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Sea level variations and their dependency on meteorological and hydrological forcing: Analysis of altimeter and surface data for the Black Sea

Emil V. Stanev
Department of Meteorology and Geophysics, University of Sofia, Sofia, Bulgaria

Pierre-Yves Le Traon
Space Oceanography Division, CLS, Toulouse, France

Elissaveta L. Peneva
Department of Meteorology and Geophysics, University of Sofia, Sofia, Bulgaria

Abstract. TOPEX/Poseidon (T/P) altimeter data in the Black Sea are analyzed for almost 5 years in parallel with available hydrological and meteorological data with the aim of studying the water balance and the dependency of sea level oscillations on meteorological and hydrological forcing. This forcing induces seasonal variations of mean sea level with oscillations of ~10-15 cm. The consistency between satellite and tidal gauge data is demonstrated in several coastal locations, and a mean ascending trend of ~3 cm yr^{-1} is found in the two data sets. The variability in all components of water balance, including the Bosphorus outflow calculated as the difference between the fresh water flux and the time rate of sea level change estimated from altimeter data, is analyzed. The T/P data give very clear signals in the patterns of amplitudes of oscillations at intraannual, seasonal, and interannual timescales that help in understanding the variability of circulation. The intraannual variations are well pronounced on the continental slope and shelf and reach highest amplitudes in the areas of Sevastopol and Batumi quasi-permanent eddies. The clearest representation of oscillations with seasonal periodicity exists in the area of Batumi Eddy. This variability is associated with the transition between states with intense cyclonic circulation in winter and weaker (sometimes anticyclonic) circulation in summer-fall period. The Sevastopol Eddy is not clearly resolved in the seasonal variability. The interannual variability has the strongest signature in the area of western gyre and southeastern Black Sea. The analysis of satellite data supports some earlier studies on the circulation based on dynamic computations and numerical modeling. They make it possible to estimate the amount of water exchanged between coastal and open ocean areas caused by the time variability in the Ekman drift. The good quality of altimeter data and the high level of signals could ensure more accurate numerical simulations by means of data assimilation.

1. Introduction

The Black Sea is an almost enclosed basin with restricted water exchange with the Mediterranean Sea through the Straits of Bosphorus. The mass balance estimates of the two-layer exchange reported by *Özsoy and Unluata* [1998] yield an average upper layer outflow of 600 km^3 yr^{-1} and a lower layer inflow of 300 km^3 yr^{-1}. These asymmetric transports are maintained by the excess precipitation (~300 km^3 yr^{-1}) and river runoff (~350 km^3 yr^{-1}) against evaporation (~350 km^3 yr^{-1}). Unlike the Mediterranean Sea (concentration basin), the Black Sea is a basin of estuarine type that is due to the large river discharge. Most of it is in the northwestern shelf area (the Danube, Dnepr, and Dnestr Rivers). The Danube contributes about one half and the Dnestr and Dnepr contribute about one third of the total river runoff. This important driving force (amounting annually to ~0.1% of its volume), along with the strong dynamical resistance of the strait to changes in sea level, shapes the most important characteristics of the Black Sea physical system and, in particular, the sea level elevation (SLE).

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As is well known in the Black Sea oceanography [*Simonov and Altman*, 1991; *Stanev and Beckers* 1999a], the seasonal variability of mean sea level (MSL), which is mostly caused by the seasonal variability in the fresh water balance, reaches amplitudes ~10-15 cm. This variability is accurately resolved by the TOPEX/Poseidon (T/P) altimeter data whose errors are below 3 cm rms. We aim to demonstrate in this paper that using altimeter data and data of the components of water balance (river runoff, precipitation, and evaporation) may contribute to understanding further the variations in the Black Sea level and its correlation with the external forcing. We remind the reader that the nonlinear hydraulic processes in the

Bosphorus Straits control the response of the MSL to atmospheric and river forcing, thus the reanalysis of water balance needs new experimental or theoretical data about the strait transport. Unfortunately, errors in the existing measurements or insufficiency of data for long periods makes it impossible to use direct measurements for the strait transport. We thus combine here seaborne and satellite data with the aim of estimating the variations in the strait outflow.

We will analyze here almost 5 years of T/P observations and meteorological and hydrological data. Our first objective is to introduce the MSL in the analysis of water balance and to prove that the altimeter data provide clear signals that may help in constraining water fluxes. There were some studies addressing the water balance of the Black Sea jointly with the variations of sea level in coastal stations [*Simonov and Altman*, 1991]. However, the lack of open sea data precluded reliable estimates. This inconsistency is eliminated here by using T/P data that cover regularly the whole sea.

The second objective in the present study is to reveal the spatial characteristics of sea level and their correlation with meteorological and hydrological forcing. We remind the reader that the consistency of survey and T/P data was recently studied by *Korotaev et al.* [1998], who addressed the possibilities of using this data for assimilation purposes, for the Black Sea. However, to our knowledge the characteristics of T/P data have not yet been analyzed in relationship with the atmospheric forcing that is one of the major aims of the present study. This 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 SLE in coastal and open sea regions estimated from dynamic calculations and model simulations is 10-20 cm, [*Oguz et al.*, 1993; *Stanev and Beckers*, 1999b]. The circulation intensifies in winter as a result of the stronger wind forcing that has been proved from the number of dynamic computations [*Filippov*, 1968, *Blatov et al.*, 1984] and numerical experiments [*Stanev*, 1990]. Recent simulations demonstrated that the amplitude of the total transport associated with the seasonal variability may reach half of the annual mean value [*Stanev et al.* 1997; *Stanev and Staneva*, 2000]. However, so far, there was no direct support to the above findings since no measurements of the position of SLE existed basin-wide. Thus our aim here is to verify these concepts using T/P data.

The paper is organized as follows: The basin mean data characteristics are first presented in section 2, and then we analyze the water balance of the Black Sea. Section 3 deals with the spatial characteristics of variability and the correlation between circulation and external forcing. Conclusions on the applicability of T/P data to the Black Sea oceanography are given in section 4.

2. Black Sea Water Balance

2.1. Seasonal Variability in the SLA and Water Fluxes

Data from different sources are used in the present study individually or in combination to address the variability of Black Sea surface elevation in time and space and the water balance. These data are altimeter data, heat flux data from atmospheric analyses, and the components of fresh water fluxes, tide gauge, and climatic temperature-salinity data. In the following we will describe each of these data types (temperature/salinity data used to calculate dynamic heights will be described in section 3) and will give some estimates about their compatibility, mainly in relationship to the variations in the fresh water balance. Almost 5 years of T/P data (from October 1992 to July 1997) of the latest version of T/P Merged Geophysical Data Records (M-GDRs) distributed by Archiving, Validation and Interpretation of Satellite Oceanographic Data (AVISO, mean geometric chard MGC-B, version 2) are used here [*AVISO*, 1996]. If not explicitly stated farther in text, all other data used in the paper are for the same period. Standard altimetric corrections are applied (for more details see *Le Traon and Gauzelin* [1997]) except for ocean tides, which are very small and are not corrected for in the Black Sea. The inverse barometer correction is also not applied as the response of the Black Sea to atmospheric pressure is not significant [*Ducet et al.*, 1999]. The sea level anomaly (SLA) relative to a 4 year mean (January 1993 to January 1997) is then obtained using a conventional repeat track analysis. Maps of SLA were finally obtained onto a regular grid of 0.2° in latitude and 0.2° in longitude once every 10 days using a sub optimal space/time interpolation method [*Le Traon et al.*, 1998]. The SLE over the whole sea is sampled by nine repeat tracks with time intervals from 1 to 3 days (Figure 1). The error map is presented in section 3 where we discuss the ratio between errors and magnitudes of signals basin-wide.

The heat flux at sea surface tends to increase/decrease the volume of the sea in summer/winter, which is known as the steric effect. This effect may substantially affect the estimates of SLA and has to be eliminated if we are interested in the oscillations caused by fresh water fluxes. To this aim we use heat fluxes Q_h derived from the European Centre for Medium-Range Weather Forcast (ECMWF) atmospheric analyses data. Thus the contribution of the steric effect is measured as

$$\frac{\partial \zeta^{st}{}_B}{\partial t} = \frac{\alpha Q_h}{\rho C_p}, \tag{1}$$

where α=1,3×10^{-4} K^{-1}, ρ, and C_p are the heat expansion coefficient, water density, and heat capacity. The basin mean steric effect (maximum upward displacement in the warm part of the year of ~5 cm) is not negligible; therefore all analyses of MSL variations based on altimeter data in this paper are corrected for this effect.

The regular coverage of the Black Sea by T/P tracks gives a confidence to basin mean SLA estimates. We can use these data to calculate precisely variations in the mean Black Sea volume. In the following we focus on the seasonal variability in the basin mean SLA. From the whole period for which we have T/P data we choose the period January 1993 to January 1997, which is exactly 4 full years. Then we produce the mean year corresponding to this period. The seasonal variability of basin mean SLA is characterized by a pronounced maximum in June and a minimum in March (Figure 2a). The dashed line in Figure 2a gives a measure of steric effect. It is noteworthy that the corresponding amplitude of variations in the Black Sea volume is 20 km^3, which is only several times smaller than the amplitude of seasonal variations caused by fresh water flux. We carried out additional tests showing that using the temperature-dependent heat expansion coefficient in the above equation does not substantially change the results presented farther in the paper.

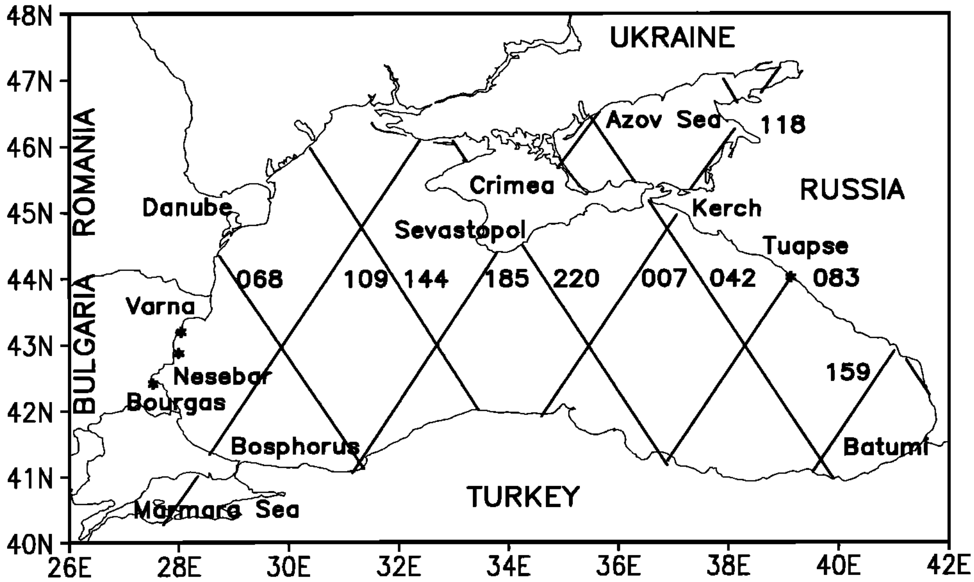

Figure 1. TOPEX/Poseidon (T/P) satellite tracks over the Black Sea. Some locations used in the text are notified with stars.

The T/P data are not validated enough in small inland basins (in particular, in the Black Sea); therefore it is instructive to make as many comparisons as possible with observations of SLA at coastal stations. Though the signal derived from altimeter data may not be reliable in some coastal areas, such comparisons are useful at least to get better insight about the magnitudes of possible errors. These may provide some motivation for introducing corrections when we further use satellite data in coastal areas. To this end we use available tide gauge data provided by the Permanent Service for Mean Sea Level (PSMSL) and described *by Woodworth et al.* [1990], *Woodworth* [1991], and *Spencer and Woodworth* [1993]. This data set includes monthly mean data in three Bulgarian stations (Varna, 43.2 N, 27.9 E; Nesebar, 42.6 N, 27.8 E; and Burgas 42.5 N, 27.5 E) and one Russian station (Tuapse, 44.1° N, 39.1° E). The data are available until December 1996. There is one important difference between the locations of the above stations (see Figure 1): while one satellite track passes over Tuapse, the Bulgarian stations are far from the tracks that might result in large errors (we will demonstrate this farther in text). Therefore we first show the seasonal variations in Tuapse (Figure 2b) calculated from tide gauge data (Figure 2b, solid line) and from T/P data (Figure 2b, dashed line). The mean for the 4-year period is subtracted from the tide gauge data to make them comparable with T/P SLA. The phases of the two signals almost coincide. It is noteworthy that the similarity between these two curves is better than between each of them and the basin mean curve (Figure 2a). Thus, unlike the basin mean situation, the sea level variations in Tuapse reveals two maxima (in June-July and January) and two minima (March and November). The agreement between the two independently obtained courses of seasonal variation, and the large level of signal versus noise (the T/P errors are <3 cm, while the sea level changes are several times larger) gives credibility to the T/P data in this coastal station.

The difference between the basin mean curve and the local ones is indicative of the specific seasonal variability in the coastal regions. It is well known in Black Sea oceanography that the winter intensification of circulation caused by winds, is associated with higher sea level along the coast in this season. This is just what we see as a secondary maximum in January. The main maximum in Figure 2b (also the maximum in the basin mean curve, Figure 2a) is associated with ascending/descending motions caused by the fresh water fluxes.

The wide use of hydrometeorological data throughout the paper necessitates to describe them in more detail. The water balance estimates in the Black Sea, starting from the end of the past century, is reviewed by *Simonov and Altman* [1991]. In most earlier works, different indirect methods have been used, thus the estimated mean water budget components range from 100 to 400 km^3 yr^{-1} revealing large inconsistencies. Another deficiency of the previous analyses was the lack of information about the seasonal and interannual variability, which is quite important taking into consideration the large changes of hydrometeorological fluxes. This deficiency has been eliminated by *Simonov and Altman* [1991], who compiled hydrometeorological data for ~60 year period. Their river runoff, precipitation and evaporation data are based on some earlier data (precipitation data of *Sorkina*, [1974], and river runoff data of *Altman and Kumish*, [1986]); however they present reanalysis with including hydrometeorological information for recent years. Water discharge has been calculated for all important rivers using observations in stations closest to the river mouths (54 miles from the sea in the case of Danube River).

The precipitation data originate from coastal and ship measurements (52,000 measurements were used by *Sorkina*, [1974]). First, monthly mean data were prepared basin wide, and second, the basin mean values were calculated. The latter are given by *Simonov and Altman* [1991] for the period 1923-1985. The mean value for this period is 0.55 m yr^{-1}, which corresponds to 230 km^3 yr^{-1}. Note that this value is ~25% less than that estimated by *Özsoy and Unluata* [1998]. Evaporation has been calculated using bulk aerodynamic formulae. For the years after 1991 these data were produced using the same techniques as for the earlier period and are

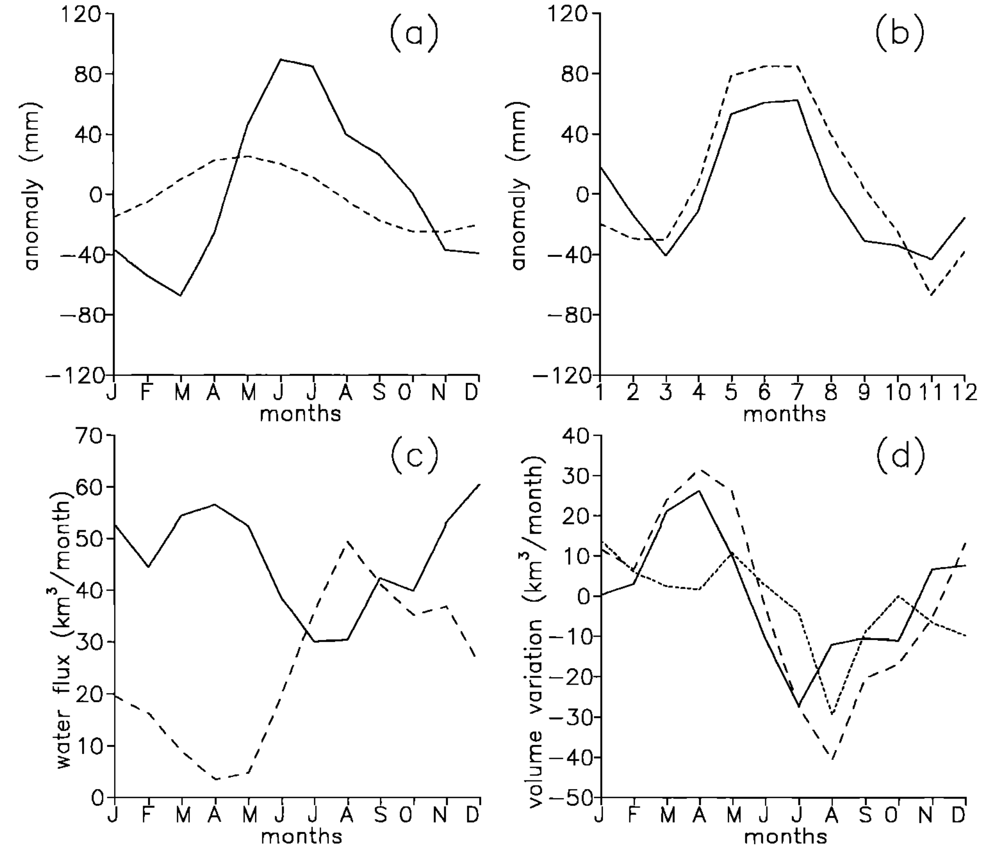

Figure 2. Seasonal variations averaged for 4 years (January 1993 to January 1997). (a) Basin mean sea level anomaly (SLA) based on T/P data (solid line). The data are corrected for the steric effect. (b) SLA in Tuapse: tide gauge data (solid line) and altimeter data (dashed line). The data are corrected for the steric effect. (c) The components of Black Sea fresh water balance: precipitation plus river runoff (solid line), evaporation (dashed line). (d) Time rate of change of the Black Sea volume anomaly: the volume defined as the SLA times the surface of the sea (corrections for the steric effect are made) (solid line), the volume from the data of the fresh water balance on Figure 2c (dashed line), and the difference between solid and dashed curves (dotted line).

kindly provided by V. Belokopitov (personal communication, 1999). For brevity we will refer to these data as the Black Sea hydrometeorological (BSHM) data.

The seasonal variability in BSHM data is shown in Figure 2c for the period of T/P observations (1993-1997) separately for the positive (river runoff and precipitation) and negative (evaporation) components of the fresh water balance at sea surface with solid and dashed lines, respectively. The sum of river runoff and precipitation shows positive anomalies from fall to spring, while the evaporation is maximal in summer. If we subtract these two components, we obtain the corresponding change of sea volume per unit time caused by rivers, precipitation, and evaporation (Figure 2d, dashed line). This sum is presented in terms of anomaly. Bellow we will illustrate the relationship between the fresh water balance and MSL oscillations. To do this, we calculate from the monthly mean values of T/P SLA the time rate of change multiplied by the surface area 4×10^5 km^2. This gives a measure of the variations in the Black Sea volume (Figure 2d, solid line) as responding to changes in the hydrometeorological forcing (river runoff, precipitation and evaporation). The correlation between the two curves in Figure 2d gives strong support to the idea that the Black Sea is a fresh water dominated basin. The individual and collective impact of water balance components on the annual variations of MSL is given by the following coefficients of correlation:

$$R(\frac{\partial\zeta_B}{dt},Q_r)=0.65,\ R(\frac{\partial\zeta_B}{dt},Q_p)=0.42,\ R(\frac{\partial\zeta_B}{dt},Q_e)=-0.74,$$

$$R(\frac{\partial\zeta_B}{dt},Q_r+Q_p)=0.86,\ R(\frac{\partial\zeta_B}{dt},Q_r+Q_p-Q_e)=0.87,$$

where ς_B is the Black Sea level anomaly, and Q_r, Q_p, and Q_e are the monthly mean climatic values of river runoff, precipitation, and evaporation. This remarkable correlation proves again that the seasonal variations of the MSL are rather well explained by the seasonal variations of evaporation, precipitation, and river runoff. We remind the reader that this is not the case in the Mediterranean Sea, where they could be related both to specific balances and signal-to-noise level in the data.

The difference between the solid and dashed lines in Figure 2d gives a measure of the seasonal variations in the transport through the Straits of Bosphorus (dotted line) provided that the exchange with the Azov Sea is considered as negligible. Some extremums are associated with the

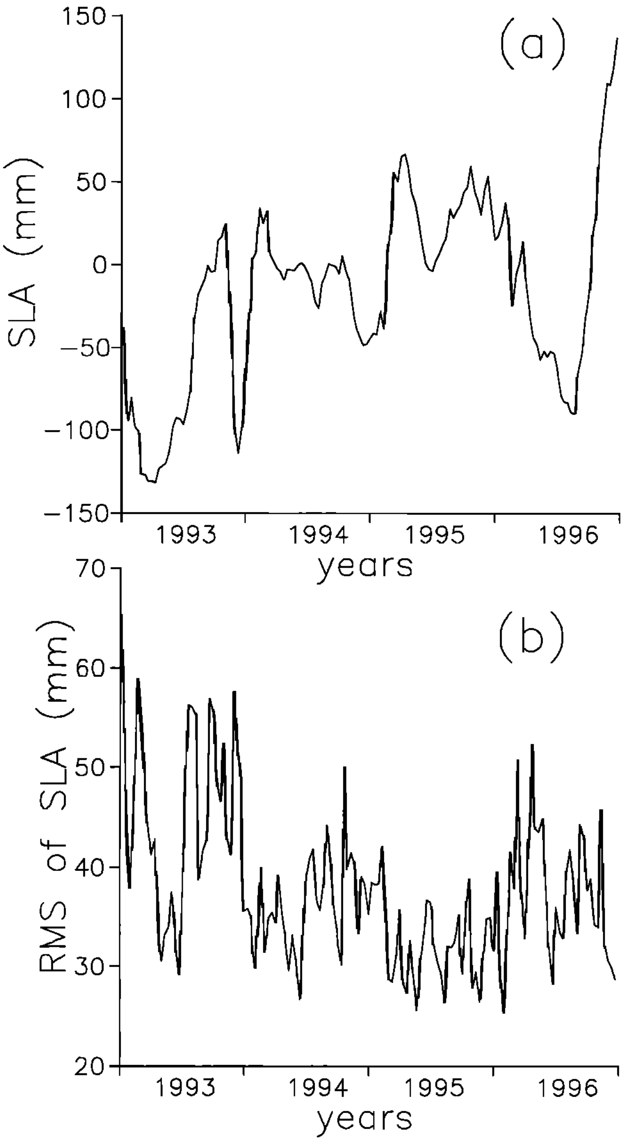

Figure 3. (a) Difference between mean sea level (MSL) anomalies and the corresponding mean anomalies for the period 1993-1997 (solid line in Figure 2a) and (b) rms deviation from the basin mean for each of the 10 days of snapshots.

increasing river runoff (in May) and the strongly negative water balance (by the end of summer). The maximum in January could be explained as due to increased precipitation. However, the secondary minimum in December is rather associated with changes in MSL, which are not forced by fresh water fluxes (we will give an explanation on this further in text). It is important to note here that the maximum negative anomaly of straits transport (>330 km^3 yr^{-1}) exceeds the annual mean values of the barotropic flow based on BSHM data (260 km^3 yr^{-1}) and even the larger value of 300 km^3 yr^{-1} reported by *Özsoy and Unluata* [1998]. This could indicate that the amplitudes of the seasonal variations of barotropic outflow estimated by T/P and hydrometeorological data are too high, unless reversal of the transport would be possible. This reversal estimated by the two types of data (provided we trust the annual mean BSHM fresh water flux value) lasts for about half a month.

2.2. Comparisons Between Seaborne and Altimeter Observations

The variability of SLA reveals clear intraannual and interannual variability, therefore we show in Figure 3a the difference between the basin mean SLA and its periodic part (the latter characterizing the seasonal cycle, Figure 2a). Three major conclusions can be drawn from this plot. (1) There is a pronounced trend of ~3 cm yr^{-1} (see also *Ducet et al.* [1999]). (2) The intervals between the maxima are ~1-2 years. (3) The maxima are higher than the ones in the seasonal cycle. Figure 3 demonstrates that the individual years have very different appearances. During most of the analyzed period the interannual variability is manifested by the changing amplitudes of seasonal cycle. However, by the end of 1996 the phase is strongly displaced compared to that of the mean year, which results in the large maximum at the end of the plot. Note that the data series shown in Figure 3 is shorter than the whole data series since we plot only the time interval (4 years) for which we can calculate the mean year from all data types.

The evolution of spatial variations in the SLA (Figure 3b) provides a valuable information about the time-space variations of Black Sea dynamics. Actually, Figure 3 gives a measure of the potential energy associated with the slope of SLA. The mean (for the whole period) rms deviation from the area mean SLA is 38 mm. The horizontal variations have smaller amplitudes than the MSL variations (the latter are caused by variations in the water balance) thus the Black Sea is characterized as very coherently responding to changes in the hydrometeorological forcing. However, the variations in the horizontal are not negligible, revealing active dynamical processes (associated with variations in the slope of sea level). It is noteworthy that these variations have higher level signals than the errors in T/P data and, as we will demonstrate in section 3, exhibit large regional dependency. The latter necessitates as many validations as possible against seaborne observations.

The variability of SLE in coastal locations are dependent on local processes as well as on the characteristics of basin circulation. Large errors in the coastal regions make the use of altimeter data questionable; thus it is important to demonstrate the similarities or differences between altimeter and seaborne observations in different locations (see Figure 1). For validation purposes we use tide gauge data obtained from the PSMSL. We take from the T/P data nearest to the coastal station grid point and show in Figure 4 and Table 1 the comparison between the two types of data. The close courses of T/P curves on the western coast are due to the very small distance between coastal stations. The tide gauge data series are shorter since no data are available from PSMSL for 1997. There are also periods with missing data. As we showed above on the example of seasonal oscillations, the two types of data correlate relatively well in Tuapse (Figure 4c and Table 1) where the track passes almost over the station (see Figure 1). There are, however, large deviations between the two types of observations on the Bulgarian coast that could trigger lots of questions about the quality of tide gauge data or the principal possibility of inferring with sea level variations in the coastal locations, which are far from the satellite tracks from T/P data. Nevertheless, we have to admit that rms deviations from the mean sea level compare well

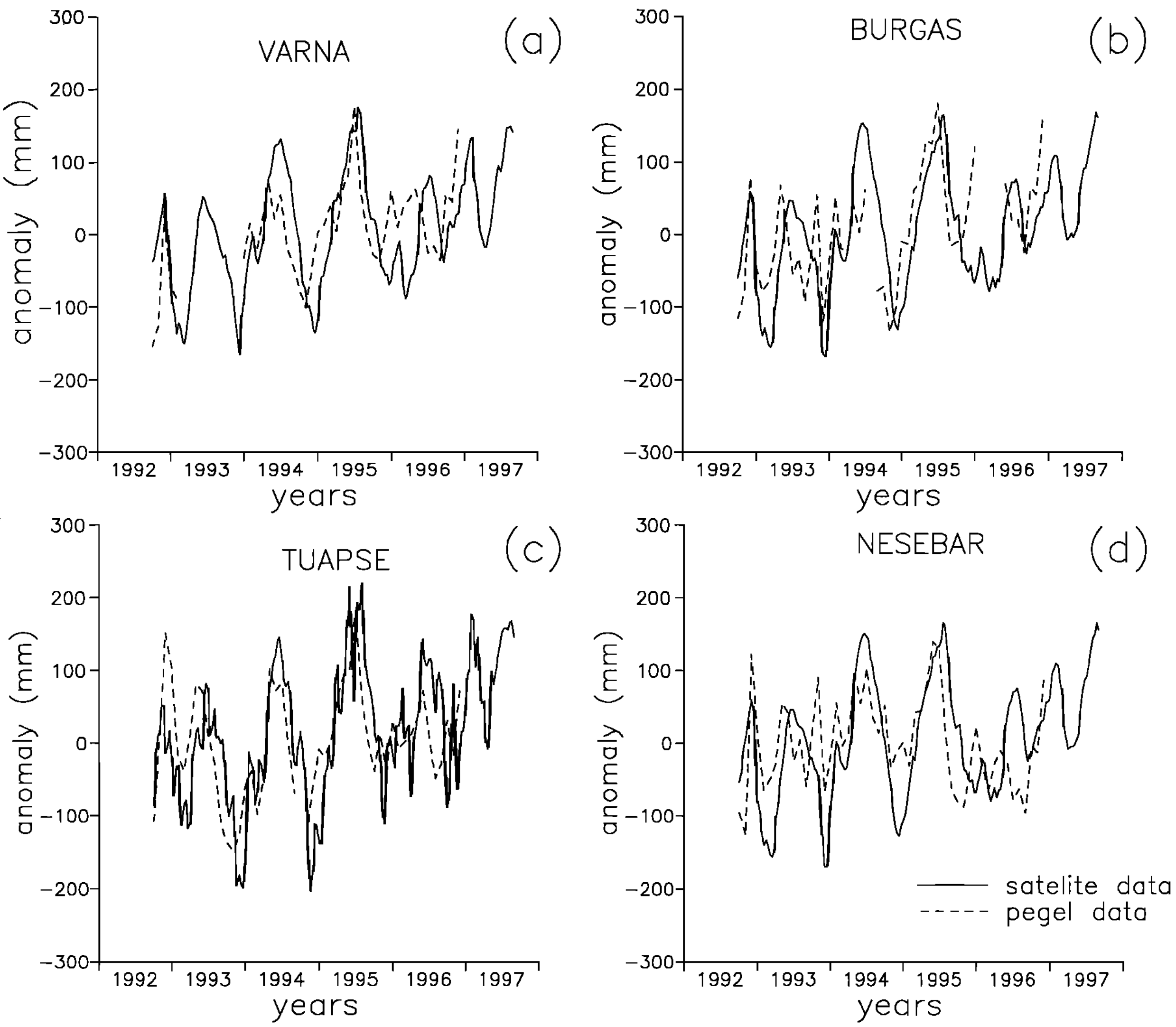

Figure 4. Comparison between SLA derived from satellites and tide gauge data: (a) Varna, (b) Burgas, (c) Tuapse, and (d) Nesebar. Records in coastal stations are not available during the whole time, thus dashed curves are broken in some time intervals. The tide gauge data are presented as anomalies. No correction for steric effect has been made.

(Table 1) with the slightly larger values in T/P data. The sea level rise in the Black Sea of ~3 cm yr^{-1} is supported by the coastal observations as well. This cannot be explained by a decrease of atmospheric pressure over the Black Sea [see *Ducet et al.*, 1999]. Global trends for this period give values of only 1 mm yr^{-1}. Neither can this trend be explained by the total heating during this period, as shown by the analysis of heat fluxes of ECMWF atmospheric analysis data. It is most plausible that the rise in the MSL has been caused by the increased fresh water input. We refer in this context to the case of the neighboring Caspian Sea (a fully enclosed basin), where the rise of MSL amounts to ~50 cm for the period 1993-1995 [*Cazenave et al.*, 1998].

Table 1. Comparison Between Satellite and Tide Gauge Data

Station	Varna	Nesebar	Burgas	Tuapse
Rms deviation from the mean (cm)	6.5 (7.9)	6.3 (7.9)	7.5 (7.4)	7.4 (8.8)
Correlation between altimeter and tide gauge data series	0.65	0.51	0.68	0.76

Values in brackets are based on T/P data.

2.3. Seasonal and Interannual Variations in the Water Balance

The basin mean components of fresh water balance calculated from the BSHM data as the volume of water (added/removed) per month show large variability (Figure 5a-5c). The river runoff, evaporation, and in particular steric effect (Figure 5d) are dominated by the seasonal variability. Note that the Y axis of Figure 5d is 3 times as stretched as the Y axis in the rest of plots. The small amplitude of the difference between the steric effect at each moment and the one corresponding to the mean year (Figure 5d, dashed line) proves that if no reliable data are available, the correction for the steric effect could be done using climatic data. Such substitution will not produce large errors; however throughout

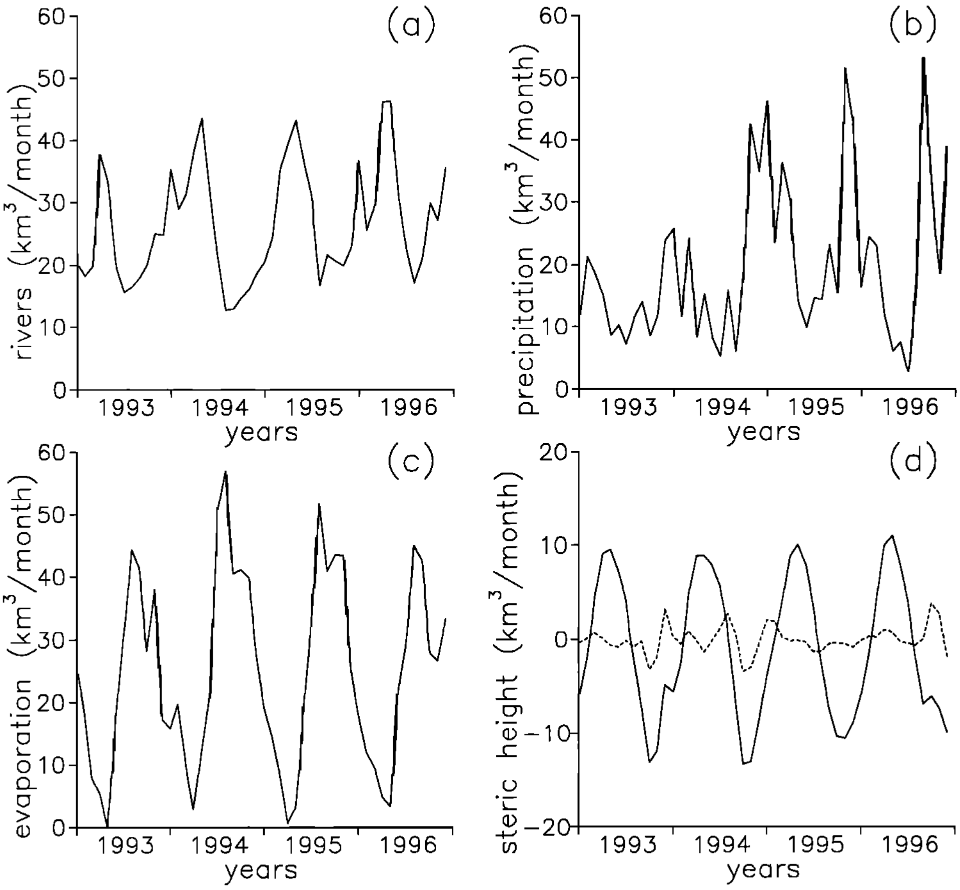

Figure 5. The components of the Black Sea fresh water balance: The data were kindly provided by V. Belokopitov (personal communication, 1999): (a) river runoff, (b) precipitation, (c) evaporation, and (d) steric effect calculated from (1) (solid line), and the steric effect with excluded mean seasonal variability (dashed line).

of paper our correction takes into consideration the interannual variability in the steric heights.

The annual mean values of water balance components and their rms (in brackets) are rivers, 318 (110) $km^3\ yr^{-1}$; precipitation 238 (150) $km^3\ yr^{-1}$; and evaporation 296 (182) $km^3\ yr^{-1}$. If we assume that the volume of the sea did not change for the period of observations, this would yield for the outflow through the Straits of Bosphorus, 260 $km^3\ yr^{-1}$ that is about 15% less than the value given by *Özsoy and Unluata* [1998]. If we take into consideration the sea level rise of 3 cm yr^{-1}, estimated for the period 1992-1997 from the T/P data, then the mean outflow should be reduced to 248 $km^3\ yr^{-1}$ (we use for the sea surface of the Black Sea the value 4×10^5 km^2).

The combination of hydrometeorological and altimeter data gives a unique possibility to assess the variability of the Bosphorus outflow for long periods. It is worth remembering here that direct measurements exist for periods up to several weeks [*Gregg et al.*, 1999], demonstrating that the oscillations associated with the inverse barometer effect dominate the variability at high frequencies (synoptic atmospheric cycle). Blocking the upper layer transport may be caused by south westerly winds in winter [*Özsoy et al.*, 1995], but so far it is not clear to what extent these intermittent processes may affect the water balance (some investigation on this issue using T/P data are made by *Ducet et al.* [1999]).

We show first in Figure 6a the sum of river runoff, evaporation and precipitation (solid line) and the change of the volume of the sea calculated as $\partial\zeta_B/\partial t$ multiplied by the surface area (dashed line). Obviously, the response of SLA is coherent with the fresh water flux. It is instructive at this point to show the outflow Q_b through the Straits of Bosphorus (solid line in Figure 6b) calculated as a residual of the changes of the Black Sea volume caused by fresh water fluxes and the ones directly measured by T/P data:

$$Q_r' + Q_p' - Q_e' - S\frac{\partial\zeta_B}{\partial t},$$

where prime denotes anomaly of the corresponding variable (the difference between two curves in Figure 6a). The amplitude of the strait outflow is ~1.5 smaller than the amplitudes of the individual components of fresh water balance. This proves that the forcing is efficiently damped, which could happen if the resistance of the strait is strong. In order to illustrate how much the individual years differ from the mean year for the observation period we plot with dashed line in Figure 6b the barotropic outflow of the mean year. The negative anomaly reaches extremum in August every year; however, the secondary extremums (see also Figure 2d) short before the end of year are very strong in 1996 and particularly strong in 1993. The appearance of the positive anomalies is

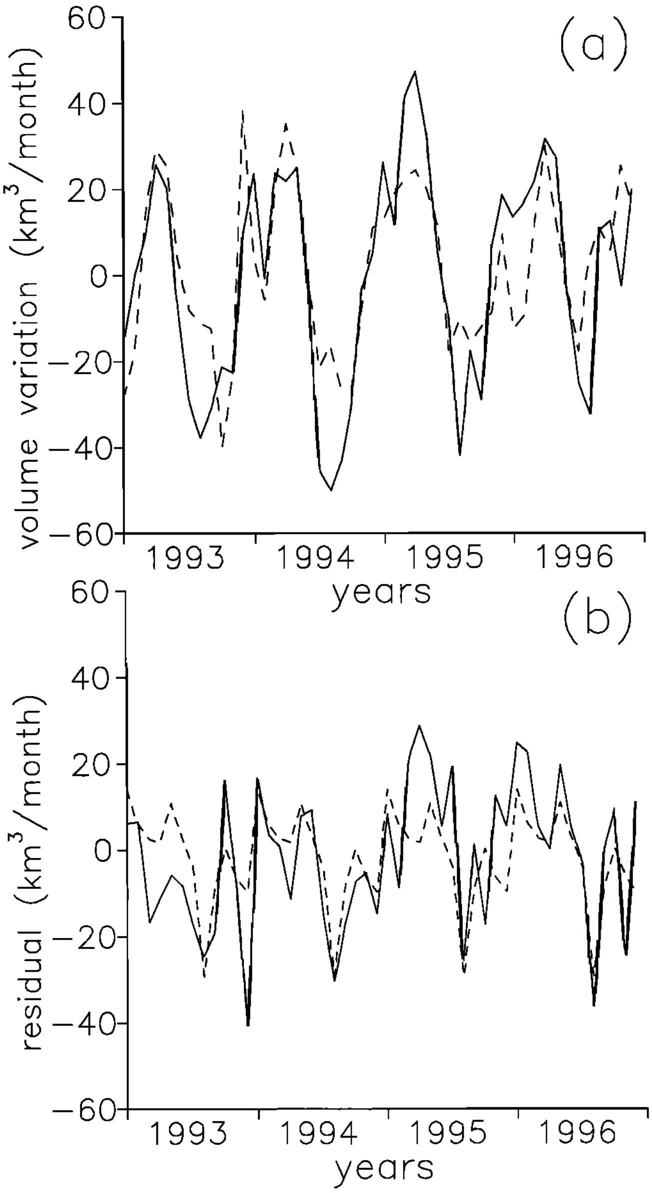

Figure 6. (a) Comparison between Black Sea volume variation derived from hydrometeorological data (solid line) and calculated as the time rate of change of MSL anomaly from T/P data times the sea surface (dashed line). Correction for the steric effect has been done. (b) The difference between the two curves in Figure 6a (solid minus dashed line) is plotted with the solid line and the monthly mean climatic values of this difference are plotted with the dashed line.

less regular (the strongest outflow in 1996 is just in the beginning of the year). The outflow anomalies range from -480 to +330 km^3 yr^{-1} and in some particular cases have resulted in a reversal of the outflow. It is very plausible that the reversal of the outflow in 1993 was due to the strong southerly winds in December (the winds used to check this hypothesis are taken from the ECMWF analysis data). This event was combined with an extremely low position of the MSL (see farther in the text and Figure 10a) at that time. All this, in combination, might have resulted in the largest outflow reversal for the period 1993-1997. Just several months before, there was a pronounced deviation of the Bosphorus transport from the mean value for October. This event occurred at the time when strong north easterly winds dominated the mechanical atmosphere forcing. Obviously, more profound analyses on the wind control in the strait could be motivated by the above correlation.

3. Seasonal Intensification of the Black Sea Circulation

3.1. Spatial Characteristics of the Variability

Before addressing the time-space variability of Black Sea circulation based on T/P data we will show the dynamic heights calculated from climatic data with horizontal resolution of $^1/_2$° in longitude and $^1/_3$° in latitude (Figure 7). The profile data and the computation of monthly mean values of temperature and salinity are described by *Altman et al.* [1987]. The reference level in our dynamic computations is taken as 500 dbar (the density anomalies below this depth are very small in the Black Sea; thus the results remain almost unchanged if we consider a deeper reference level). The results support the well-known earlier results of *Filippov* [1968] and *Blatov et al.* [1984], demonstrating that the SLE reaches highest positions along the coast (Figure 7a). The slope between the coastal and open sea ranges in different seasons between 8 and 12 cm, with the largest values located along the continental slope. This value compares well with the slope obtained from model simulations with active free surface [*Stanev and Beckers*, 1999a, b].

Though the general circulation in the Black Sea does not reverse and remains cyclonic during the whole year (exceptions can be found in the area of Batumi Eddy), it undergoes large variability in time, which is illustrated in the seasonal anomaly (Figure 7b-7e). The intensification of cyclonic circulation in winter and spring (December-May) is identified by the negative anomalies in the basin interior and the positive ones in the coastal areas. In the rest of the year (June-November) the SLA in the basin interior displaces upward, thus the currents weaken. The amplitude of the seasonal wave reaches 3-6 cm in different areas (compare with Figure 2a), which is about half of the sea level difference between the coastal and open sea. Our earlier simulations (cited above) proved that the dynamics of the Black Sea, is to a large extent controlled by the seasonal atmospheric forcing having pronounced variability. One of the most spectacular transitions of the circulation is observed in the easternmost Black Sea (Figure 7b-7e). This is the well-known area of the Batumi Eddy where the circulation in the warm part of the year becomes anticyclonic, thus contributing to a very deep penetration of vertical mixing and sinking of surface and intermediate waters [*Stanev et al.*, 1997; *Stanev and Beckers*, 1999a, b].

The seasonal variability, as seen in the altimeter data (Figure 8), correlates with the estimates based on dynamic computations. The positive values of SLA in the coastal regions (negative values in the basin interior) are well pronounced during winter and spring. In summer and fall this situation reverses, as is the case with the climatic data; however, the amplitude of the signal is larger in the T/P data. The second important characteristic of the SLE variations is that they are dominated by spatial inhomogenity associated

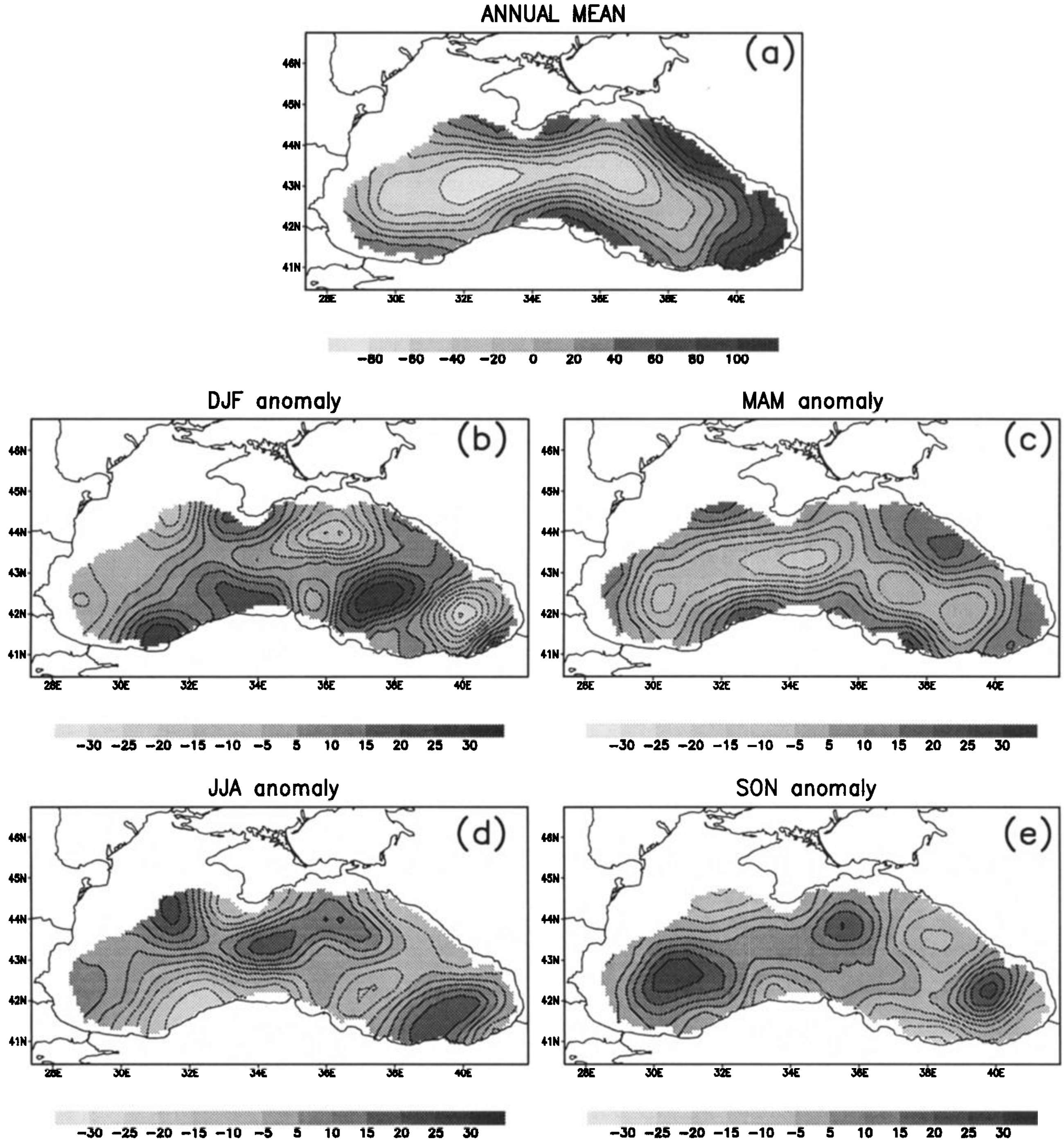

Figure 7. (a) Annual mean SLE (millimeters) based on dynamic computations: (b)-(e) Seasonal anomalies of the dynamic heights based on climatic data. The dynamic topography is in milimeters and the reference level is 500 m.

with several sub basin-scale eddies. The analysis of the data for every season separately (not shown here) demonstrates that this type of local variability is quite robust and repeats almost every year, giving ~7-8 cm for the amplitude of seasonal oscillations.

Since we want to address the contribution of oscillations with different frequencies in the variability of Black Sea surface, we first produce the gridded mean year of SLA from the 4 years of data series. Then we subtract the mean year from the original data series and decompose the obtained signal into a high- and low- frequency component (a cosine filter with a window of 1 year is used). The corresponding magnitude of interannual, seasonal, and intraannual oscillations is shown in Figure 9. The latter pattern (Figure 9c) reveals the strongest variability in the coastal and continental slope area that is associated with the baroclinic instability of the front and formation of coastal anticyclones there. Three areas at this frequency with quite strong

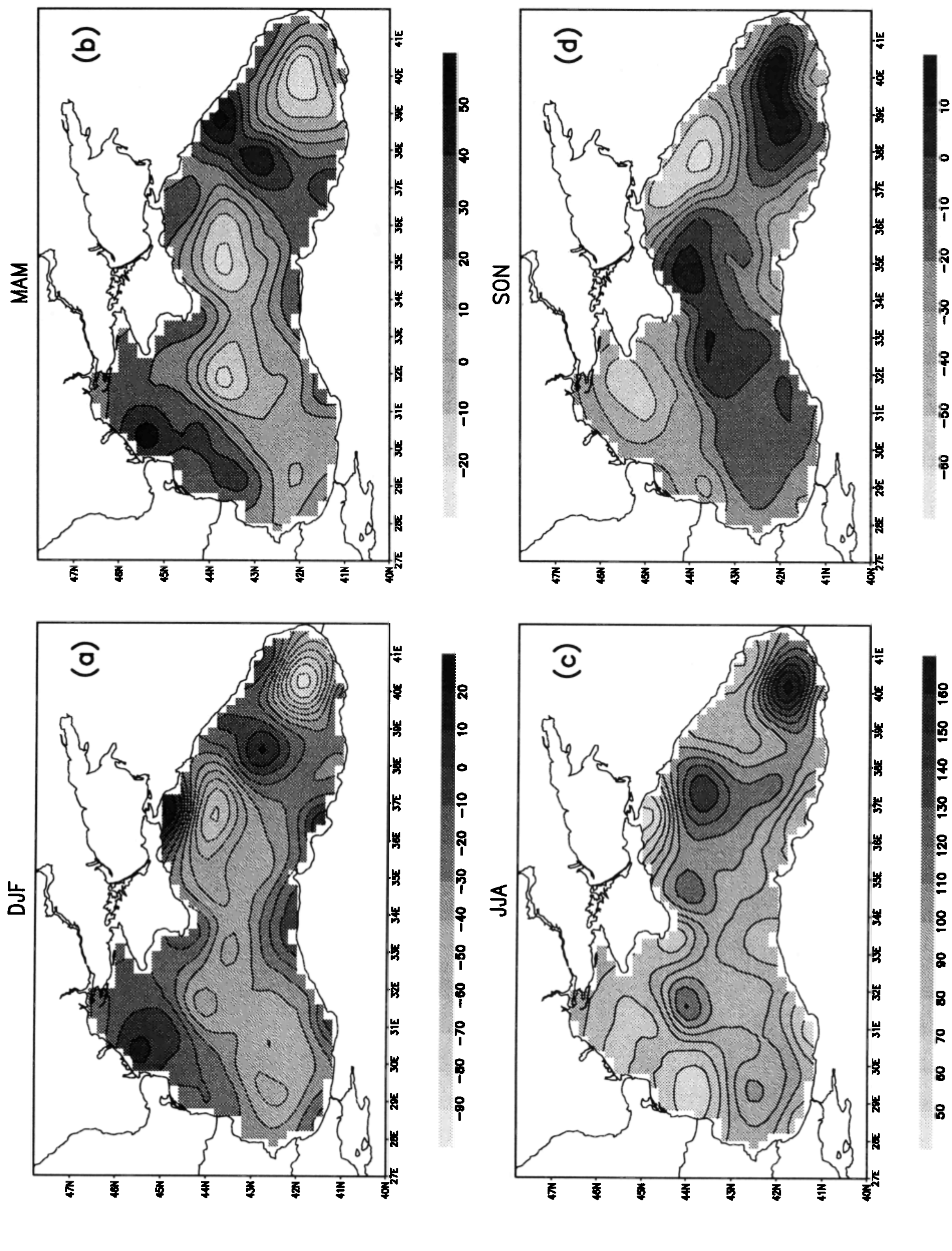

Figure 8. Seasonal SLA (millimeters) estimated from T/P data. To eliminate the effect of MSL variations caused mainly by fresh water fluxes, we subtract the basin mean SLA, thus revealing the spatial inhomogeneties.

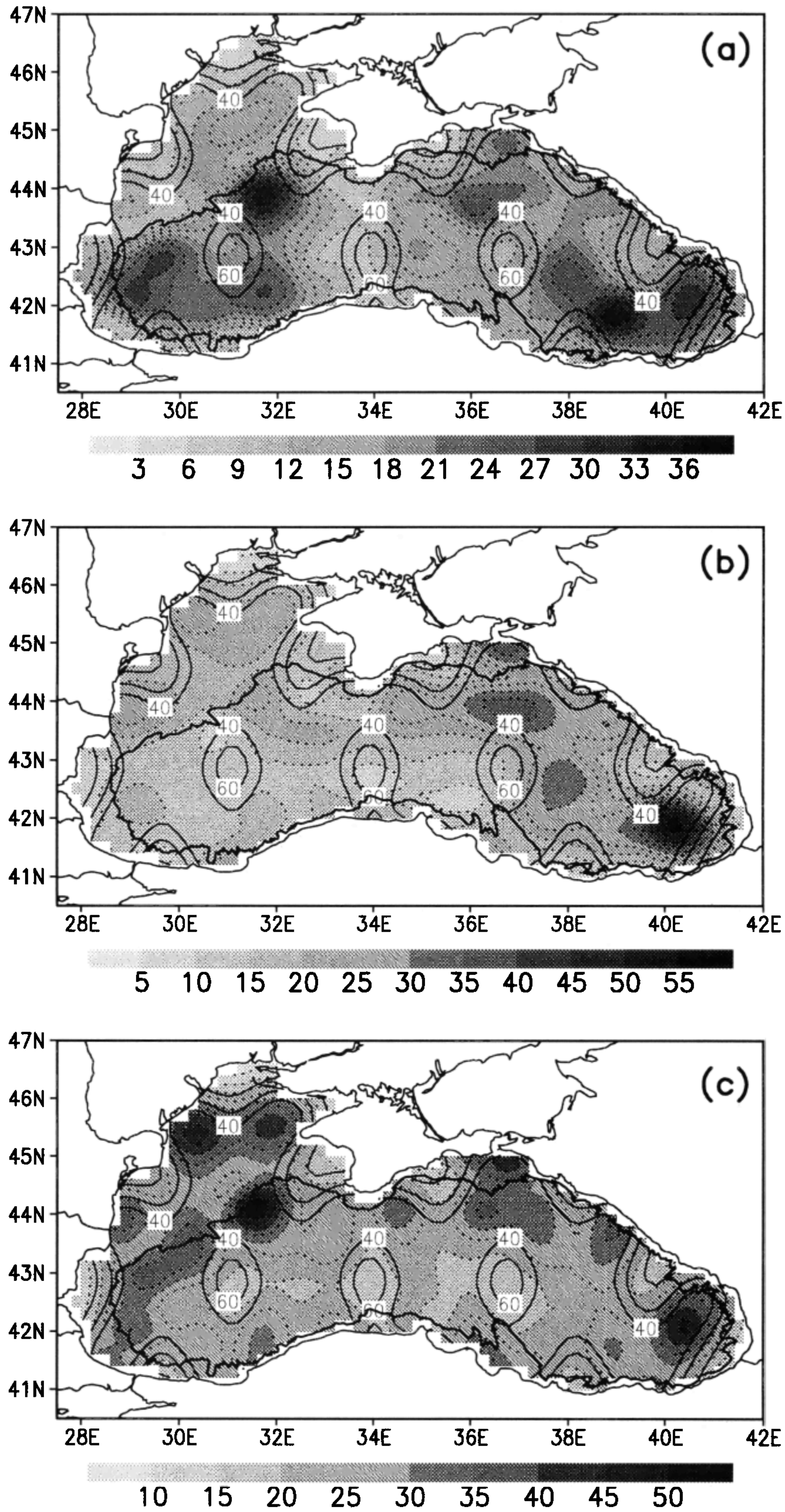

Figure 9. Amplitude of the SLA oscillations [millimeters]. Isobath 1000 m is plotted with the thick line. All isolines are plotted with dotted lines. The T/P interpolation errors are plotted with solid lines (40, 60 and 80% of the signal). Contributions of (a) interannual, (b) seasonal, and (c) intraannual variabilities are shown.

magnitudes of oscillations are well pronounced: (1) the area of Batumi Eddy, (2) the area of Sevastopol Eddy, and (3) the shelf area. In order to avoid misinterpretations of the results, an error map (errors >40% of the signal) is plotted with solid lines.

The seasonal and intraannual amplitude patterns demonstrate that the zone of most pronounced variability is located in the easternmost Black Sea. This area is characterized by strong oscillations giving rise to the westward wave propagation controlled by basin oscillations, topographic beta effect, and baroclinicity [*Rachev and Stanev*, 1997; *Stanev and Staneva*, 2000]. The area of maximum magnitudes of oscillations at seasonal timescales (Figure 9b) follows the Caucasian coast that correlates with the earlier theoretical studies revealing similar path of the signals (Hovemoller diagrams are shown by *Stanev and Rachev*, [1999]). Farther west, the magnitude of oscillations decreases in the Black Sea narrow section, which is also consistent with the estimates given in the above cited works. We admit that with better resolution in space and time the role of synoptic processes would be more clearly demonstrated. As shown by numerical simulations and survey data, better discretization in space is needed to resolve the processes associated with frontal instability [*Korotaev* et al., 1998].

The area west of Crimea Peninsula is well known as the region of the Sevastopol anticyclonic eddies. We see from Figure 9c that the oscillations in this area have their largest magnitudes at intraannual timescales. However, unlike the case in the area of Batumi Eddy, the amplitudes of oscillations decrease at annual timescales. According to the numerical simulations of *Stanev and Staneva* [2000] this eddy moves in west and southwest directions in the narrow band between the main jet current and the continental slope. Thus it has to pass over the large bottom depression (see the thick line following the isobath 1000 m) that disturbs it. As could be shown also by the movie of snapshots, this eddy is trapped by the topographic depression and often intensifies there, which might explain the large variance. The separation of the two high-amplitude areas in the western Black Sea (on the shelf and in the area of Sevastopol eddies) might indicate that the shelf processes do not strongly interact with the ones in the deep ocean. The second maximum in the western Black Sea (along the continental slope) might be associated with the anticyclonic eddies that appear quasiperiodically in this region [*Stanev et al.*, 1988].

The interannual variations have smaller amplitudes than the intraannual and seasonal ones. We see again an intensification of oscillations in the region of Sevastopol Eddy (Figure 9a). The overlapping maxima of amplitude patterns in intraannual and interannual variability in the western Black Sea allows us to speculate that changing the intensity of high-frequency processes (they bear more energy) may locally amplify the low-frequency oscillations in the area of Sevastopol Eddy. The same could also happen south of the Kerch Strait and in the region of Batumi Eddy, where the amplitude of oscillations with different periodicity show maxima.

3.2. On the Correlation Between the Circulation and Hydrometeorological Forcing

In order to quantify the seasonal and interannual intensification of the Black Sea circulation we consider two areas separated by the isobath 1500 m. The coastal area is representative of anticyclonic circulation (high SLE); the deep interior area is representative of a cyclonic type of circulation (see also Figure 7 and the opposing phases in winter-spring and summer-fall periods in Figure 8). Actually, the altimeter data give the anomalies, thus the two areas are not as easily detected in the T/P data as in Figure 7a. We define the anomaly of the volume of coastal zone V_c' as the surface area (s_c=2×10^5 km^2) times the deviation of the area mean SLA from the basin mean $(\bar{\zeta}^c - \bar{\zeta})$, where overbars are the mean for the basin and overbars with a c superscript are the mean for the coastal area. Then the above equation is indicative of the relative change of the volume of coastal waters (the solid line in Figure 10a). The positive anomaly in winter is consistent with the largely accepted concept for the intensification of Black Sea circulation in this season. This intensification is associated with the ascending sea surface in the coastal area and the compensating descending trend in the open sea caused mainly by wind. The results in Figure 10a support the above concept and give a measure of the seasonal variability associated with the winter intensification. It is amazing that in some years (1993-1995) the oscillations are very strong, while in others (1997) they are much weaker.

The variability of the volume anomaly $s\bar{\zeta}$ is plotted in Figure 10a with a dashed line. This line reveals the changes in the Black Sea volume caused by the changing fresh water fluxes. As seen by the scales on the Y axis corresponding to the two curves in Figure 10a, the oscillations associated with the changing volume of the sea (caused mainly by the fresh water flux) have much higher amplitudes than the oscillations associated with the displacement of waters from coastal to open sea and back (the latter are indicative of changing the intensity of circulation caused by wind). The amplitudes of both curves are higher than the errors in T/P data, indicating that these data provide reliable tool for studies of the circulation and its variability.

There is a weak negative correlation between the amplitudes of MSL and the SLA in the coastal region. This correlation changes from year to year, demonstrating that the fresh water balance does not directly drive the intensification of circulation. Note that the amplitudes of both curves are high in 1992-1996, while in 1996-1997 it is only the area mean volume that has large amplitudes. During the second period the mean for the coastal zone volume anomaly varies in a very limited range. To make these results more conclusive, we produce a mean year and show in Figure 10b, with a dashed line, the difference between SLA in the coastal zone and the basin mean multiplied by coastal area surface $s(\bar{\zeta}^c - \bar{\zeta})$. This curve illustrates the variations of the volume in the coastal zone associated with the periodic upward (in winter) and downward (in summer) displacements of sea level (Figure 7). The wind stress curl estimated from climatic data [*Staneva and Stanev*, 1998] is also plotted in Figure 10b. The coherence between the two curves gives additional support to the results of numerical simulations [*Stanev*, 1990], demonstrating that the wind stress acts as the main external force affecting through the variability of Ekman drift the seasonal variability of circulation. The time lag of 1-2 months could be indicative of the time needed for adjustment of the density field to external forcing. This time lag is supported also by the numerical experiments [*Staneva and Stanev*, 1998, Figure 9].

Different alternative hypotheses could be formulated to explain the intensification of circulation. In the context of

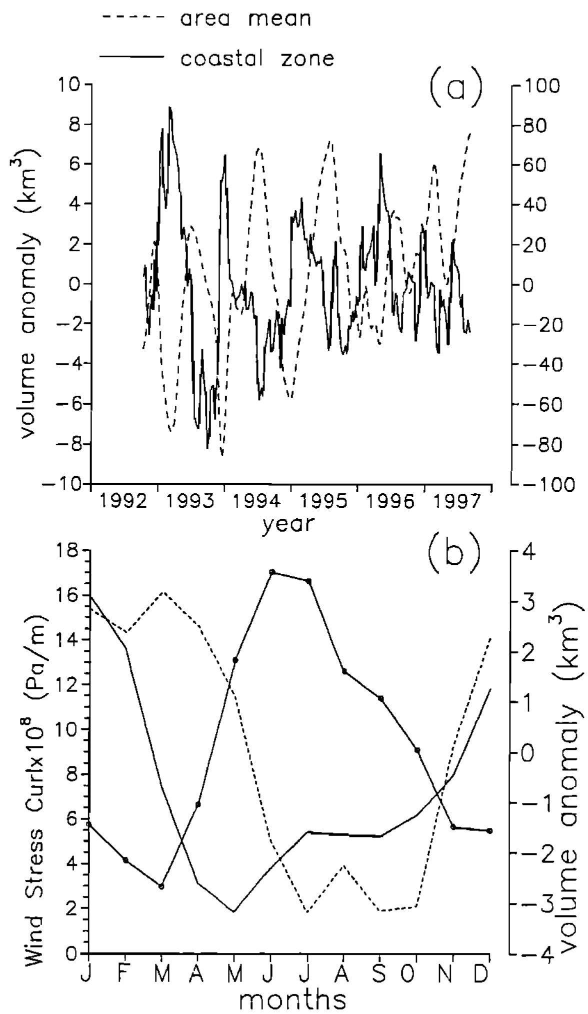

Figure 10. Variability of SLA:
(a) variability of the SLA in the coastal zone minus basin mean SLA (left Y axis) (solid line) and variability of the basin mean SLA (right Y axis) (dashed line) and (b) seasonal variability of the wind stress curl estimated from climatic data [*Staneva and Stanev*, 1998] (solid line), and SLA in the coastal zone minus basin mean SLA times the area of coastal zone (dashed line). The curve with circles is the mean for the 4 year period SLA, corresponding to the solid line in Figure 2a scaled by 10^{-1} to be comparable with the dashed line curve.

issues addressed in this paper one could speculate that the intensification could be related to the fresh water fluxes. In order to check this we show with the line marked with circles in Figure 10b the anomaly of Black Sea volume. This line presents the mean year corresponding to the dashed line in Figure 10a (note that the scale on the Y axis has to be multiplied by 10 for this curve). The comparison of the three curves does not give much support to the idea that the fresh water balance directly affects the intensity of circulation. One could speculate that there is an indirect mechanism related to the increasing contrast between coastal and open sea water in late spring caused by the fresh water fluxes (see Figure 2d). However, the variations in the fresh water flux are delayed compared to the ones of circulation intensity, which excludes this driving force from the major candidates explaining the winter intensification. Another hypothesis explaining the displacement of water between coastal and open ocean might take into consideration the contribution of atmospheric pressure. Its annual amplitudes estimated from climatic data reach 10-15 mbar [*Simonov and Altman*, 1991]. The maximum is in winter, and the minimum is in summer. The possible effects of these changes have been analyzed by *Ducet et al.* [1999]. The horizontal patterns from November to March show low pressure in the open sea and high pressure in the coastal areas, the difference reaching 2 mbar. From here we could conclude that (1) the inverse barometer effect could give only a small contribution in the horizontal patterns of SLE and (2) the inverse barometer effect is in phase opposition to the changes in SLA, eliminating atmospheric pressure as a candidate for explaining the winter intensification observed in T/P data.

4. Conclusions

When analyzing the water balance in the Black Sea, we took advantage of the nature of this basin characterized by (1) the strong impact of fresh water fluxes on all important large-scale physical processes and (2) the limited exchange with the Mediterranean Sea. The parallel analysis of fresh water fluxes and satellite data made it possible to estimate the consistency between the two types of data. We demonstrated also that the altimeter data correlate well with tide gauge data, particularly in the locations where the tracks are not far from the stations.

The strong response of the Black Sea MSL to the fresh water balance and the large variability in the latter explain the pronounced signals in the sea surface variations. This variability is well identified both in seaborne and satellite data. The governing role of the fresh water balance in creating the oscillations of MSL is well resolved at seasonal and interannual timescales; therefore we focused our discussion on these oscillations. Unlike previous studies [*Simonov and Altman*, 1991] where parallel analysis on fresh water balance and sea level data in coastal stations were carried out, our analyses have as an advantage the use of data over the entire Black Sea. As we demonstrated (Figure 2a, 2b, 4, and 5), the differences between characteristics of oscillations in different areas preclude correct balance estimates when using only coastal station data. These arguments and the results that we demonstrated throughout the paper prove that the altimeter data could contribute to (1) obtaining new estimates (independent from earlier ones) of the variations in the Bosphorus outflow for long periods and (2) specifying more correctly the Black Sea water balance and, in particular, its time variability.

The strong signals in the fresh water fluxes and satellite data at seasonal and interannual scales made it possible to obtain a remarkable correlation between the variations of the Black Sea volume as seen in the satellite data and the estimates based on hydrometeorological data and calculations. Remember that this does not hold for the Mediterranean Sea, basically because of the lower levels of signals in this sea.

It is well known that the Black Sea surface undergoes large changes throughout the year, but this concept is mostly a result of earlier dynamic analyses and simulations. No direct support of these findings existed since no measurements of the SLE were available basinwide. One spectacular demonstration of the value of altimeter data is their ability to prove directly the intensification of cyclonic circulation in winter and spring that is well pronounced in the positive SLA anomalies in the coastal areas. We showed that the amplitude of seasonal variability may reach half of the value of the annual mean difference between sea surface height in coastal and open sea regions. This demonstrates that the amplitude of seasonal variability in the transport reaches half of the mean transport value, which agrees with earlier model estimates [*Stanev et al.*, 1997]. The strong correlation between seasonal oscillations of wind stress curl and sea level in coastal stations supports the results of earlier theoretical studies, demonstrating that the wind is the major force driving the seasonal intensification of circulation.

Lots of speculations exist in Black Sea oceanography about the local circulation in the eastern basin. To our knowledge the first evidence from remote sensing about the existence of Batumi Eddy was given by *Kaz'min and Sklyarov* [1982]. Since then there were a number of analyses on remote sensing data in the infrared or visible spectrum describing this part of the sea as favorable for eddy formation (the only one published so far analysis on satellite altimeter data is by *Korotaev et al.*, [1998]). However, unlike the T/P data, this type of data cannot give a measure of the dynamic significance of this eddy. As we proved, this area exhibits not only a tendency for anticyclonic circulation in summer but is also characterized by the highest level of variability, supporting the theoretical results of *Rachev and Stanev* [1997] and *Stanev and Staneva* [2000] that the oscillations in the eastern Black Sea give the major sources of disturbances, propagating farther westward.

The impact of Sevastopol eddies on the Black Sea dynamics is still not well understood. These eddies appear less regularly than the Batumi one, but as seen from the T/P data, the area west of Crimea is characterized by extremely strong variability. Unlike the case with the Batumi Eddy, the Sevasopol ones are more pronounced at intraannual and interannual frequencies. This can stimulate further studies on the impact of the eddy field on the processes with comparable timescales, e.g. the water mass formation.

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P.Y. Le Traon, Space Oceanography Division, CLS, 31526 Ramonville Saint-Agne, France

E. L. Peneva and E. V. Stanev, Department of Meteorology and Geophysics, Univeristy of Sofia, 5 James Bourchier Street, 1126 Sofia, Bulgaria. (stanev@phys.uni-sofia.bg)

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