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Key Points:
- Black Sea elevation responds to intraseasonal Mediterranean sea level and lags behind it
- Amplitude and phase of Black Sea response are mainly defined by friction and geometry of Bosphorus
- Atmospheric forcing and freshwater fluxes may alter Black Sea response amplitude but not phase

Supporting Information:
- Supporting Information S1
- Figure S1
- Figure S2
- Figure S3
- Figure S4

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Dynamic response of the Black Sea elevation to intraseasonal fluctuations of the Mediterranean sea level

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Abstract Response of the Black Sea elevation to intraseasonal sea level changes in the Mediterranean is studied using satellite altimetry data and a linear analytical model. Satellite observations show that the nonseasonal sea level in the Black Sea (η_1) is coherent with that in the Aegean and Marmara Seas (η_0) but lags behind them by 10–40 days at subannual periods. The observed time lag is mainly due to friction that constrains the exchange through the Bosphorus Strait. Using realistic friction and characteristic η_0 forcing in the model, we find that the amplitude of η_1 reaches the amplitude of η_0 at about 1 year period, and the time lag increases from 10 to 22 days at periods 50–250 days. Freshwater fluxes, atmospheric pressure, and to a smaller extent the along-strait wind also influence the Black Sea elevation, but sea level fluctuations in the Mediterranean appear to be the dominant forcing mechanism.

1. Introduction

Regional sea level variability reflects both the global mean sea level change and thermodynamical processes of local and remote origin. The global mean sea level rise makes coastal communities and ecosystems particularly vulnerable to local sea level fluctuations. The almost fully enclosed Mediterranean and Black Seas communicate with the Atlantic Ocean through the Strait of Gibraltar and between each other through the Turkish Straits, composed of the shallow and narrow Straits of Bosphorus and Dardanelles, and the Sea of Marmara (Figure 1a). The exchange of water and properties occurring in straits exerts far-reaching influence over the surrounding water areas and plays an important role in the sea level budget of interconnected basins [e.g., *Garrett*, 1983; *Candela et al.*, 1989; *Özsoy et al.*, 1998; *Johns and Sofianos*, 2012].

The Black Sea features the largest drainage basin in Europe, hosting some major European rivers (Danube, Dnepr, and Don). The almost twofold excess of precipitation (~300 $km^3 yr^{-1}$) and river discharge (~350 $km^3 yr^{-1}$) over evaporation (~350 $km^3 yr^{-1}$) in the Black Sea is balanced by the net outflow (~300 $km^3 yr^{-1}$) through the Bosphorus Strait [*Ünlüata et al.*, 1990]. It is widely acknowledged that the Black Sea level budget on the seasonal and interannual timescales is dominated by freshwater fluxes [e.g., *Stanev et al.*, 2000; *Peneva et al.*, 2001]. On the intraseasonal timescales, however, the along-strait wind affects the outflow and, ultimately, the Black Sea level [*Ducet et al.*, 1999]. Strong winds are able to significantly reduce or even reverse the net volume flux through the Turkish Straits [*Jarosz et al.*, 2011, 2012].

One of the forcing mechanisms, not yet discussed in the literature, is the sea level on the Mediterranean side of the straits. Based on monthly records, *Volkov and Landerer* [2015] (henceforth *VL*15) revealed that the nonseasonal (seasonal cycle subtracted) sea level fluctuations in the Aegean and Black Seas are significantly correlated, with the Black Sea lagging behind the Aegean Sea by approximately 1 month. This time lag suggests that the Black Sea responds to sea level in the Aegean Sea and, hence, in the entire Mediterranean, because satellite observations and ocean models have shown that the nonseasonal fluctuations of the Mediterranean sea level are nearly basin uniform and driven by the net mass exchange through the Strait of Gibraltar [*Landerer and Volkov*, 2013; *Fukumori et al.*, 2007]. On the timescales considered, water is forced in or out of the Mediterranean by wind over the strait and just west of it until the wind stress is balanced by the along-strait pressure gradient.

It has been reported that the North Atlantic Oscillation (NAO) influences the Mediterranean sea level, which responds to the NAO-related interannual variations of the atmospheric pressure loading, local wind field

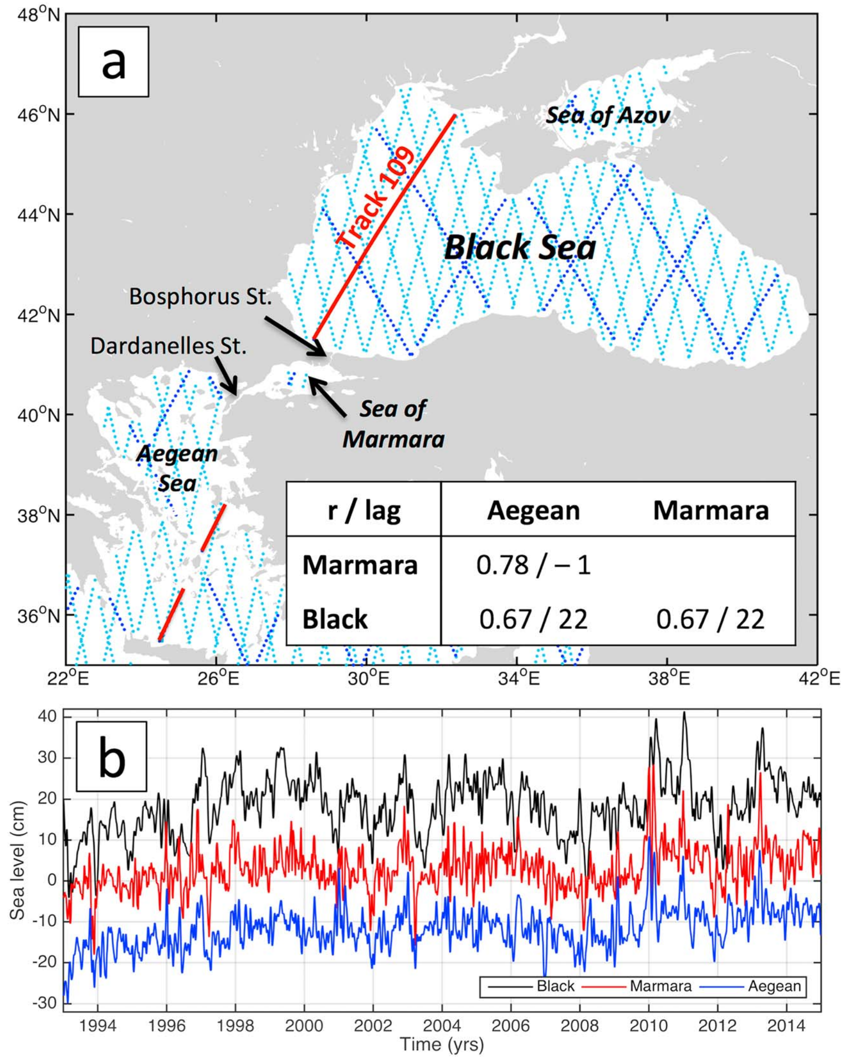

Figure 1. (a) Map of the study region with tracks of altimeter satellites: Topex/Poseidon, Jason-1, OSTM/Jason-2 (red and blue); ERS-1/2, Envisat, and Saral (light blue). (b) Time series of satellite altimetry nonseasonal sea level averaged over the Aegean (blue), Marmara (red), and Black (black) Seas. Curves are offset for clarity. The correlation coefficients and time lags between the time series averaged over the respective basins are shown in Figure 1a.

changes, and precipitation and evaporation over the basin [*Tsimplis and Josey*, 2001; *Calafat et al.*, 2012; *Tsimplis et al.*, 2005]. The higher-frequency month-to-month changes of wind stress near the Strait of Gibraltar and the resulting Mediterranean sea level are also related to the NAO: the low/high NAO periods are associated with westerly/easterly wind anomalies over the Strait of Gibraltar [*Landerer and Volkov*, 2013]. At the same time, a local maximum in northerly/southerly wind anomalies takes place over the Aegean Sea (*VL*15). These latter winds, being part of the large-scale NAO pattern, can amplify the local sea level changes and impact the Black Sea outflow.

The objective of this study is to investigate how intraseasonal sea level changes over the Aegean Sea, and consequently over the entire Mediterranean, affect sea level over the Black Sea. In particular, we aim to understand what determines the time lag between the Aegean and Black Seas, reported in *VL*15. In addition, we analyze how intraseasonal fluctuations in sea level pressure over the Black Sea, wind over the Turkish Straits, and the net freshwater flux into the Black Sea alter the response of the Black Sea elevation to the external (Mediterranean) sea level forcing.

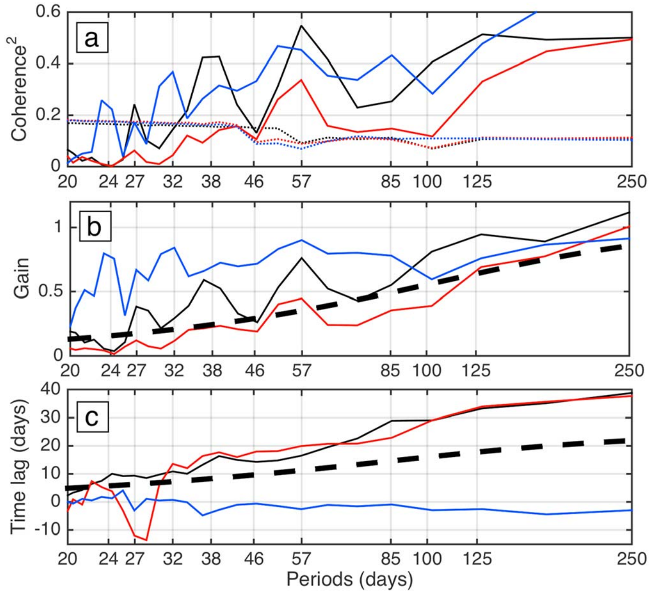

Figure 2. (a) Magnitude-squared coherence, (b) gain, and (c) phase (time lag in days) between the pairs of detrended sea level: averaged in the Aegean and Marmara Seas (blue curves), in the Aegean and Black Seas (black curves), and in the Marmara and Black Seas (red curves). The dotted curves in Figure 2a show the 95% significance level for each pair of the time series. The dashed black curves shown in Figures 2b and 2c are the following: the analytically derived response amplitude of the Black Sea elevation to normalized sea level forcing in the Aegean/Marmara Sea (Figure 2b) and the corresponding time lags (Figure 2c). The 95% confidence intervals for gain and phase are shown in Figure S3.

2. Sea Level Observations

We use regional daily maps of sea level anomalies (SLA) for the Black and Mediterranean Seas spanning the period from 1 January 1993 to 27 December 2014 (8031 days), produced by Ssalto/Duacs and distributed by Aviso (www.aviso.oceanobs.com). Each SLA map is based on measurements by up to four satellites, using all missions available at a given time (satellite tracks are shown in Figure 1a). The repeat cycle is about 10 days for Topex/Poseidon and Jason missions, and 35 days for ERS-1/2, Envisat, and Saral missions. The minimum resolved period is thus about 20 days. The mapped SLA compares reasonably well with tide gauge records in the Mediterranean [*Marcos et al.*, 2015], Marmara (see Texts S1–S4 and Figure S1 in the supporting information), and Black (*VL*15) Seas. We expect that using multisatellite data with a better spatial and temporal coverage will provide more robust estimates at high frequencies, but to demonstrate that our results are robust we also use SLA records along the track 109 (Figure 1a) that crosses the southern Aegean and western Black Seas.

The seasonal cycle was calculated by a least squares fit of the sum of two sinusoids with the annual and semiannual frequencies and subtracted from the SLA records (Texts S1–S4, Figures S1–S4, and Table S2 in the supporting information). Displayed in Figure 1b are the nonseasonal SLA records averaged over the Black Sea, the Sea of Marmara, and the Aegean Sea (north of 38.5°N). The Black Sea elevation is significantly correlated ($r = 0.67$) with both the Aegean and the Marmara sea level lagging behind them by 22 days. Given the temporal resolution of satellite altimetry data, this time lag is significant. In contrast, no significant time lag is observed between the elevations in the Aegean and Marmara Seas. The maximum correlation between the elevations in these basins is 0.78 at 1 day time lag. This suggests that the Dardanelles Strait does not represent a serious obstacle to significantly delay the response of sea level in the Sea of Marmara to fluctuations in the Aegean Sea.

The power transfer between the sea level in the Aegean, Marmara, and Black Seas is investigated in terms of the magnitude-squared coherence between the sea level records. The interannual variability was estimated with a yearly moving average and removed from the time series prior to the calculation. To maximize the statistical confidence in the results, the cross spectra and individual spectra are calculated by dividing the full 8031 day time series into a number of segments with lengths of 512 days, which are then windowed with a Hamming window of that length and overlapped by 50%. The resulting spectral estimates are then ensemble averaged and presented over the band spanning the periods from 20 to 250 days leaving the near 1 year periods out of consideration, because they may contain the residual seasonal power (Figure 2). The 95% significance level is estimated at each frequency by carrying out Monte Carlo simulations of 1000 pairs of random time series with a unit standard deviation. Because the observed time series are autocorrelated (even after filtering), the pairs of random time series are generated such that they have the same number of degrees of freedom (the same zero crossing of the autocorrelation function) as the observed time series. The 95% confidence intervals for the gain and phase factors, calculated using the methodology of *Bendat and Piersol* [1966], are presented in Figure S3 of the supporting information. The confidence intervals demonstrate that the lags shown in Figure 2c are robust.

The Aegean and Marmara sea levels are significantly coherent at periods near 24 days and greater than 28 days with nearly zero phases (Figures 2a and 2c). The Black Sea elevation is significantly coherent with sea level in the Aegean Sea at 27 day period and at periods greater than 32 days, except for a dip in coherence at 46 days, and with sea level in the Sea of Marmara at periods greater than 46 days (Figure 2a). The coherence between the Black and Marmara Seas is lower than that between the Black and Aegean Seas, which is probably due to the poorer data quality in the Sea of Marmara. The Black Sea elevation shows considerable peaks in gain (amplitude response) to the Aegean and Marmara sea level forcing at the same periods as the corresponding peaks in the coherence (Figure 2b). The phase relationships (Figure 2c) between the sea level in the Aegean and Black Seas show a smooth behavior with the time lag steadily increasing with period from a few days at 20 day period to nearly 40 days at 250 day period. The time lag between the sea level in the Marmara and Black Seas has a similar behavior for the periods greater than 30 days.

Significant coherence at periods greater than 50 days is also estimated between the records averaged along the track 109 in the Aegean and Black Seas (Figure S4). Compared to the results obtained from gridded data (Figure 2), the coherence and gain for the along-track averages have lower values, probably because the along-track averages are less representative for the basin averages, while the time lags are similar. This comparison demonstrates that our results are robust and not an artifact of the optimal interpolation of multisatellite measurements.

3. Analytical Model and Results

To investigate the Black Sea elevation response to sea level in the Aegean and Marmara Seas, we employ a simple linear analytical model (similar to *Garrett* [1983]). The fact that sea level fluctuations in the sea of Marmara are nearly in phase with those in the Aegean Sea allows us to consider the response of a single basin (the Black Sea) of area S_1, separated by a strait (Bosphorus) of effective depth H_s from a water body (Marmara and Aegean Seas) which experiences oscillations of sea level near the strait given by $Re[\eta_0 e^{-i\omega t}]$. The equation of motion along the strait ignoring the advective and Coriolis terms but accounting for wind forcing is

$$\frac{\partial u_s}{\partial t} = -\frac{1}{\rho}\frac{\partial P}{\partial x} + \frac{\tau_s}{H_s \rho} - F_s, \tag{1}$$

where u_s is the barotropic flow along the strait, P is the subsurface pressure, τ_s is the along-strait wind stress, ρ is density, and F_s is friction, which is linearized to $F_s = \lambda_s u_s$, where λ_s is a friction coefficient. It is assumed that long waves travel quickly enough inside the Black Sea to make sea level spatially uniform on intraseasonal timescales. This assumption is valid for the Black Sea where the timescale for long waves, i.e., length scale (1000 km) divided by $c = \sqrt{gH}$ (average depth $H = 1250$ m), is about 2.5 h. If the sea level pressure (SLP), P_a, varies uniformly over the Black Sea and the along-strait SLP gradient is assumed negligible, then the subsurface pressure anomalies on both sides of the strait are

$$\begin{aligned} P_0 &= P_a + \rho g \eta_0 \\ P_1 &= P_a + \rho g \eta_1, \end{aligned} \tag{2}$$

where P_0 and η_0 are the pressure and sea level on the Aegean/Marmara side of the strait, P_1 and η_1 are the basin-uniform pressure and sea level in the Black Sea, and g is gravity. We assume that, due to the free connection to the wider Mediterranean, η_0 responds to P_a isostatically, so that $\eta_0 = \eta_0^{'} - P_a/\rho g$, where $\eta_0^{'}$ is the dynamic sea level. When $\eta_0^{'} = 0$, we have a pure inverted barometer (IB) response (1 cm per 1 mbar). The response of the entire Mediterranean to P_a is close to IB at periods longer than 30 days [*Le Traon and Gauzelin*, 1997]. Inside the Black Sea, the IB response is not valid [*Ducet et al.*, 1999], because the basin is almost fully enclosed with restricted communication through the Bosphorus, but P_a can reinforce or reduce the outflow through the strait.

Table 1. Description and Values of the Parameters Used in the Analytical Model

	Description	Value
S_1	Surface area of the Black Sea	4.36×10^{11} m^2
A_s	Cross-sectional area of Bosphorus	2.50×10^4 m^2
L_s	Length of the strait	31000 m
W_s	Width of the strait	1000 m
H_s	Effective depth of the strait	25 m
λ_s	Characteristic friction coefficient	3.8×10^{-5} s^{-1}
$\sigma(P_a)$	Standard deviation of SLP over the Black Sea	240 Pa (2.4 mbar)
$\sigma(\tau_s)$	Standard deviation of the along-strait wind stress	0.1 N m^{-2}
$\sigma(Q_{fw})$	Standard deviation of the net freshwater flux into the Black Sea	7×10^3 m^3 s^{-1}

Plugging (2) into (1), letting u_s, η, P_a, and τ_s behave as $e^{-i\omega t}$, and approximating $\partial/\partial x \approx 1/L_s$, we obtain

$$u_s = \frac{\frac{g}{L_s}\left(\eta_0' - \eta_1\right) - \frac{P_a}{\rho L_s} + \frac{\tau_s}{\rho H_s}}{-i\omega + \lambda_s}, \qquad (3)$$

where L_s is the length of the strait and ω is the frequency of fluctuations. Neglecting the steric effects (due to changes of temperature and salinity), the volume conservation of the Black Sea requires

$$S_1 \frac{\partial \eta_1}{\partial t} = A_s u_s + Q_{\text{fw}}, \qquad (4)$$

where S_1 is the Black Sea surface area, $A_s = W_s H_s$ is the cross-sectional area of the Bosphorus, W_s is the width of the strait, and Q_{fw} is the net fresh water flux into the Black Sea. Letting Q_{fw} behave as e^{-iwt} as well and combining (3) and (4), the Black Sea elevation is expressed as follows:

$$\eta_1 = \left[\eta_0' - \frac{P_a}{\rho g} + \frac{\tau_s L_s}{\rho g H_s} + \frac{Q_{\text{fw}} L_s}{g A_s}\left(-iw + \lambda_s\right)\right] \Big/ \left[1 - \omega^2 \frac{S_1 L_s}{A_s g} - i\omega\lambda_s \frac{S_1 L_s}{A_s g}\right]. \qquad (5)$$

The response amplitude is then $a = \text{abs}(\eta_1)$, and phase is $\varphi = \arctan(\text{Im}[\eta_1]/Re[\eta_1])$. Equation (5) shows that η_1 is the combined result of the dynamic sea level forcing on the Mediterranean side of Bosphorus, the SLP forcing over the Black Sea, the along-strait wind, and the net freshwater flux into the Black Sea. Since the model is linear, the response of the Black Sea elevation to each forcing term (η_0', P_a, τ_s, and Q_{fw}) can be considered separately.

If $P_a = \tau_s = Q_{\text{fw}} = 0$ and $\omega_r = \sqrt{A_s g / S_1 L_s}$, then equation (5) simplifies to

$$\eta_1 = \eta_0' / \left(1 - \omega^2/\omega_r^2 - i\omega\lambda_s/\omega_r^2\right). \qquad (6)$$

In the absence of friction, the solution (6) permits a Helmholtz-type resonance of the Black Sea communicating with the Sea of Marmara through Bosphorus at the Helmholtz frequency ω_r. For $\omega < \omega_r$ and significant values of friction, η_1 will lag η_0' and have reduced amplitude. In the limit of $\omega << \omega_r$, the amplitude of the response will be near unity ($\eta_1 \approx \eta_0'$), and the phase lag will be greatly reduced. For the geometrical characteristics of the Black Sea and the Bosphorus (Table 1) the corresponding Helmholtz period is about 17 days. It is interesting to note that for the geometrical characteristics of the Sea of Marmara and the Dardanelles Strait (surface area = 1.15×10^{10} m^2, length of the strait = 1×10^5 m, and the cross-sectional area of the strait = 6×10^4 m^2) the Helmholtz period is about 3 days. This explains the nearly in-phase relationship between the elevations in the connected Aegean and Marmara Seas, and the significantly more delayed response of the Black Sea elevation.

Based on the above considerations, the exchange between the Mediterranean and Black Seas on the timescales considered is largely constrained by friction and geometry of the Bosphorus Strait (and not the Dardanelles). Using equation (6) we estimate the analytic amplitudes and phases of the Black Sea response to an increase of sea level in the Aegean/Marmara Sea by 10 cm ($\eta_0' = 10$), which is characteristic for the region (Figure 1b). Because friction is the most uncertain parameter in our analytical model, the response amplitudes (Figure 3a) and phases (Figure 3b) are estimated at different friction coefficients ranging from $\lambda_s = 0.1 \times 10^{-5}$ to $\lambda_s = 5 \times 10^{-5}$ s^{-1}. At subannual periodicities, the response amplitude decreases with increasing friction. At longer periods, the amplitude of the Black Sea response becomes insensitive to the value of λ_s used. At the same time, the time lag (phase) increases with increasing friction, e.g., from ~3 days at $\lambda_s = 0.5 \times 10^{-5}$ s^{-1} to over 25 days at $\lambda_s = 5 \times 10^{-5}$ s^{-1} and periods greater than 200 days.

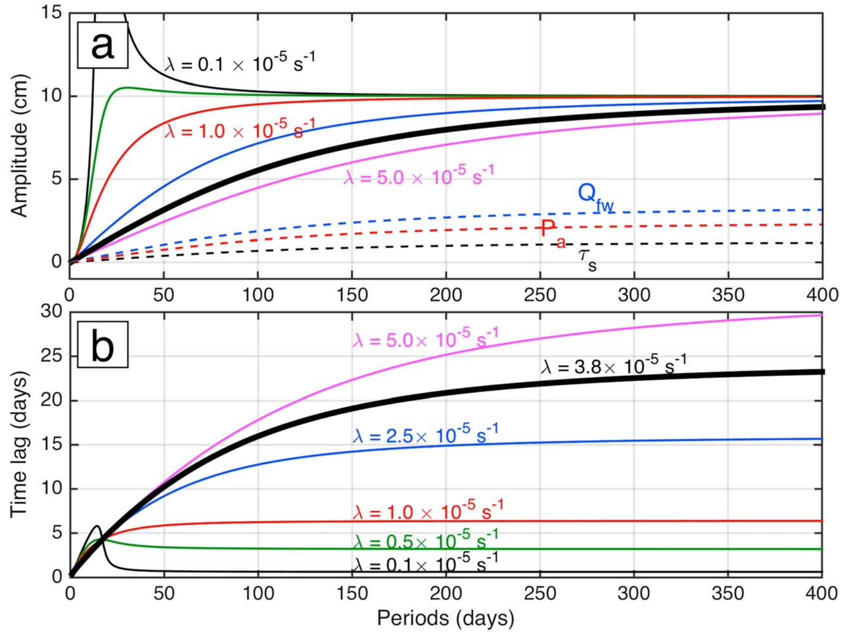

Figure 3. (a) Amplitude (cm) and (b) time lag (days) of the response of the Black Sea elevation to an increase of sea level in the Aegean/Marmara Sea by 10 cm, computed using equation (6) for different friction coefficients. The dashed curves in Figure 3a show the response amplitudes to individual forcing terms in equation (5) at $\lambda_s = 3.8 \times 10^{-5}$ s^{-1}: the net freshwater flux (blue), SLP over the Black Sea (red), and the along-strait wind stress (black).

Following *Candela et al.* [1989], a reasonable value for λ_s can be obtained from $\lambda_s = C_d u_s / H_s$, where C_d is the drag coefficient. Because the average net outflow of the Black Sea is about 300 km^3 yr^{-1} [*Ünlüata et al.*, 1990], which is approximately 9.5×10^3 m^3 s^{-1}, and the cross-sectional area of the Bosphorus is 2.5×10^4 m^2, it is reasonable to assume that $u_s = -0.38$ m s^{-1}. With $C_d = 2.5 \times 10^{-3}$ [*Garrett*, 1983] and $H_s = 25$ m, we obtain $\lambda_s = 3.8 \times 10^{-5}$ s^{-1}. The amplitude and phase of the Black Sea response to a 10 cm increase of sea level in the Sea of Marmara (disturbance) at $\lambda_s = 3.8 \times 10^{-5}$ s^{-1} calculated from equation (6) are shown in Figure 3 by bold black curves. The response amplitude is 5 cm at about 90 day period, and it reaches the disturbance amplitude (10 cm) at periods greater than 1 year. The time lag increases from 10 to 23 days at periods between 50 days and 1 year.

The solution at $\lambda_s = 3.8 \times 10^{-5}$ s^{-1} is compared to gain and phase relations obtained from satellite altimetry observations (Figures 2b and 2c) by setting $\eta_0 = 1$ (normalized value). The analytical amplitude of the response (Figure 2b, dashed black curve) appears to be rather close to the gain between the nonseasonal sea level in the Aegean/Marmara and Black Seas, but underestimated by up to 50–70% at the most energetic periodicities (around 38 and 57 days). The analytical time lag (Figure 2c, dashed black curve) is almost linearly increasing as the observed one, but it is systematically underestimated by the model and explains approximately 50–70% of the observed time lag. The difference between the observed and analytic values can be due to the neglect of other forcing components and their combined effect, and due to uncertainties in friction and geometrical characteristics of the Bosphorus Strait.

Based on SLP, wind stress, precipitation, and evaporation from ERA-Interim reanalysis (www.ecmwf.net), and river runoff from Dai and Trenberth Global River Flow and Continental Discharge Data Set [*Dai et al.*, 2009; www.cgd.ucar.edu/cas/catalog/surface/dai-runoff/], reasonable values for standard deviations are $\sigma(P_a) = 240$ Pa (2.4 mbar), $\sigma(\tau_s) = 0.1$ N m^{-2}, and $\sigma(Q_{fw}) = 7 \times 10^3$ m^3 s^{-1}. We use these values as characteristic amplitudes of the other forcing terms in equation (5) and consider each forcing term individually by setting the other terms to zero, with $\lambda_s = 3.8 \times 10^{-5}$ s^{-1}. The response amplitude of the Black Sea elevation to $|P_a| = 240$ Pa (Figure 3a, red dashed curve) reaches about 2 cm at 250 day period. At interannual periods it becomes a pure IB response: 2.4 cm sea level rise per 2.4 mbar P_a decrease. Wind in the direction of the Black/Aegean Sea tends to increase/decrease the Black Sea elevation, but the response amplitude to $|\tau_s| = 0.1$ N m^{-2} on intraseasonal timescales is below 1 cm (Figure 3a, black dashed curve). A freshwater flux anomaly of $|Q_{fw}| = 7 \times 10^3$ m^3 s^{-1} causes a stronger response with an absolute amplitude reaching 3 cm at an annual period (Figure 3a, blue dashed curve). It should be noted that the response amplitude of the Black Sea elevation to 1 sigma sea level forcing in the Aegean/Marmara Seas ($\sigma(\eta_0^{'}) \approx 5$ cm) is about 5 cm at an annual period, so that the SLP and freshwater influence is significant. The response phases to individual forcing terms at $\lambda_s = 3.8 \times 10^{-5}$ s^{-1} are the same (Figure 3b, solid black curve).

4. Summary and Discussion

Satellite observations have revealed a significant correlation between the intraseasonal sea level variability in the Aegean, Marmara, and Black Seas, with the sea level averaged over the Black Sea lagging behind the sea level averaged over both the Aegean and Marmara Seas. The magnitude-squared coherence between the sea level in the Black and Aegean/Marmara Seas is significant at periods generally greater than 1 month. The time lag between the elevations in the Aegean/Marmara and Black Seas increases from approximately 10 days at about 1 month period to nearly 40 days at 250 day period. The observed time lag suggests that besides the importance of fresh water fluxes in the Black Sea level budget, sea level fluctuations in the adjacent Aegean and Marmara Seas also affect sea level in the Black Sea. No significant time lag is found between the altimetry records averaged in the Aegean and Marmara Seas.

The response of the Black Sea elevation is due to barotropic flow anomalies through the Bosphorus Strait constrained mainly by friction and the strait geometry. The analytical model, employed in this study, is able to partially explain the amplitude and phase of the observed Black Sea elevation with respect to sea level changes in the Aegean and Marmara Seas. Using a realistic friction coefficient and considering only the sea level forcing on the Mediterranean side of Bosphorus, we find that the response amplitude increases from 50 to 90% of the disturbance amplitude and the time lag increases from 15 to 23 days at periods between 90 and 300 days. The analytic amplitude is generally close to what has been observed with satellite altimetry, while the analytic time lag accounts for only 50–70% of the observed time lag.

While the Aegean/Marmara sea level fluctuations appear to be the dominant forcing mechanism on intraseasonal timescales, the Black Sea elevation is also forced by SLP over the Black Sea, wind stress along the Bosphorus, and the net freshwater flux into the Black Sea. The individual response amplitudes to SLP over the Black Sea and the net freshwater flux into the Black Sea are considerable (up to 2–3 cm). The response amplitude to the along-strait wind stress is rather small (<1 cm). If all or some of these forcing terms act in phase, then the response amplitude is amplified. This may have happened during the large anomalies observed in 2010–2013 (Figure 1b). For this period, *VL*15 reported on concurrent NAO-modulated intraseasonal fluctuations of SLP over the Black Sea and the entire subtropical North Atlantic, southerly winds over the Aegean Sea, terrestrial water storage over the Black Sea drainage basin and, hence, river runoff, and the Black Sea elevation. Summing up the individual responses to SLP, wind, and freshwater flux gives the upper and lower bounds of the uncertainty for the response amplitude to the Aegean/Marmara sea level forcing (e.g., approximately ±4 cm at 120 day period).

The analytical model and empirical results presented here suggest that useful predictions of the Black Sea elevation in response to its largest forcing component on intraseasonal timescales—the sea level fluctuations in the Mediterranean—can be made from a few weeks to a month in advance, which may be of societal and economic value for the region.

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