# On the forcing of sea level in the Black Sea

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[1]  Forcing mechanisms for sea level variability in the Black Sea are investigated in the context of an observed increase in the sea level of this basin by 2.5 mm/yr over the last 60 years. Temperature and salinity variations computed from the Mediterranean Data Archeology and Rescue (MEDAR) data set exhibit significant interdecadal variability. However, the corresponding steric height variation does not show a long-term increase and thus cannot account for the observed change in sea level. The impact of surface freshwater flux (P-E) changes is also investigated using two independent data sets. The first data set, which is based on measurements collected in the basin, can explain most of the sea level variability, with only 0.8 mm/yr remaining unexplained. The second data set, output from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis, is unable to explain any of the observed trend. Potential contributions from changes in river runoff and surface pressure are quantified but found to be minor terms. By comparing the observed salinity changes with the sea level rise and the P-E variability in the first data set, we infer that the P-E variations are the primary cause for the observed sea level rise, while land movements are likely to partly contribute, too. The relationship of Black Sea temperature and salinity variability with corresponding variability in the connected Aegean Sea has also been explored. A significant correlation is found between the salinity of the upper water of the Aegean Sea and the layer between 50 and 300 m in the Black Sea, indicating that the latter layer is a product of the Mediterranean inflow.    INDEX TERMS: 4556 Oceanography: Physical: Sea level variations; 4504 Oceanography: Physical: Air/sea interactions (0312); 4215 Oceanography: General: Climate and interannual variability (3309); 9320 Information Related to Geographic Region: Asia; KEYWORDS: climatology, steric sea level, North Atlantic Oscillation, interbasin water and salt exchange, Black Sea

## 1.  Introduction

[2]  Global sea level has been rising by $1-2$ mm/yr over the last century, and it is expected to continue rising mainly because of the thermal expansion of the oceans in response to global warming [*Church et al.*, 2001]. Observations of sea level in the Black Sea have shown a continuous multidecadal increase of about 2 mm/yr between 1960 and the early 1990s, a period during which the neighboring Mediterranean Sea experienced sea level fall [*Tsimplis and Baker*, 2000]. More recently, between the early 1990s and 1998, sea level rise in both basins has been observed with accelerated values in the Black Sea of

the order of 27 mm/yr [*Stanev et al.*, 2000; *Cazenave et al.*, 2002]. During the same period the sea surface temperature in the Black Sea has been increasing, thus leading *Cazenave et al.* [2002] to conclude that this recent increase was steric in nature. In most of the Eastern Mediterranean a significant sea level rise ($\sim$9 mm/yr) took place during the same period, the exception being the Ionian Sea where a significant sea level fall ($-11.9$ mm/yr) was observed [*Fenoglio-Marc*, 2002; *Tsimplis and Rixen*, 2002]. The cause of the earlier multidecadal increase in the sea level of the Black Sea in the period from 1960 to the early 1990s remains to be established. Several factors may be expected to play a role, including thermal expansion, changes in the air-sea freshwater flux to the basin, variations in river runoff [*Stanev and Peneva*, 2002], and subsidence of the surrounding land.

[3]  At seasonal timescales, the forcing of sea level in the Black Sea is dominated by the freshwater balance [*Stanev*

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*et al.*, 2000]. The amplitude of seasonal oscillations of precipitation and river outflow are approximately of the same magnitude, while the evaporation signal is twice as large, the relative values being 90, 88, and 160 km³/yr, respectively [*Stanev and Peneva*, 2002]. The changing balance between these different terms results in seasonal sea level oscillations of up to 20 cm [*Arkhipkin and Berezhnoi*, 1996]. At longer timescales, up to decadal, variability in the hydrological data also exhibits a significant correlation with the variations in sea level [*Stanev and Peneva*, 2002] suggesting that the water balance continues to play an important role [*Peneva et al.*, 2001]. However, at multidecadal timescales the importance of variations in the water balance and the other factors described above has not yet been determined. As a consequence, it is not yet possible to say whether the multidecadal Black Sea sea level trend simply reflects the larger-scale thermal expansion of the global ocean or whether it is due to some other process.

[4] We address the cause of the multidecadal sea level trend in the Black Sea in the present paper by quantifying the relative contributions from thermal expansion and changes in the surface freshwater flux. For our study we utilize temperature and salinity observations from the MEDAR data set [*Brankart and Brasseur*, 1998]. We compare the sea level variability observed by tide gauges in the Black Sea over the period 1945–1998 to estimates of the steric variability, i.e., to sea level changes due to changes in the temperature and salinity within the water column. We also present new estimates of the variability due to change in the surface freshwater flux, i.e., the net precipitation obtained from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis [*Kistler et al.*, 2001]. These estimates are combined with the independent freshwater flux data set used by *Stanev and Peneva* [2002] to determine an upper limit on the contribution from this term to the observed sea level trend. By further combining our results with separate analyses of the other contributing factors we will infer that the sea level trend must be primarily due to local land subsidence.

[5] In addition to the cause of the sea level trend, the relationship between temperature and salinity variability in the Black Sea with that in the Aegean Sea, to which it is connected via the Bosphorous, remains an open area of research. Low-pass temperature and salinity variations in the Aegean Sea have been shown to relate to large-scale changes in the atmospheric forcing and in particular to the North Atlantic Oscillation (NAO) [*Tsimplis and Rixen*, 2002]. Correlation of river outflow within the Black Sea with the NAO has also been identified [*Stanev and Peneva*, 2002]. This finding was further supported by *Oguz et al.* [2003], who extended the analysis on the sensitivity of Black Sea to the NAO toward the response of the ecosystem. Nevertheless, it is unclear whether there is an influence of the NAO on the upper surface parameters of the Black Sea either directly, through a response to changes in the surface fluxes, or indirectly, through changes in the water mass characteristics of the Mediterranean inflow. We explore the links to the NAO through a combined analysis of the temperature and salinity variability in each of these basins using the MEDAR data set.
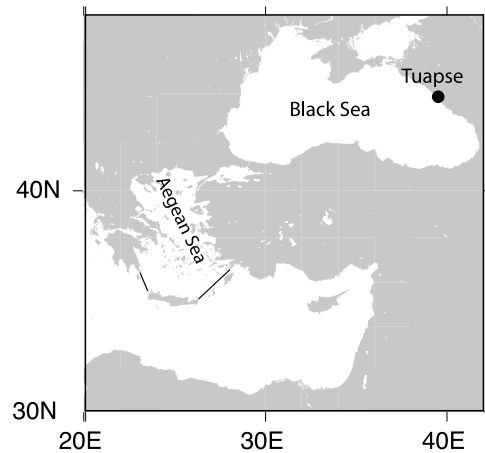


**Figure 1.** Areas for which the steric height variations have been estimated. The location of the long-term, high-quality tide gauge available at the Permanent Service for Mean Sea Level is also shown.

[6] Details of the data sets employed and our analysis methodology are given in the next section. In section 3, we present our main results on the cause of the sea level trend, and this is followed in section 4 by a discussion of the relationship between the Black Sea and Aegean Sea temperature and salinity variability and water exchange. In the final section, we draw some conclusions from our analysis.

## 2. Data and Methodology

[7] The MEDAR climatology (1945–1998) was used to calculate the effects that temperature (T) and salinity (S) variations have on sea level. The climatology is based on data collected by national and international projects in the Mediterranean. The quality control and analysis are detailed at www.ifremer.fr/sismer/program/medar/ and in the project report [*MEDAR Group*, 2002]. The in situ data were combined in T and S fields on a $0.2° \times 0.2°$ grid through the use of the Variational Inverse Method, which has been extensively employed in the Mediterranean context [*Brankart and Brasseur*, 1998]. This approach, statistically equivalent to traditional objective analysis, is numerically more efficient and more suitable given the complexity of the Mediterranean geometry [*Rixen et al.*, 2001]. Calibration of the correlation length and the signal-to-noise ratio was obtained by Generalised Cross Validation [*Brankart and Brasseur*, 1998]. The error fields for the database are available on www.modb.oce.ulg.ac.be/medar. In order to obtain yearly values for the different standard levels, a moving Gaussian weighted window of 3 years was used. The MEDAR database was then averaged spatially to produce mean T and S at 25 standard depths for the Mediterranean and Black Seas. We have employed the MEDAR database to investigate temperature, salinity, and steric height variability in the Black Sea and the Aegean Sea (Figure 1).

[8] The MEDAR climatology is based on observations going back to the mid-1920s (Figure 2). Nevertheless, only after 1955 does the coverage becomes consistent in time. Figure 2 also indicates that the spatiotemporal coverage of salinity data was similar to that of the temperature data.
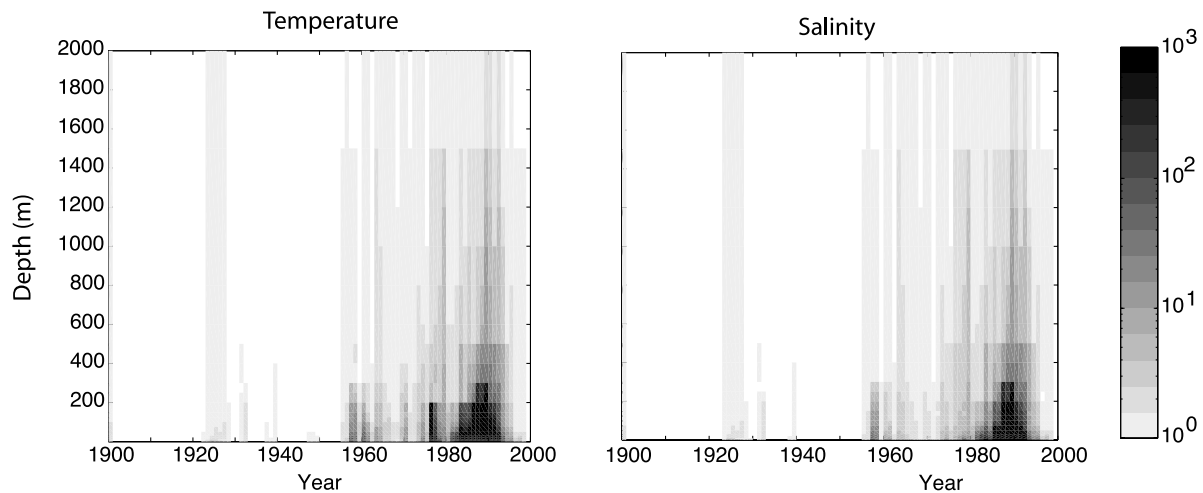
**Figure 2.** Yearly/depth coverage (in number of profiles) of the Black Sea in the MEDAR data set. The 25 standard levels used for the construction of the climatology are at 2000, 1500, 1200, 1000, 800, 600, 500, 400, 300, 250, 200, 150, 125, 100, 75, 50, 30, 20,10, 5, and 0 meters. See color version of this figure at back of this issue.

Nevertheless, because the salinity measurements are inherently more difficult, it is expected that the reliability of the two records will be different. Basin averages of the temporally smoothed T and S were determined for the Black and Aegean Sea regions shown on Figure 1 in three different layers. In the Black Sea, the upper layer is defined to be 0–30 m, the intermediate layer is 30–150 m, and the lower layer is 150–500 m. Note that no significant changes were observed below 300 m in the Black Sea. These layers correspond to the major water masses of the Black Sea [see, e.g., *Konovalov and Murray*, 2001]. Specific volume was calculated by the use of the Equation of State for Seawater 1980 [*U.N. Educational, Scientific, and Cultural Organization*, 1980] for each of the 25 standard depths with reference to 1000 m and then integrated upward to produce the steric height for each layer. Steric height anomalies were produced by removing the mean steric height for each layer.

[9] The steric height anomalies are compared with mean sea level observations from Port Tuapse extracted from the Permanent Service for Mean Sea Level Database [*Woodworth and Player*, 2003]. As demonstrated by *Stanev et al.* [2000] and *Peneva et al.* [2001], these data are consistent with the basin mean sea level from TOPEX/Poseidon data and thus are expected to provide a reliable indicator about long-term variability of sea level in the Black Sea.

[10] Data for the net surface freshwater flux (i.e., precipitation-evaporation, P-E) have been taken from two sources, the first of which is the NCEP/NCAR reanalysis [*Kistler et al.*, 2001], which consists of output from an atmospheric general circulation model that assimilates a wide range of observations for the period 1949 to the present. In addition, P-E and river runoff data between 1920 and 1997 are taken from *Altman and Kumish* [1986] and *Simonov and Altman* [1991]. The data for P-E of *Simonov and Altman* [1991] are a compilation of hydrometeorological data described by *Sorkina* [1974] supplemented by additional data up to the year 1985. The precipitation data originate from coastal and ship measurements (a total of 67, 000 open sea measurements were used by *Sorkina* [1974]). The gridded data were

computed from monthly mean coastal station data, which are interpolated over the sea using empirical coefficients based on correlation between coastal and open sea stations. Evaporation was computed by *Simonov and Altman* [1991] using bulk aerodynamic formulae. Extensive analyses of these data and their temporal and spatial variability, as well as their correlation with the NCEP and European Centre for Medium-Range Weather Forecasts (ECMWF) reanalyses [*Gibson et al.*, 1996] are given by *Staneva and Stanev* [1998] and *Schrum et al.* [2001]. Water budget components computed from the monthly mean gridded data are given by *Simonov and Altman* [1991] as time series for the period 1923–1985. Data for the more recent period 1986–1997, based on new observations, were kindly made available by V. Belokopitov. River discharge is estimated from observations for the Danube, Dniepr, Bug, Don, and Kuban Rivers [*Altman and Kumish*, 1986], and the contribution of the remaining rivers (small value) is calculated using empirical relationships. The same data for the net surface freshwater flux and river runoff have been used by *Stanev and Peneva* [2002], where they were referred to as the Black Sea Hydro-Meteorological (BSHM) data set.

## 3. Cause of the Multidecadal Trend in Sea Level

[11] In this section, we examine various potential sources of the multidecadal increase in the sea level of the Black Sea. First, we consider the variability in the temperature and salinity fields and examine whether these could have had a significant impact by calculating the corresponding steric height anomalies. We then examine the potential role played by changes in the net precipitation before finally considering the other factors described in the Introduction.

### 3.1. Temperature and Salinity Variations

[12] Time series of temperature and salinity determined from the MEDAR data set for the three Black Sea layers defined earlier are shown in Figure 3. The upper 30 m of
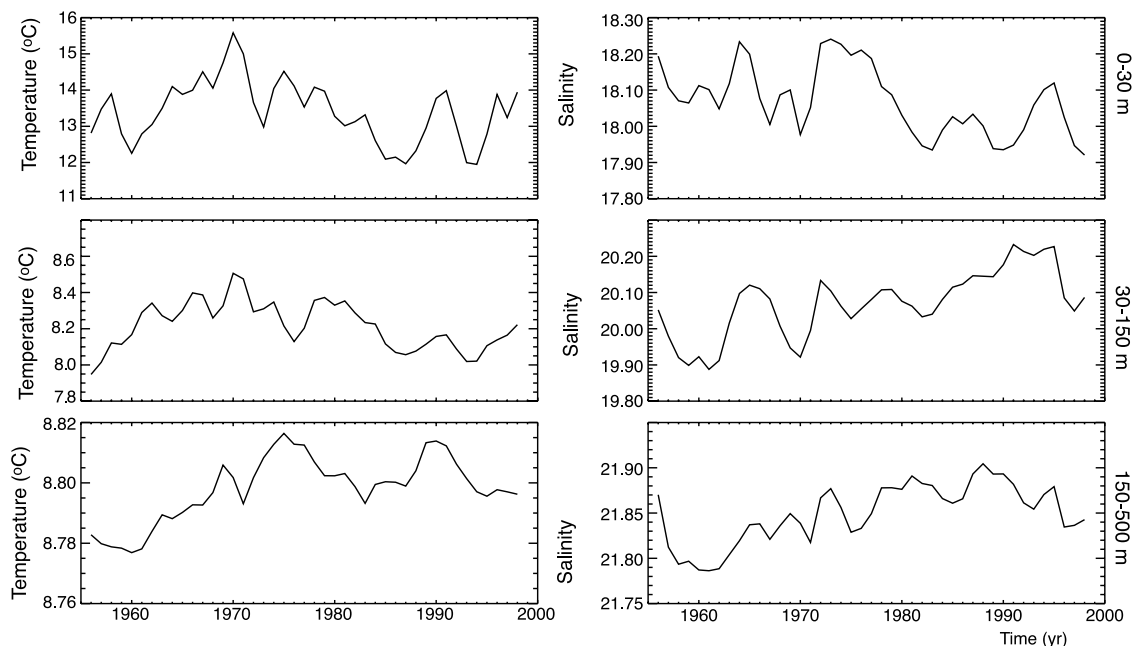
**Figure 3.** Temperature and salinity changes for the Black Sea. Note that there are temperature measurements available for the early part of the record in the upper 150 m but not for the deeper parts or for salinity. Thus the analysis is focused on the period 1955–1998.

water shows interannual variability of up to 2°C super-imposed on a longer-term increase between 1960 and 1970, which is followed by a steady decline to the mid-1990s. Note that the upper 5 m, not shown, has significantly stronger interannual variability of order 5°C. The variations in the intermediate layer show essentially the same features as the upper layer but are approximately a quarter in magnitude. In the deep layer, the temperature variations are much smaller, of the order of 0.02°C, but there is again some indication of an increase to 1970, although no decline after that time is apparent.

[13] The salinity time series show somewhat different behavior from the temperature data in that the upper and intermediate layer salinity trends are not strongly correlated. The upper layer has variations in salinity of about 0.4 psu with some freshening during the last 20 years of the measurements. In contrast, the intermediate layer shows an increase in salinity between the 1960s and 1990s of 0.1– 0.2 psu. The deep layer also shows a persistent increase in salinity between the 1960s and 1990s, albeit somewhat smaller in magnitude. The lack of agreement between the salinity trend in the upper layer and either the deep or intermediate layers suggests that the cause of the trend in the lower two layers cannot be surface forcing in the Black Sea. It must instead represent an advective process from the neighboring Aegean Sea; this possibility is explored further in section 4.

[14] In order for the long-term increase in sea level of the Black Sea to be explained by steric (both T and S) anomalies, either the temperature must increase or the salinity must decrease throughout the period under consideration. No such trends are observed in the time series shown in Figure 3, suggesting that the sea level change cannot be ascribed to a process of thermal or haline expansion. The trend in the upper water (0–30 m) salinity

between 1960 and 1998 is $-0.004 \pm 0.014$ psu/yr, thus not significant. To confirm that temperature and salinity changes are not responsible for the observed sea level changes, we have calculated the steric height anomaly for the whole water column and compared it with the change in sea level as measured by the tide gauge at Tuapse (Figures 4a and 4b). Note that the time series of salinity-related change in Figure 4a refers to the thickness of the upper layer and will be discussed in section 3.3.

[15] The tide gauge data show a linear trend of 2.2 mm/yr in the period 1960–2000. In comparison, the steric height trend is significant but negative for the subperiod 1960– 1998 with a value of $-0.9 \pm 0.2$ mm/yr, and thus it cannot account for the observed sea level increase. The contribution of the thermal (T) and the haline (S) terms individually can be explored by calculating the steric height changes with the other parameter (S and T, respectively) held constant to its 1956 value (Figure 5). In the upper layer the temperature variation determines most of the signal. In contrast, in the intermediate and deeper waters the salinity changes determine the steric sea level variability. Our finding that the sea level rise in Tuapse appears to be unconnected with the steric variation is in agreement with *Peneva et al.* [2001], who used a less extensive data set. Note that the rapid rise in steric height after 1993 coincides with the sea level rise reported by *Cazenave et al.* [2002], but most of the steric sea level rise appears to be related to salinity reduction rather than an increase in temperature. Moreover, this steric sea level increase partly represents a recovery from an earlier reduction in the late 1980s. Although the sea level record cannot be considered as long in respect to climatological scales, it is clear that the rapid increase in steric sea level observed during the last decade is not unprecedented but within the range of the previously observed variability. These results are in agreement with
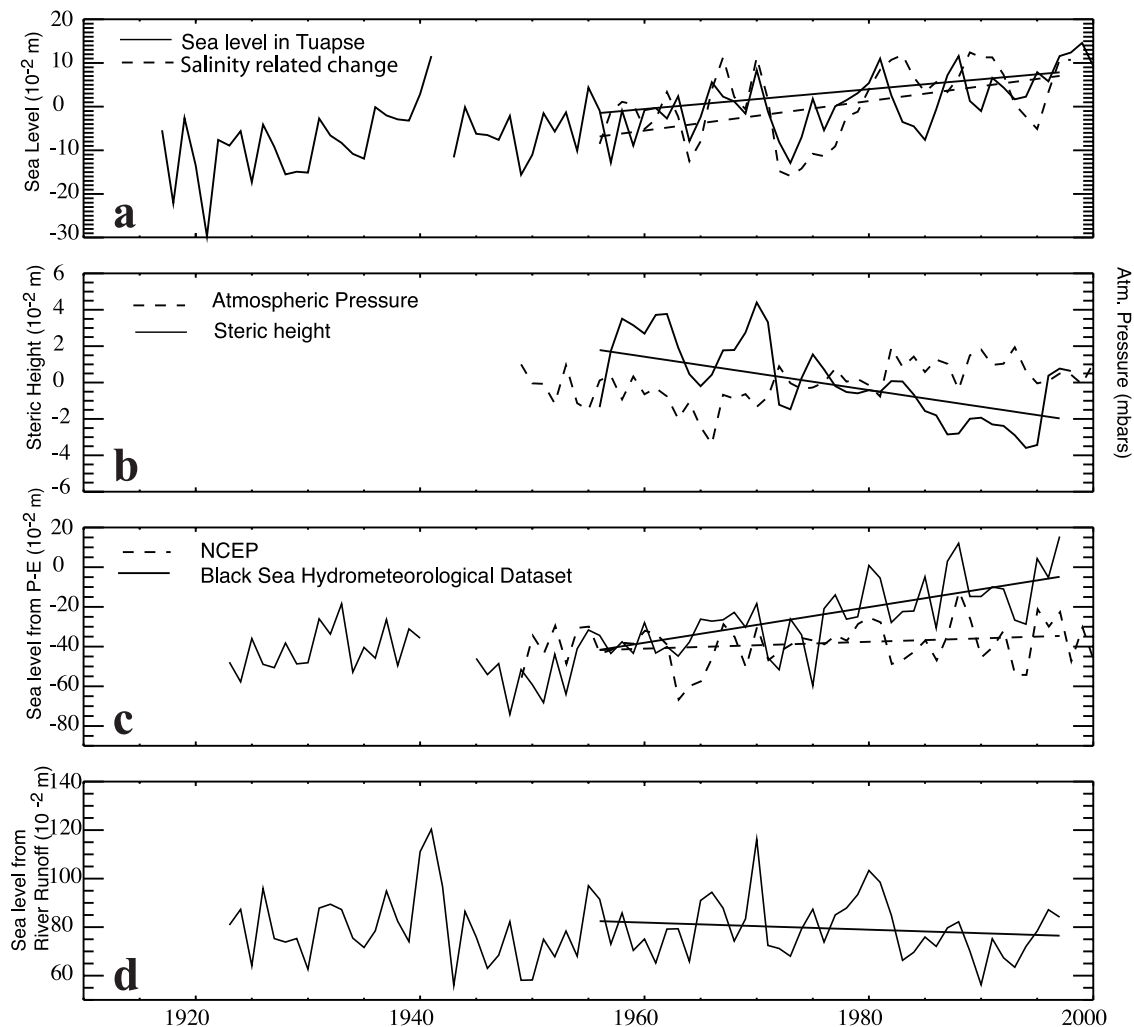
**Figure 4.** Variability of climatic parameters and sea level. (a) Tide gauge data from Tuaspe (solid line) and inverse salinity (dotted line). (b) Steric sea level calculated from MEDAR (solid line) and atmospheric pressure changes (dashed line). (c) P-E from the Black-Sea hydrometeorological data set (solid line) and from NCEP (dashed line). (d) River runoff. The inversed salinity time series shown in Figures 4a and 4c have been arbitrarily scaled.

results for the Mediterranean Sea [*Tsimplis and Rixen*, 2002]. Given the discrepancy between the steric height variability and the observed sea level trend, one or more of the other factors (P-E, runoff, atmospheric pressure, land movements) must be responsible for the increase in sea level. We explore the contributions from changes in the surface freshwater flux and river runoff in the next section.

### 3.2. Surface Freshwater Flux and River Runoff

[16] The components of freshwater balance reported by different authors show not only different long-term trends but also different mean values [*Schrum et al.*, 2001]. The latter has been documented also by *Stanev and Peneva* [2002] when comparing the mean values of the BSHM data set [*Altman and Kumish*, 1986; *Simonov and Altman*, 1991] with the mass balance estimates of *Ozsoy and Unluata* [1998]. It is also known that the sensitivity of ocean models to different freshwater balances is very high. The consequences of using inaccurate mean values of surface water balance are demonstrated in the paper of *Stanev et al.*

[1997], where it is found that the response of salinity stratification to different freshwater forcing is much more realistic if the mean values correspond to these of *Ozsoy and Unluata* [1998]. The salinity signals within the MEDAR database allow us to examine below in more detail the consistency between salt content and freshwater fluxes in the Black Sea and the inconsistencies that exist between the two different data sets at timescales from interannual to interdecadal. This presents an important development in comparison with the work of *Stanev and Peneva* [2002] where detrended data were analyzed and only interannual variability was addressed.

[17] Time series of the two P-E data sets and river runoff are presented in Figures 4c and 4d. The time series are divided by the surface area of the Black Sea to turn them into sea level changes directly comparable with the Tuapse data (Figure 4a). Note that at this stage we have not considered the effect of changes in the outflow to the Mediterranean Sea, which will be discussed later. River runoff (Figure 4d) shows noticeable interannual variability
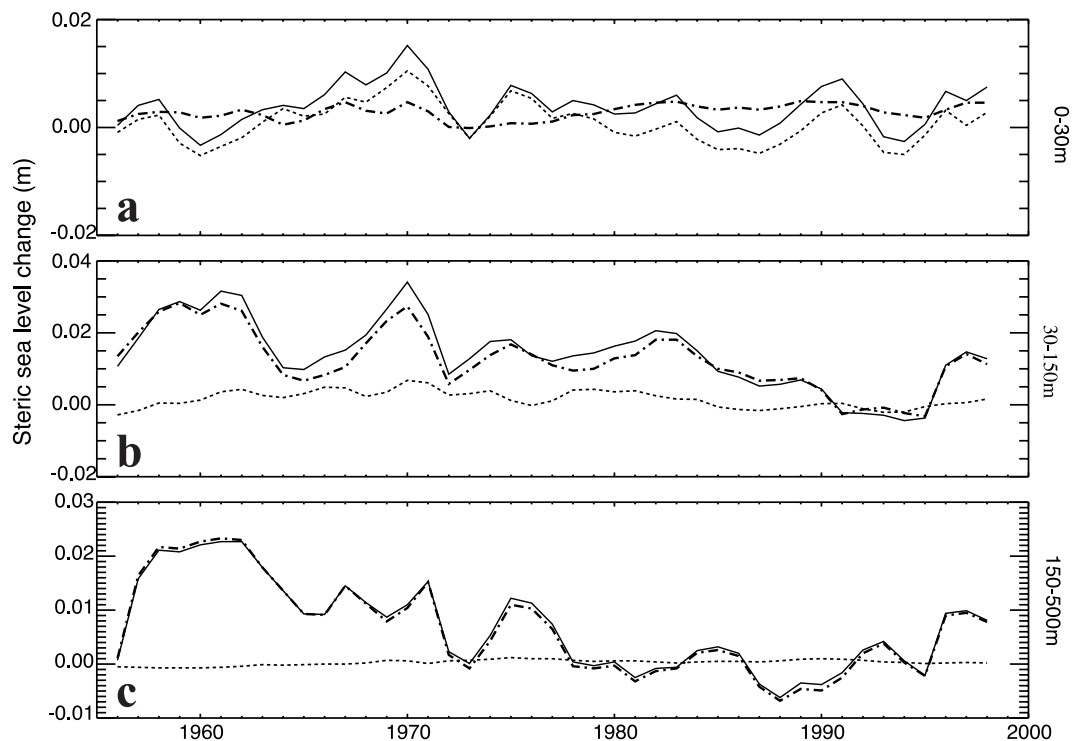
**Figure 5.** Steric variability at each layer (solid line). Contribution of the temperature (dotted line) and salinity (dash-dotted line) variation is estimated by repeating the calculation keeping the other variable (S and T, respectively) constant to its first valid measurement.

but no significant trend over the period considered and so cannot be responsible for the observed sea level change.

[18] The two P-E data sets have discrepancies mainly in the long-term trend but also in the decadal and interannual shape of the variation. The NCEP time series shows no evidence for a trend, while the BSHM data set shows a general increase in P-E, which is due to a reduction in E [*Stanev and Peneva*, 2002]. The same trend is identified also by *Ilyin et al.* [2002], who suggest that it is a consequence of global warming. The salinity of the upper 30 m is determined by P-E, river outflow, and mixing with more saline waters below. The P-E trend in the BSHM data set is consistent with the small reduction in near-surface salinity (Figure 3) and an increase in sea level (the magnitude of which is discussed below).

[19] We have estimated the impact of freshwater flux changes on the sea level in the Black Sea by using the salinity of the upper 30 m and the method recently advanced by *Munk* [2003]. The ratio of the global eustatic sea level change over the steric changes due to oceans freshening was found by *Munk* [2003] to be equal with the ratio of the seawater density over the density difference between seawater and freshwater. Thus $\delta h_{eustatic} = h_{steric}(\frac{\rho}{\rho - \rho_w})$, where $\rho$ is the seawater density, $\rho_w$ is the freshwater density, $h_{steric}$ is the steric sea level change due to the decrease in salinity, and $\delta h_{eustatic}$ is the change in sea level height due to the addition of freshwater, which caused the freshening. The temperature is assumed to be unaffected in the above estimation.

[20] The same calculation for the upper water of the Black Sea can be made if we assume that the exchange is steady and that the mixing with the lower saltier water does not increase when freshwater is added. The $h_{steric}$ is then the

salinity related variation of the upper layers (Figure 5c). The upper density in the Black Sea is about 1018 kg/m$^3$, and its ratio to the difference term (1018–1000 kg/m$^3$) gives a multiplication factor of 56.6. The resulting "eustatic" curve is shown in Figure 4a. It resembles well the sea level variability, especially when one considers that it is based on a basin average of salinity, while the sea level data are a point measurement from a tide gauge. Thus, provided the assumptions made are valid, eustatic changes appear consistent with increased freshwater fluxes within the Black Sea in agreement with the trend shown within the BSHM data set. The agreement of the eustatic changes with the tide gauge measured variability at decadal and interdecadal timescales (Figure 4a) is good. Moreover, the trend estimated for the period 1956–1998 from the tide gauge is 2.27 mm/yr while the trend from the eustatic plus steric change (the sum of the curves shown in Figure 4a and 4b) is 2.34 mm/yr, which is in good agreement. Nevertheless, we must stress that the upper water salinity trend was not statistically significant for the period under investigation. The salinity curve as well as the resulting eustatic change has a correlation coefficient of −0.54 with the BSHM P-E but is uncorrelated with the river outflow. Thus the salinity variations are consistent with changes in the P-E. Part of this correlation is due to the linear trends included in the time series. The correlation of the salinity curve with NCEP is −0.20, which is not significant at the 95% level.

### 3.3. Comparison of the Observed Changes in Forcing With the Sea Level Changes

[21] The differences between the two P-E data sets are a source of concern. In order to resolve the discrepancy, we

**Table 1.** Trends in the Parameters Examined Expressed as Sea Level Rates[a]

| Parameter | 1954–1997 Trend, mm yr$^{-1}$ | Mean Trend, mm yr$^{-1}$ | Correlation Coefficient |
|---|---|---|---|
| Tuapse sea level | 2.27 | 2.39 ± 0.28 | 0.48 |
| Steric height | −0.92 | −1.35 ± 0.27 | −0.53 |
| Eustatic height (Munk) | 3.38 | 3.14 ± 0.46 | 0.48 |
| P-E (BSHM) | 8.97 | 10 ± 0.84 | 0.68 |
| P-E (NCEP) | 1.73 | 2.7 ± 0.96 | 0.21 |
| River outflow | −1.46 | −2.27 ± 1.3 | −0.16 |

[a]In order to assess the dependence of the trends on the starting point, we calculated the trend for a starting point between 1956 and 1969. The end point was always 1997. The mean trend and the standard deviation of these trends are given in the second column.

first examine the trends in the time series for the common period 1954–1997 (Table 1). Because of the large interdecadal variability in some of the records, we run a test on the validity of the trends by moving the starting point from 1954 to 1969 successively and keeping the end point the same. From these 15 estimates of the trend, we use the average and its standard deviation as indicators of the stability of the trend (second column in Table 1). On the basis of these trends, one can try and understand the variability of sea level as follows: The eustatic trend expresses the addition of freshwater in the upper layer. When the steric height is added, this gives the resulting sea level change within the basin. This addition gives a trend for the full period 1954–1997 of 2.46 mm yr$^{-1}$, which is consistent with the Tuapse sea level changes. The corresponding values for the mean trend obtained by varying the starting point is 1.79 ± 0.73 mm yr$^{-1}$. These values represent the amount of water retained in the basin and its volume and when they are combined with the climatology of the freshwater balance, should give an estimate of the additional water in the basin that is not retained but outflows to the Aegean Sea. Thus the combination of the trend in the BSHM P-E (8.94 mm yr$^{-1}$) with the river outflow reduction (−1.35 mm yr$^{-1}$) gives a total addition of water of 7.62 mm yr$^{-1}$ of which 2.46 mm yr$^{-1}$ is retained in the basin and the difference of 5.16 mm yr$^{-1}$ has to outflow. This would cause an increased outflow of 0.075 10$^{-3}$ Sv. The climatological mean outflow as calculated from the mean BSHM P-E (−187 ± 173 mm) and river outflow (793 ± 125 mm) is 606 mm of water per year outflowing or 8.8 10$^{-3}$ Sv. Thus such a trend causes differences of about 0.9% in the outflow.

[22] The combination of the NCEP P-E trend (1.73 mm yr$^{-1}$) with the river outflow trend (−1.46 mm yr$^{-1}$) produces a trend of 0.27 mm yr$^{-1}$, which, when combined with the eustatic plus steric trend (2.46 mm yr$^{-1}$), suggests a net change of −2.19 mm yr$^{-1}$ or −0.38 10$^{-4}$ Sv that is a net decrease in the outflow that corresponds to a change of about −0.5% of the mean. Thus, on the basis of the trends, in spite of the significant differences in the two climatologies the resulting changes in the mean outflow are small. Nevertheless, the NCEP P-E values require a reduction of the Black Sea outflow in order to increase the amount of freshwater retained within the basin and thus justify the increase in sea level. However, it is difficult to see how this can happen if the Mediterranean Sea level has not been increasing faster than the Black Sea, and, although there are

no reliable long-term tide gauge records in the North Aegean, the published studies [*Tsimplis and Baker*, 2000; *Tsimplis and Josey*, 2001] suggest that the Mediterranean Sea sea level has been reducing. In the Northern Aegean, the tide gauge in Alexandroupolis, which is closest to the straits, gives a trend of about 0.3 mm yr$^{-1}$ between 1969 and 1997 (1.35 mm yr$^{-1}$ between 1969 and 2002), which is considerably smaller than the Black Sea value. Thus it appears that the BSHM trend is to be preferred over NCEP on the basis of known changes in the level of the Northern Aegean and sets an upper limit to the changes in the Black Sea outflow.

[23] So far, we have discussed the trends in the parameters used. Nevertheless, the trend is not the major feature of the observed signals, and it is the interannual variability that characterizes all the time series in Figure 4. Thus, in order to confirm the results from the comparison of the trends, we must examine the relationship between the various climatologies and the sea level record at the interannual and decadal scale. This is done by running a linear multiple regression model with sea level as the independent parameter for the period 1954–1997. Such a model of sea level in Tuapse with the BSHM E-P and the river outflow "explains" 55% of the variance. The residual time series have a linear trend of only 0.8 mm yr$^{-1}$. Thus a large part of the observed linear trend in sea level can be explained by the statistical model. Correcting for steric variation increases the variance explained by only about 1%. Using the NCEP E-P and the river outflow as independent variables, 35% of the variance is explained, while the residual signal has a trend of 2.3 mm yr$^{-1}$; that is, the NCEP fields cannot account for the trend.

[24] By estimating a linear trend as an independent parameter, the BSHM and NCEP models improve the percentage of the variance explained to 68% and 60%, respectively. The trends calculated are then 1.9 mm yr$^{-1}$ for the BSHM and 2.5 mm yr$^{-1}$ for the NCEP climatology, respectively. Nevertheless, the regression coefficients of the E-P and the river outflows are reduced.

[25] Thus the NCEP climatology appears unable to explain the trend in the sea level signal and requires an additional trend of 2.3–2.5 mm yr$^{-1}$. In contrast, the BSHM data set can explain a significant amount of the variability in sea level and requires only a smaller trend of about 0.8 mm yr$^{-1}$ to explain the observed variability. The regression coefficients for the P-E and the rivers are 0.21 and 0.19, respectively thus indicating that approximately 20% of the freshwater changes around the mean contribute to sea level rise while 80% outflows in the Aegean Sea. In contrast, when a linear trend is included in the BSHM model from the beginning, the regression coefficient of the P-E is reduced to 0.08 while that of the river outflow is increased to 0.27. Thus the resulting statistical model appears inconsistent, as there is no apparent mechanism by which the sea level variability can distinguish between the two sources of freshwater. Thus we consider the determination of the linear trend from the residuals of the regression as more closely resembling the physical processes.

### 3.4. Atmospheric Pressure Variability

[26] In the Black Sea, atmospheric pressure changes do not have a significant influence on the sea level, as the
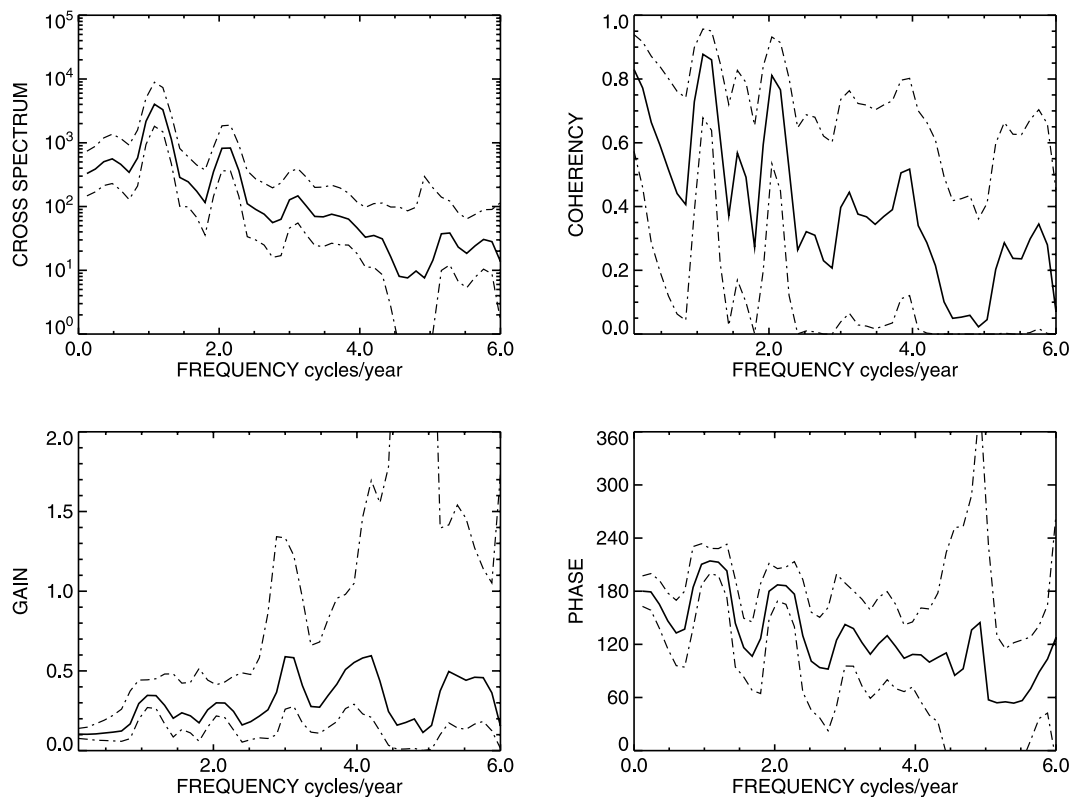
**Figure 6.** Results of cross-spectrum analysis between mean monthly values of sea level and atmospheric pressure in Tuapse (solid line). Confidence levels of 95% are also shown (dash-dotted lines).

exchange through the Dardanelles and the Bosphorous restricts the response of sea level to traveling systems [*Garrett*, 1983; *Ducet et al.*, 1999]. *Garrett* [1983] and *Candela* [1991] have suggested different mechanisms to demonstrate how straits constrain the exchange of water between a semi-enclosed basin and the open ocean, causing departures from the inverse barometer response. *Ducet et al.* [1999] applied Candela's model to the Black Sea and found, as expected, that the role of the atmospheric pressure in forcing the Black Sea level is severely under-isostatic. They identified pressure as the most influential forcing for periods at 50–70 days. Nevertheless, their analysis was only valid for periods shorter than 140 days, due to the length of their data set. Thus a question remains as to whether at annual and semiannual frequencies the response of the Black Sea is or is not isostatic.

[27] *Lascaratos and Gacic* [1990] derived from *Garrett* [1983] a timescale $T = \frac{Af}{gH}$ defining the upper limit above which the geostrophic control does not restrict the flow. In this formula, $A$ is the area of the semi-enclosed basin, $f$ is the Coriolis parameter, $g$ is the acceleration due to gravity, and $H$ is the depth of sill at the strait. Using the values suggested by *Ducet et al.* [1999] for the Bosphorous Strait, i.e., $A = 4.2 \ 10^{11} \ \text{m}^2$, $H = 35 \ \text{m}$, $f = 10^{-4} \ \text{s}^{-1}$, and g = 10 m s$^{-2}$, one can calculate that for signals with periods longer than 33 days the strait does not geostrophically control the exchange. In Figure 6 the results of cross-spectrum analysis for mean monthly values of sea level and atmospheric pressure for Tuapse for the period between 1955 and 1971 are shown. The period of analysis

was determined by the availability of station atmospheric pressure data. The cross spectrum has peaks at the annual and the semi-annual signal where the coherency is above 0.8 and the gain is about 0.3. Thus, although the response is generally under-isostatic (less than 0.6 for all frequencies), there is statistically significant coherency at least at the annual cycle with phase differences of about 180° for the semi-annual cycle and slightly more for the annual cycle. Thus, although the sea level response to atmospheric pressure of the Black Sea is of secondary importance, it nevertheless has a signature on the sea level record. This result qualifies earlier studies with shorter time span [*Ducet et al.*, 1999]. Moreover, it supports the finding of *Peneva et al.* [2001] that the Bosphorous Strait is characterized by a very high resistance for high-frequency signals (including atmospheric pressure or short-time pulses in river runoff), while for interannual signals the resistance and, correspondingly, the retention of water in the Black Sea are relatively small.

[28] The atmospheric pressure signal ranges by ±2 mbar over the period 1950–2000 (Figure 4b), and therefore the effects on sea level are expected to be about ±0.6 cm (as the response of sea level to the pressure signal, from the cross-correlation analysis, is of order 20–30%). Thus atmospheric pressure effects are minor and can be ignored. Nevertheless, it is worth mentioning that the atmospheric pressure increased between 1960 and the early 1990s, which is consistent with the reduction in the water temperature (Figure 3) and with the NAO-related atmospheric pressure increase during the same period over the Mediterranean Sea [*Tsimplis and Josey*, 2001]. Moreover *Tsimplis and Rixen*

[2002] discuss similar decadal variability with temperature reduction in the upper waters of the Mediterranean between 1960s and the mid-1990s. Thus it appears that the behavior of the Black Sea as far as upper water temperature and atmospheric pressure is concerned is consistent with that of the Mediterranean.

[29] We have also explored the gradient of atmospheric pressure between the Eastern Mediterranean and the Black Sea on the basis of NCEP data. The interannual variability of the two signals (not shown) is similar to differences of less than 2 mbar. Only in the period 1962–1967, the differences are up to 4 mbar. There is no trend in the differences; thus the possibility that the sea level increase within the Black Sea is due to an increase of pressure at the entrance of the Straits due to changes in the atmospheric gradients can be excluded.

### 3.5. Sea Level Dependence on Other Processes

[30] We have considered changes in the E-P, river runoff, atmospheric pressure, and steric effects. The BSHM trends in the different parameters examined can be used to produce a consistent scenario where the increased freshwater is partly retained in the basin and partly exported. Moreover, the multiple regression models indicate that most of the observed trend is due to changes in the freshwater balance, and a residual trend of 0.8 mm yr$^{-1}$ remains unexplained. In contrast, the NCEP P-E cannot explain any of the observed trend, and 2.5 mm/yr remains to be explained. We now consider the other remaining processes that could be responsible for these residual trends.

[31] Owing to lack of observations, we have not been able to examine in detail the potential contribution to the sea level rise from changes in the strength of the basin circulation or the exchange with the Mediterranean. Nevertheless, we note that sea level variability from various Black Sea tide gauges are highly coherent and that these data are consistent with the basin mean sea level from TOPEX/Poseidon data [Stanev et al., 2000; Peneva et al., 2001]. Thus changes in the circulation are not likely to be responsible for the observed variability.

[32] The global isostatic rebound value for Tuapse is 0.13 mm/yr [Douglas et al., 2001], which is an order of magnitude smaller than the observed trend. Hence isostatic effects can also be ruled out as a major driver of the sea level increase. The only remaining factor to be considered is land subsidence. Reported values for changes in the land height lie in the range 0–2 mm/yr [see Reva, 1997, and references therein]. The upper limit for changes in the land level is thus consistent with the value required to explain the residual trend in sea level in the NCEP model noted above. Further analysis of the magnitude and cause of the land subsidence is beyond the scope of the present paper. Thus we restrict ourselves to noting that it is possible that the small contributions we have obtained from detailed analysis of the NCEP data set are consistent with land subsidence. Further evaluation of this possibility will require detailed analysis by others of land-based measurements.

[33] Although land subsidence provides a possible explanation for the sea level trend, if the small NCEP P-E trend is correct, we feel this is unlikely to be the case for the following reason. The recent sea level trend, in the period 1992–2002, is also observed in altimetric data, which are not in principle affected by coastal subsidence. The small residual trend values (0.8 mm yr$^{-1}$, which is reduced further if the isostatic adjustment is taken into account) coming out of the BSHM database are consistent with the altimetric observations, and they imply small coastal subsidence less than 0.65 mm yr$^{-1}$.

## 4. Interaction of the Black Sea With the Aegean Sea

### 4.1. Cause of Salinity Changes in the Black Sea

[34] Time series of the temperature and salinity in the upper and intermediate layers of the Black Sea and the Aegean Sea have been investigated. Three layers have been defined for the Aegean Sea as follows: upper (0–200 m), intermediate (200–400 m), and deep waters (more than 400 m). The Aegean Sea data also come from MEDAR, but the Gaussian filter used in processing them was 3 years long and consequently has less high-frequency variability.

[35] The salinity and temperature variability of the upper waters in the Aegean Sea and the upper (T) and intermediate (S) waters of the Black Sea are shown in Figure 7. For both temperature and salinity the low-frequency part of the signal after 1960 in each basin shows similar behavior. The temperature of the upper waters falls by about 2°C in the period after 1970. For salinity, the increase in the intermediate waters of the Black Sea is of the same order of magnitude and very similar to the salinity changes in the Aegean Sea. Given that no upper water salinity trend was found in the Black Sea data (Figure 3), we infer that the salinity increase in the Black Sea intermediate water between 1960 and the early 1990s must have been due to the increased salinity of the Mediterranean inflow. As regards the lower layer, we have also investigated relationships between the T and S characteristics of the deep water of the Black Sea and the Aegean Sea (not shown), but have found no significant connection.

### 4.2. Black Sea Outflow

[36] As noted earlier, a portion of the increased freshwater flux into the Black Sea is retained within the basin and increases the sea level, while the balance is exported to the Aegean Sea. Thus, by using the available data sets for sea level, P-E, and river inflow, we can determine the volume flux of water between the Black and Aegean Seas. We have carried out this calculation using both the BSHM and NCEP P-E data sets; the resulting net outflow in each case is shown in Figure 8. The volume flux time series obtained from the BSHM data set show an outflow which is increasing with time (see Table 1). In contrast, the time series obtained from the NCEP data sets shows an almost constant net outflow. Nevertheless, the interannual and decadal signal is much larger than the trend in the time series. Both estimates of the outflow have local minima around the 1990s, the period when the Eastern Mediterranean Transient appeared.

### 4.3. Relationship to the North Atlantic Oscillation

[37] Correlation coefficients between the NAO and T and S for the Black and Aegean Sea layers described previously are shown in Table 2. We have used an NAO index,
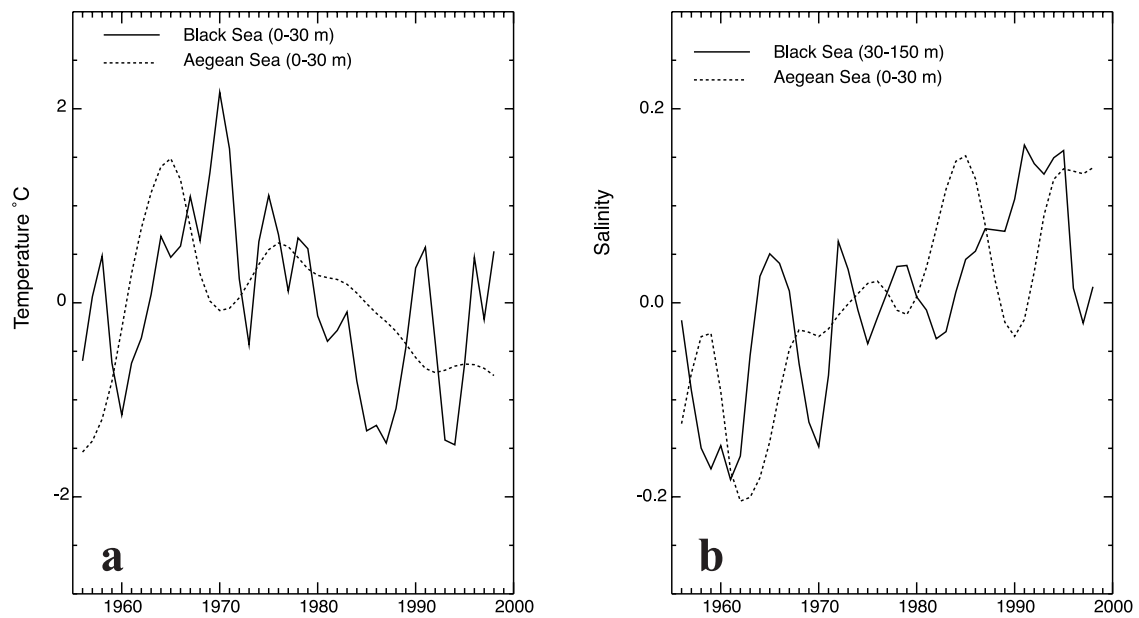
**Figure 7.** (a) Variability of upper water temperature around the mean in the Black Sea and the Aegean Sea. (b) Variability of upper water salinity in the Aegean with the intermediate water salinity in the Black Sea.
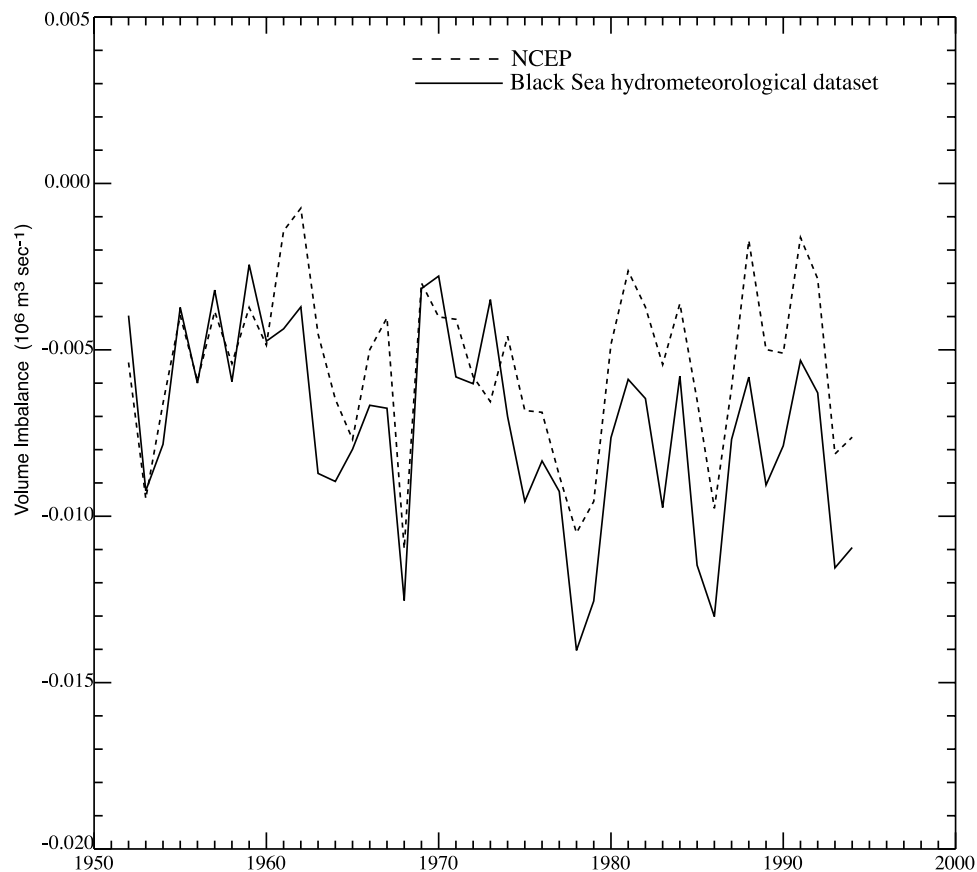


**Figure 8.** Net outflow into the Aegean Sea calculated from the rate of change of sea level and the contribution of E-P, and river runoff from the Black-Sea hydrometeorological data set (solid line) and NCEP (dashed line).

**Table 2.** Correlation Coefficients Between a 5-Year Averaged Winter NAO Index and the Time Series of Temperature T (Boldface) and Salinity S

|  | Correlation Coefficient |
|---|---|
| *Aegean* | |
| 0–200 m | **−0.79**/0.54 |
| 200–400 m | **−0.79**/0.59 |
| 400–2000 m | **0.13**/0.42 |
| | |
| *Black Sea* | |
| 0–30 m | **−0.57**/−0.42 |
| 30–150 m | **−0.29**/0.50 |
| 150–500 m | **0.39**/0.42 |

calculated for December–March of each year, which is defined to be the normalized difference in pressure between Reykjavik (Iceland) and Ponte Delgado (Azores) [*Hurrell*, 1995]. The NAO time series have been smoothed by a 5-yr moving average filter in accordance with *Hurrell* [1995]. A conservative estimate of 10 degrees of freedom is obtained by dividing the 50 years of data by the longest filter length of 5 years. With this estimate, values for the correlation coefficient above 0.71/0.58 are statistically significant at the 99/95% levels. The strongest correlations with the NAO are found for the temperature of the upper and intermediate layers in the Aegean for which $r = -0.79$ in each case. In contrast, the deep layer T is not significantly correlated with the NAO. The correlation coefficients for salinity are somewhat weaker in the top two layers, although the intermediate layer is still significantly correlated ($r = 0.59$) with the NAO at the 95% level. By comparison, the relationship between the Black Sea T and S characteristics and the NAO are not as strong as for the Aegean Sea. The highest value is for the upper layer temperature, $r = -0.57$, which falls just below the 95% significance level and is thus probably indicative of a physical connection, particularly given the conservative estimate of the number of degrees of freedom. Colder and drier winters associated with higher atmospheric pressure are the likely cause of the correlation.

[38] We have also examined possible relationships between the NAO and sea level in each basin. The sea level in the Black Sea was significantly correlated with the winter NAO only in spring, in which case the correlation coefficient was $r = 0.45$. *Stanev and Peneva* [2002] have shown that river outflow is an important component of seasonal variations in the Black Sea level variability where the seasonal cycle peaks in spring [*Tsimplis and Woodworth*, 1994]. The NAO is known to affect precipitation over a broad European region [*Hurrell*, 1995], and as the catchment area of the Black Sea rivers is of significant extent within Europe, it is likely that the NAO significantly affects the river input to the basin. This contrasts with the results of the analysis for the Aegean Sea where significant anticorrelation (−0.55) of the winter sea level with the NAO was found.

## 5. Conclusions and Discussion

[39] In this paper we have investigated forcing mechanisms for sea level variability in the Black Sea in the context of an observed increase in the sea level of this basin by 2.5 mm/yr over the last 80 years. Using the MEDAR data set, we have examined the variability in temperature and salinity in the basin and found a significant degree of interdecadal variability. The corresponding steric height variability has also been determined, and although it also shows strong interdecadal variability, there is no evidence for a long-term increase in this term, and thus it cannot account for the observed change in sea level.

[40] The impact of changes in the surface freshwater flux (P-E) has been investigated using two independent data sets. The two data sets are not in agreement with each other. By examining the trends of the BSHM data set as well as statistical models of the interannual sea level variability, we have concluded that with the exception of a residual trend of 0.65 mm yr$^{-1}$ we can explain the sea level trend as a result of increased P-E, which dilutes the upper water and obscures a small reduction in the steric sea level due to increases of salinity in the intermediate waters. The residual 0.65 mm yr$^{-1}$ may be due to local land movements but could also just reflect uncertainties within the data sets. Potential contributions from changes in river runoff and surface pressure have also been quantified but these were found to be minor terms. A simple calculation of sea level rise due to freshening of the upper water [*Munk*, 2003] appears to be capable of describing the observed sea level variability and trend well.

[41] In contrast, the use of the NCEP climatology requires a rate of subsidence in excess of 2 mm yr$^{-1}$. This must be considered as the upper limit of the subsidence value. Such a large value is unlikely given that the recent sea level increase is also seen in altimetric data that is not affected by coastal subsidence. A more likely scenario is that the relatively coarse resolution model used for the NCEP reanalysis has not been able to adequately represent the processes responsible for the P-E increase in the Black Sea region. Both our lowest and upper estimates are consistent with independent estimates of the change in land level that are based on direct observations [*Reva*, 1997, and references therein]. Further work is, however, required to confirm our suggestion that land movements contribute only a small fraction to the relative sea level rise in the Black Sea.

[42] The change in the freshwater balance in the Black Sea results in a small increase of the outflow with the BSHM P-E or the outflow remains constant (with NCEP) in the long term in spite of a small negative trend in the river runoff after 1956. Thus the calculations of *Tsimplis and Josey* [2001] in respect to the effects of the river runoff reduction on the Black Sea outflow need to be revised, as they did not include the P-E contribution, which appears to be significantly different than that of the Mediterranean Sea because of the reduction in evaporation [*Stanev and Peneva*, 2002].

[43] Our study has also enabled us to put into context analyses of recent altimetric observations of sea level and sea surface temperature that have led to claims of unprecedented rapid sea level rise due to warming during the last decade [*Cabanes et al.*, 2001; *Cazenave et al.*, 2002]. It appears that although the temperature has been rising in the upper and intermediate waters of the Black Sea and the Aegean, it has not yet reached levels not experienced earlier this century. Moreover, the resulting steric heights are less than the observed sea level rise in the Black Sea and are

dominated by a reduction in salinity rather than an increase in temperature. Although the steric contribution to recent sea level rise is important, the use of steric sea level cannot explain the upward trend and variability of the level of the Black Sea since 1960. Thus the conclusion by *Cabanes et al.* [2001] that temperature is the dominant forcing parameter of sea level in the open ocean appears not to be true for the Black Sea.

[44] The relationship of Black Sea temperature and salinity variability with corresponding variability in the neighboring Aegean Sea has also been explored. A significant correlation has been found between the salinity of the upper waters of the Aegean Sea and the layer between 50 and 150 m in the Black Sea, indicating that the latter layer is a product of the Mediterranean inflow. Thus the steric sea level changes of the Black Sea are caused not only by changes in the upper water characteristics but also by the salinity of the water inflowing from the Mediterranean.

[45] We have also investigated whether the temperature and salinity of the Black and Aegean Sea are influenced by the North Atlantic Oscillation, extending previous work by *Tsimplis and Josey* [2001] and *Tsimplis and Rixen* [2002] for the broader Mediterranean basin. A strong correlation was found between the temperature of the Aegean Sea and the NAO, while for the Black Sea the level of correlation was somewhat weaker, suggesting that it lies at the border of the region directly influenced by the NAO.

[46] It is well known that historical oceanographic data sets are not as comprehensive as corresponding meteorological ones in the region of our study. Nevertheless, we have demonstrated the insights that can be gained by analysis of the MEDAR data set, which was formed by collecting many nonsystematic surveys. We anticipate that subsequent analyses of the data set, together with land-based measurements, particularly river runoff, will provide enhanced understanding of the oceanography and climate of not only the Black Sea but also the broader Mediterranean basin.

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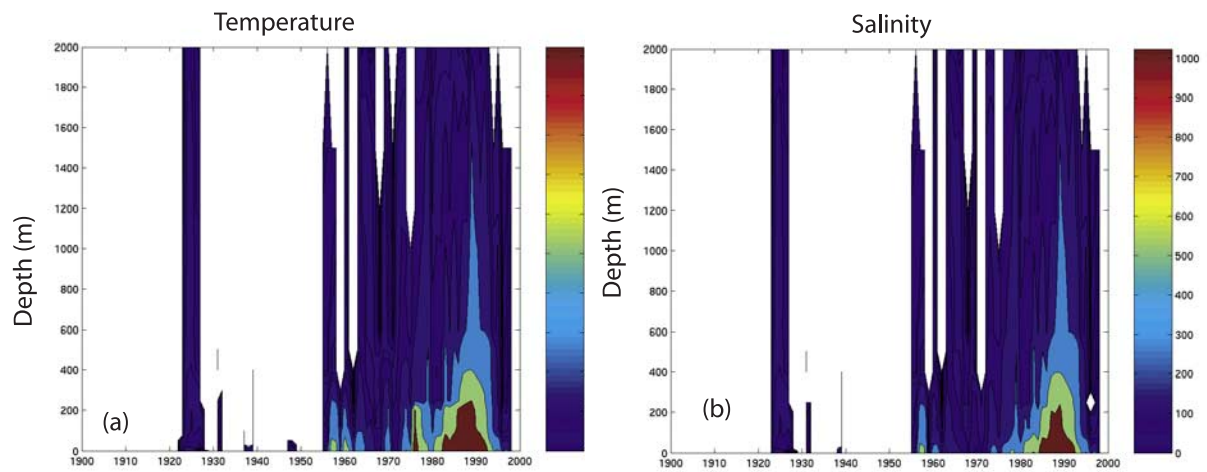E. V. Stanev, ICBM, University of Oldenburg, Postfach 2503, D-26111, Oldenburg, Germany. (e.stanev@icbm.de)

**Figure 2.** Yearly/depth coverage (in number of profiles) of the Black Sea in the MEDAR data set. The 25 standard levels used for the construction of the climatology are at 2000, 1500, 1200, 1000, 800, 600, 500, 400, 300, 250, 200, 150, 125, 100, 75, 50, 30, 20,10, 5, and 0 meters.