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Effects of the basin dynamics on sea level rise in the Black Sea

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Abstract. Satellite altimetry measurements show that magnitude of the Black Sea level trends is spatially uneven. While the basin-averaged sea level was increasing at a rate of 3.15 mm/year from 1993 to 2014, the sea level rise varied from 0.15-2.5 mm/year in the central part to 3.5-3.8 mm/year in coastal areas and 5 mm/year in the southwestern part of the sea. These differences are caused by changes in the large- and mesoscale circulation of the Black Sea. A long-term increase of the cyclonic wind curl over the basin from 1979 to 2014 strengthened divergence in the center of the Black Sea that led to an increase of sea level near the coast and a decrease in the center of the basin. Changes in the distribution and intensity of mesoscale eddies caused the formation of the local extremes of sea level trend. The variability of the dynamic sea level (DSL) – the difference between the local and the basin-averaged sea levels - contributes significantly (up to ~50% of the total variance) to the seasonal and interannual variability of sea level in the basin. The DSL variability in the Black Sea depends strongly on the basin-averaged wind curl and is well reconstructed using the ERA-Interim winds from 1979 to present, including the time when altimetry data was unavailable. The reconstruction can be used to correct historical tide gauges data for dynamic effects, which are usually neglected in the analysis of the Black Sea tide gauge records.

1 Introduction

The global mean sea level rise has been observed for more than a century. It is mainly caused by the freshwater input from melting glaciers and thermal expansion of the ocean due to the global warming (Cazenave et al., 2010). It has been reported that in 1992-2008 the rate of sea level rise has increased to ~3.1 mm/year compared to the 20th century average of ~ 1.8 mm/year (Church et al. 2004, 2013; Jevrejeva et al., 2006; Cazenave et al., 2010). The sea level rise leads to flooding of low-lying coastal areas, coastal erosion, and as a result, has a negative impact on human activities in the coastal zone (Alpar, 2009; Avsar et al., 2016). Coastal erosion has been identified as one of the major problems for the Black Sea beaches (Demirkesen et al., 2009; Kosyan et al., 2012). Estimates show that an increase of sea level by 1 cm results in 1-2 meters of coastal erosion (Goryachkin and Ivanov, 2006). An increase of sea level by 50 cm will reduce the area of the Black Sea beaches by approximately 50% (Allenbach et al., 2015).
Historically, sea level has been studied using coastal tide gauges. The advent of high-accuracy satellite altimetry more than two decades ago has revolutionized our view on ocean dynamics. Basin-wide altimetry measurements have shown that sea level variability is spatially strongly heterogeneous and the sea level rise along the coast and in the central part of the ocean is different (Holgate and Woodworth, 2004; Prandi, et al, 2009; Merrifield and Maltrud, 2011). For example, according to altimetry measurements in 1992-2007, sea level fell at a rate of ~ 2 mm / year in the eastern part and rose at a rate of ~ 7 mm / year in the western part of the Pacific Ocean (Cazenave et al, 2010.).

These differences are primarily due to dynamic factors that cause spatial redistribution of water masses (Merrifield and Maltrud, 2011; Palanisamy et al, 2015).

The Black Sea level rise over the 20th century, estimated from tide gauge data, varies from 1.5 to 2.5 mm/year (Boguslavsky et al., 1998; Reva, 1997; Goryachkin and Ivanov 1996; Tsimplis and Spencer, 1997; Goryachkin and Ivanov 2006), which is in a reasonable agreement with the global mean sea level rise (Church et al. 2004; Cazenave et al, 2010). Both the tide gauge and altimetry data show that sea level trends in the Black Sea have significant interannual variations (Goryachkin and Ivanov 2006; Kubryakov and Stanichnyi, 2013): sea level was rising at a very high rate of 28 mm/year in 1993-1999 (Goryachkin et al., 2003; Vigo et al., 2005; Yildiz et al., 2008), in 1999-2007 it fell by 3 mm/year (Yildiz et al., 2008; Ginzburg et al., 2011) and then after 2008 again rose (Avsar et al. 2015). The basin-averaged sea level rise in the Black Sea is related to water balance and steric expansion of the water volume due to warming. The impact of different components of water balance on the Black Sea level has been investigated by a number of authors (e.g. Goryachkin and Ivanov, 2006; Graek et al, 2010; Ilyin et al., 2012; Volkov and Landerer, 2015; Volkov et al., 2016; Aksoy, 2016).

Vigo et al. (2005) and later Kubryakov and Stanichnyi (2013) showed that the Black Sea level trends are spatially non-uniform, with the coastal sea level rising 1.5-2 times faster than the sea level in the center of the basin. It is reasonable to hypothesize that the observed spatial variability of sea level rise is related to the interannual variability of the Black Sea dynamics that redistributes water masses within the basin. The goal of this study is to investigate the dynamic sea level temporal and spatial variability in the Black Sea, its imprints on the sea level rise in different parts of the basin, and its relation to atmospheric forcing.

2 Data

In this study, we used the regional satellite altimetry maps of sea level anomalies from Jan 1993 to Dec 2014. The regional Black Sea satellite altimetry product is produced by Ssalto/*Duacs* and distributed by *Aviso*, with support from *CNES* (http://www.aviso.altimetry.fr/duacs/). The maps are provided on a daily basis with a horizontal grid spacing of 1/8°. We calculated the absolute dynamic topography as a sum of the mapped sea level anomalies and a “synthetic” mean dynamic topography of Kubryakov and Stanichny (2011). The absolute dynamic topography was used to calculate surface geostrophic currents.

The dynamic sea level (DSL) at a particular location (x,y) is defined as the difference between the total sea level signal S(x,y) and the basin-averaged sea level <S>: DSL(x,y)=S(x,y) – <S>.

The variability of the basin-averaged sea level is caused by changes in (i) the amount of water in the basin and (ii) the basin-averaged steric sea level due to the temperature and salinity variability. The variability of DSL is mainly due to the redistribution of water mass within the basin.

The 6-hourly ERA-Interim winds at 10 meters height over the 1979-2014 time interval were used to analyze the wind curl variability (Dee et al., 2011). The ERA-Interim winds over the Black Sea agree well with in-situ meteorological measurements (Garmashov et al., 2016). The wind curl is calculated as $W = \frac{\partial V}{\partial x} - \frac{\partial U}{\partial y}$, where U and V are the zonal and meridional wind velocity components, respectively.

3 Results

3.1 Sea level trends

The variability of the basin-averaged sea level <S> is shown in fig.1a. Over the 1993-2014 period, the Black Sea mean sea level was rising at a rate of 3.15 mm per year, in agreement with Avsar et al. (2015). This value coincides well with the estimates of the global mean sea level rise in 1992-2008 (e.g. Cazenave et al., 2010). The trend has not been constant: sea level was rising at a rate of 26.2 mm/year in 1992-1999; then it was falling at a rate of 3 mm/year in 2000-2007; and in 2007-2014 it rose again at a rate of 10 mm/year (fig. 1b). The rates of sea level change during the first two periods agree with the estimates of Vigo et al. (2005) and Yildiz et al. (2008), based on the analysis of satellite altimetry and gravimetry data. Changes in the amount of water in the Black Sea (water balance) are the main reason for the basin-averaged sea level variability (Ilyin et al., 2012; Volkov and Landerer, 2015; Volkov et al., 2016). An extensive review of the Black Sea level variability and water balance in the 20th century is provided in Goryachkin and Ivanov (2006).

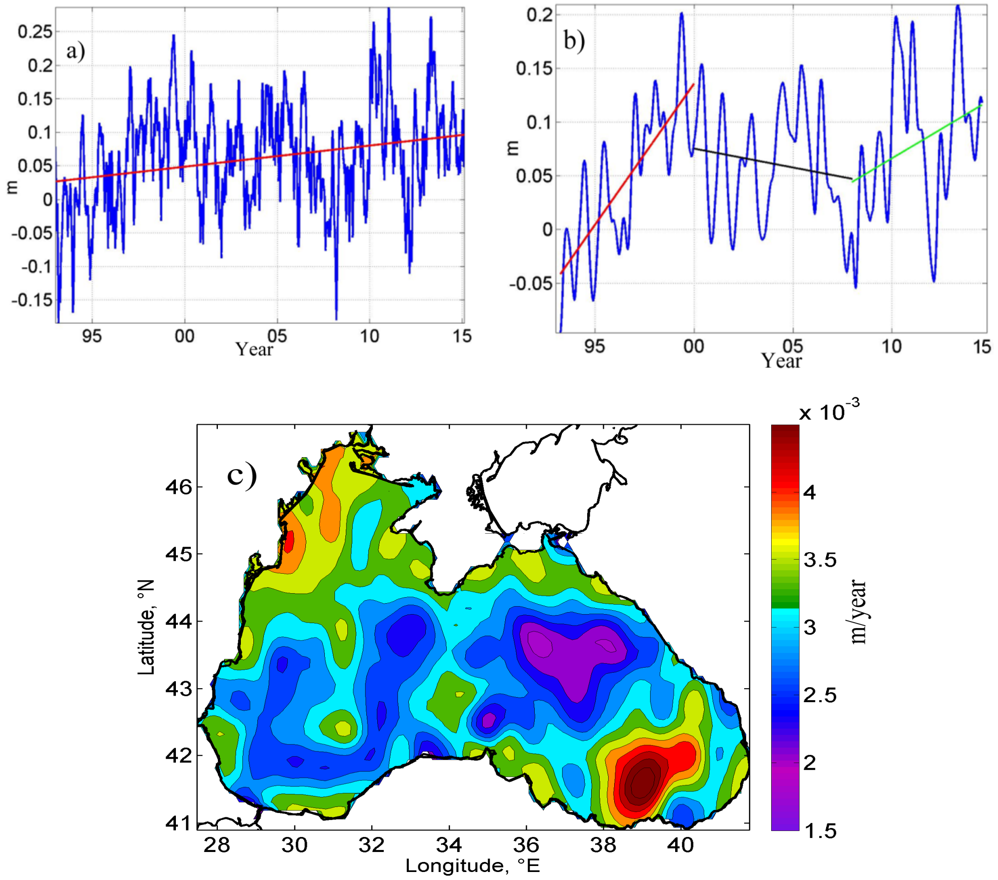

Fig.1 The basin-averaged Black Sea level from satellite altimetry data: a) daily time series (blue curve) and a linear trend for the 1993-2014 time interval; b) time series smoothed with a 90-day moving average and trends for 1993-1999, 2000-2007, 2017-2014; c) spatial distribution of the 1993-2014 sea level trends (m/year)

A map of sea level trends in the Black Sea over the 1993-2014 time period is demonstrated in Fig.1c. It is well-seen that the sea level change is significantly spatially heterogeneous in agreement with an earlier analysis of the along-track altimetry data (Kubryakov and Stanichniy, 2013). Sea level in the coastal areas was rising at a rate of 3.2-4 mm/year, which is approximately 1.5-2 times greater than in the center of the basin (1.5-2.5 mm/year). The largest trend exceeding 5 mm/year is observed in the southwestern part of the basin. The observed spatial differences in the sea level rise are related to the basin dynamics.

3.2 Dynamic sea level variability

The main feature of the Black Sea dynamics is the cyclonic Rim current encircling the basin over the continental slope. As a result of the cyclonic circulation, the DSL is lower in the center of the basin and higher along the periphery (Oguz et al., 1993; Korotaev et al., 2001).

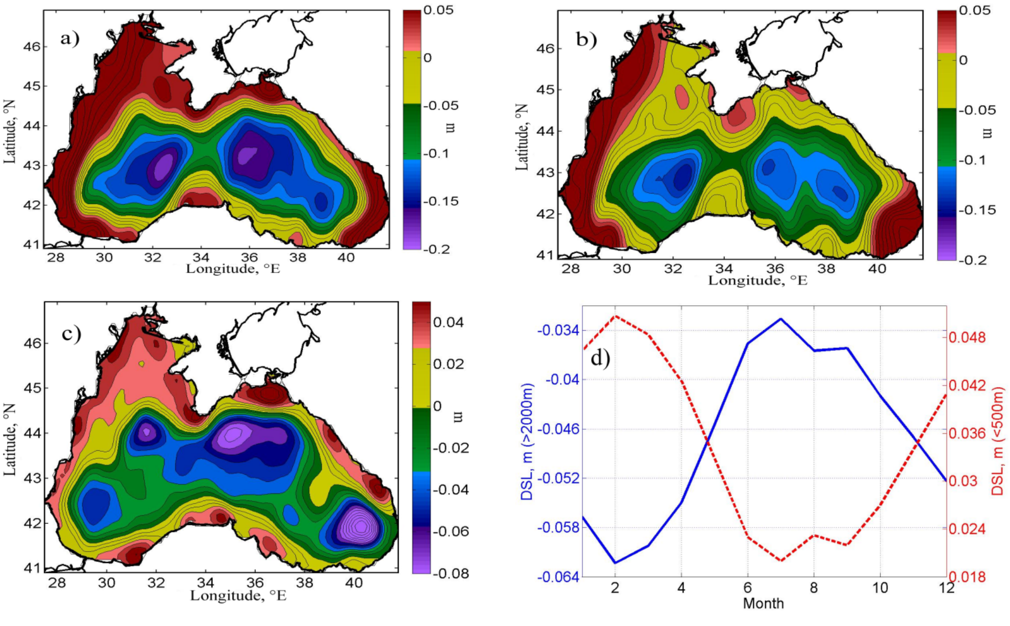

Fig. 2 Average DSL distribution in (a) February, (b) July, and (c) their difference (February minus July); (d) seasonal cycle of DSL averaged over the central part (depths more than 2000 meters) and along the basin's periphery (depths less than 500 meters).

The seasonal variability of the Black Sea circulation is driven by changes in the wind curl averaged over the basin (Stanev, 1990; Korotaev, 2001, Graek et al., 2010). In winter, the cyclonic wind curl and, therefore, the onshore Ekman transport increase and cause divergence in the center of the basin by moving water to the basin's periphery. The compensating vertical uplift (Ekman suction) in the center of the sea brings dense deep water masses to the surface, while light surface waters move towards the coast (Korotaev, 2001; Kubryakov et al., 2016). The redistribution of mass and volume results in a decrease of sea level in the basin's center, and an increase along the coastline. In summer, the cyclonic wind curl weakens, Ekman divergence decreases and the water accumulated along the coast flows back into the basin's interior (Zatsepin et al., 2002; Kubryakova, Korotaev, 2016). The time required for the Black Sea circulation to adjust to changes in the wind curl is approximately two weeks (Kubryakov et al., 2016).

The seasonal cycle of DSL in the Black Sea is shown in Fig.2. During both the warm and the cold periods of a year DSL is higher at the basin's periphery (fig. 2a,2b). In winter, the difference between the center and the periphery of the basin is maximum. As expected, the seasonal time series of DSL in the coastal (depths less than 500 meters) and central (depths more than 2000 meters) parts of the basin are negatively correlated (fig.2d). In summer, DSL in the central part increases and in the coastal areas decreases. The coastal DSL is maximum in winter after the wind curl increases, and it is minimum in summer when the wind curl decreases. On contrary, the DSL in the center of the sea is maximum in July and minimum in February.

The magnitude of the annual change of DSL in both parts of the sea is on average about 3 cm. The spatial distribution of the seasonal amplitudes of DSL is shown in Fig. 2c. The maximum amplitudes of DSL are observed in the center of the sea, where they reach 0.08-0.10 m in the northeastern, northwestern, and southeastern parts of the basin. These maxima are related to intense eddy dynamics in these areas (Kubryakov et al., 2015a). .

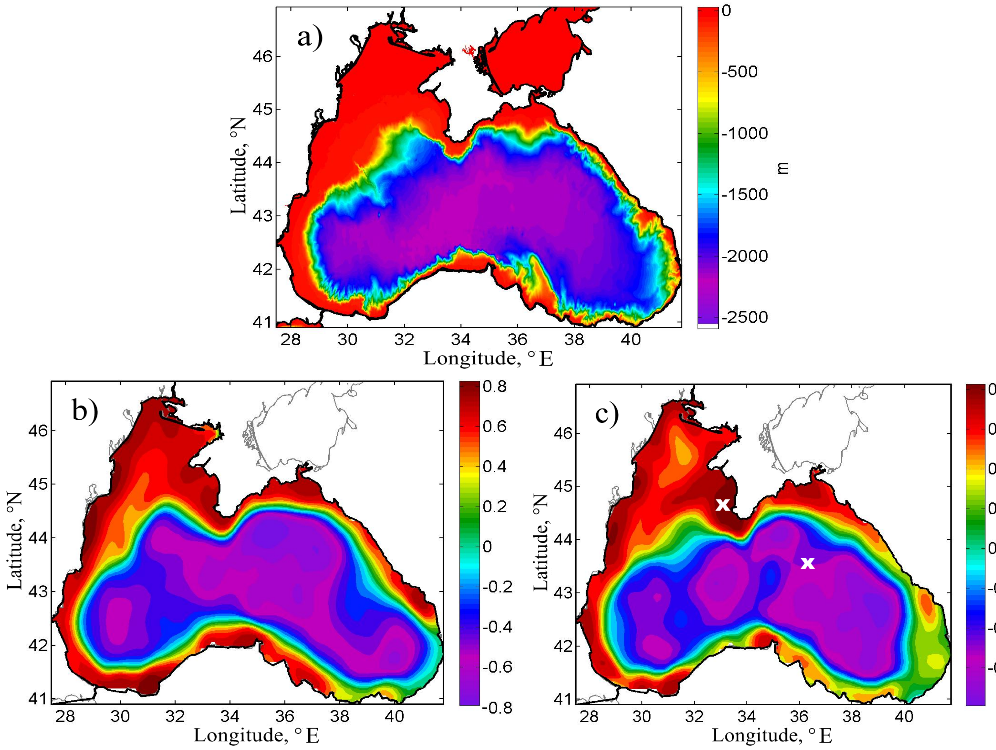

Fig. 3 a) Black Sea bathymetry; b,c) Correlation coefficients between the basin-averaged wind curl and DSL for the time series smoothed with (b) a 90-day moving average (both the seasonal and interannual signals retained) and (c) a 365-day moving average (only interannual signals are retained)

Figure 3a shows the bathymetry of the basin and figures 3b,c presents correlation maps between the wind curl averaged over the basin and DSL at each grid point for the time series smoothed by a 90-day moving average (i.e. seasonal variability is kept, Fig. 3a) and a 365-day moving average (only interannual variability is retained; Fig. 3b).

The strong coincidence between basin bathymetry and correlations patterns is well seen. On both the seasonal and interannual time scales the correlation coefficients are significantly positive at the basin's periphery (0.6..0.8), including the entire northwestern shelf (depths less than 1000 meters), and significantly negative in the center of the basin (-0.6..-0.8) (depths less than 1000 meters). The wind curl determines the intensity of water divergence from the center to the periphery, and this is why DSL and wind curl are in phase in the coastal Black Sea and out-of-phase in the center.

For example, Figures 4a and 4b demonstrate the variability of DSL at two locations shown by crosses in Fig. 3b: the first is characteristic for the basin's periphery (33.2°E; 44.7°N) and the second is characteristic for the central part of the basin (35.4°E, 44.0°N). The time series of DSL (red curve) and the basin-averaged wind curl (blue curve) are strongly correlated for the first point on both the seasonal and interannual time scales. The correlation coefficient is 0.75 for the time series smoothed with a 90-day moving average and it is 0.89 for the time series smoothed with a 365-day moving average. The maximum values of the wind curl and DSL on the interannual time scale were observed in 1996, 2002, 2006, 2008 and 2010. The minimum values were detected in 1998-2001, which is the period of the weakest circulation reported in Kubryakov et al. (2016). The range of the interannual oscillations of DSL at the basin's periphery is about 0.05-0.06 m. The seasonal amplitudes of the altimetry-measured DSL reached 0.10 m in 2003 and 0.08 m in 2006, 2008. Based on tide gauge measurements, the seasonal amplitudes of sea level is about 0.20 m (Goryachkin, Ivanov, 2006). The seasonal changes of DSL explain up to 50% of the sea level variance and, therefore, play an important role in the total sea level variability.

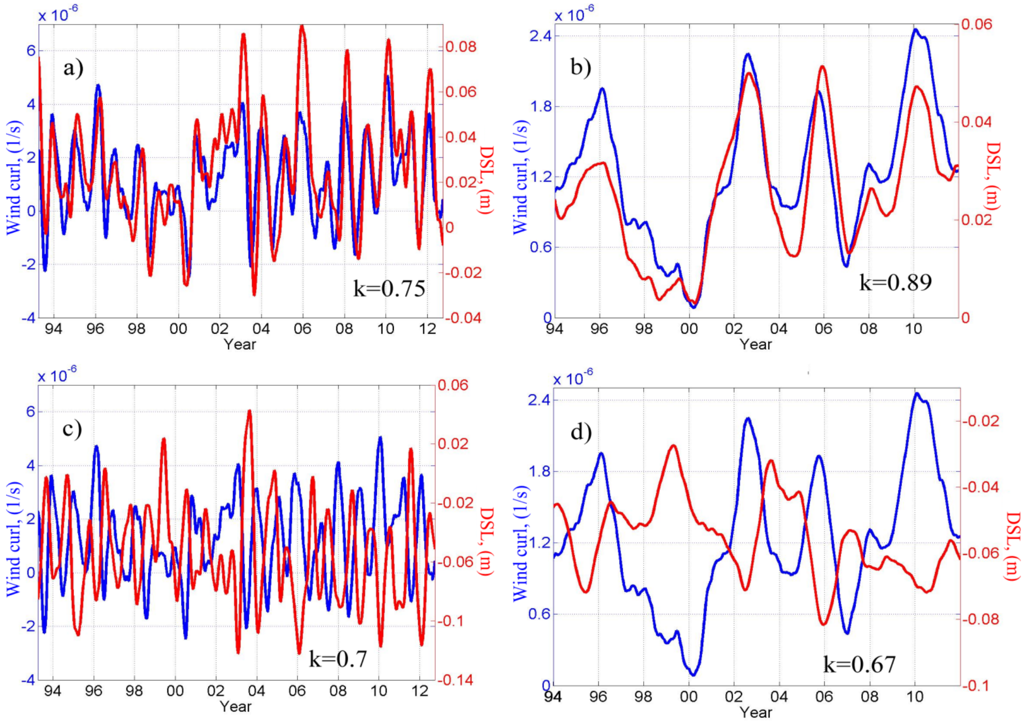

Figure 4. The time series of DSL (red curves) and the basin-averaged wind curl (blue curves): (a, b) at 33.2°E and 44.8°N (the basin's periphery) and (c, d) at 35.4°E and 44.0°N (center of the basin); the time series are smoothed (a, c) with a 90-day moving average time series and (b, d) with a 365-day moving average.

For the second location, characteristic for the basin center, the relationship between the sea level and wind curl is inverse. Here, the correlation is -0.7 for the time series smoothed with a 90-day moving average (Fig. 4c) and -0.66 for the time series smoothed with a 365-day moving average (Fig. 4d).

The interannual variability of the basin-averaged wind curl computed from ERA-Interim winds for the time period from 1979 to 2015 is rather complex with several sharp minima in 1983, 1990, 2000, and 2007, and several less prominent maxima (Fig.5a). At the same time, it is well-seen that the wind curl is linearly increasing over the entire period, including the period when the high-accuracy altimetry measurements are available (1993-2015). The value of the linear trend is ~10^(-8) 1/s per year or about 0.5% of the average value per year. It has been shown that the strength of the Black Sea circulation is significantly correlated with the wind curl on interannual time scales (Kubryakov et al., 2016). The long-term trend of the wind curl induces the intensification of the basin's cyclonic circulation observed in 1992-2014 in satellite altimetry data (fig.5a – blue line) (Kubryakov et al., 2016). The mean speed of currents in the basin was rising at an approximate rate of 5 mm/s per year, i.e. by 0.3% of the average value per year. The strongest intensification of the Black Sea currents occurred in 2002-2003 after a prolonged minimum in the 1998-2002 (fig.5a).

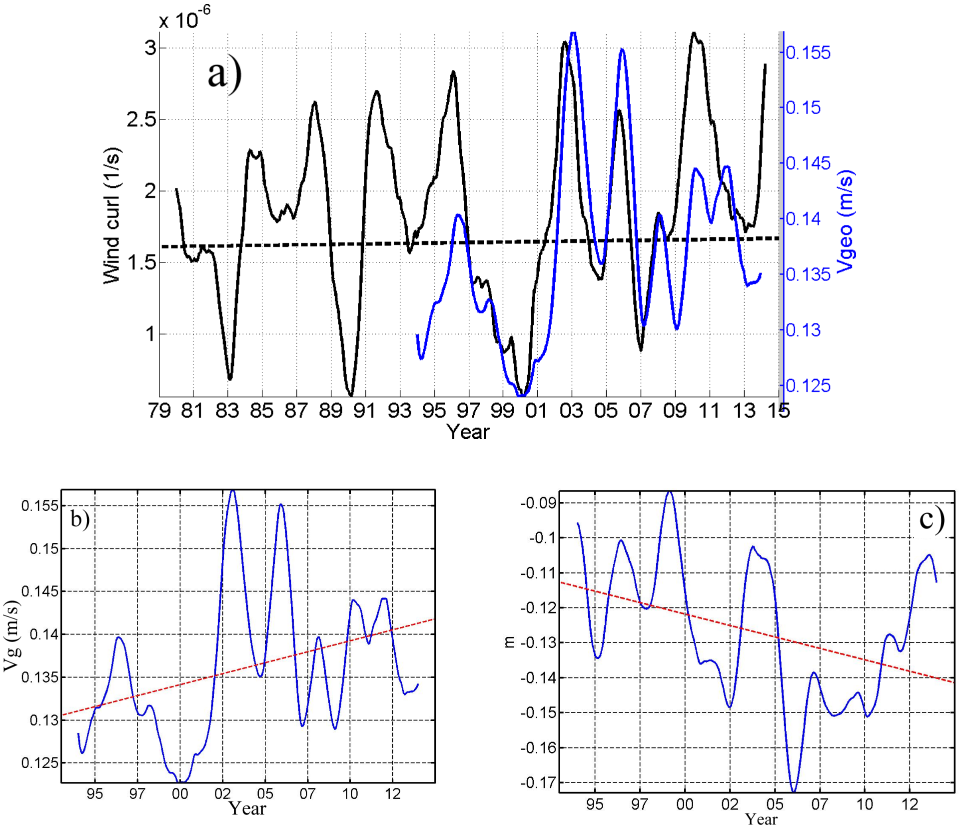

Fig. 5. The interannual variability of a) the basin-averaged wind curl in 1980-2014 and (b) the basin-averaged geostrophic velocity in 1992-2014, b) DSL at 33.2°E and 44.8°N (the Black Sea periphery), and c) DSL at 36.5°E and 43.5°N (the central part of the basin). The time series are smoothed with a 1-year moving average.

A positive/negative trend of wind curl strengthens/weakens Ekman divergence, which lowers/raises sea level in the center of the basin, and raises/lowers sea level along the coast. Such opposite trends of DSL are distinctly observed in the center and at the periphery of the sea (fig.5b,c). The trend is equal to +0.05 mm/year at a point in the coastal zone (33.2°E; 44.7°N) and -0.13 mm/year at a point in the basin's interior (35.4°E, 44.0°N).

Therefore, the spatial distribution of the Black Sea trends presented in fig.1c can be explained by two factors: a) the rise of the mean Black Sea level by 3.15 mm/year due to the change of water mass/volume in the basin and b) the increase of Ekman divergence in the center of the sea due to the strengthening of the cyclonic wind curl over the basin. The total sea level trend at the periphery is S=<S>+DSL, while the total sea level trend in the central part is S=<S>-DSL. The DSL trend (Fig. 6a) is equal to approximately 0-0.5 mm/year at the basin periphery and approximately 0.1-0.15 mm/year in the basin's interior , while the total sea level (S) trend is 3.15 mm/year. The DSL trend is related to the strengthening of the large-scale circulation and the divergence in the basin. Note that the dynamic trend amplitude is significantly higher in the interior, which means that the divergence is more important in the central part of the basin. The value of the DSL trend constitutes about 15%-50% of the basin-averaged sea level rise and, therefore, plays an important role in coastal sea level rise estimates.

3.3 The impact of mesoscale variability on the Black Sea level trends

Several local mesoscale maxima are observed in the spatial distribution of the Black Sea level trends. The largest positive maximum is observed in the southeastern part of the basin (centered around 39°E, 41.5°N). This area corresponds to the position of the intense quasi-stationary Batumi anticyclone (Oguz et al., 1993; Korotaev et al., 2003, Kubryakov, Stanichny, 2015c). The anticyclonic motion leads to convergence and sea level rise in the center of the eddy. The coincidence of the local maximum of sea level trend and the Batumi eddy position suggests that this maximum is related to eddy intensification.

We used an automated "winding angle" (Chaigneau et al., 2008) eddy identification method, described in detail in Kubryakov and Stanichny (2015a), to study the variability of eddy dynamics in the Black Sea. This method allows to identify each relatively large and long-lived eddy observed by altimeters during the 1993-2014 period. A descriptive analysis of eddy characteristics and their seasonal and interannual variability based on altimetry data is provided in Kubryakov and Stanichny (2015a,b). For each eddy we define its radius and maximum orbital velocity. We also define the frequency of eddy observation, i.e. the percent of the total time when a particular grid point is located within an eddy. Because the Black Sea anticyclones are larger and more powerful that cyclones (Kubryakov and Stanichny (2015a)), here we only consider the properties of anticyclones.

Displayed in Fig. 7 are the interannual variability of (a) the frequency of anticyclones (% of time) and (b) the maximum orbital velocity of anticyclones at the point (39°E, 41.5°N), located where the local sea level trend is maximum. Both the number of eddies detected at this point and their intensity was increasing with time. The frequency was increasing by 0.005 per year (0.5% per year) from 5% in 1990s to 15% in the 2010s (fig. 7a). The maximum orbital velocity of anticyclones also increased from 0.13 m/s in 1995 to 0.26 m/s in 2014 (fig. 7b).

Our analysis shows that the observed trends are not related to the formation of strong eddies at this point. Instead, they are related to an expansion of the Batumi anticyclone (i.e. an increase of its radius - not shown) and its slight displacement to the west. These changes are well reflected by the trends of frequency, radius and orbital velocity of anticyclones (fig. 6 b, c, d). Strong trends in the radius and orbital velocity of anticyclones are observed in the southeastern part of the basin at around 39°E and 42°N near the western periphery of the Batumi anticyclone.

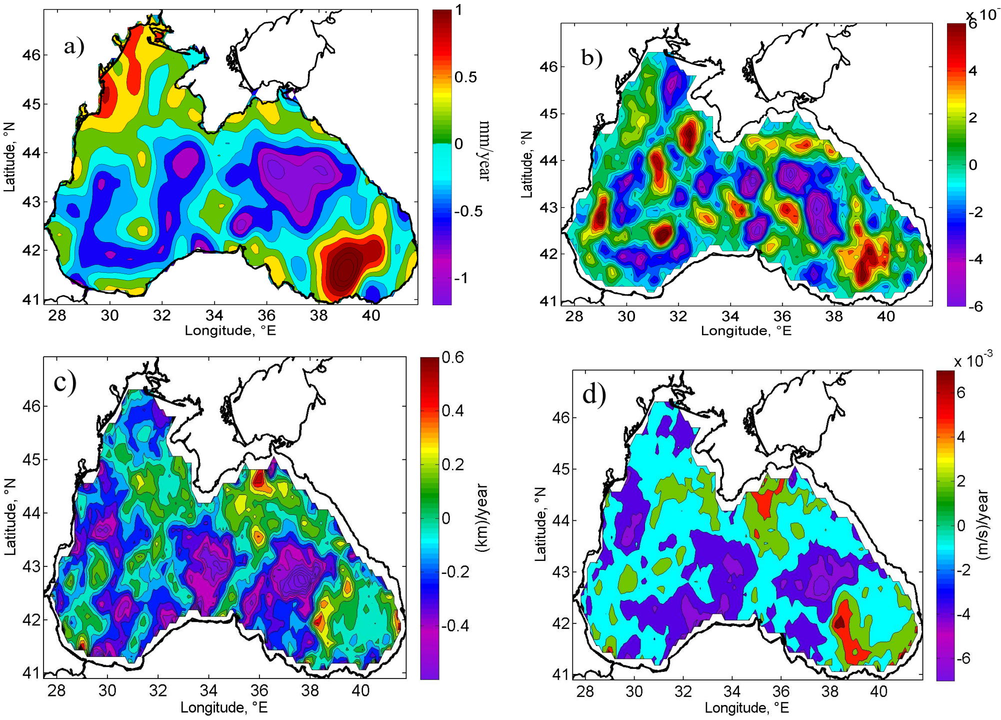

Fig.6 Spatial distribution of a) DSL trends; b) Trends in the frequency of anticyclones in 1993-2014; c) Trends in the radius of anticyclones in 1993-2014; d) Trends in the maximum orbital velocity of anticyclones in 1993-2014;

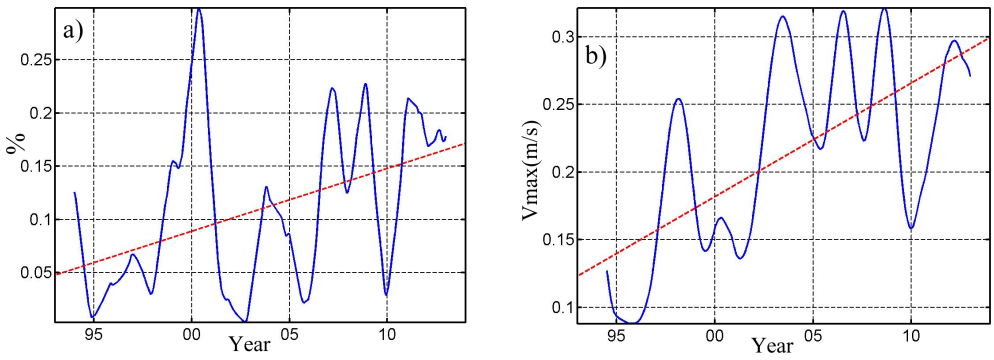

Fig.7 a) Frequency of anticyclones and b) the maximum orbital velocity in anticyclones at 39°E and 41.5°N, derived form altimetry data.

The expansion of the Batumi anticyclone to the west in the 2010s led to a strong increase of DSL and to maximum sea level trends in the southeastern part of the basin. The other local maxima in the trends of the frequency of anticyclones coincide with the position of increased sea level trends. For example, a local DSL maximum near 31.5°E and 44°N (Fig. 6a) is close to a local maximum in the trend of the frequency of anticyclones in the western part near 31.5°E and 42.5°N. These trends are probably associated with a larger number of anticyclones crossing these points, i.e. with a change of the anticyclonic eddy propagation pattern in the basin.

3.4 Reconstruction of DSL variability from atmospheric reanalysis data

Before the advent of high-resolution altimetry data in 1992, the estimates of the sea level rise were based on tide gauge measurements. The results presented above show that the basin-averaged sea level rise estimated from tide gauges should be corrected for dynamic effects. To determine this correction we computed the linear regression coefficients (k) between the basin-averaged wind curl and DSL at each grid point: DSL=k*W+C (fig.8).

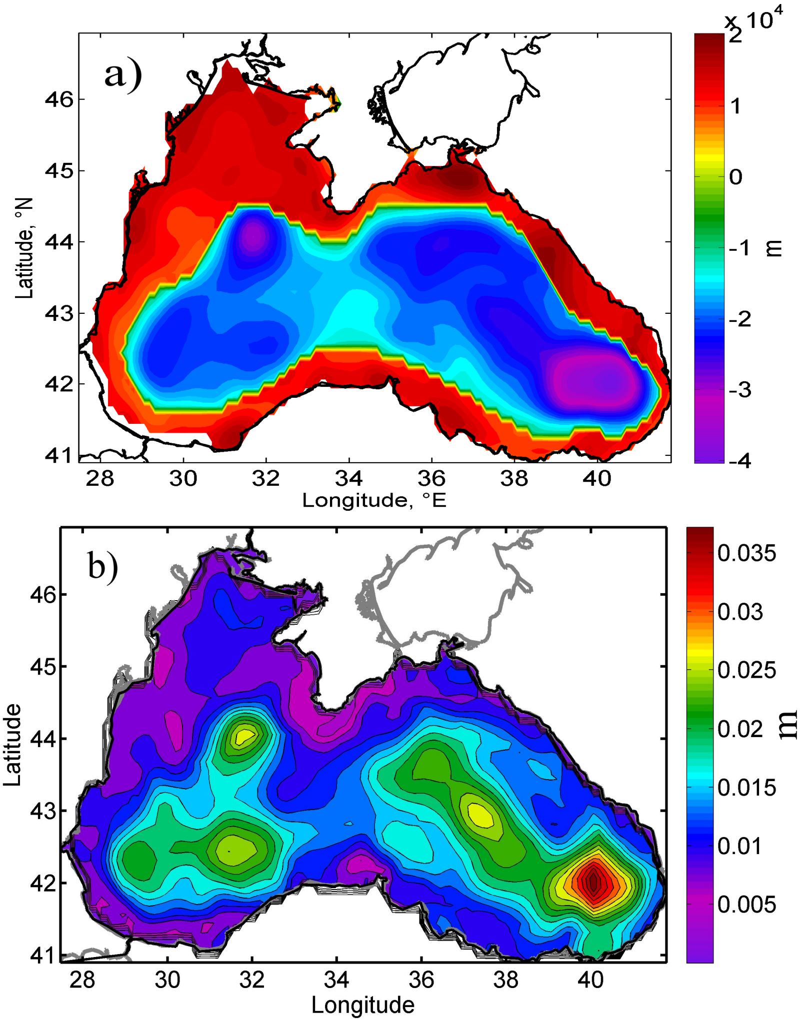

Fig. 8 a) Coefficient of linear regression (k) between the basin-averaged wind curl and DSL (DSL=k*W); b) Standard deviation between altimetry-derived and reconstructed DSL (data series are smoothed with 1-year moving average)

Then we reconstructed DSL using the regression coefficients and the wind curl. The root-mean-square differences between the reconstructed and altimetry-derived DSL on the interannual time scale (the time series are smoothed with a 1-year moving average) are rather small at the basin periphery (fig. 8b), where the standard deviation is only about 0.005-0.01 m. In the center of the basin the errors are larger (0.02-0.03 m), which apparently due to the impact of mesoscale dynamics. A comparison between the reconstructed DSL and the altimetry-derived DSL (red line) at a point near the south Crimean coast (33.2°E; 44.7°N) shows a very good agreement (fig.9a,b). A simple regression allows to reconstruct both the seasonal and interannual variability of DSL from the wind data alone. The correlation coefficients between the altimetry-derived and reconstructed DSL are 0.85 and 0.88 for the time series smoothed by 90-day and 365-day moving averages, respectively.

Since the ERA-Interim winds are available for a longer period (since 1979) than altimetry data, the obtained regression coefficients can be used to reconstruct the DSL variability in the past and correct the estimates of the Black Sea level rise based on tide gauges. For example, if the DSL trend over the 1979-1992 period at a given location is 0.5 mm/year, this value should be subtracted from tide gauge data to obtain the mean sea level rise in the Black Sea. This method accounts for changes in the large-scale circulation, but does not account for the impact of trends in mesoscale dynamics. The mesoscale dynamics affects mostly the basin's interior, while the increasing Ekman divergence mostly affects the coastal sea level variability (fig. 8b).

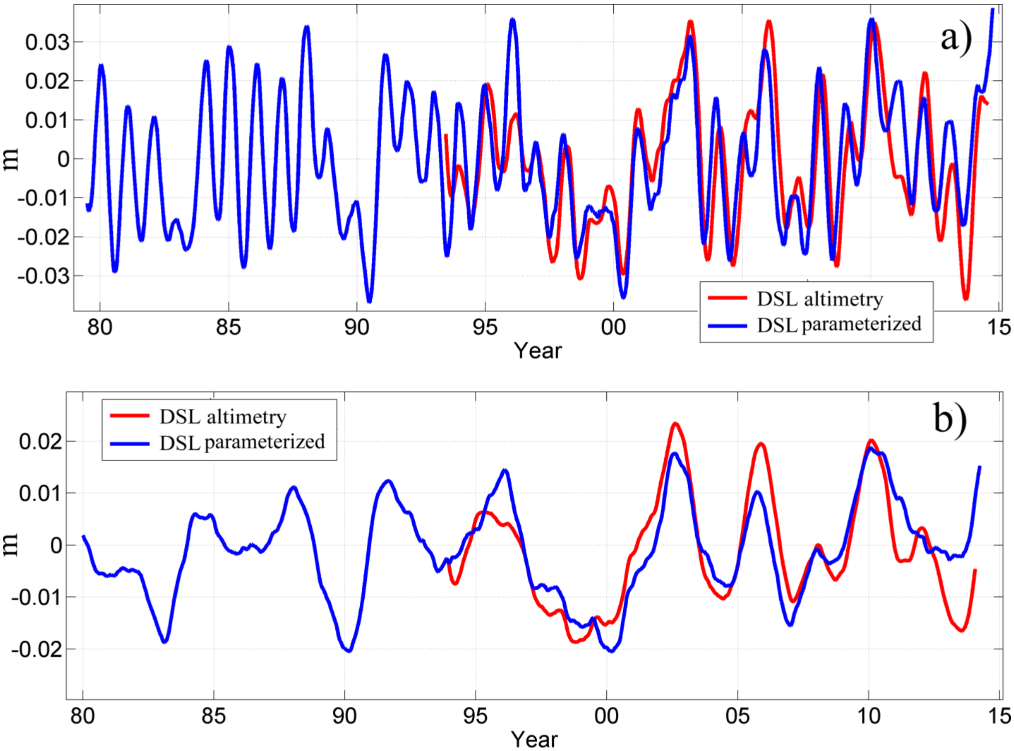

Fig.9. The time series of the altimetry-derived DSL (red curve) and DSL reconstructed from the wind curl (blue curve): the time series are smoothed (a) with a 90-day moving average and (b) with a 365-day moving average.

4 Conclusions

The climatic changes of the large-scale and mesoscale Black Sea dynamics significantly impact sea level trends in different parts of the Black Sea. While the basin-averaged sea level increases at a rate of 3.15 mm/year, sea level rise varies from 1.5 mm/year in the central eastern part to 3.5-3.8 mm/year in coastal areas and to 5 mm/year in the southwestern part of the sea. The observed long-term intensification of the cyclonic wind curl strengthened divergence in the center of the basin, which caused an increase of sea level at the Black sea periphery and a decrease in the center.

Changes in the distribution and intensity of mesoscale eddies led to the local extremes in sea level trends. In particular, an extension of the Batumi anticyclone to the west resulted in an excess sea level rise in the southwestern part of the basin by ~1.2 mm/year.

The DSL associated with the redistribution of water masses varies significantly on seasonal and interannual time scales. The amplitudes of the DSL variability can reach 0.1 m in different years that can contribute up to 50% of the total annual sea level signal. The dynamic sea level in the basin correlates well with the basin-averaged wind curl, which is the main driver of the Black Sea circulation. Using the relationship between the wind curl and DSL, we have reconstructed the DSL in the Black Sea back to 1979, when the high-resolution altimetry data was not available. These estimates can be used to correct tide gauge data for dynamic effects that can significantly impact the estimates of the Black sea level rise. Including the DSL in the analysis could change our view on the climatic sea level variability in the past.

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