Interannual variability of wind stress curl in the Black Sea and its response to changes in prevailing wind frequency

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Abstract. The purpose of this study is to identify trends in the long-term variability of the wind stress curl in the Black Sea and to analyze its response to changes in the direction of the prevailing wind flow over the sea. NCEP/NCAR reanalysis (1948–2016) and ERA Interim reanalysis (1979–2016) wind data at 10-m height are used. The temporal and spatial characteristics of the wind stress curl are compared by using these reanalyses with various spatial resolutions. Interannual changes in the wind stress curl are examined with long-term time series data of NCEP/NCAR reanalysis. The wind stress curl seasonal cycle, the dependence of its magnitude on wind direction, and the frequency of wind direction are in good agreement for the two reanalyses. There are multi-year periods of predominant positive and negative anomalies of the curl according to annual mean and winter data. The cyclonic wind stress curl increases in the late 1960s and early 1970s and weakens at the end of the 1990s. There is a weak positive trend in the curl time series in summer. The long-term variations of the wind stress curl are related to changes in the wind frequency of certain directions. High values of positive correlation coefficients have been obtained between the time series of the basin-averaged wind stress curl and the frequency of northeastern, eastern winds, and negative coefficients for the frequency of southwestern, western winds.

1. Introduction
The Black Sea is the inland sea of the Mediterranean Basin. The main feature of the sea is weak mixing between the surface and deep waters because of a positive water balance at the sea surface – the excess flow of rivers and precipitation over evaporation [1]. Wind impact is an important factor determining the nature and intensity of currents in the sea and affecting the vertical mixing in the upper layer [2]. Spatial heterogeneity in the wind field leads to the appearance of a vertical velocity at the lower boundary of the Ekman layer. The magnitude and direction of the velocity depend on the magnitude and sign of the wind stress curl. On average, a positive wind curl prevails over the Black Sea [3–5]. This leads to the upwelling of water in the deep water area of the basin, its divergence to the coast, the emergence of a horizontal pressure gradient, and the formation of gradient currents. Along with the river flow, the positive wind curl supports the cyclonic character of large-scale circulation in the sea [2, 6]. All this makes it important to study the variability of the wind stress curl.

Numerical estimates and analysis of the temporal and spatial variability of the wind curl and the wind stress curl were performed based on reanalyses [3, 5, 7–9], regional models [4], and satellite measurements [10] data to study the impact of wind on the circulation in the Black Sea. The seasonal cycle demonstrates an increase in the cyclonic wind stress curl in winter and its weakening in summer.
The interannual changes of the wind stress curl were studied using reanalyses data from 1950s to 2000s in [8, 12] and reanalyses and satellite measurements data over the past decades since 1980s in [9, 10].

The large-scale atmospheric circulation, together with local orographic effects in the Black Sea region, determines the direction of the wind above the sea [13] and the spatial structure of the wind curl [3, 10, 11, 14]. Statistical analysis of the magnitude of the wind stress curl and its spatial distribution showed that they depend on the direction of the wind prevailing over the sea [11, 15]. In this research it is examined whether these results are valid for the interannual changes of the wind stress curl.

The purpose of this study is to detect long-term trends of the wind stress curl in the Black Sea and to analyze the response of the wind stress curl magnitude to changes in the direction of the prevailing winds using long-term time series data. The study of the relationship between the wind stress curl and the wind directions is one of the intermediate stages in the research of the relationship between the long-term variability of the Black Sea currents and changes in the atmospheric synoptic situation in the region.

High temporal resolution of data is needed to accurately determine the frequency of each wind direction. NCEP/NCAR reanalysis wind data since 1948 (4 times daily) [16] satisfy such requirements. However, as a rule, long-term series data have insufficient spatial resolution. Therefore, a comparison between the spatial-temporal variability of the wind stress curl based on wind data of NCEP \ NCAR reanalysis and of ERA Interim reanalysis was performed. ERA Interim reanalysis has a shorter time series (since 1979), but a higher spatial resolution [17].

In Section 2, the data and research methods are described. The seasonal cycle and interannual changes of the basin-averaged wind stress curl and its correlation with the frequency of winds with different directions are presented in Section 3. The main conclusions and a discussion are presented in Section 4.

2. Data and methods

Data sets of 4 times daily wind at 10-m height of NCEP/NCAR reanalysis for 1948–2016 (1.905° × 1.875°) [16] and of ERA-Interim reanalysis for 1979–2016 (0.75° × 0.75°) [17] are used. For each 6-hourly time interval, the wind stress, the wind stress curl, and the prevailing wind direction were calculated.

The wind stress was calculated using the bulk formula

$$\tau = \rho_{\text{air}} C_d |V| V, \quad (N \cdot m^2),$$

where (kg m$^{-3}$) is the air density; $C_d$ is a dimensionless drag coefficient, and $V = (u, v)$ is the 10-m height wind velocity (m s$^{-1}$). The drag coefficient was taken to be $1.2 \times 10^{-3}$ for a wind speed <11 m s$^{-1}$ and $(0.49+0.065 V) \times 10^{-3}$ for a wind speed >11 m s$^{-1}$ [18].

The wind stress curl was calculated using the formula

$$\text{rot}_z \tau = \frac{\partial \tau_y}{\partial x} - \frac{\partial \tau_x}{\partial y}, \quad (N \cdot m^3).$$

The curl values were calculated at the centers of cells of the reanalyses data (Figure 1a).

The correspondence between the magnitude of the wind stress curl and the direction of the wind flow prevailing over the sea is examined. The prevailing wind direction is determined for each 6-hourly time interval by averaging the wind vector components $V = (u, v)$ using the grid points located in the sea area. The resulting direction refers to one of the geographical directions: northern (N), northeastern (NE), eastern (E), southeastern (SE), southern (S), southwestern (SW), western (W), and northwestern (NW). Thus, there were the prevailing wind direction and the corresponding curl field for each time interval.

Composites of the wind stress curl fields were formed for events with each wind direction. The annual mean wind stress curl corresponding to an individual wind direction was calculated by averaging over a set of situations with this wind direction. The annual mean frequency of the wind directions was calculated in percent of the total number of situations.
In order to examine the relationship between the long-term time series data of the wind stress curl and the frequency of the winds, the correlation between them was calculated. The two-monthly mean frequency of the wind directions and the two-monthly mean basin-averaged wind stress curl were calculated for every year and every season in this case.

All average quantities were calculated by averaging the data located in the area bounded by the 50-meter isobath (Figure 1a).

3. Results

3.1. Seasonal variability

3.1.1. Spatial distribution. The spatial distributions of the annual mean and January-February wind stress curl have a similar structure according to both reanalyses for 1979-2016 (Figure 1, b, c). Positive values (the cyclonic curl) of the wind stress curl are located in the northeastern and southwestern parts of the sea; negative values (the anticyclonic curl) are located near the western and southeastern coasts. In July-August and in January-February, the main differences between the reanalyses are located in the southeastern part of the sea (Figure 1, c, d). These differences are probably caused by the insufficient spatial resolution of the long-term NCEP/NCAR reanalysis.

Figure 1. Spatial grid of reanalysis data (the bold line marks the border of the region with depths exceeding 50 m) (a); annual mean of the wind stress curl (×10⁻⁷ N m⁻³) (b), in January-February (c), in July-August (d) according to the data of reanalysis NCEP/NCAR for 1979-2016 (top) and ERA Interim (bottom).

3.1.2. Basin-averaged wind stress curl. The seasonal cycle of the basin-averaged wind stress curl is presented in Figure 2a. The curl magnitude according to ERA Interim reanalysis is higher throughout the year with the predominance of the cyclonic curl compared with NCEP/NCAR reanalysis. A maximum positive value of the wind stress curl is in February. In summer, the anticyclonic curl prevails over the sea only in June according to ERA Interim data and during all summer months according to NCEP/NCAR.

The magnitude of the wind stress curl varies with change in the direction of the wind prevailing over the sea area (Figure 2b). On average over the year, the maximum cyclonic wind stress curl is observed during synoptic situations with northeastern and eastern winds prevailing over the sea, and the maximum anticyclonic curl occurs during southwestern and western winds. High values of the curl are associated with high heterogeneity of the wind velocity field. The northeastern, southwestern, and western winds have the highest speeds [11] and, therefore, they have the greatest speed shifts. Land-sea surface change and tall mountains on the eastern and southern coasts contribute to an increase in
the heterogeneity of the wind speed field [3, 14]. A high cyclonic curl occurs in the eastern and southwestern parts of the sea during the northeastern winds flow around the Caucasus Mountains and around the Pontic Mountains (Figure 3a). A high anticyclonic curl was found in the southern part of the sea during the western or southwestern winds flow around the Pontic Mountains (Figure 3b).

Figure 2. Annual cycle of the basin-averaged wind stress curl ($\times 10^{-7}$ Nm$^{-3}$) (a); wind stress curl at different wind directions (b); the wind direction frequency (%) (c). NCEP/NCAR: 1948-2016 – blue solid line, 1979-2016 – blue dashed line; ERA Interim – red line.

The northeastern winds have maximum frequency, and the southeast winds have minimum frequency (Figure 2c). The frequency of the wind of each individual direction changes throughout the year, but the northeastern wind has a high frequency in all months [11, 13]. Therefore, there are high values of the cyclonic curl in the eastern part of the sea in all seasons (Figure 1, b–d).

Figure 3. Mean wind stress curl ($\times 10^{-7}$ Nm$^{-3}$) under northeastern winds (a) and southwestern winds (b) in January-February according to ERA Interim data.

3.2. Interannual variability

3.2.1. Comparison of reanalyses. A comparison of the time series of the basin-averaged wind stress curl anomalies calculated on the basis of different reanalyses wind data shows good agreement between them for 1979-2016, which is common for two reanalyses (Figure 4, top row). The correlation coefficients between them have high significant values in all seasons (Table 1). Thus, despite the difference in the absolute values of the wind stress curl, the character of its interannual variability is similarly reproduced by reanalyses with high and low spatial resolution.

Next, we will examine the interannual variability of the wind stress curl using the long-term wind data of NCEP/NCAR reanalysis.
Table 1. Correlation coefficients between annual mean time series (1979-2016) of basin averaged wind stress curl in the Black Sea from NCEP/NCAR and ERA Interim wind data.

| Wind stress curl (ERA-Interim) | Year | Jan-Feb | Apr-May | Jul-Aug | Oct-Nov |
|--------------------------------|------|---------|---------|---------|---------|
| Wind stress curl (NCEP/NCAR)   | 0.81 | 0.87    | 0.74    | 0.88    | 0.89    |

3.2.2. Long-term trends. There are evident periods of positive and negative anomalies in the basin-averaged wind stress curl time series (Figure 4, top row). According to the annual mean data, the cyclonic curl increased in the late 60s – early 70s and weakened in the late 90s (Figure 4a). In winter, the same trends are observed, but the changes have a larger amplitude (Figure 4b). In the summer months, there is a weak positive trend of the curl (Figure 4c). Similar results were obtained in earlier studies using shorter data series. The decrease of the wind stress curl from the 1960s to the 2000s was revealed earlier in [12], and its increase since 2000s was obtained in [10].

3.2.3. Connection with winds directions frequency. To analyze the relationship between the long-term changes of the wind stress curl and the synoptic situation over the sea, the correlation between the curl and the prevailing winds frequency time series was calculated. The largest positive correlation coefficients were obtained for the north-eastern wind, and a negative one for the south-western and western winds (Table 2). The values of the correlation coefficients with winds of other directions are smaller. Thus, the dependence of the curl on the wind direction obtained from the annual mean data (Figure 2b) is also detected in long-term data series.

![Figure 4](image_url)

Figure 4. Top: basin-averaged wind stress curl ($\times10^{-7}$ Nm$^{-2}$) anomalies from NCEP/NCAR (blue), ERA Interim (red); bottom: frequency of north-eastern and eastern (NE+E - green) and south-western and western (SW+W - brown) winds in annual mean (a), in January-February (b) and in July-August (c) in the Black sea. Smoothing curves are polynomials of order 5.

The maximum significant correlation coefficients are in winter and autumn, when the wind velocity is high. The correlation with the total frequency of northeastern and eastern winds (NE+E) and southwestern and western winds (SW+W) has higher values than for individual wind directions for winter, autumn, and the annual mean (Table 2). The interannual variability of the total frequency of
these winds on average for the year, in January-February, and in July-August is shown in Figure 4 (bottom row).

The relationship between the frequency of winds and the wind stress curl is well expressed in the annual means (Figure 4a) and January-February (Figure 4b) data. Long-term changes in the frequency of northeastern and eastern winds occur simultaneously with changes in the wind stress curl. High values of the cyclonic curl occur when the frequency of these winds increases. High values of the anticyclonic curl take place when the frequency of the western and southwestern winds grows. The variability of the total frequency of SW+W winds and NE+E winds has opposite trends.

### Table 2. Correlation coefficients between time series of the basin-averaged wind stress curl and the frequency of prevailing winds (NCEP/NCAR) in the Black Sea (maximum positive and negative correlation coefficients for individual wind directions are shown in bold).

| Wind stress curl | Frequency of wind | Total frequency |
|------------------|-------------------|-----------------|
|                  | N     | NE    | E     | SE    | S     | SW    | W     | NW    | NE+E   | SW+W   |
| Annual           | 0.23  | **0.68** | 0.42  | 0.11  | **-0.41** | **-0.60** | -0.58 | -0.44 | 0.72    | -0.64   |
| Jan-Feb          | 0.04  | **0.77** | 0.75  | 0.37  | 0.01  | -0.57 | **-0.70** | -0.54 | 0.87    | -0.77   |
| Apr-May          | -0.02 | **0.74** | 0.16  | -0.06 | -0.40 | -0.41 | **-0.44** | -0.24 | 0.72    | -0.50   |
| Jul-Aug          | 0.02  | **0.49** | 0.08  | -0.20 | -0.04 | -0.47 | -0.20  | **-0.51** | 0.43    | -0.35   |
| Oct-Nov          | -0.11 | **0.73** | 0.44  | 0.15  | -0.35 | -0.59 | **-0.65** | -0.54 | 0.75    | -0.73   |

The total frequency of northeastern and eastern winds was high from the 1950s to the early 1980s, and has been low since the 1990s in January-February (Figure 4b). The period from 1960s to 2000s was the time of decreasing frequency of northeastern and eastern winds. The weakening of the frequency of strong winds and wind speed in this period was obtained earlier using data of meteorological measurements [19, 20]. The western and southwestern winds dominated from the mid-1980s in January-February over the Black Sea.

The relationship between long-term variations of the wind stress curl and changes in the wind direction is less expressed in summer, when the wind velocity is low (Figure 4c, Table 2).

### 4. Discussion and conclusions

Analysis of the seasonal and interannual variability of the wind stress curl in the Black Sea and its dependence on the frequency of prevailing wind directions was performed using NCEP/NCAR and ERA Interim reanalyses wind data with various spatial resolutions and lengths of data series.

The seasonal variability of the basin average wind stress curl, the dependence of the curl magnitude on wind direction and the frequency of wind directions are in good agreement for the two reanalyses. However, according to the ERA Interim reanalysis with a higher spatial resolution, the magnitude of the wind stress curl has a larger value throughout the year with a predominant cyclonic curl.

The long-term variations of the wind stress curl magnitude depend on changes in the frequency of wind directions. The wind stress curl time series has a positive correlation with the frequency of northeastern and eastern winds, and a negative correlation with the frequency of western and southwestern winds. The increase in the frequency of northeastern end eastern winds is accompanied by intensification of the cyclonic wind stress curl and of the anticyclonic one in the western and southwest winds.

The direction of the prevailing wind is determined by the large-scale atmospheric synoptic situation, the position of large-scale atmospheric cyclones and anticyclones in particular [13]. Changing the synoptic situation leads to a change in the wind direction and a change in the position and sizes of the areas with cyclonic and anticyclonic wind stress curls [11].

The orographic effects due to the presence of high and elongated Caucasus and Pontic Mountains make an additional contribution to the creation of the wind stress curl [3, 4]. The seasonal change in
the temperature contrasts between the sea and the surrounding land makes a great contribution to the seasonal variability of the wind curl [3, 4, 21]. In winter, when the sea is warmer than the land, a cyclonic circulation is formed over the sea. In summer, the situation is reversed, and an anticyclonic circulation is formed.

The interannual variability of the wind stress curl and the frequency of individual direction winds are probably related to long-term changes in the trajectories and position of large-scale atmospheric cyclones and anticyclones [13].

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