

Answer to Reviewer 1

Reviewer: Review on “Impact of basin dynamics on the regional sea level trends in the Black Sea” by Kubryakov et al.

This manuscript deals with the relationship between wind curl and circulation in the Black Sea. The successful reconstruction of circulation from the wind without using numerical model is the basic message. As the authors state, the underlying relationships have been known from earlier studies, however they give a good illustration. The idea of the paper is understandable. However, as presented, it needs a major revision. Here are some comments. For the role of the Ekman pumping and its relationship with the distribution of mass, authors could consult also the work of Stanev et al. (2004).

Answer: Thank You, we added the reference

Reviewer: p. 2, line 20-23. There is text-repetition.

Answer: Thank You, we corrected the text

I wonder whether the right title of section 3.1 should be “Sea level trends”. What authors describe is the sea level variability with interannual time-scales over-imposed on the global trend.

Answer: We have changed the title to “Interannual variability of the Black Sea level”

Reviewer: The same comment applies to the title of paper” Impact of basin dynamics on the regional sea level trends in the Black Sea”. What authors show, is that the long-term changes of sea level are characterized by certain spatial variations. And that these spatial patterns are reminiscent of, or related to, some circulation patterns. However, when reading the title one could expect to learn how (quantification of mechanisms) the basin dynamics modulate the sea level change.

Answer: We agree with the Reviewer and change the title to “Quantifying the impact of basin dynamics on the regional sea level rise in the Black Sea “

P. 7, line 20. Authors could mention that this time lag was estimates by Stanev et al. (2000) as 1-2 months that is they demonstrate a good consistence with previous research in this field based on longer record.

Answer: We have added a corresponding sentence and the reference to the text: “The similar time lag (1-2 months) between DSL and wind curl variability was obtained in the earlier study of (Stanev et al., 2000).”

Reviewer: P. 8, caption Figure 6. Perhaps better normalize the wind curl by f .

Answer: In this study, we decided to use wind curl and not Ekman pumping, because here the wind curl describes only the external forcing. More detailed investigation of the Ekman pumping variability and its connection with the Black sea dynamics was done in our previous study “Kubryakov, A. A., Stanichny, S. V., Zatsepin, A. G., & Kremenetskiy, V. V. (2016). Long-term variations of the Black Sea dynamics and their impact on the marine ecosystem. *Journal of Marine Systems*, 163, 80-94.”

Reviewer: P. 9. There is a double use of “6” in Fig. numbers.

Answer: Thank You, we have corrected the figure numbering

Reviewer: P. 9. Avoid repeating Fig. 1 in Fig. 6a-horizontal pattern.

Answer: These figures are very similar, but Fig. 1c shows the total sea level trends, while Fig. 7a shows DSL trends. The figure 7a is shown to demonstrate the magnitude of the DSL trends and highlight the local features of the DSL trends, which are attributed to the mesoscale eddy variability, discussed in this section.

Reviewer: P. 9, line 10. The trends in Fig. 6 (b, c, d) are small-scale and patchy. An estimate of their confidence needs to be provided. These figs are not sufficiently considered/explained in the text. Their patchiness makes me think that there is a problem with statistics. Perhaps the whole section “3.3. The impact of mesoscale variability on the sea level trends” can be omitted. Actually, the title of this section is too promising. We see small scale patterns (or noise) but the explanation of how the mesoscale variability impacts the sea level trends is missing (not presented in a convincing quantitative way).

Answer: As we see from the figures 1, 6a we can observe a spurious local maximums of the sea level rise in several areas of the basin. These maximums can not be explained by the large-scale Ekman dynamics. Here we use eddy statistics in order to show that at least part of them (e.g. largest maximums in the south-east part) can be explained by the observed changes of the eddies characteristics. Also the methods of automated eddy identification allows to obtain a large statistical array about eddy characteristics, eddy dynamics can be very complex and patchy. Nevertheless we still can observe some more or less high trends of the anticyclone radius and eddy velocity in several places that coincide with the values of the increased sea level. This give

the idea about the effect of long-term eddies variability on the dynamic sea level changes in the basin, that is valuable for this study “Quantifying the impact of basin dynamics on the regional sea level rise in the Black Sea”. The detailed investigation of the reason of these changes f eddy dynamics is an interesting and complex task that is out of the scope of our study.

According to Your comments we rewrite this section, redraw the figure 7 and figure 8, slightly extended the text in this section and added a brief explanation of how the mesoscale variability impacts the sea level trends.

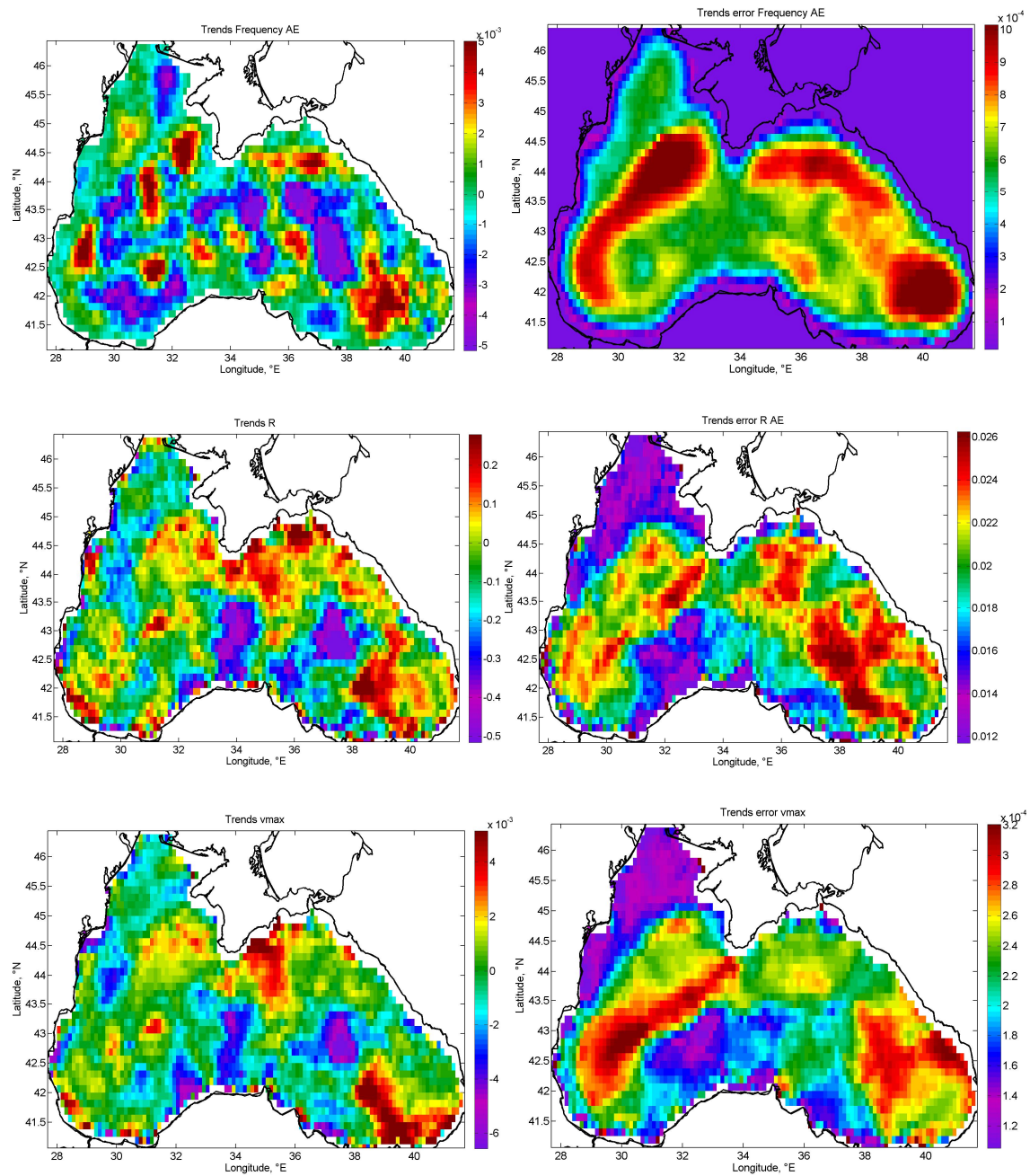


Figure 1. Trends (left) and their errors (confidence intervals) (right) for: top - frequency of anticyclones observation, middle - their radius (km), bottom - maximum orbital velocity (m/s).

In Figure 1 we also provide the estimates of the confidence intervals (right panel) for the computed trends (left panel) for frequency of anticyclones observation, their radius (km) and maximum orbital velocity (m/s). As You can see in the most of the areas of the basin the errors are not more than approximately 10% of trend value

Answer to Editorial comments

Editor: Page 1 Lines 15, 16. I prefer “rise”, “fall” (or perhaps “lowering”) of sea level, not “increase”, “decrease”.

There are many later places in the text where this also applies, e.g. page 2 line 1, page 3 line 39 (“falling”), page 12 line 8 (“rising”), page 12 Line 11 (“a rise”), page 12 line 12.

Answer: Corrected

Editor: Line 32. Better “. . Black Sea MSL then rose at a faster rate . .”

Answer: Corrected

Page 2

Editor: Line 14. “reduces” -> “decreases”

Answer: Corrected

Editor: Line 19. “sea level is rising . .”

Answer: Corrected

Editor: Lines 20-22. This sentence is a duplicate.

Answer: Thank You, we corrected the text

Editor: Line 28 and many other places including notation on figures. I prefer “metre” (European spelling) since Napoleon defined it and to avoid ambiguity with a measuring instrument. Also page 3 line 20, figure 2c and its caption, figure 3 caption

Answer: Corrected

Page 3

Editor: Line 11. “derived”. How? Especially, how do you go from a current vector everywhere to one value which you compare with wind curl.

Answer: We have added an explanation to the text:

“The absolute dynamic topography of the Black Sea was computed as the sum of the mapped SLA and a “synthetic” mean dynamic topography of Kubryakov and Stanichny (2011). Surface geostrophic currents (u,v) was computed from absolute dynamic topography the using geostrophic equations: $u_g = -\frac{g}{f} \frac{\partial h}{\partial y}$; $v_g = \frac{g}{f} \frac{\partial h}{\partial x}$.

Here, u_g and v_g are the zonal component and meridional component of geostrophic velocity; h is the absolute dynamic topography; f is the Coriolis parameter; g is the gravitational acceleration; and x, y are the longitude and latitude, respectively. To describe the basin-scale variability we use the magnitude of geostrophic velocity $U = \sqrt{u^2 + v^2}$ ”

Editor: Line 18. You need “:” after first “MSL”

Answer: Thank You, we corrected the text

Editor: Lines 29-30. Better “it rose again”

Answer: Corrected

Editor: Line 37. “southeastern”

Answer: Thank You, we corrected the text

Page 4

Editor: Line 3 (3rd of figure caption). “2017” -> “2007”.

Thank You, we corrected the text

Page 5

Editor: Line 1. “DSL falls in the centre . . .”

Answer: Corrected

Page 6

Editor: Figure 3 caption line 3. “isobaths” (spelling).

Answer: Thank You, we corrected the text

Editor: Lines 5-6. “including most of the north-west shelf”? (Something is missing)

Answer: This phrase is excluded from the revised version.

Editor: Line 7. Delete “,” after “least”.

Answer: Corrected

Editor: Line 18. “mean speed of surface geostrophic currents” c.f. comment on page 3 line 11; how is this derived?

Answer: We have added an explanation to the text in the Section 2

Editor: Line 19. “rising” -> “increasing” (refers to current speed). “0.5” -> “0.05”. “per year”.

Answer: Corrected, Thank You.

Page 7

Editor: Lines 7-8. Figure 2c (caption) refers to “basin’s periphery”. Please explain “averaged over the shallow areas” which needs to be something different to find “close agreement”.

Answer: Thank You, we **have rewritten this part of the text** . “The average range of the interannual oscillations of DSL at the first point is about 5 cm, in close agreement with the amplitudes of the DSL averaged along the basin’s periphery (depths less than 500 metres) (Fig.2c)”

Page 8.

Editor: Figure 5 caption line 4. Needs completion.

Answer: Corrected

Editor: Line 12. This is not the definition of DSL in section 2.

Answer: We agree, and we have rewritten this part of the text.

Editor: Line 13. “. . while the total Black-Sea-average sea level (S) trend . .”

Answer: We have rewritten this part of the text.

Page 9

Editor: Figure 6b, colour scale needs units.

Answer: The units of frequency is fraction, so they are dimensionless

Page 10

Editor: Line 3 and figure 7a. Text and figure disagree. I think the figure is not % but simply fraction of time. C.f. figure 6b.

Answer: This is right. We have corrected the text accordingly.

Page 12

Editor: Figure 9 line 3 (caption line 1). “. . DSL at 33.2°E, 44.7°N reconstructed . .”

Answer: Corrected

Editor: Line 10. “southeastern”

Answer: Thank You, corrected

Editor: Line 14. “southeastern”

Answer: Corrected

Quantifying the impact of basin dynamics on the regional sea level rise in the Black Sea

Kubryakov A.A.^{1,2}, Stanichny S.V.¹, Volkov D.L.^{3,4}

¹Federal State Budget Scientific Institution "Marine Hydrophysical Institute of RAS", Sevastopol, Russia

5 ²Institute of Earth Sciences, Saint Petersburg State University, St. Petersburg, Russia

³Cooperative Institute for Marine and Atmospheric Studies, University of Miami, Miami FL, USA

⁴NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami FL, USA

Correspondence to: Kubryakov A.Arseny (arskubr@ya.ru)

10 **Abstract.** Satellite altimetry measurements show that the magnitude of the Black Sea level trends is spatially uneven. While the basin-mean sea level rise from 1993 to 2014 was about 3.15 mm/year, the local rates of sea level rise varied from 1.5-2.5 mm/year in the central part to 3.5-3.8 mm/year at the basin periphery and over the northwestern shelf and to 5 mm/year in the southeastern part of the sea. We show that the observed spatial differences in the dynamic sea level (anomaly relative to the basin-mean) are caused by changes in the large- and mesoscale dynamics of the Black Sea. First, a long-term intensification of the cyclonic wind curl over the Black Sea observed in 1993-2014 strengthened divergence in the center of the basin and led to the rise of sea level in coastal and shelf areas and a lowering in the basin's interior. And second, an extension of the Batumi anticyclone to the west resulted in ~1.2 mm/year higher rates of sea level rise in the southwestern part of the sea. Further, we demonstrate that the large-scale dynamic sea level variability in the Black Sea can be successfully reconstructed using the wind curl obtained from an atmospheric reanalysis. This allows to correct historical tide gauge records for dynamic effects in order to derive better estimates of the basin-mean sea level change in the past, prior to satellite altimetry era.

1 Introduction

25 The mean sea level (MSL) rise in the Black Sea, as well as in the World Ocean, is mainly caused by the basin's freshwater budget and the thermal expansion of the water column due to warming (Stanev et al., 2000; Goryachkin and Ivanov 2006; Jevrejeva et al, 2006; Cazenave et al., 2010). The relative contribution of different components of the Black Sea level budget has been investigated in a number of earlier studies (e.g. Simonov and Altman, 1991; Stanev et al., 2000, 2002; Peneva et al., 2001; Tsimplis et al., 2004; Goryachkin and Ivanov, 2006; Graek et al, 2010; Ilyin et al., 2012; Volkov and Landerer, 2015; Volkov et al., 2016; Aksoy, 2016). The estimates of the Black Sea level rise over the 20th century, based on tide gauge records, range from 1.5 to 2.5 mm/year (Boguslavsky et al., 1998; Reva, 1997; Tsimplis and Spencer, 1997; Goryachkin and Ivanov 2006), which agrees with ~1.8 mm/year of the global MSL rise during the 20th century (Church et al. 2004). Based on satellite altimetry measurements during 1993-2010, the global and the Black Sea MSL then rose at a faster rate of ~3.1 mm/year (Church et al., 2011; Avsar et al. 2015). Both the tide gauge and altimetry records show that sea level trends in the Black Sea are not constant over time (e.g. Goryachkin and Ivanov 2006, Kubryakov and Stanichnyi, 2013): MSL was rising at a very high rate of ~28 mm/year in 1993-1999 (Ducet et al., 1998, Stanev et al., 2000; Cazenave et al,

Удалено: I

Удалено: basin

Удалено: long-term

Удалено: basin

Удалено:

Удалено: changes

Удалено: trends

Удалено: changes

Удалено: and its intensification

2002, Goryachkin et al., 2003; Vigo et al., 2005; Yildiz et al., 2008), and then it began to **fall** by ~3 mm/year in 1999-2007 (Ginzburg et al., 2011).

The basin-wide satellite altimetry measurements have revealed that the Black Sea level change is not uniform, which is related to the dynamic factors that redistribute water within the basin (Stanev et al., 2000, 2001; Korotaev et al., 2001). The main feature of the Black Sea dynamics is the cyclonic Rim current flowing along the continental slope. The general cyclonic circulation results in a lower sea level in the interior of the basin and a higher sea level along the coast (Blatov et al., 1984; Simonov and Altman, 1991, Oguz et al., 1993; Stanev et al., 1990, 2000; Korotaev et al., 2001). It has been shown that the seasonal and interannual variability of the Black Sea circulation is driven by changes in the wind curl averaged over the basin (Blatov et al., 1984; Stanev, 1990, 2000; Korotaev, 2001; Graek et al., 2010; Kubryakov et al., 2016). 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 towards the coast. The compensating vertical uplift (Ekman suction) in the center of the sea brings cold and saline deep water to the surface, while warm and fresher surface water is pushed towards the coast, **where downwelling motions occur** (Stanev, 2000, 2004; Korotaev, 2001; Kubryakov et al., 2016). 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, 2017).

Long-term changes of the Black sea dynamics impact on the spatial heterogeneity of the sea level rise in the basin. Particularly, Vigo et al. (2005) and later Kubryakov and Stanichnyi (2013) showed that the Black Sea coastal **sea level is rising** 1.5-2 times faster than the sea level in the center of the basin. In this paper, we investigate the spatial structure of the Black Sea level trends, its relation to dynamic processes in the basin and atmospheric forcing. We also explore whether historic tide gauge measurements (prior to satellite altimetry era) can be corrected for dynamic effects in order to obtain better estimates of the basin-mean sea level change in the past.

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 Black Sea 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 **metres** 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). That is why the investigation of the spatial variability of the sea level rise in the Black Sea and its reasons is an important task for the coastal applications.

2. Data and Methods

In this study, we used the regional satellite altimetry maps of sea level anomalies (SLA) from Jan 1993 to Dec 2014, produced by Ssalto/Duacs and distributed by Aviso, with support from CNES (www.aviso.oceanobs.com). The maps are based on measurements by up to four satellites and produced on a daily basis with a horizontal grid spacing of 1/8°. The data are routinely corrected for instrumental errors and geophysical effects.

A dynamic atmospheric correction (DAC) is applied to account for the dynamic response of the sea level to atmospheric pressure and wind forcing (Carrere and Lyard, 2003). The DAC combines the high frequencies (periods < 20 days) of a barotropic model of Lynch and Gray (1979) with the low frequencies (periods > 20 days) of the inverted barometer correction, and it significantly reduces the aliasing of the high-frequency sea level variability, especially in coastal regions (Volkov et al., 2007). While it has been suggested that the IB correction may not be necessary in the almost enclosed Black Sea (Ginzburg et al., 2011), a recent study by Volkov et al. (2016) showed

that on the interannual and longer time scales the Black Sea level responds to changes in atmospheric pressure in an inverted barometer manner, i.e. 1 mbar change of pressure corresponds to approximately 1 cm change in sea level.

Over the recent years, a great progress in improving the near-coast measurements has been achieved, which has benefited the regional altimetry products, such as the Mediterranean and Black Sea products. The improvement in the coastal areas of the Mediterranean Sea has recently been demonstrated by Marcos et al. (2015). A reasonable agreement between tide gauge records and near-coast SLA in the Black Sea has also been documented (Volkov and Landerer, 2015; Korotaev et al., 1998; Stanev et al., 2000, 2001; Goryachkin et al., 2003, 2003; Kubryakov et al., 2013; Avsar et al., 2015).

The absolute dynamic topography of the Black Sea was computed as the sum of the mapped SLA and a “synthetic” mean dynamic topography of Kubryakov and Stanichny (2011). The zonal and meridional components of the surface geostrophic velocities (u_g, v_g) were computed from the absolute dynamic topography using geostrophic

equations:
$$u_g = -\frac{g}{f} \frac{\partial h}{\partial y}; \quad v_g = \frac{g}{f} \frac{\partial h}{\partial x},$$

where h is the absolute dynamic topography; f is the Coriolis parameter; and g is the gravitational acceleration. To

describe the basin-scale variability we use the magnitude of geostrophic velocity $U = \sqrt{u^2 + v^2}$

The variability of the Black Sea level is decomposed in two parts (e.g. Stanev et al, 2000; Graek et al, 2010): i) the basin-averaged sea level change related to the time-variable amount of water contained in the basin and steric effects and ii) the dynamic sea level (DSL) change due to the redistribution of water within the basin. Because the response of SLA to the low-frequency variability of the Black Sea water budget is almost spatially uniform (Korotaev et al., 2001), the DSL at a particular location (x, y) is defined as the difference between the local SLA(x, y) and the basin-mean sea level, MSL : $DSL(x, y) = SLA(x, y) - MSL$.

In addition to satellite altimetry data, to compute the wind curl over the Black Sea in 1979-2014, we used the 6-hourly ERA-Interim winds at 10 metres height (Dee et al., 2011). It has been shown that the ERA-Interim winds over the Black Sea coincide well with in-situ meteorological measurements, and describe the variability of the wind direction better than other reanalyses (e.g. MERRA, NCEP, WRF) (Garmashov et al., 2016).

To study the variability of eddy dynamics in the Black Sea, we used an automated “winding angle” (Chaigneau et al., 2008) eddy identification method, described in detail in Kubryakov and Stanichny (2015a,b). For each eddy, the method defines its radius and maximum orbital velocity. At each grid point, it also defines the frequency of eddy observation, i.e. the fraction of the total time when the grid point is located within an eddy. Because the Black Sea anticyclones are larger and more powerful than cyclones (Oguz et al, 1993; Kubryakov and Stanichny (2015a)), in this study we only consider the properties of anticyclones.

3. Results

3.1 Interannual variability of the Black Sea level

The variability of the Black Sea MSL is shown in Fig.1a. In 1993-2014, MSL was rising at a rate of 3.15 ± 0.13 mm per year, in agreement with Avsar et al. (2015). This value coincides well with the global MSL 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 ± 0.07 mm/year in

Удалено: ¶

Удалено: Sea level trends (

1992-1999; then it was **falling** at a rate of -3.0 ± 0.15 mm/year in 2000-2007; and in 2007-2014 it **rose** again at a rate of 10.0 ± 0.15 mm/year (Fig. 1b). Similar rates of sea level change during the first two periods have already been reported by Vigo et al. (2005) and Yildiz et al. (2008), based on the analysis of satellite altimetry and gravimetry data.

- 5 The spatial distribution of sea level trends in the Black Sea over the 1993-2014 time period (Fig. 1c) shows that the sea level change is spatially non-uniform in agreement with earlier analyses of the along-track altimetry data (Vigo et al. 2005, Kubryakov and Stanichniy, 2013). Sea level in coastal and shelf areas was rising at rates $3.2-4 \pm 0.2$ mm/year, which is approximately 1.5-2 times greater than in the center of the basin ($1.5-2.5 \pm 0.25$ mm/year). The largest trend exceeding 5.0 ± 0.25 mm/year is observed in the southeastern part of the basin. The observed spatial differences in the sea level rise are related to the redistribution of water mass within the basin.
- 10

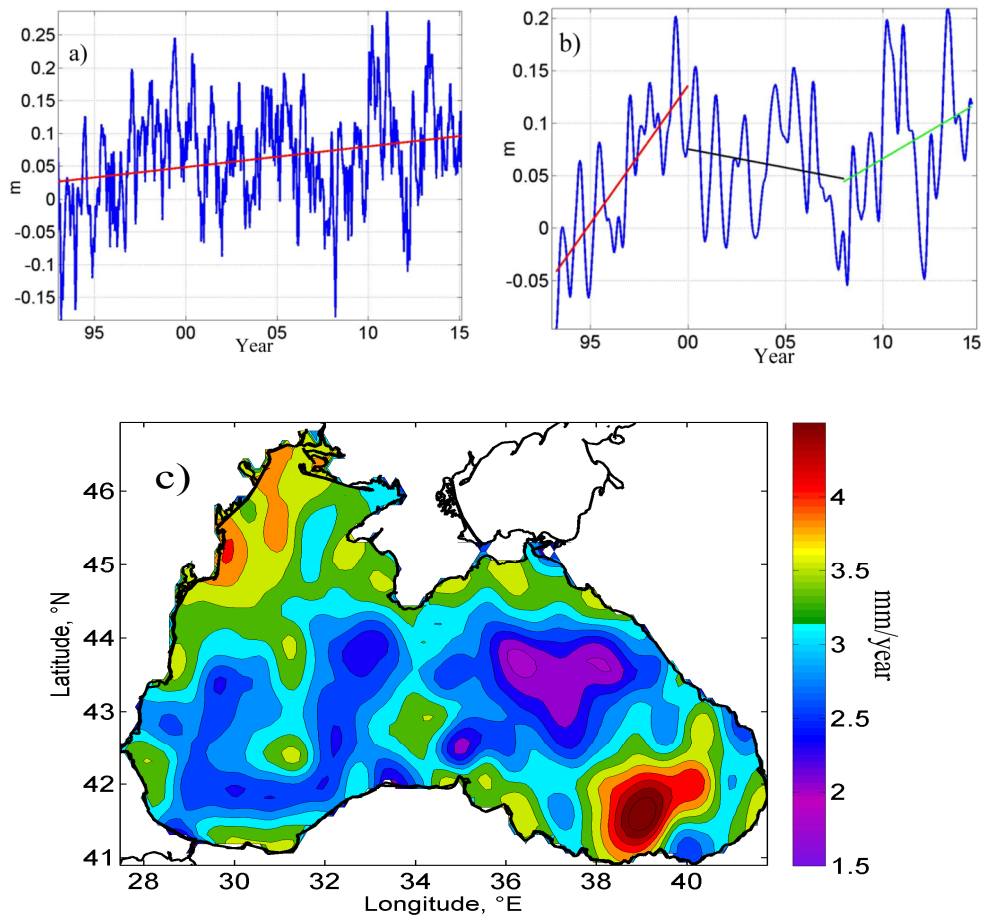


Figure 1: The basin-averaged Black Sea level from satellite altimetry data: a) daily time series (blue curve) and a linear trend for the 1993-2014 time interval; b) time series smoothed with a 90-day moving average and trends for 1993-1999, 2000-2007, **2007-2014**; c) spatial distribution of the 1993-2014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

15

3.2 Wind-driven dynamic sea level variability

The main feature of the Black Sea dynamics is the cyclonic Rim current encircling the basin over the continental slope. The predominantly cyclonic wind curl over the basin causes the near-surface divergence in the basin's interior and downwelling motions and associated deepening of pycnocline near the continental slope. This process generates horizontal density gradients that drive the along-slope baroclinic flow (Stanev et al., 1990, 2000; Korotaev et al., 2001).

The seasonal variability of the Black Sea DSL is driven by the seasonal changes of the wind curl (Stanev et al., 2000; Korotaev et al., 2001). In winter, the wind curl increases and intensifies the Ekman divergence, as a result the DSL falls in the center of the basin and rises at the basin periphery (Fig.2a). In summer the wind curl and divergence weakens and the water accumulated along the coast flows back into the basin's interior (Fig.2b).

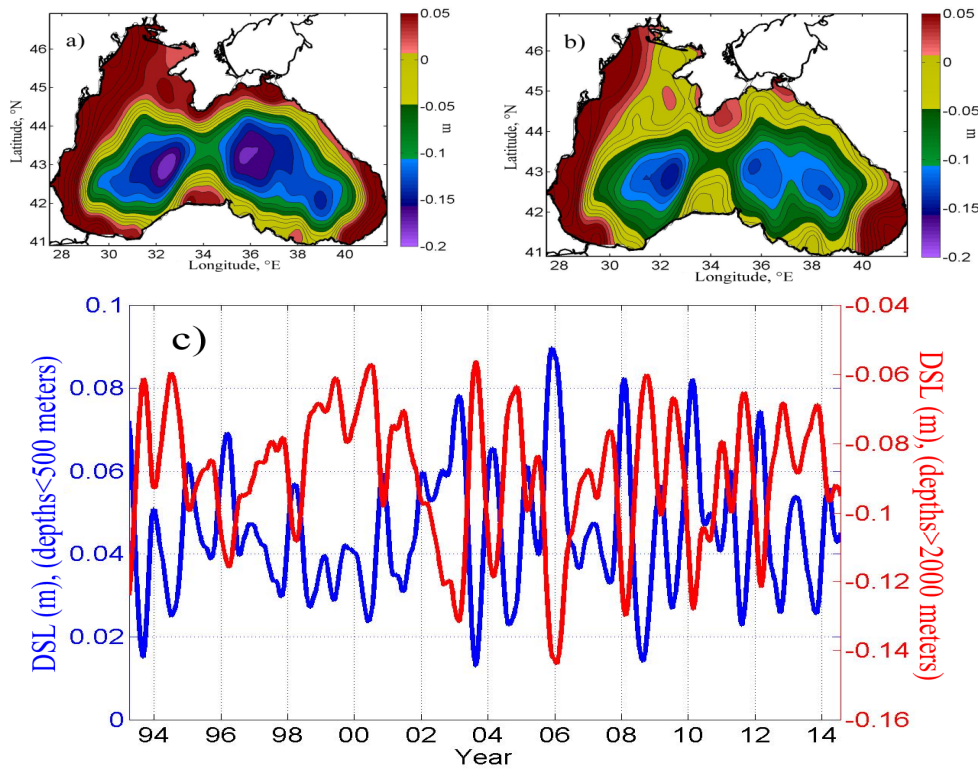


Figure 2: Average DSL distribution in (a) February, (b) July and (c) DSL variability averaged over the central part (depths more than 2000 metres) and along the basin's periphery (depths less than 500 metres). Time series are smoothed by 90-days moving average

By the means of Ekman dynamics, fluctuations in the wind curl over the Black Sea lead to changes in DSL also on the longer time scales: strengthening of the wind curl increase the DSL at the basin periphery and lower DSL at the basin center. As a result, the DSL in the basin's interior and periphery have an opposite variability with correlation coefficient ($k=-0.91$) (fig.2c) that was shown in previous studies (Stanev et al.,2000; 2001).

Displayed in Figure 3 is correlation map between the wind curl averaged over the basin and DSL at each grid point for the time series smoothed by a 365-day moving average (only interannual variability is retained). The correlation coefficients are significantly positive (>0.6) in shallow regions, with depths generally <500 m, and they are significantly negative in the deep interior of the basin (<-0.6). The correlation map is consistent with the second EOF of the altimetry-derived sea level, which has been attributed to the effect of the wind curl (Grayek et al.,2010).

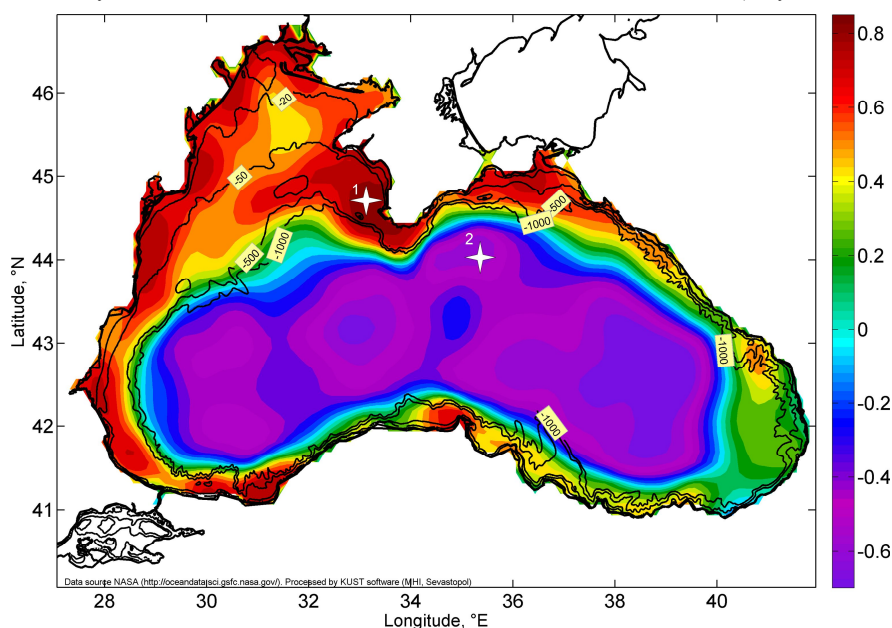


Figure 3: Correlation coefficients between the basin-averaged wind curl and DSL for the time series smoothed with a 365-day moving average (only interannual signals are retained). Solid black lines show isobaths (20, 50, 500, 1000 metres).

Удалено: е

The correlation coefficients are high over the continental slope of the basin and the shelf areas, including large north-west shelf. Over the continental slope the rise of DSL leads to the downwelling motions, lowering of the pycnocline, that drives the Rim current. In the shallow shelf areas, where stratification is weak, at least in winter months, the observed DSL variability is primarily caused by barotropic motions. The correlation is smaller in the south-east area of the basin, which is known as the area of the Batumi eddy (Oguz et al., 1993; Staneva et al., 2001; Korotaev et al., 2003; Kubryakov, Stanichny, 2015c). Here, the intense eddy dynamics can alter the large-scale DSL changes caused by Ekman transport.

The interannual variability of the basin-averaged wind curl 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.4). At the same time, it is well-seen that the wind curl is 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 $\sim(1 \pm 0.4) \cdot 10^{(-8)}$ 1/s per year, which constitutes about 0.5% of the average value per year. The long-term trend of the wind curl induces a long-term intensification of the basin's cyclonic circulation that is indeed observed by satellite altimetry (Kubryakov et al., 2013, 2016). The mean speed of surface geostrophic currents U in the basin (Fig.4 – blue curve) was rising at an approximate rate of 0.05 ± 0.003 cm/s per year, i.e. by 0.3% per year of the average value.

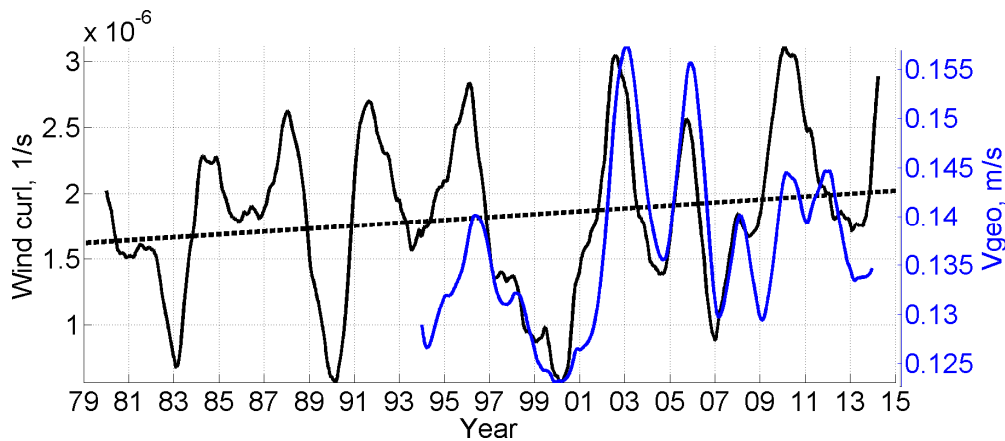


Figure 4: The interannual variability of the basin-averaged wind curl (black curve) in 1980-2014 and the basin-averaged speed of surface geostrophic currents (blue curve) smoothed with a 1-year moving average.

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. For example, figures 5 demonstrate the variability of DSL at two locations shown by crosses in Fig. 3: on the northwestern shelf (33.2°E; 44.7°N) and in the central 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, with the time lag of about two weeks (Kubryakov et al., 2016). The correlation coefficient for the lagged time series is 0.75 for 90-day moving average smoothing, and it is 0.9 for the 365-day moving average smoothing. For the second location, characteristic for the basin's interior, the relationship between the sea level and wind curl is inverse (Fig. 5c,d). Here, the correlation is -0.84 for the time series smoothed with a 90-day moving average and -0.66 for the time series smoothed with a 365-day moving average.

The average range of the interannual oscillations of DSL at the first point is about 5 cm, in close agreement with the amplitudes of the DSL averaged along the basin's periphery (depths less than 500 metres) (Fig.2c). The seasonal amplitudes of DSL reached 10 cm in 2003 and 8 cm in 2006, 2008. Based on tide gauge measurements, the characteristic seasonal amplitudes of sea level at the Black Sea coastal stations is about 20 cm (Goryachkin, Ivanov, 2006). Thus, the seasonal variability of DSL explain up to 50% of the sea level variance and, therefore, makes an important contribution to the total sea level variability in agreement with previous findings (Stanev et al., 2000; Graek et al, 2010).

The linear trends of the DSL and wind curl (Fig. 5) are unidirectional (positive) in the basin's periphery and opposite in the basin's interior. The maximum increase of the cyclonic wind curl over the basin is observed in winter months (Fig. 6). As a result, the strongest intensification of the Black Sea circulation and DSL at the basin periphery (depth less than 500 metres) occurs in winter (Kubryakov et al., 2016). The time required for the Black Sea circulation to adjust to changes in the wind curl is approximately two weeks (see Fig.5a). That is why on the graph of seasonal variability, we see that the maximum DSL trend (March) lags behind the maximum wind curl trend (February) by ~one month (Fig. 6). The similar time lag (1-2 months) between DSL and wind curl variability was obtained in an earlier study of Stanev et al. (2000). Winter-early spring months are characterized by the maximum coastal vulnerability to the DSL rise, which reaches ~1mm/year.

Удалено: ¶

Удалено: usual

Удалено: (Kubryakov et al., 2016)

Удалено: the

Удалено: (

Удалено: ,

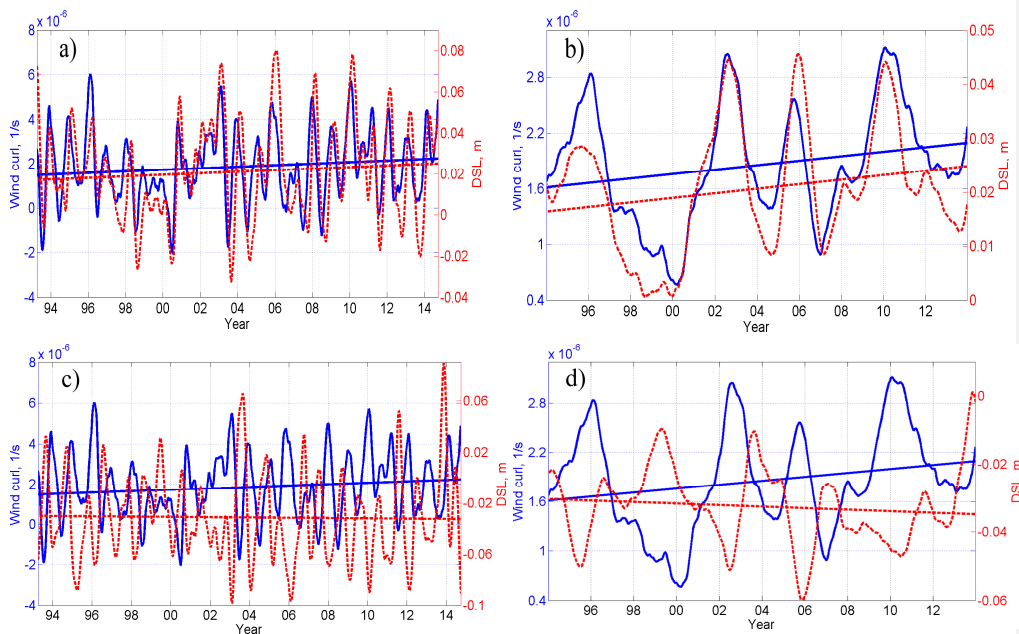


Figure 5: The time series and the linear trends of DSL (red curves) and the basin-averaged wind curl (blue curves): (a, b) at 33.2°E and 44.8°N (the basin's periphery) and (c, d) at 35.4°E and 44.0°N (center of the basin); the time series are smoothed (a, c) with a 90-day moving average time series and with a 365-day moving average.

5

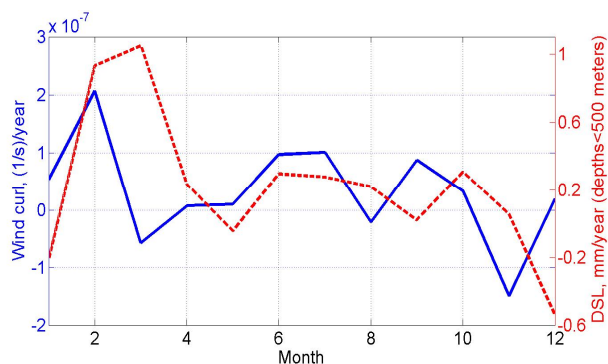


Figure 6: Monthly distribution of the (blue curve) wind curl (1/s per year) and (red curve) DSL trends (mm/year) at the basin periphery

10 Based on the above considerations, the spatial distribution of the Black Sea trends presented in fig.1c can be explained by two factors: a) the rise of the average 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 magnitude of the sea level rise related to the strengthening of the large-scale circulation and the Ekman divergence in the basin can be estimated from Fig.7a, which shows the DSL=S-MSL trends map. It is equal to approximately 0-0.5 mm/year at the basin periphery and approximately 1-15

Удалено: the

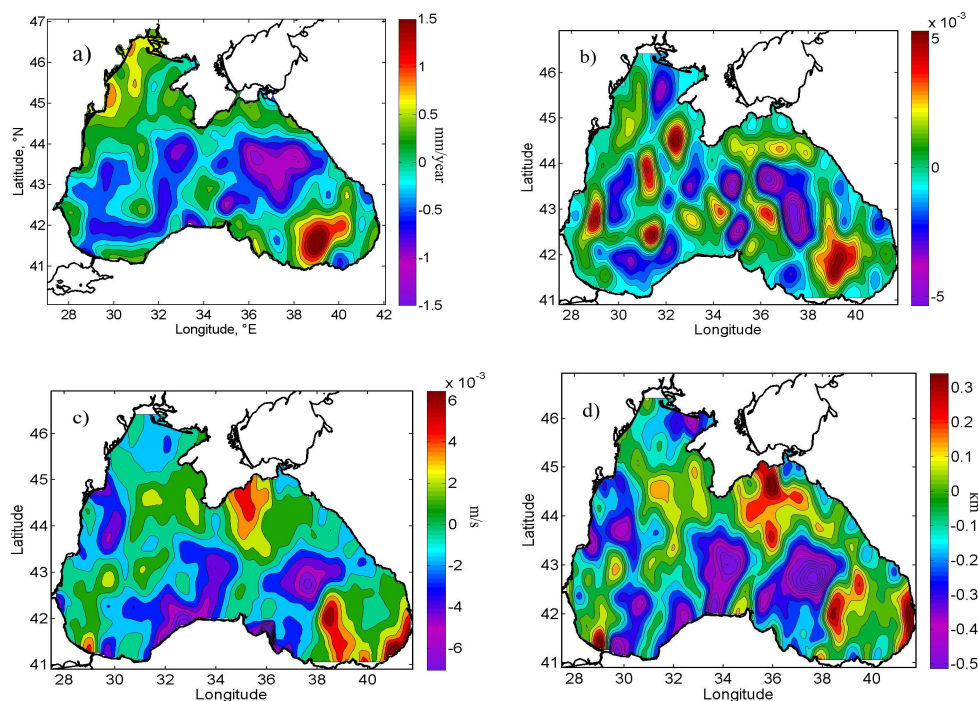
Удалено: f

mm/year in the basin's interior, The value of the DSL trend constitutes about 15%-50% of the basin-averaged sea level rise (3.15 mm/year) and, therefore, plays an important role in sea level rise estimates.

3.3. The impact of mesoscale variability on the sea level trends

Удалено:

- 5 Several localized maxima are observed in the spatial distribution of the Black Sea DSL trends (Fig. 7a). 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 coincidence of the local maximum of sea level trend and the Batumi eddy position suggests that this maximum is related to the eddy intensification.



10 **Figure 7: 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;**

- 15 Displayed in Figures 7b-7d are the linear trends of (b) frequency, (c) orbital velocity, and (d) radius of the Black sea eddies, estimated using the “winding angle” method. Although the estimated trends are rather patchy due to complex eddy dynamics, it is still possible to identify some significant trends of the radius and orbital velocity of anticyclones that coincide with the areas of stronger sea level rise. The spatial pattern of the largest DSL trend (Fig. 7a) is located in the area of quasi-stationary Batumi anticyclone in the southeast corner of the Black Sea. It is corresponded well with the spatial pattern of the largest eddy frequency trend (Fig. 7b). Risen values of trends of eddy radius and orbital velocity are observed on the western and eastern sides of this pattern. This suggests that the Batumi anticyclone was expanding in the zonal direction, and began to occupy larger area in the south-east part of
- 20

Удалено: and

the basin. Anticyclonic Batumi eddy induces convergent motions, which depends on their intensity. Convergence leads to the consequent rise of the dynamic sea level in the areas in which eddy expands.

The interannual variability of the anticyclonic eddy properties at the point 38.5°E, 42°N, that corresponded to the largest DSL trend in the southeast of the Black Sea is shown in Figures 8. Both the frequency of eddies and their intensity were increasing with time. The frequency of eddies doubled from 4% in the early 1990s to ~8% in 2010s (Fig. 8a). The maximum orbital velocity of anticyclones at this point almost tripled from 0.14 m/s in 1995 to ~0.4 m/s in 2014 (Fig. 7b). Observed intensification of anticyclonic motions cause the largest sea level rise in the southeast corner of the Black sea. Several other local maxima in the trends of the frequency of anticyclones coincide with the positions of increased sea level trends. For example, a local DSL maximum near 31.5°E and 44°N (Fig. 7a) is close to a local maximum in the trend of the frequency and velocity of anticyclones. The variability of the eddy dynamics is one of the reasons of the observed patchiness of the Black Sea level trends.

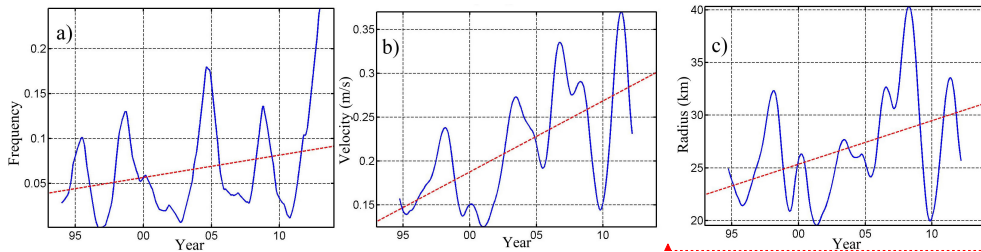


Figure 8: a) Frequency b) the maximum orbital velocity c) radius of anticyclones at 38.5°E and 42°N, derived from altimetry data.

- Удалено: cornerselevatededdy radius
- Удалено: The Displayed in Fig. 7 are the i
- Удалено: I
- Удалено: is illustrated
- Удалено: f
- Удалено: of (a) the frequency of anticyclones (% of time) (b) the maximum orbital velocity of anticyclones, at the point (39°E, 41.5°N
- Удалено:)
- Удалено: illustrate the changes of anticyclones properties at the point (38.5°E, 42°N)
- Удалено: , located where the local sea level trend is maximum.
- Удалено: number
- Удалено: detected at this point and
- Удалено: as
- Удалено: was increasing by 0.005 per year (0.5% per year) from 5% in 1990s to 15% in the 2010s
- Удалено: increased
- Удалено: two times from average values
- Удалено: fig
- Удалено: 7
- Удалено: also
- Удалено: in
- Удалено: increased more than twice
- Удалено: 13
- Удалено: 26
- Удалено: fig
- Удалено: Theincreased. Tpattern of the largest eddy frequency trend (Fig. 7b) Black Seas and sthe location The largest of eddy radius and orbital velocityernernspatternssize of the was expandingin the zonal direction
- Удалено: 6
- Удалено: in the western part near 31.5°E and 42.5°N
- Удалено:
- Отформатировано: Английский (США)
- Удалено: 8

3.4. Reconstruction of DSL variability using wind data

Before the advent of high-resolution altimetry in 1992, tide gauges were used to estimate the basin-averaged sea level rise. As demonstrated above, coastal sea level measurements include DSL, but the latter does not reflect changes in the Black Sea water volume (Stanev et al., 2001). Therefore, the tide gauge trends should be corrected for DSL in order to obtain better estimates of the basin-averaged sea level trends. To determine the DSL correction, we computed the linear regression coefficients (k) between the basin-averaged wind curl (W) and DSL at each grid point: $DSL=k*W+\epsilon$ (Fig 9), where ϵ is the error term.

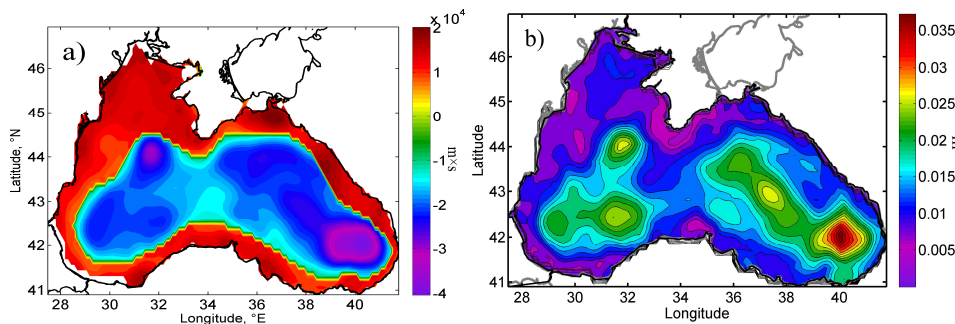


Figure 9: a) Linear regression coefficients (k) between the basin-averaged wind curl and DSL ($DSL=k*W+\epsilon$); b) Standard deviations of the error term (the difference between the altimetry-derived and reconstructed DSL); time series are smoothed with a 1-year moving average.

Удалено: 8

Then we reconstructed DSL using the regression coefficients and the wind curl. Standard deviations of the error term on the interannual time scale (the time series are smoothed with a 1-year moving average) are rather small along the coast and over the northwestern shelf (Fig. 9b), generally less than 1 cm. In the interior of the basin and, in particular, in the area of the Batumi anticyclone, the errors are larger (2-3 cm), which is apparently due to the impact of mesoscale dynamics. Displayed in Fig. 10 are the altimetry-derived and reconstructed DSL at a location near the south Crimean coast (33.2°E; 44.7°N). The correlation coefficients between the time series are 0.85 and 0.88 for the time series smoothed by 90-day (Fig. 10a) and 365-day (Fig. 10b) moving averages, respectively. Our analysis suggests that a simple linear regression is capable of capturing both the seasonal and interannual variability of DSL from the wind data alone.

Удалено: 8b

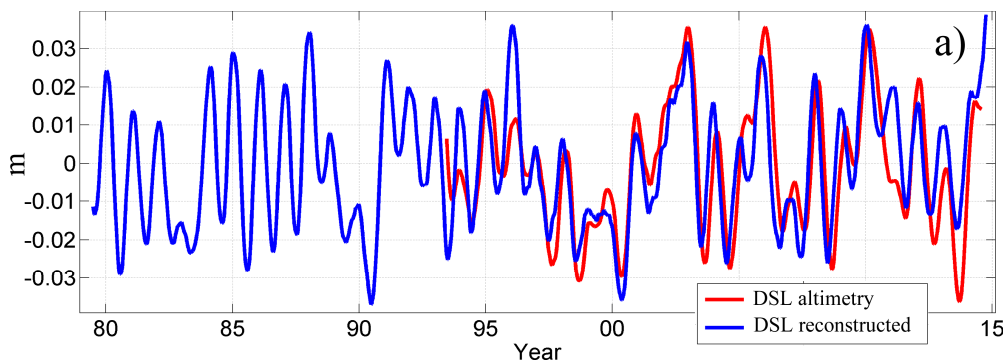
Удалено: 9

Удалено: 9a

Удалено: 9

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, the DSL trend over the 1979-1992 period at a point near the south Crimean coast (33.2°E; 44.7°N) is 0.3 mm/year. Then, this value should be subtracted from nearby tide gauge records that are used to compute the basin-averaged sea level change in the Black Sea. It should be noted that this method accounts only for changes in the large-scale circulation, but does not account for trends in mesoscale dynamics. Nevertheless, based on our analysis it is reasonable to assume that the mesoscale dynamics mostly affects the basin's interior, while the coastal sea level variability is mostly driven by Ekman dynamics (fig. 9b).

Удалено: 8b



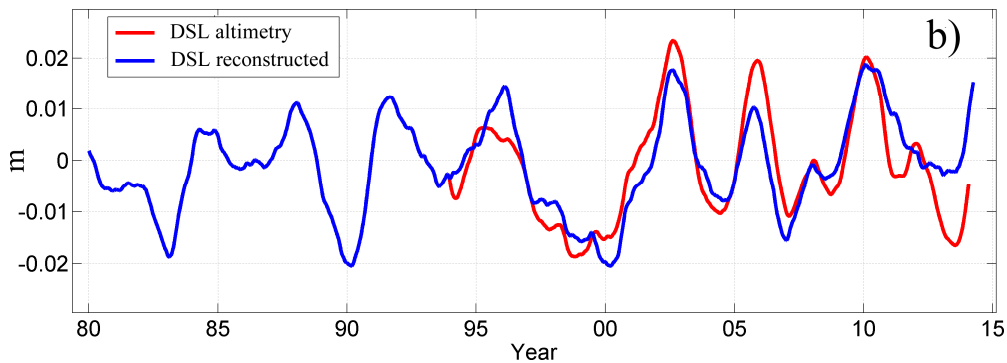


Figure 10: The time series of the altimetry-derived DSL (red curve) and DSL at 33.2°E, 44.7°N, reconstructed from the wind curl (blue curve): the time series are smoothed (a) with a 90-day moving average and (b) with a 365-day moving average.

Удалено: 9

Удалено: DSL

Удалено:

5 4 Conclusions

The climatic changes of the large-scale and mesoscale dynamics in the Black Sea significantly impact sea level trends in different parts of the basin. While the basin-averaged sea level has been rising by 3.15 mm/year, sea level trends vary from 1.5 mm/year in the interior to 3.5-3.8 mm/year in coastal areas and to 5 mm/year in the southern part of the sea. We have shown that the observed long-term intensification of the cyclonic wind curl strengthened divergence in the center of the basin, which caused a rise of sea level along the Black Sea coast and over the northwestern shelf, and a lowering of sea level in the interior of the basin. In addition, we show that 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 resulted in an excess sea level rise in the southern part of the basin by ~1.2 mm/year.

Удалено: increasing

Удалено: w

Удалено: an increase

Удалено: decrease

Удалено: a westward

Удалено: w

15 The DSL associated with the redistribution of water masses within the Black Sea varies considerably on seasonal and interannual time scales. For example, the maximum trend of the wind curl causing an associated DLS rise of ~1 mm/year is observed in winter months. The amplitudes of the DSL variability can reach 10 cm in different years, and they contribute up to 50% of the total annual sea level signal in agreement with Stanev et al. (2000). We have demonstrated that the DSL variability can be reconstructed using the linear regression between the wind curl and
20 DSL. The reconstructed DSL can be used to correct historical (prior to altimetry era) estimates of the basin-averaged sea level rise, based on coastal tide gauge measurements.

Acknowledgments

Kubryakov A.A. was supported by RFBR, according to the research project No. 16-35-60036 mol_a_dk. Stanichny S.V. was supported by RSF, the research grant 15-17-20020. D.L. Volkov was supported by the NASA Ocean Surface Topography Science Team program (grant NNX13AO73G) and by the base funds of NOAA Atlantic Oceanographic and Meteorological Laboratory.

References

Aksoy, A. O. (2016). Investigation of sea level trends and the effect of the north atlantic oscillation (NAO) on the Black sea and the eastern Mediterranean sea. Theoretical and Applied Climatology, 1-9.

- Alpar, B. 2009, Vulnerability of Turkish coasts to accelerated sea-level rise, *Geomorphology*, 107: 58–63.
- Allenbach, K., Garonna, I., Herold, C., Monioudi, I., Giuliani, G., Lehmann, A., & Velegrakis, A. F. (2015). Black Sea beaches vulnerability to sea level rise. *Environmental Science & Policy*, 46, 95-109.
- Avsar, N. B., Kutoglu, S. H., Erol, B., & Jin, S. (2015). Coastal risk analysis of the Black Sea under the sea level rise. In FIG Working Week (pp. 17-21).
- Avsar, N. B., Jin, S., Kutoglu, H., & Gurbuz, G. (2016). Sea level change along the Black Sea coast from satellite altimetry, tide gauge and GPS observations. *Geodesy and Geodynamics*, 7(1), 50-55.
- Boguslavsky, S. G., Kubryakov, A. I., & Ivashchenko, I. K. (1998). Variations of the Black Sea level. *Physical Oceanography*, 9(3), 199-208.
- 10 Blatov, A. S., Bulgakov, N. P., Ivanov, V. A., Kosarev, A. N., & Tujilkin, V. S. (1984). Variability of hydrophysical fields in the Black Sea. *Gidrometeoizdat, Leningrad*, 239.
- Cazenave, A., Bonnefond, P., Mercier, F., Dominh, K., & Toumazou, V. (2002). Sea level variations in the Mediterranean Sea and Black Sea from satellite altimetry and tide gauges. *Global and Planetary Change*, 34(1), 59-86.
- 15 Cazenave, A., & Llovel, W. (2010). Contemporary sea level rise. *Annual review of marine science*, 2, 145-1
- Carrère, L., & Lyard, F. (2003). Modeling the barotropic response of the global ocean to atmospheric wind and pressure forcing: comparisons with observations. *Geophysical Research Letters*, 30(6).
- Chaigneau, A., Gizolme, A., & Grados, C. (2008). Mesoscale eddies off Peru in altimeter records: Identification algorithms and eddy spatio-temporal patterns. *Progress in Oceanography*, 79(2), 106-119.
- 20 Church, J. A., White, N. J., Coleman, R., Lambeck, K., & Mitrovica, J. X. (2004). Estimates of the regional distribution of sea level rise over the 1950-2000 period. *Journal of climate*, 17(13), 2609-2625.
- Church, J.A.; Clark, P.U.; Cazenave, A.; Gregory, J.M.; Jevrejeva, S.; Levermann, A.; Merrifield, M.A.; Milne, G.A.; Nerem, R.S.; Nunn, P.D.; Payne, A.J.; Pfeffer, W.T.; Stammer, D.; Unnikrishnan, A.S.: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* ed. by: Stocker, T.F.; Qin, D.; Plattner, G.-K.; Tignor, M.; Allen, S.K.; Boschung, J.; Nauels, A.; Xia, Y.; Bex, V.; Midgley, P.M., Cambridge, UK, 1137-1216, 2013.
- 25 Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., ... & Vitart, F. (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, 137(656), 553-597.
- 30 Garmashov, A. V., Kubryakov, A. A., Shokurov, M. V., Stanichny, S. V., Toloknov, Y. N., & Korovushkin, A. I. (2016). Comparing satellite and meteorological data on wind velocity over the Black Sea. *Izvestiya, Atmospheric and Oceanic Physics*, 52(3), 309-316.

- Ginzburg, A. I., Kostianoy, A. G., Sheremet, N. A., & Lebedev, S. A. (2011). Satellite altimetry applications in the Black Sea. In *Coastal Altimetry* (pp. 367-387). Springer Berlin Heidelberg.
- Goryachkin, Y. N., Ivanov, V. A., Lemesko, E. M., & Lipchenko, M. M. (2003). Application of the altimetry data to the analysis of water balance of the Black Sea. *Physical Oceanography*, 13(6), 355-360.
- 5 Goryachkin, Y. N., Ivanov, V. A. (2006). The Black Sea Level: Past, Present and Future. MHI NASU, Sevastopol (in Russian).
- Grayek, S., Stanev, E. V., & Kandilarov, R. (2010). On the response of Black Sea level to external forcing: altimeter data and numerical modelling. *Ocean dynamics*, 60(1), 123-140.
- Ilyin, Yu.P., Repetin, L.N., Belokopytov, V.N., Goryachkin, Yu.N., Dyakov, N.N., Kubryakov, A.A., Stanichny, S.V., 2012. Meteorological conditions of the seas of Ukraine. Black Sea, vol. 2. ECOSY-Gidrofizika, Sevastopol p. 421 (in Russian).
- Jevrejeva S, Grinsted A, Moore JC, Holgate S. 2006. Nonlinear trends and multiyear cycles in sea level records. *J. Geophys. Res.* 111:C09012, doi:10.1029/2005/JC003229
- 15 Korotaev, G. K., Saenko, O. A., Koblinsky, C. J., Demishev, S. G., & Knyshev, V. V. (1998). An accuracy, methodology, and some results of the assimilation of the TOPEX/Poseidon altimetry data into the model of the Black Sea general circulation. *Earth Res. Space*, 3, 3-17.
- Korotaev, G.K., Saenko, O.A., Koblinsky, C.J. (2001), Satellite altimetry observations of the Black Sea level. *Journal of Geophysical Research* 106, 917-933.
- 20 Korotaev G., Oguz T., Nikiforov A., and C. Koblinsky (2003), Seasonal, interannual, and mesoscale variability of the Black Sea upper layer circulation derived from altimeter data. *J. Geophys. Res.*, 108 (C4), 3122, doi:10.1029/2002JC001508.
- Kos'yan, R., Kuklev, S., Khanukaev, B., & Kochergin, A. (2012). Problems of the coasts erosion in the North-Eastern Black Sea Region. *Journal of Coastal Conservation*, 16(3), 243-250.
- 25 Kubryakov, A. A., & Stanichny, S. V. (2011). Mean Dynamic Topography of the Black Sea, computed from altimetry, drifter measurements and hydrology data. *Ocean Science*, 7(6), 745-753.
- Kubryakov, A. A., & Stanichnyi, S. V. (2013). The Black Sea level trends from tide gages and satellite altimetry. *Russian Meteorology and Hydrology*, 38(5), 329-333.
- 30 Kubryakov, A. A., & Stanichny, S. V. (2015a). Mesoscale eddies in the Black Sea from satellite altimetry data. *Oceanology*, 55(1), 56-67.
- Kubryakov, A. A., & Stanichny, S. V. (2015b). Seasonal and interannual variability of the Black Sea eddies and its dependence on characteristics of the large-scale circulation. *Deep Sea Research Part I: Oceanographic Research Papers*, 97, 80-91.

- Kubryakov, A. A., & Stanichny, S. V. (2015c). Dynamics of Batumi anticyclone from satellite data, *Marine Hydrophysical Journal*, 2015,2, p.67-78
- Kubryakov, A. A., Stanichny, S. V., Zatsepin, A. G., & Kremenetskiy, V. V. (2016). Long-term variations of the Black Sea dynamics and their impact on the marine ecosystem. *Journal of Marine Systems*, 163, 80-94.
- 5 Kubryakova, E. A., & Korotaev, G. K. (2017). Mechanism of Horizontal Mass- and Salt-Exchange between the Waters of Continental Slope and Central Part of the Black Sea. *Izvestiya, Atmospheric and Oceanic Physics*, 2017, Vol. 53, No. 1, pp. 102–110.
- Le Traon P-Y., F. Nadal, N. Ducet (1998), An improved mapping method of multisatellite altimeter data. *J. Atmos. Oceanic Technol.* 15:522–534. doi:10.1175/1520-0426(1998).
- 10 Lynch, D. R., & Gray, W. G. (1979). A wave equation model for finite element tidal computations. *Computers & fluids*, 7(3), 207-228.
- Marcos, M., Pascual, A., & Pujol, I. (2015). Improved satellite altimeter mapped sea level anomalies in the Mediterranean Sea: A comparison with tide gauges. *Advances in Space Research*, 56(4), 596-604.
- Oguz, T., V. S. Latun, M. A. Latif, V. V. Vladimirov, H. I. Sur, A. A. Makarov, E. Ozsoy, B. B. Kotovshchikov, V. Eremeev, and U. Unluata (1993), Circulation in the surface and intermediate layers of the Black Sea, *Deep Sea Res., Part I*, 40, 1597– 1612.
- 15 Peneva, E., Stanev, E., Belokopytov, V., & Le Traon, P. Y. (2001). Water transport in the Bosphorus Straits estimated from hydro-meteorological and altimeter data: seasonal to decadal variability. *Journal of Marine Systems*, 31(1), 21-33.
- 20 Palanisamy, H., Cazenave, A., Delcroix, T., & Meyssignac, B. (2015). Spatial trend patterns in the Pacific Ocean sea level during the altimetry era: the contribution of thermocline depth change and internal climate variability. *Ocean Dynamics*, 65(3), 341-356.
- Prandi P., Cazenave A. and Becker M. Is coastal mean sea level rising faster than the global mean? A comparison between tide gauges and satellite altimetry over 1993-2007 / *Geophysical Research Letters*. – 2009. – V.36. - pp. 5602–5606
- 25 Reva, Y. A. (1997). Interannual oscillations of the Black Sea level. *Oceanology of the Russian Academy of Sciences*, 37(2), 193-200.
- Stanev EV (1990) On the mechanisms of the Black Sea circulation. *Earth-Sci Rev* 28:285–319
- Stanev, E. V., Le Traon, P. Y., & Peneva, E. L. (2000). Sea level variations and their dependency on meteorological and hydrological forcing: Analysis of altimeter and surface data for the Black Sea. *Journal Of Geophysical Research-Oceans*, 105(C7), 17203-17216.
- 30 Stanev, E. V., & Peneva, E. L. (2001). Regional sea level response to global climatic change: Black Sea examples. *Global and Planetary Change*, 32(1), 33-47.

Отформатировано: Английский (США)

Отформатировано: Английский (США)

Stanev, E. V., Staneva, J., Bullister, J. L., & Murray, J. W. (2004). Ventilation of the Black Sea pycnocline. Parameterization of convection, numerical simulations and validations against observed chlorofluorocarbon data. Deep Sea Research Part I: Oceanographic Research Papers, 51(12), 2137-2169.

Перемещено вниз [1]: Stanev, E. V., Staneva, J., Bullister, J. L., & Murray, J. W. (2004). Ventilation of the Black Sea pycnocline. Parameterization of convection, numerical simulations and validations against observed chlorofluorocarbon data. Deep Sea Research Part I: Oceanographic Research Papers, 51(12), 2137-2169.

Перемещено (вставка) [1]

Отформатировано: Шрифт: (по умолчанию) Times New Roman, 10 пт, Цвет шрифта: Авто, Английский (Великобритания), Узор: Нет

5 Staneva, J. V., Dietrich, D. E., Stanev, E. V., & Bowman, M. J. (2001). Rim current and coastal eddy mechanisms in an eddy-resolving Black Sea general circulation model. Journal of Marine Systems, 31(1), 137-157.

Tsimplis, M. N., & Spencer, N. E. (1997). Collection and analysis of monthly mean sea level data in the Mediterranean and the Black Sea. Journal of Coastal Research, 534-544.

10

Tsimplis, M. N., Josey, S. A., Rixen, M., & Stanev, E. V. (2004). On the forcing of sea level in the Black Sea. Journal of Geophysical Research: Oceans, 109(C8).

15

Vigo, I., Garcia, D., Chao, B.F. Change of sea level trend in the Mediterranean and Black seas / Journal of Marine Research. – 2005. – V. 63 - pp. 1085-1100

Volkov, D. L., Larnicol, G., & Dorandeu, J. (2007). Improving the quality of satellite altimetry data over continental shelves. Journal of Geophysical Research: Oceans, 112(C6).

Volkov, D. L., & Landerer, F. W. (2015). Internal and external forcing of sea level variability in the Black Sea. Climate Dynamics, 1-14.

20

Volkov, D. L., Johns, W. E., & Belonenko, T. V. (2016). Dynamic response of the Black Sea elevation to intraseasonal fluctuations of the Mediterranean sea level. Geophysical Research Letters, 43(1), 283-290.

Yildiz, H., Andersen, O. B., Kilicoglu, A., Simav, M., & Lenk, O. (2008). Sea level variations in the Black Sea for 1993-2007 period from GRACE, altimetry and tide gauge data. Geophysical Research Abstracts, Vol. 10, EGU2008-A-08684

25

Zatsepin, A. G., Kremenetskiy, V. V., Poyarkov, S. G., Ratner, Y. B., & Stanichny, S. V. (2002). Influence of wind field on water circulation in the Black Sea. Complex Investigation of the Northeastern Black Sea. Nauka, Moscow, 91-105.a