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Regional sea level response to global climatic change: Black Sea examples

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Abstract

The sensitivity of Black Sea level to variations in the global forcing is studied here using tide gauge and satellite altimeter data, as well as hydro-meteorological data for the fresh water flux components. The consistency between satellite and sea borne data is analyzed and the characteristics of variability with monthly to interannual time scales are revealed. The analysis of 6-year-long data series of TOPEX/Poseidon altimeter shows that the first EOF accounts for 85% of the total variance and is associated with the water cycle, the latter forced by the air–sea exchange, continental hydrological budgets and straits outflow. This result is a demonstration that the Black Sea level integrates the variations of global forcing over vast catchment area, thus making them quite distinguishable. The second EOF describes the seasonal variability of circulation. The third and higher EOFs describe synoptic and basin-oscillations, and the corresponding principal components are characterized by strong interannual variability. By analyzing the correlation of sea level and water balance in the last 70 years, we quantify the response to the external forcing. The mean sea level trend during 1993–1997, derived from the TOPEX/Poseidon data, of ~12 cm is much lower than the largest trends of this type observed in the last 120 years, which are associated with interannual-to-decadal variability and reach ~20–30 cm. The correlation between the sea level and NAO index, starting from 1870s, is well pronounced, suggesting that future variations of sea level could be predicted using global climate indices. It is shown that the long-term changes of water balance are strong enough to substantially affect the exchange between Black Sea and Mediterranean Sea. This in turn might result in changing the conditions of water mass formation in the Aegean Sea and motivates further studies on the prediction of extreme events of deep water mass formation in the Eastern Mediterranean Sea as function of the global and regional water cycles.

Keywords: Black Sea; hydrological cycle; sea level; climatic controls; Mediterranean Sea deep water formation

1. Introduction

The multidisciplinary studies addressing various aspects of Global Change are often based on exploitation of data and models of different type and origin. Though some promising results in this field have been recently documented, in particular in the field of coupled studies of atmospheric and ocean systems,

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some important aspects associated with the water cycle need further efforts. The enormous difficulties in this field result from the low level of signals, specificity of precipitation (patchiness, poor data coverage), the practical impossibility to measure evaporation, as well as from the incomplete/inaccurate consideration of the continental hydrological budgets in the coupled models of atmosphere and ocean. The above problems motivate us to look for areas in the world ocean, where the water cycle exhibits pronounced and measurable variability. One such region is the Black Sea, providing an excellent possibility to estimate water cycle regimes in order to carry out pilot studies and to further apply the results to other ocean regions.

The exchange with the world ocean trough the narrow Bosphorus Straits, linking the estuarine-type Black Sea with the lagoon-type Mediterranean Sea, is controlled by the two-layer hydraulic transport. The mass balance estimates reported by Özsoy and Ünlüata (1998) yield an average upper layer outflow of 600 km^3 $year^{-1}$ and a lower layer inflow of 300 km^3 $year^{-1}$. These asymmetric transports are maintained by the excess precipitation ($\sim$300 km^3 $year^{-1}$) and river runoff ($\sim$350 km^3 $year^{-1}$) against evaporation ($\sim$350 km^3 $year^{-1}$). However, these numbers represent not more than the mean situation since the flow through the Bosphorus Straits is characterized with complex dependence on the atmospheric factors and fresh water flux, as well as with pronounced transient variability (Özsoy et al., 1998; Ducet et al., 1999). The resistance of the straits prevents the immediate export of the excess water coming from rivers and air–sea exchange, thus the response to external forcing is amplified, making the signals quite distinct both in the tide gauge data (Simonov and Altman, 1991; Boguslavsky et al., 1998), as well as in the satellite altimetry (Korotaev et al., 1998, 2001; Stanev et al., 2000). The control of the Bosphorus Straits makes the Black Sea a good overall integrator of the various kind of forcing and internal variability and maintains a strong correlation between the fresh water fluxes and sea level variability (Stanev et al., 2000). Number of unique consequences follow: the salinity is two times lower that in the ocean, the stratification is extremely stable, the ventilation of deep layers is very small, the latter explaining why the Black Sea became the largest anoxic basin in the world ocean.

The changes in the water balance govern not only the entire Black Sea system, but may have far reaching consequences in the neighboring Mediterranean Sea. Comparisons of observations carried out in the Mediterranean Sea from surveys in 1987 and 1995 (Roether et al., 1996) showed an increased deep water salinity in vicinity to Crete Island. The authors hypothesized that this change could be caused by increased influx of Aegean waters, which could result from changes in either circulation pattern or large-scale fresh water balance. Their explanation on the observed event included calculations showing that changes in evaporation of $\sim$0.2 m $year^{-1}$ could cause the observed deep salinity increase. In our opinion, the decrease in the Black Sea outflow could also work in this direction. Here is our simple example. Let us admit that the above perturbation in the air–sea exchange over the Aegean Sea (area of $\sim$200 000 km^2) would be sufficient to trigger the anomalous deep water mass formation. The corresponding fresh water deficit is then 40 km^3 $year^{-1}$. The question now is would it be possible to obtain the same or comparable effect by reducing the amount of low salinity water of Black Sea origin. According to the data given by Simonov and Altman (1991), reductions of the fresh water flux in the Black Sea from 300 to 200 km^3 $year^{-1}$ are quite realistic. This would result in a deficit of dilution of Aegean Sea corresponding to $\sim$100 km^3 $year^{-1}$ water with salinity of 18. Since the Mediterranean Sea salinity is two times larger than that of the Black Sea, the corresponding deficit of fresh water in the Aegean Sea would amount to 50 km^3 $year^{-1}$, which is more than the fresh water deficit associated with the excess evaporation of $\sim$0.2 m $year^{-1}$ over the Aegean Sea. On the contrary, the increase of the transport of Black Sea water into the Mediterranean Sea could block (or lead to a decrease in the rates of) the deep water formation in Aegean Sea. Thus, we aim to prove in this paper that the long-term thermohaline variability in the Mediterranean Sea might reflect changes in the water cycle of Black Sea.

The fundamental question about how the Black Sea level responds to atmospheric oscillations has not yet been addressed (some ideas in this field are given in the work of Polonsky, 1997; Polonsky et al., 1997).

This sea lies approximately at the frontier where the dependency of precipitation on the global climatic variability, the latter identified in this paper by the North-Atlantic Oscillation (NAO), reverses — negative correlation between precipitation and NAO index over Europe and positive one over Minor Asia, (Leetmaa et al., 1999; Özsoy, 1999). This makes the issue of the sensitivity of the Black Sea water cycle to global and regional climate variations quite important, particularly in the context of inferring climatic changes by analyzing river runoff and strait outflows. The Black Sea river catchment area is several times larger than the Black Sea surface (Fig. 1) suggesting that the atmospheric circulation over large part of Europe would have direct impact on the Black Sea water balance through the river runoff, the latter integrating the variations of global forcing over vast area thus making them quite distinguishable. This motivates us to address here the dependency of sea level variation on the global forcing and the structure of time variability (characteristic periods and correlation with NAO). This would allow understanding of the sensitivity of the regional climate (seen as changing volume of the sea) to global variability.

The sea level variations in the Back Sea are shaped not only by forcing at sea surface (wind and buoyancy fluxes and river runoff), but also by internal dynamics (e.g. coastal trapped waves, frontal and open sea baroclinic eddies, sub-basin oscillations, etc., Stanev et al., 2001). Some of these oscillations have pronounced footprints in satellite altimetry, and our aim here is to extract useful physical information from these data and to demonstrate their usefulness when quantifying the water cycle.

The paper is structured as follows: in Section 2, we address the major horizontal patterns and characteristic time scales obtained through EOF analyses and give some interpretations; in Section 3, we describe the interannual variability and trends of fresh water fluxes and sea level, as well as the correlation between them, and look for footprints of NAO and ENSO in the variations of the Black Sea water balance and mean sea level variations; the paper ends with summary of the main results.

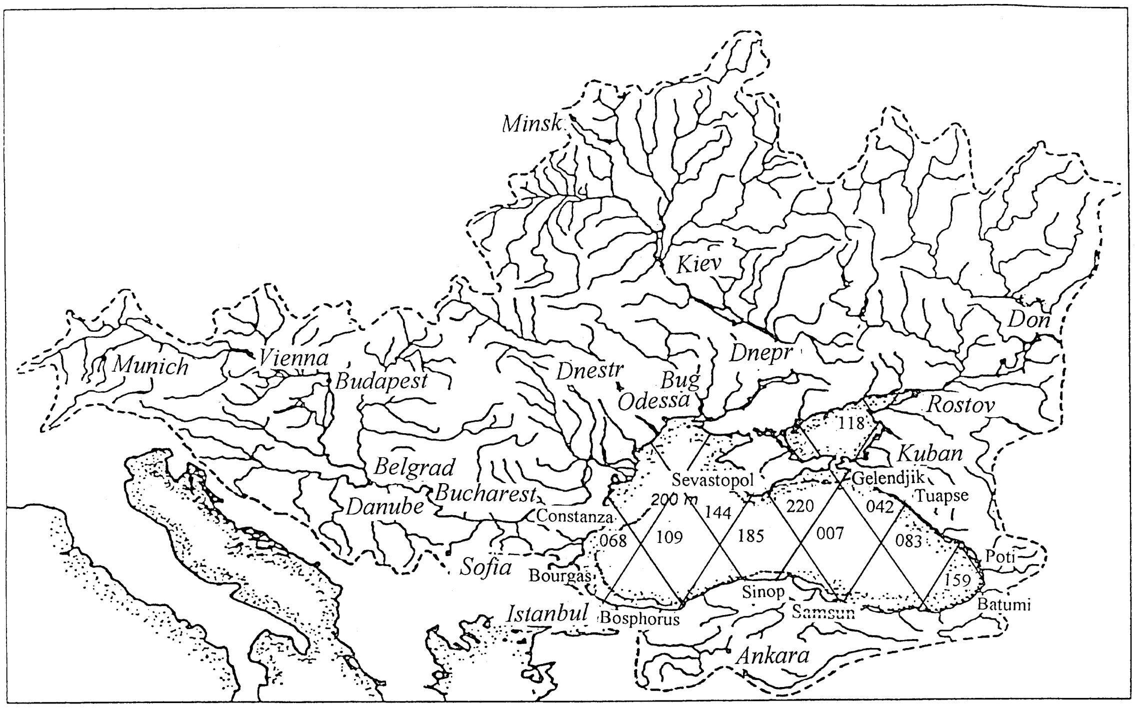

Fig. 1. The Black Sea and its catchment area. Some locations referred in paper, as well as the tracks of T/P, are plotted.

2. Spatial patterns and temporal variability of sea level

The characteristics of Black Sea level known from the earlier studies could be roughly separated in two categories: (1) characteristics obtained from coastal measurements and (2) characteristics based on hydrological survey data. The characteristics of the first type usually reveal the response of sea level to water balance, while the second-type characteristics focus on the anomaly of sea level associated with the nonregular distribution of the field of mass (wind and thermohaline-driven circulation). To our knowledge, no systematic analysis on the temporal and spatial variability of the full signal exists so far. However, this is of utmost importance when deciding how reliable are the estimates, which are based on coastal data only. The fundamental issue here is that the oscillations of different type are interconnected, and signals of quite different origin might be misinterpreted in the analyses if the dominating characteristics of temporal and spatial variability are not well known. This gives the justification of the data analysis presented in this section.

The data from the TOPEX/Poseidon (T/P) mission for the period 1993–1998 (10 days repeat time) provide a reliable source for integrated analysis of variability from monthly to interannual time scales over the whole sea. A detailed description of the T/P altimeter data can be found in AVISO (1996) (the position of tracks over the Black Sea is shown in Fig. 1). As found by Korotaev et al. (1998, 2001), Stanev et al. (2000, 2001) and Sokolova et al. (in press), the T/P altimeter data resolve the major horizontal patterns, as well as the statistics of variability, which motivates us to extend here the above analyses towards inferring the dominating spatial and time scales.

The meteorological forcing, along with the relatively simple coastal line and topography, favors the establishment of basin-wide cyclonic circulation. The main jet current has the coast on its right (the difference between the sea level elevation in coastal and open sea regions estimated from dynamic calculations and model simulations is 10–20 cm, Oguz et al., 1993; Stanev and Beckers, 1999). Vigorous mesoscale eddies, meanders and filaments are superimposed on the mean circulation, which pinch off the coast or the Rim Current. Spatially and temporally evolving meanders and sub-basin scale eddies have wavelengths of $\sim$125–250 km (Oguz et al., 1994). The most prominent sub-basin scale feature are the quasi-permanent Batumi eddy located in the easternmost part of the Black Sea basin and the Sevastopol eddy west of Crimea peninsula.

The EOF analysis (Preisendorfer, 1988) gives a possibility to identify the main patterns of spatial and temporal variability (Fig. 2) and to evaluate the contribution of different components of variability, as well as to look for significant correlation with the external forcing. The most important result here is that the first EOF gives $\sim$85% of the total signal. The comparison between the variability of the first Principle Component (PC-1) plotted by solid line in Fig. 2b and area Mean Sea Level Anomaly (MSLA) derived from T/P data set (dashed line in Fig. 2b) shows that the former reflects the changes in Black Sea volume. These changes are mostly due to the seasonal variability in fresh water flux and to a minor degree to the steric effects caused by the air–sea heat exchange (Stanev et al., 2000). The above peculiarities are very specific for this sea, unlike to this case, the response of the neighboring Mediterranean Sea to water cycle is much weaker.

The horizontal patterns of the first EOF are characterized with the same sign basin-wide, which indicates that they occur synchronously over the whole sea. The horizontal gradients are small (much smaller than the ones in the higher EOFs). Though the dominance of spectral maximum 365 days^{-1}, the secondary oscillations in the PC-1, particularly in the second half of T/P period, indicate that the seasonal signal is sometimes very irregular.

The second EOF has very clear physical explanation, seen by the opposite phase of oscillations in the coastal and open sea areas (Fig. 2c). In early winter, the sea level increases in the coastal regions (the positive anomalies in Fig. 2c are associated with ascending part of PC-2 curve in Fig. 2d), which is accompanied with compensating sinking of sea level in the open sea. In such a way, the slope of sea level increases, demonstrating the intensification of geostrophic currents in winter-to-spring months. As seen by the time-variability pattern, the occurrence of seasonal intensification is quite robust (it repeats every year); however, its appearance changes from year to year. For the 6-year

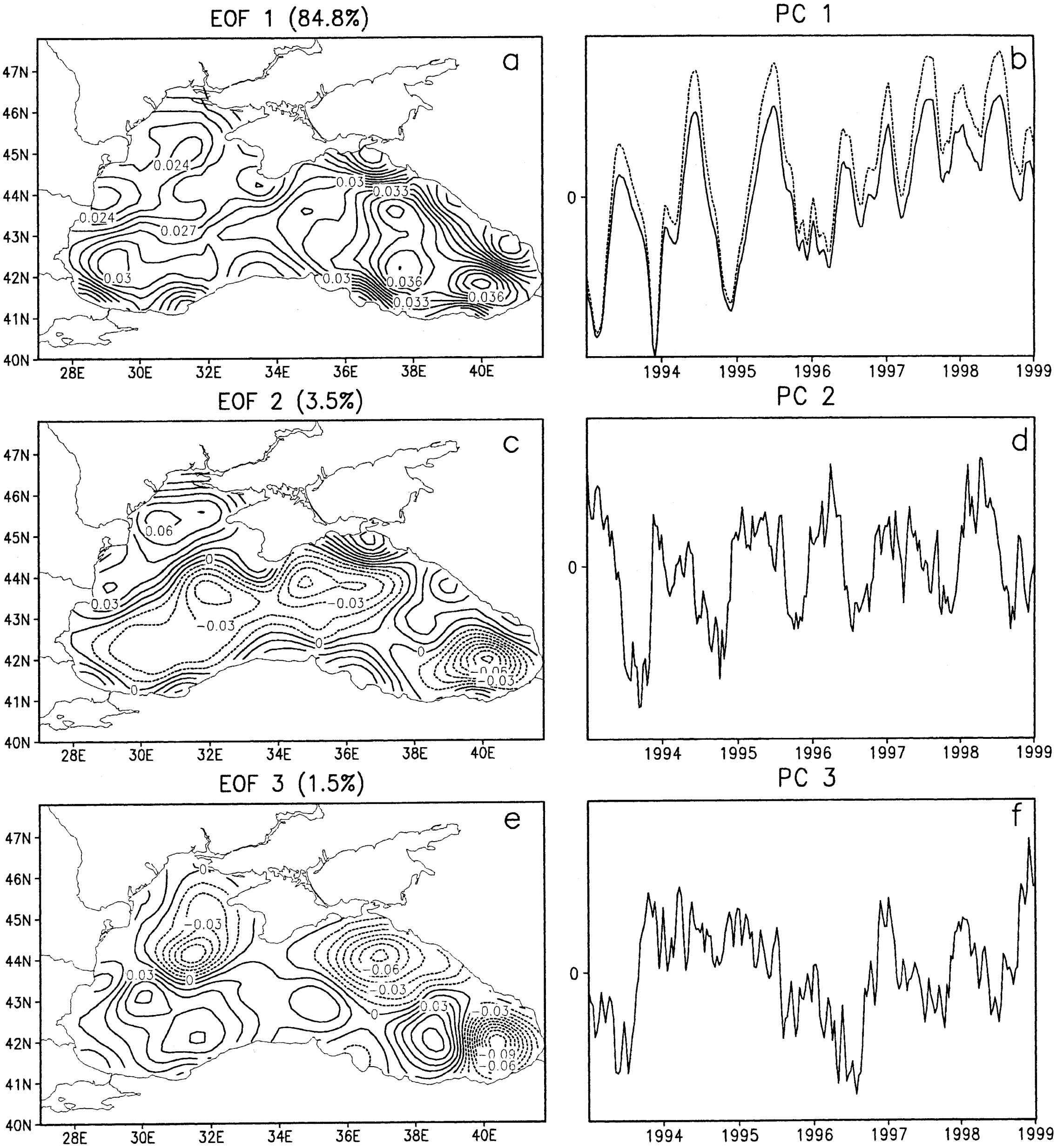

Fig. 2. EOF analysis of T/P data. The first three EOFs are shown (spatial patterns on the left and principal components time series on the right). The dashed line in (b) gives the variability of MSLA.

period analyzed here, the amplitude of seasonal oscillations change more than two times (strong intensification in 1993 and much weaker in the period 1997). Our results support earlier speculations, based on insufficient amount of observations (Blatov et al., 1984), that in the area of Batumi eddy, the circulation tends to reverse in summer from cyclonic to anticyclonic. The second EOF reveals that the amplitude of seasonal oscillations is the strongest in this area, which makes the reversals possible and proves that, locally, the seasonal intensification can reach amplitudes exceeding the mean sea level difference between coastal and open ocean. The novelty here is that the eastern Black Sea is decoupled with respect to the seasonal signal and the oscillation pattern extending approximately along the line Samsun–Tuapse shows synchronous oscillations with rather low amplitude. This splitting of oscillation pattern indicates that the coastal region characteristics with seasonal time scales could penetrate the open ocean along this line.

The temporal and spatial characteristics of sea level variability associated with the circulation could be better revealed if before carrying out the EOF analysis we subtract from the original data series of sea level anomalies the current basin mean sea level anomaly (that is subtract the signal plotted with dashed line in Fig. 2b). Then, the newly calculated first EOF pattern, as well as the corresponding PC-1 (not shown here), almost coincide with what is plotted in Fig. 2c and d. However, the ''circulation-oriented'' first EOF explains now $\sim$25% of the variability in the modified data series.

The higher-number EOFs are associated with synoptic and sub-basin processes (Rachev and Stanev, 1997; Stanev and Rachev, 1999; Stanev and Staneva, 2000), the corresponding PCs revealing clearly synoptic and interannual variability. The basin oscillations originate in the easternmost part of the sea, propagate to the west, and their modal structure adjusts to the basin shape. In the narrow eastern Black Sea, there is only one anomaly-couple (Fig. 2e). Further east, with the enlarging of north–south section, this configuration is replaced by mosaic of anomaly-patterns. In the central part of the sea, where the occurrence of nodal line is quite plausible (Stanev and Rachev, 1999), the amplitude of oscillations is low. The largest spatial anomalies of the third EOF in the western Black Sea are associated with the area where the Sevastopol eddy is usually observed.

We will end the analysis of temporal and spatial variability of sea level by reminding that the T/P signals resolve quite well the major large-scale oscillations of Black Sea level. The coherency of the first EOF over the entire sea, as well as the small deviation between PC-1 and MSL variability (Fig. 2b), justifies the applicability of coastal stations observations when analyzing the overall variability of Black Sea volume as a response to external forcing.

3. The response of the black sea level to external forcing

3.1. The data used

We will analyze below the available hydrological and sea level data series. The water balance components used here include monthly precipitation (P) and river runoff (R) data based on observations, as well as the evaporation (E) calculated using bulk aerodynamic formulae (Fig. 3a). These data cover the period 1923–1997 and we further refer to them as to the Black Sea Hydro-Meteorological (BSHM) data. A complete description of these data is given in the book of Simonov and Altman (1991) and by Altman and Kumish (1986). The observations were interrupted during the wartime (1941–1945), and there is a gap in the precipitation and evaporation time series during this period.

We extract from the tide gauge database of Permanent Service for Mean Sea Level (PSMSL, Woodworth et al., 1990; Woodworth, 1991; Spencer and Woodworth, 1993) the monthly mean data series in several coastal stations (see further in text). The intercomparison between different data series shows that the Russian station of Tuapse (latitude 44.1°N, longitude 39.1°E) is quite representative for the whole set of observations. The data in this station are available for the period 1923–1998 and several missing months in 1942 are replaced with the climatic monthly mean values before calculating annual mean SLA (Fig. 3b, dashed line). This station is chosen for further analyses since it is just below the satellite track no. 083, which makes possible to quantify the consistency between the altimetry and tide gauge data (Stanev et al., 2000).

3.2. Recent trends and statistics in the Black Sea level

The sea level anomalies from the T/P data span for about 6 years only, which makes it impossible to use them for estimations of long-term changes. However, provided a clear correlation exists between mean sea level and sea level in some coastal locations, we would be in a position to reconstruct from coastal station data (tide gauge) the variations in the Black Sea volume. An illustration of this approach is given in the paper by Peneva et al. (in press), and we show here only the

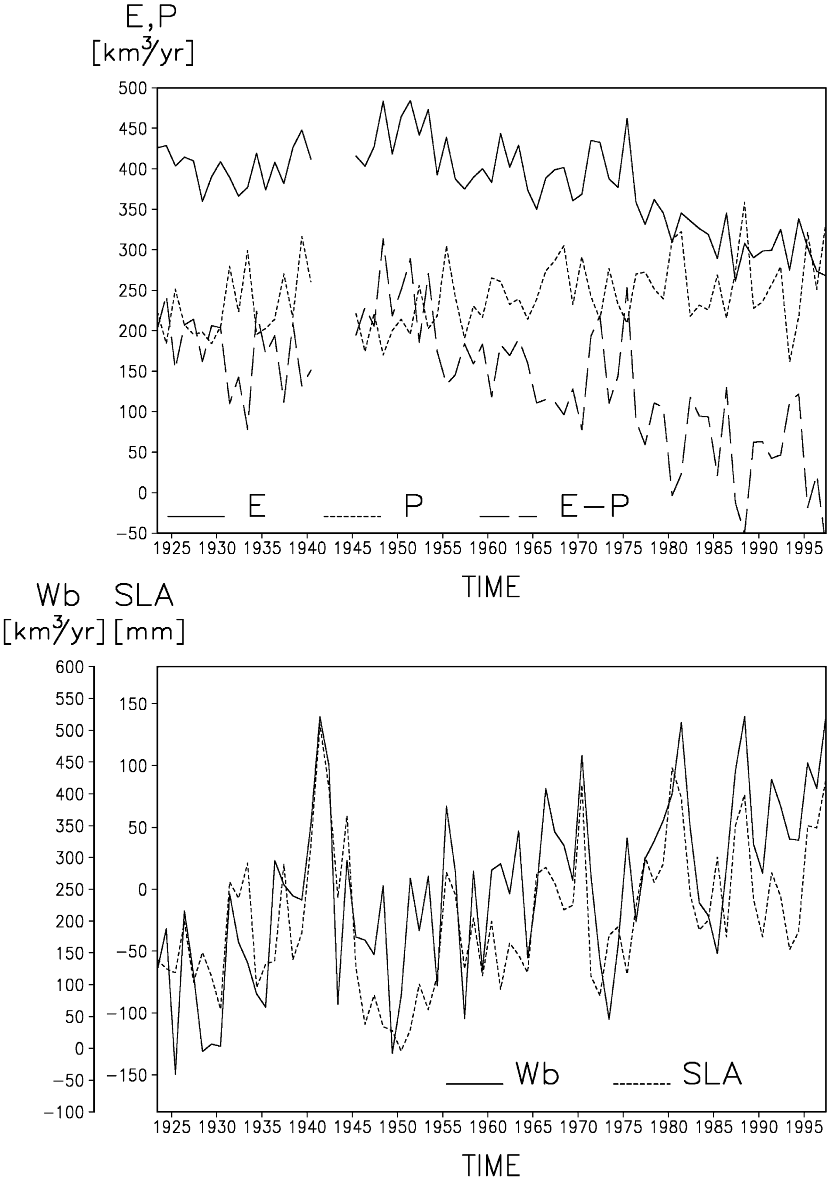

Fig. 3. Annual mean time series of: (a) water balance components: evaporation (E) and precipitation (P), dashed line represents the difference $E-P$; (b) fresh water flux (precipitation plus river runoff minus evaporation, solid line) and mean sea level anomaly (dotted line). The data for the fresh water flux during the Second World War period are based on the river inflow only.

correlation between annual MSLA from T/P data and SLA in Tuapse (Fig. 4). The fresh water flux ($R+P-E$) from the BSHM data is plotted in this figure only for the period 1993–1997, as there are no data available after this time so far. Thus, it seems obvious that during the above period, the constant sea level rise of 12 cm (much larger than the global eustatic rate of sea level rise, and much smaller than the corresponding rise in the completely enclosed Caspian Sea, Cazenave et al., 1998) is mostly due to the increased water flux and is easily detected both in the MSLA derived from altimetry, as well as in tide

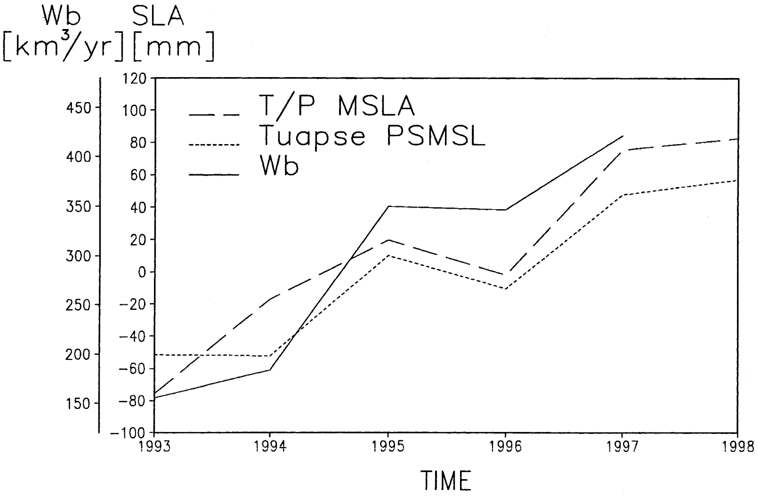

Fig. 4. Annual mean fresh water flux (solid) in km^3 year^{-1}, MSLA from T/P data (long-dashed) and sea level anomaly in Tuapse from PSMSL data (short-dashed line) in mm. The solid line is shorter as no water balance estimates are available after 1997.

gauge data. The RMS difference between the T/P and tide gauge data is ~2 cm only, which gives credibility when using the long-term tide gauge data to calculating changes of sea volume and quantifying the response of Black Sea to global processes.

The amplitudes associated with the interannual variability of different components of fresh water flux (Fig. 3a) are comparable ($\mathrm{rms}_{\mathrm{RIV}}=55$, $\mathrm{rms}_{\mathrm{PREC}}=69$, $\mathrm{rms}_{\mathrm{EVAP}}=50$ km^3 year^{-1}) and lower than the amplitudes of seasonal oscillations ($\mathrm{rms}_{\mathrm{RIV}}=88$, $\mathrm{rms}_{\mathrm{PREC}}=90$, $\mathrm{rms}_{\mathrm{EVAP}}=160$ km^3 year^{-1}). The air–sea exchange components (the mean for the whole period $E-P=135$ km^3 year^{-1}) are about two–three times smaller than the river runoff (340 km^3 year^{-1}), thus the freshening effect is mostly due to rivers. The river runoff and $E-P$ tends to oppose in phase which reflects the positive correlation between precipitation over the Black Sea river catchment area and over the basin itself. This correlation also indicates that under relatively dry climate (with less precipitation), the effect of evaporation is enhanced. However, there are some periods (e.g. 1923–1928, 1947–1954) when the river runoff and $E-P$ variations are coherent. Such behavior repeats about every 25 years and continues for approximately 5 years; however, its explanation is not quite clear.

A fundamental characteristics in the last 50 years is the trend of fresh water flux of ~6 km^3 year^{-1} consistent with the earlier estimates of Goryachkin and Ivanov (1996). According to the data used here, this trend is mostly due to air–sea exchange. The resulting increase of sea level (of ~15 cm in the last 50 years, Fig. 3b, dashed line) has been earlier documented by Simonov and Altman (1991), Goryachkin and Ivanov (1996) and Boguslavsky et al. (1998). Some of these authors relate this trend to the global sea level rise (1–2 mm year^{-1}), which seems plausible. However, the Black Sea level trend is ~0.3 cm year^{-1}, which is higher than the global trend and might be partially associated with the local water cycle. The alternative explanation (Goryachkin and Ivanov, 1996) accounts for the subsidence in almost all locations (of ~1 mm year^{-1}). We assume that the explanation of the MSL trend requires further efforts and perhaps analysis on the strait control (governed by atmospheric forcing, as well as by water mass structure in the Black Sea and Mediterranean Sea). Man-induced changes could not be excluded as possible candidates to precisely quantify the rate of sea level rise in the Black Sea (Boguslavsky et al., 1998).

3.3. The relevance of Black Sea water cycle to Mediterranean Sea water mass formation

The analysis on the correlation between forcing (fresh water flux) and response (sea level change) in

Fig. 3b indicates that the main extremums coincide in time (with little exceptions), sometimes with 1 year shift in both directions. This suggests that not only the seasonal variability, which is associated with the strong seasonal variation of fresh water flux, but also the interannual and decadal ones are governed by the water cycle. However, it is noteworthy that there are periods with very good correlation (1935–1945, 1970–1987), and also periods when the changes in the two curves in Fig. 3b are not well correlated (1946–1955, 1961–1965). The discrepancy might come from observation errors and from inconsistency between tide gauge records and basin MSL resulting from vigorous coastal processes of different time and length scales and intensity of general sea circulation. There are other factors that might also affect the mean sea level variability, such as the response of Bosphorus Straits system to fresh water flux and wind forcing.

In any case, complete agreement between fresh water fluxes and the response of sea level has not to be expected. Such situation would correspond to the case of enclosed basin, or at least neglect the transport through the strait. The latter tends to reduce the amplitude of sea level variability (we mentioned already that the recent trends in the Black Sea surface are much smaller than what is observed in the enclosed Caspian Sea), or induce periodicity associated with the nonlinear straits dynamics, as well as with the variability in the Mediterranean Sea level and regional wind conditions. In the following, we focus on the interannual variability, thus we detrend the data series. The anomalies of the transport through the straits estimated as a difference between (1) the changes of Black Sea volume corresponding to the fresh water, and (2) the changes calculated from tide gauge data, give an idea about the temporal variability in the water exchange between Black Sea and Mediterranean Sea (Fig. 5). Here, we will not enter in deep details on the straits control, which is the focal point of the study of Peneva et al. (in press). What is interesting to mention now is that there are relatively long periods when the anomaly of the outflow could have caused larger increase in the Aegean Sea salinity, which was what Roether et al. (1996) required to explain the event of formation of anomalous increase in deep water salinity.

The difference between the mean values of Bosphorus transport for the period 1923-1960 and 1960-1997 indicates that, in the second period, the Aegean Sea was dominated by higher outflow from the Black Sea (compared to the mean for the total period). One could speculate that such conditions would have contributed to dilution of this regional basin, but

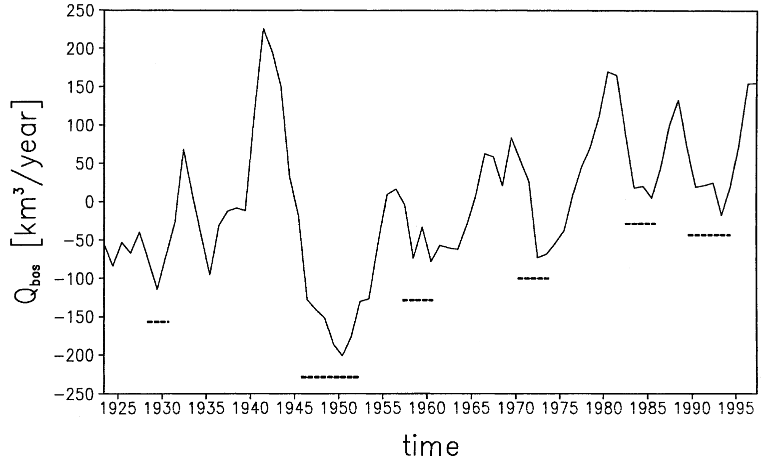

Fig. 5. The anomalies of the transport through the Bosphorus Straits taken as the residual from the fresh water flux $R+P-E$ and the sea volume change calculated from the time rate of change of the sea level in Tuapse. The data are smoothed with a time-window of 3 years. The periods when the outflow could result in substantial increase of salinity in the Aegean Sea are also shown.

more plausible would be to assume that the exchange at the open boundaries and at air–sea interface tended to compensate for this slow trend. Unfortunately, at present, we do not know much (and with sufficient accuracy) about the temporal variability of salinity in the Aegean Sea for this 70-year period, neither about the water balances of this sea, in order to make more detailed analyses on salinity balances and evolution. The most robust information which we get from Fig. 5 is that the periods of increasing/decreasing outflows repeat almost regularly once per 10 years. If we assume that prior to the reduced-inflow-conditions a balance had been reached in the Aegean Sea between the dilution from Black Sea and positive salt fluxes due to exchange at the open boundaries and at air–sea interface, then the decrease of the outflow would trigger "rapid" change in the salinity balance in the Aegean. Therefore, we interpret the descending parts of the curve in Fig. 5 as an indication of salinification of the Aegean Sea. The dotted horizontal lines in this figure show the periods (longer than 3 years) during which the decrease of freshening effect of Black Sea inflow could have produced an increase in the Aegean Sea salinity, which was equal or larger than the salinification explained by Roether et al. (1996) assuming increased evaporation over the Aegean Sea of 20 cm year^{-1}. Obviously, these results complement the hypothesis of Roether et al. (1996). Actually, the increased evaporation over the Aegean Sea and the reduced fresh water flux in the Black Sea might have had the same origin associated with the planetary climatic change (see next section). In any case, these results indicate that more attention should be given in the Mediterranean Sea oceanography on the impact of Black Sea outflow.

3.4. The dependency of Black Sea level on the global forcing

Below, we will represent the global forcing by NAO (the winter difference between normalized atmospheric pressure in Gibraltar and Reijkiavik, Jones et al., 1997) and ENSO (calculated from pressure data in Darwin and Tahiti, Allan et al., 1991) indices. The NAO is of great significance for the European region since it controls the intensity of the westerlies and some important characteristics of atmospheric circulation (including tracks and activity of Atlantic and Mediterranean cyclones) redistributing precipitation over the continent. Periods of high NAO index are usually accompanied with wet climate conditions in Scandinavian and North European regions and dry in Central and Southern Europe. This situation is reversed in periods of low NAO index. The impact of ENSO on the European climate is not as clear, though the study of Arpe et al. (1999) on the sea level variations of Caspian Sea suggest a strong impact of ENSO on the local climate.

Long-term NAO and ENSO indices (dashed lines in Fig. 6a and b) reveal large interannual oscillations correlating with river runoff (solid lines in Fig. 6a and b) and the SLA (Fig. 7). The correlation coefficient between NAO and river runoff of -0.47 is small (the correlation with ENSO is even smaller), but there is a clear appearance of extremums in the two signals almost at the same time, revealing the dependency of local conditions on the global forcing. The variations in river runoff (solid line) and NAO index (dashed line) tend to oppose each other during the whole 70-year-long period with short-term exceptions (for example, 1935–1940), when they are more coherent. Note that almost every extremum in the river runoff coincides in time with the corresponding extremum in NAO index. Furthermore, the global trends in the two curves are also related, as seen by the linear trends of NAO index and river runoff in the period 1945–1970. The NAO index reaches its minimum in 1970, after which it increases during the last 25 years, and drops again in 1997. The situation with the river runoff is inverse: the positive trend in period 1945–1970 is followed by a negative trend until 1990s. The river runoff maxima in 1941, 1956, 1970 and 1980 are accompanied with minimum NAO index; on the contrary, the river runoff minima in 1930, 1950 and 1991 — with maximum NAO index. However, there are exceptions from this rule (e.g. 1965), which suggest that other important factors could substantially modify this situation. It is noteworthy that the global minimum of NAO index in 1970 is accompanied by a huge maximum in the river runoff (slightly smaller than the absolute maximum in 1941).

The lower panel of Fig. 6 suggests that though the correlation between local climatology and ENSO is not very clear, some amplification of NAO and ENSO seems possible, as in the case of 1941–1942 when the large ENSO index coincided with the absolute max-

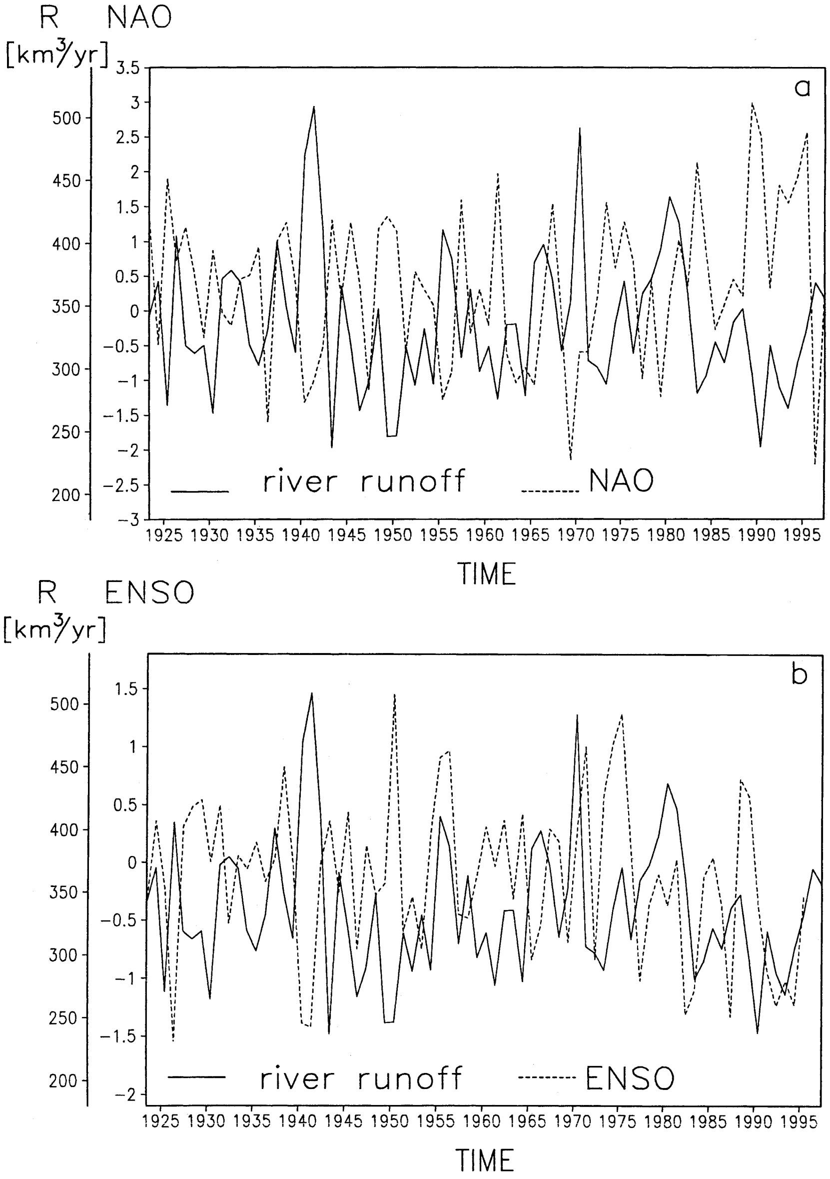

Fig. 6. Correlation between annual mean river runoff (solid) and (a) NAO, (b) ENSO (dashed lines).

imum in the river runoff. The opposite situation might have happen in 1950, when the reduced river runoff was perhaps due to the impact of both high NAO and ENSO indices.

The PSMSL data (starting from 1870-ties in the Black Sea) reveal a good correlation with the NAO index (and much weaker with the ENSO one, the latter is not shown in Fig. 7), demonstrating that the Black Sea level (Fig. 7) responds energetically to the variability in global forcing. To make the correlation more clear, we plot the inverted NAO index in the bottom panel of Fig. 7. Detrending the time series avoids the pronounced long-term subsidence trends in some stations (e.g. Poti and Batumi, see also the caption of Fig. 7 and the paper of Boguslavsky et al., 1998), making the sea level variations in all

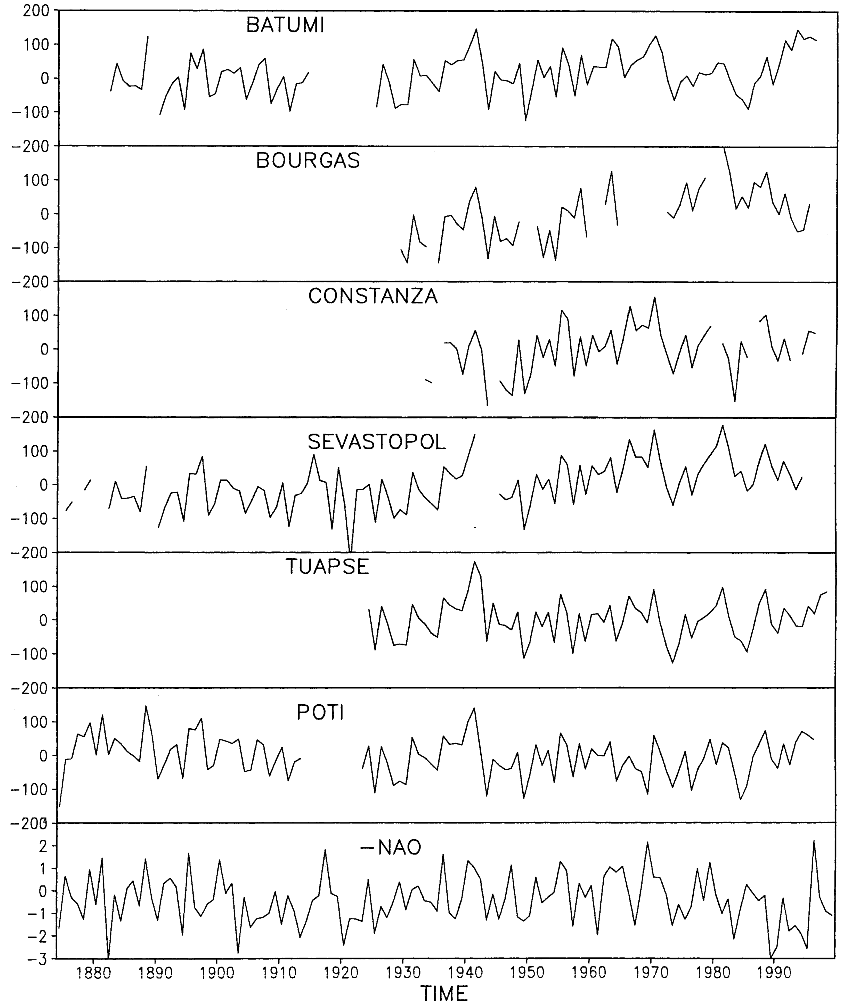

Fig. 7. Annual mean sea level anomalies [mm] in several coastal stations and the inverse NAO index. Except for Sevastopol and Constanza, the sea level data series are detrended (2 mm year^{-1} in Tuapse, 7 mm year^{-1} in Poti, 3 mm year^{-1} in Bourgas, and 2.5 mm year^{-1} in Batumi). The gaps in the data series (longer than 1 month) are not filled; therefore, data series are cut sometimes at several places. Only the 1-month gaps are filled by linear interpolation before calculating annual mean value.

stations comparable. Most of the major events of sea level rise/drop occur almost in the same time. All stations in the eastern Black Sea (Tuapse, Poti, Batumi) reveal well correlated signals. In the western Black Sea (Sevastopol, Constanza, Burgas), where the exposure to direct river influence is stronger and the sea level oscillations are affected by oscillations on the shelf, the correlation between different station is weaker (see also the paper of Boguslavsky et al., 1998). The global forcing (measured here by the NAO index) shows spectral maxima at 8 and 4–5 years, and the sea level in Poti at 20, 8 and 4–5 years, correspondingly. Not only are the equal periods indicative about the response of Black Sea level to global forcing. With small exceptions, the extremums in NAO index and sea level occur almost at the same time (the time lag could reach 2 years). The above analysis makes possible to conclude that the dramatic decrease of NAO index in mid-1990s (see Fig. 6a) is the main reason of the Black Sea level rise in recent years (see also Fig. 4). The analysis of the trends in the last several years gives some confidence to speculate that the reversal of the NAO curve in 1997 (the value of NAO index for 1996 is − 2.2 against 0.3 for 1997, 0.9 for 1998, and 1.1 for 1999) will further tend to reverse the sea level trend.

4. Conclusions

The aim of this paper is to assess the extent of sea level variability in order to clarify the projections of rapid climatic changes on the regional climatic system. We demonstrated here that the Black Sea is a unique region of the world ocean, where the physical processes of the ocean surface can be addressed in a verifiable way, based on well-detected signals of various kinds of observations. The consistency of data from different sources is more than satisfactory and contributes to increasing the synergy and interdisciplinarity by combining satellite observations and ground measurements.

We found that the space-time variability of sea level was accompanied with pronounced (and measurable from satellites) signals revealing the character of seasonal evolution of circulation and mesoscale eddies. For the first time, the T/P data made possible to assess the main statistics of Black Sea level variations with time scales from monthly to interannual. The quantification of variability in a broad range of time and space scales contributes to improve the knowledge on the physical mechanisms of circulation, based so forth on insufficient amount of basin-wide observations, or theoretical results. Furthermore, the high-quality signals in satellite altimetry give enough motivations to develop assimilation techniques and predictive ocean models for processes with monthly-to-seasonal time scales.

Of particular interest are some new results, namely the space-time variability of sea level. We demonstrated that the first EOF carries most of the information about the variations of MSL, but there is no substantial horizontal inhomogeniety in this mode (Fig. 2a). Pronounced spatial inhomogenieties associated with different characteristics of circulation are observed in higher EOFs. The latter respond to the global change (the seasonal intensification of circulation, as well as the sub-basin scale dynamics, show significant changes in the last 5–6 years, Fig. 2), which is quite fundamental when identifying the specificity of regional responses. The latter is of utmost importance if one wants to address the possible transitions in the behavior of regional systems after the external forcing exceeds some limits.

The second novelty in this study is that we proposed a new (or at least complementary to the existing one) explanation of the mechanisms triggering events of formation of anomalously saline water in the Aegean Sea. The data analyzed here give clear indications that the Black Sea control on the Mediterranean Sea water mass formation has to be considered in further studies in this field.

The third novelty is that the regional sea level variations, associated with the hydrological cycle over vast area of Europe, responds energetically to the NAO. The clear correlation between sea level and the water balance components provides an excellent possibility to detect responses to global change processes and to establish methodologies to forecast regimes of water cycle in the Black Sea. The recent 6 years, when the T/P data provide a high-quality signal to estimate changes in the volume of Black Sea, are characterized by a steady increase of sea level of ∼ 12 cm. Comparing this trend with the observed changes in the last 120 years (Fig. 7), we could see that the former is relatively low (compared to the changes in sea level from 1939–1942, or 1970–1972). From the quantitative examination of the relationship between NAO index and sea level variations, we could expect that the sea level rise in recent years will reverse in the next years (actually, there are no periods lasting for more than 7–8 years with stable change in sea level). Developing deeper understanding on the straits control regimes, as well as involving more reliable data from meteorological analyses, could further increase the accuracy of predictions.

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