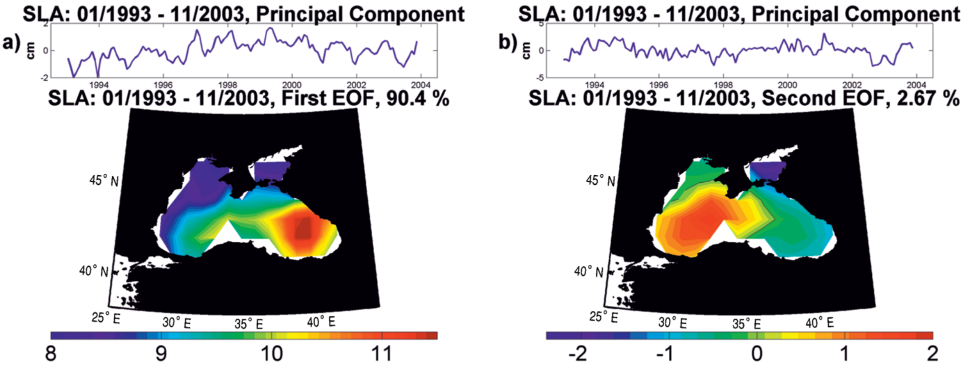

Figure 6. EOF/PC mode of SLA in the Black Sea for the whole period of 01/1993 – 11/2003: (a) First mode explains 90% of the variance of the data, (b) Second mode explains 2%.

associated with the 1999 kink and observed in Figure 4a,b as follows. The positive points in the EOF pattern undergo the same variations as the PC, and the negative ones undergo the variation of the inverse of the PC. In both cases, the relation to the PC is proportional to the magnitude of the value of the point in the EOF pattern. The PC shows a positive trend up to mid-1999 and a negative one afterward. As the third and subsequent EOFs do not explain a significant percentage of variance (not shown), it can be inferred that the information related to the linear trends is summarized in the second EOF. Therefore, a positive region with high values will undergo a positive linear trend up to 1999 and a negative one afterward, and vice versa. We can observe negative high values in the Ionian Sea and positive high values in the Levantine Basin and the Aegean Sea, meaning an SLA drop in the former and a rise in the latter till 1999, and a reversal of the pattern after 1999. This leads us to break down the Mediterranean into 6 regions as done in Figure 2. The change in trend before and after 1999 is about 0.7 cm/year, agreeing with those found in Figure 1a and Table 1 above.

The first two EOF/PC modes of SST in the Mediterranean for the whole period explain 54% and 22.8% of the variance, respectively (not shown). In the first mode, a positive trend is observed in the time series with a positive pattern, meaning that SST has been rising in the Mediterranean for that period, and in the second mode the PC time series does not undergo any significant trending. In neither case does the EOF map pattern correlate well with the rate-of-change maps of SST. These results agree with those reported by Cazenave *et al.* (2001) who also found a positive linear trend in the first mode of SST (without any signal shorter than 1 year) for the period 1993 – 1999, with no spatial correlation with SLA behavior in the first two EOF/PC modes.

Unlike the Mediterranean, it is the first EOF/PC mode of SLA in the Black Sea (explaining as much as 90% of the variance, see Fig. 6a) that agrees quite well with the rate-of-change map for the whole period, since both maps show a focus in the southeastern part of the basin. This EOF has a positive value in the entire basin and the PC time series

Table 3. Linear rate of change for every TG before and after 06/1999.

			Linear rate of change (cm/year)	
	Name	Location	Pre-06/1999	Post-06/1999
1	Trieste	45 39 N 13 45 E	1.1	0.0
2	Luka Koper	45 34 N 13 45 E	−0.6	−0.6
3	Patrai	38 14 N 21 44 E	2.3	−1.9
4	Katakolon	37 38 N 21 19 E	1.5	1.8
5	Kalamai	37 01 N 22 08 E	1.6	−5.6
6	Khalkis North	38 28 N 23 36 E	0.6	2.1
7	Thessaloniki	40 37 N 23 02 E	1.6	−1.9
8	Alexandroupolis	40 51 N 25 53 E	0.7	0.3
9	Leros	37 05 N 26 53 E	1.1	−0.4
10	Erdek	40 23 N 27 51 E	2.7	−1.1
11	Mentes/Izmir	38 26 N 26 43 E	2.6	−0.8
12	Antalya ii	36 50 N 30 37 E	4.4	1.0
13	Hadera	32 28 N 34 53 E	1.8	−0.4
14	Tel Aviv	32 05 N 34 46 E	0.6	−1.3
15	Tuapse	44 06 N 39 04 E	2.3	−3.6
16	Poti	42 10 N 41 41 E	2.6	−0.8

has a positive trend till mid-1999 and a negative one afterward, agreeing with that found earlier in Figure 1b. The second EOF/PC mode (Fig. 6b), which only explains 3% of the variance, divides the basin in two symmetric parts and executes an east-west seesaw of (presumably) mass transport.

The first EOF/PC mode of SST in Black Sea (not shown) explains 80% of the variance, the second one explains 9%, and both are very well correlated, respectively, with the first and second EOF of SLA. The PC time series show a lower correlation, except for the second PC time series.

c. *Tide gauge (TG) data analysis*

The available TG data, from PSMSL, with sufficient time span to study the change of trend in 1999 are described in Table 3 and located in Figure 2. We examine the TGs in the North Ionian Sea, Adriatic Sea, Levantine Basin, Aegean Sea and Black Sea, where the change of trend is observed. In order to determinate the linear trends before and after mid-1999, the seasonal signals have been removed from the data and a linear regression has been applied to the data in both periods, (see Fig. 7). The linear rates of change for each station are given in Table 3.

Here we see that 8 TGs (Patrai, Kalamai, Thessaloniki, Leros, Erdek, Mentes/Izmir, Hadera and Tel Aviv) in the Mediterranean and 2 in the Black Sea (Tuapse and Poti) show a reverse change of trend in 1999, while the rest in the Mediterranean present different situation: Antalya does not show a reverse of trend but a reduced trend; Trieste shows a reduction in the rate of change, whereas the neighboring Luka Koper shows no change;

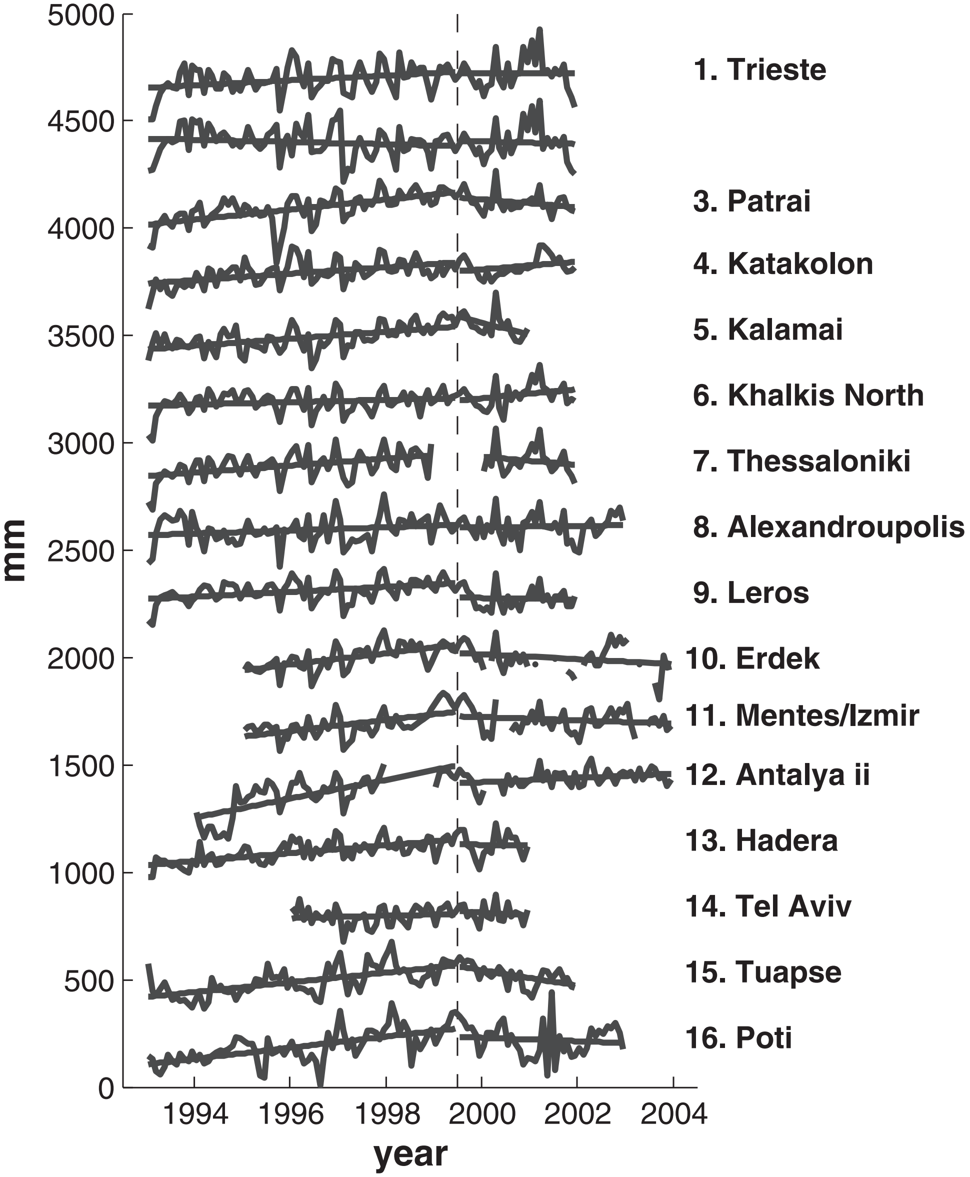

Figure 7. The non-seasonal sea level time series from the TGs. Separate linear regression is applied for periods before and after 1999, to indicate possible change in the linear trend, some are stronger than others.

neither do the 3 TGs at Katakolon, Khalkis North and Alexandroupolis. Thus, 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 (Cazenave *et al.*, 1999; Nerem and Mitchum, 2002). It should also be noted that all TGs do not span the same period of time, hence introducing extra discrepancies in these estimates.

3. Discussion and conclusions

An abrupt change of linear trend of SLA that occurred in the Mediterranean and Black seas in mid-1999 has been identified. The rate of change of the overall MSL, positive in Period I of the altimetry data (01/1993 – 06/1999), abruptly changed into a negative trend afterward, producing a kink in the MSL temporal trend for both Mediterranean and Black seas. Sub-regions of the Mediterranean individually exhibit similar kinks but with differing characteristics, with the North Ionian Sea doing the reverse trending. MSL has been dropping in the North Ionian up to mid-1999, where even an acceleration can be observed from early 1996, unlike the rest of Mediterranean and the Black Seas where the sea level was rising; after 1999 this pattern was reversed.

During Period I the Mediterranean SLA's linear rate-of-change map correlates well with the SST counterpart, in sharp contrast with Period II (07/1999 – 11/2003) when this correlation virtually disappeared. We can conclude that the abrupt change in the Mediterranean in 1999 caused the steric effects to become less important as a forcing factor of SLA variations. EOF/PC analysis has further revealed more details of the SLA variations in the Mediterranean and the Black seas, as well as their relationships with the SST variation.

Whether the changes in trends are related to the change of state in the thermohaline circulation or part of some decadal fluctuation in sea level is a key question. Hydrographic data in the eastern Mediterranean show that the main source of deep water in the last century was the Adriatic Sea. A change of that pattern occurred between 1987 and 1995 when a new source of deep water, called the Eastern Mediterranean Transient (EMT), appeared in the Aegean Sea (Roether *et al.*, 1996). As predicted by Klein *et al.* (2000), after some extremely cold winters, the Adriatic restored its role as a main deep water source in the 1997-99 period (Manca *et al.,* 2003). Manca *et al.* (2003) also confirmed the recovery of the westward transit of Levantine Intermediate Waters through the Cretan Passage into the Ionian. The open thermohaline cell circulation was restored in 1999. The change in SLA reported here is stronger in the regions related to the restitution of pre-EMT situation; namely, the Adriatic Sea, Ionian Sea, Levantine Basin and Aegean Sea. Larnicol *et al.* (2002) already suggested that the changes observed in the SLA during 1995-99 in the Levantine and during 1997-99 in the Ionian are related to variations in the deep and intermediate water masses distributions in the whole Eastern basin.

It is reasonable, therefore, to hypothesize that the SLA change in the Mediterranean Sea in 1999 is related to the return to the pre-EMT situation. The Black Sea has been largely controlled by an interannual or decadal steric effect according to the 11-year-long data, not agreeing with Tsimplis *et al.* (2004) who reported that the long-term SLA variations for the last 40 years were not driven by steric variations but probably by P-E variations. We can conclude that the cause and effect of the SLA variations in the Mediterranean and Black seas is not straightforward and highly time-dependent; our findings represent only a short segment in the longer-term fluctuations. As far as our results are concerned, the Mediterranean and Black seas appear to be two separate and distinct dynamic systems. Despite their close geographical proximity, this is conceivable because they are under different meteorological and hydrological regimes and their physical connection, via the Straits of Dardanelles and Bosphorus, is quite restricted. It is important to understand the meteorological and oceanographic conditions that led to the recent evolution of the SLA variations, particularly the 1999 event and its evolution and consequences. The present study is based on the analysis of surface data and from the surface we can already tell that something is going on. Further investigations are needed, incorporating *in situ* water column data (such as from XBT or drift ARGO buoys) and particularly oceanographic models.

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