Answer to Reviewer 1

Answer: Thank You for your comments. At first we would like to clarify - the main goal of the study is quantitative estimation of spatial heterogeneity of sea level rise (i.e. average trends of sea level – important climatic signal) in the Black Sea and its relation with dynamic processes.

We don't discuss the water balance, we do not want to introduce the new mechanism driving the Black Sea dynamics, because it is well known from previous studies. We provide this information in the article text during the discussion of the "3.2 Dynamic sea level variability": Here we provide the references on the major researches (not all, of course) dedicated to the study of the impact of the wind curl on the dynamic sea level. Sorry, during the manuscript preparation, we missed one really important reference "Stanev, E. V., P.-Y. Le Traon, and E. L. Peneva, 2000, Seasonal and interannual variations of sea level and their dependency on meteorological and hydrological forcing. Analysis of altimeter and surface data for the Black Sea, J. Geoph. Res., 105, 17203-1721", which is one of the basic studies of altimetric sea level in the Black Sea . However, the results of the (Stanev et al., 2000) are advanced in the later study (Graek et al., 2010) that is cited in the text.

All cited studies provide an explanation about the simple mechanism of the reaction of the basin sea level on the change of the cyclonic wind curl: wind curl intensify the cyclonic circulation, as a result sea level rises on periphery and decreases in the basin center. Again, this is well known issue of the Black sea dynamics, and we do not want to "discover" it.

However, we feel that it is important to illustrate this mechanism to the reader. That is why we provide the figure 2, that brings no new information, but just needed for illustrative purposes (for our opinion). This is in agreement with reviewer comments.

The new in this article is the description of the long-term trends of the Black Sea level related to the long-term trends of the Black Sea dynamics and wind changes. We, for the first gave the quantitive estimations of the impact of the large-scale and mesoscale circulation changes (DSL) on the Black sea level rise and its spatial heterogenity. This is the main novelty of the manuscript.

According to Your comments in the revised version of the manuscript we change the Introduction part completely to more clearly define the manuscript goals and the state of art in this field. We also significantly extend the reference list and we noticeable change the part of the manuscript dedicated to the impact of the wind curl on the large-scale dynamic sea level variability.

Below we provide answers on the reviewer comments step by step:

1) Reviewer: "Unfortunately, the material is presented in such a way that the reader, who is not aware of the research in this field, could get an impression that the analysis of satellite altimeter data in the Black Sea and the understanding based on these data starts in 2016. "

Answer: This is not exactly true, as it was shown above. Article has at least 20 references on papers interpreted altimetry data for the Black Sea since 2001 till 2016. Particularly, one of the first paper describing the Black Sea level from altimetry data is Korotaev, 2001, that is cited in the text. During the discussion of the Black Sea dynamic sea level variability we missed one really important reference "Stanev, E. V., P.-Y. Le Traon, and E. L. Peneva, 2000, Seasonal and interannual variations of sea level and their dependency on meteorological and hydrological forcing. Analysis of altimeter and surface data for the Black Sea, J. Geoph. Res., 105, 17203-1721", which is one of the basic studies on altimetric sea level in the Black Sea. However, the results of the (Stanev et al., 2000) are advanced in the later study (Graek et al., 2010) that is cited in the text.

As, the main goal of this study is the investigation of the sea level trends, the introduction is mostly dedicated to the studies of the Black sea level rise. The review of the studies dedicated to the dynamic sea level variability in the Black Sea is given in section "3.2 Dynamic sea level variability". We believe moved this part in the Introduction to avoid the false impression.

According to Your comments we change the Introduction part completely to more clearly define the manuscript goals and the state of art in this field. We also significantly extend the reference list and we noticeable change the part of the manuscript dedicated to the impact of the wind curl on the large-scale dynamic sea level variability.

2) Reviewer: "I do not know whether the authors are unaware of the research in this field or they purposely presented completely unbalanced presentation of the state of the art… One example is the basic idea of the relationship between wind stress curl and sea level observed from satellites, which is known short after the first satellite altimeter missions…. The second example is the dynamics of coastal and open-ocean sea level (Fig. 2d)."

Answer: Also, we cannot fully agree with the reviewer. The information about previous researches on the dynamic sea level variability is given in section "3.2 Dynamic sea level variability". We provide a shot review about the previous and modern studies, which highlight the basic idea of the relationship between wind stress curl and sea level in a first paragraph:

"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). 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 figure 2 is given to illustrate the basic ideas given in the cited studies, which are crucial to understand the impact of the wind curl on the sea level rise. For our opinion, it is useful for the illustrative purposes. Some readers can be unfamiliar to the Black Sea dynamics (for example specialists that work with tide gauges data), that is why figure 2 is in the text.

We believe that we can improve the phrase in the text:" 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). " to "As it is known (Stanev et al., 2000; Korotaev et al., 2001), 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)."

We significantly extend the reference list and we noticeable change the part of the manuscript dedicated to the impact of the wind curl on the large-scale dynamic sea level variability.We replace the phrase :" 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). " to "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)."

3) Reviewer: Knowing this example, I find nothing new in the statement of authors (p. 11: A simple regression allows to reconstruct both the seasonal and interannual variability of DSL from the wind data alone.)

Answer: As far as we know, the reconstruction of the DSL spatial field from the wind curl data on the interannual time scales was not done before. We'll be very appreciated to obtain references on previous study demonstrated such reconstruction. We think that the results obtained are important for the correction of the sea level rise from the historical tide gauges measurements.

4) **Reviewer:**: "The strong coincidence between basin bathymetry and correlations patterns is well seen". They have to know that this is not coincidence at all. Fig. 3 is just an illustration of the role of the Ekman pumping, which is largely addressed in the Black Sea literature. This "coincidence" reflects the dynamics of pycnocline (sea level just mirrors it)."

Answer: We agree that "Coincidence" is not good term, "similar spatial patterns" is better.

However the reviewer not exactly true interprets observed phenomena. The dynamics of pycnocline is the secondary process defined by wind curl. The wind curl determines the intensity of water divergence from the center to the periphery. The redistribution of the sea level driving by the Ekman transport causes the downwelling motions over the continental slope, and consequent pycnocline displacement.

Moreover, in the shelf areas, (for example in the very large North-Western shelf), where the correlation is also positive and high, we can not talk about pycnocline at all. There is no main pycnocline in this shallow zone. In winter there is no stratification at all, and the dynamic sea level redistribution is caused by barotropic motions.

That is why in manuscript we wrote:

"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)."

And again “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”

In the revised version of the manuscript we rewrite this part of a text as:”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. “

5) Reviewer: I would ask what new they would find when using about a 20-year long data set.

Answer: The main new results of the paper are:

1) The impact of the long-term wind curl change on the intensification of the Black Sea large-scale circulation and increase of the sea level rise in the coastal zone
2) The impact of the changes of the Black sea mesoscale circulation on the sea level rise in the basin
3) The reconstruction of the DSL spatial fields using reanalysis data. It should be used to correct previous estimates of the Black sea level rise in the basin
4) Spatial distribution of the Black Sea dynamic sea level trends

Answer to Reviewer 2

This paper investigates changes in the Black Sea circulation as evidenced by altimetry. These changes are linked, as expected, with the wind forcing which is then used to reconstruct this variability for a period before altimetry started. The work is interesting but not presented carefully and detailed enough and includes a number of significant omissions and misinterpretations. Therefore it cannot be published in its present form. It will require rethinking and rewriting so major revision is recommended. But there is merit in it and can become a useful addition to the existing literature after careful consideration.

Suggested changes:

1. The title would have been better if it was something like “Interannual and decadal changes in the circulation of Black Sea as evidenced from altimetry”. The suggested sea level trends are neither basin wide trends nor coastal trends.

Answer: The goal of this study is to investigate the sea level trends in the basin with the focus on its spatial heterogeneity. It is not dedicated to the study of the Black sea dynamics, which was investigated earlier in the number of studies (e.g. Stanev et al., 2000, 2001; Korotaev, 2001; 2003, Kubryakov et al., 2016.) In this study we provide the quantitative estimates of the spatial variability of the sea level rise in the basin and describe the main reasons of its heterogeneity, which are the long-term changes of the Black sea large-scale and mesoscale dynamics. This is the main novelty of the study, which is dedicated to the understanding of the effects of the Black sea dynamics on the sea level rise in the basin.

Due to Your comments we decided to change the manuscript title on “Impact of basin dynamics on the regional sea level trends in the Black Sea”

2. lines 8-10: altimetry does not measure at coastal areas. Either tide-gauges should be used to substantiate a difference between coastal and open-sea sea level variance or this statement should be changed.

Answer: We respectfully disagree with the reviewer. Altimetry does measure near the coast, but these measurements are less accurate being constrained by the size of the altimeter footprint. Nevertheless, in the recent years, a great progress in improving the near-coast measurements has been achieved, which has affected 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. (Advances in Space Res., 2015). The nearest points of the altimetry along-track measurements is situated at ~ 7 km distance from the coast (see fig.S1 in the attached file). The resolution of the Black sea mapped regional product is 1/8° or ~12.5 km. Regional Black Sea array of mapped altimetry sea level anomalies (MSLA) is produced by the CLS Space Oceanography Division and distributed by Aviso, with support from Cnes (http://www.aviso. oceanobs.com/). In order to be precise we should change the phrase in the Introduction "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" to "the sea level rise varied from 0.15-2.5 mm/year in the central part to 3.5-3.8 mm/year at the periphery of the basin and 5 mm/year in the southwestern part of the sea"

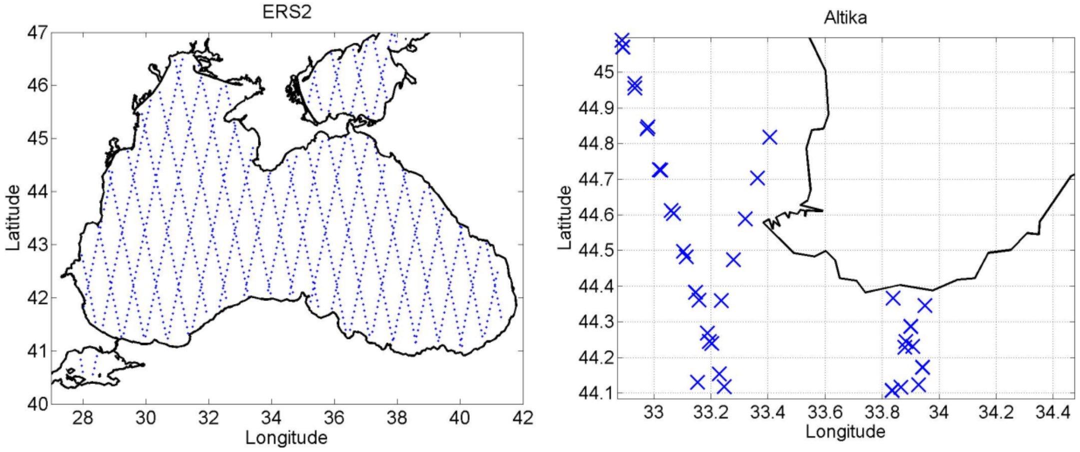

Fig.1 Left - Track position of ERS-2 altimetric measurements from the Black Sea regional dataset; Right – track position of the Saral\Altika near the Crimea. The distance between coast and nearest coastal point is ~ 7 km

We significantly extend the description of the altimetry dataset in the revised version of the manuscript and add information about near-coast measurements of modern altimeters

3. Lines 11-14: If the explanation concerns the period 1993-2014 the relevant forcing should be the same not a different time period.

Answer: We agree with the reviewer. The phrase "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" should be changed to "A long-term increase of the cyclonic wind curl over the basin 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"

We changed the abstract according to Your comments

4. Lines 16-19: How do you know that the variability is "well reconstructed" for the period before altimetry as you have no data?

Answer: We agree with the reviewer. The phrase "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." should be changed to "The DSL variability in the Black Sea depends strongly on the basin-averaged wind curl. In the study we show that the DSL variability on interannual and seasonal time scales can be reconstructed with a reasonable accuracy using simple linear regression of wind curl data from atmospheric reanalysis. Before the emergence of altimetry data the measurements at the periphery of the basin (e.g. coastal tide gauges) were used to estimate the basin-averaged sea level rise. As the DSL trends at the basin periphery do not reflect the change of mean water volume, they should be subtracted for the correct estimation of the basin-averaged sea level trends. The method presented in the study can be used to correct historical estimates of basinaveraged sea level rise on dynamic effects using atmospheric reanalysis data."

We changed the abstract according to Your comments

5. Lines 18-19: Why do tide gauges need corrections for what happens away from the coast? They provide direct measurements of sea level. In any case as altimetry does not provide information closer to ∼30km from the coast this suggestion is erroneous.

Answer: We agree with the reviewer. This statement should be rewritten more precisely. The estimates of the basin-averaged sea level rise from tide gauges needs correction on the dynamic effects, not tide gauges themselves. DSL trends impact on the estimates of the sea level rise, if we measure only at the periphery of the basin. This impact can be subtracted using given in the study method. The nearest points of the altimetry along-track measurements is situated at ~ 7 km distance from the coast (see fig.S1 in the attached file). The resolution of the Black sea mapped regional product is 1/4° or ~12.5 km. Several studies have shown that the data in the closest point of altimetry-track is well correlated with the tide gauges measurements (Korotaev et al., 1998 (in russian); Stanev et al., 2000; Peneva et al., 2001; Goryachkin et al., 2001, 2003 (in russian); Kubryakov et al., 2013; Avsar et al., 2015; Volkov and Landerer, 2015).

We changed the abstract according to Your comments and add information about near-coast measurements of modern altimeters in the Section 2

6. There is significant literature concerning sea level rise for the Black Sea (for example Stanev et al., 2000; 2002; Tsimplis et al, 2004 and Volkov and Landerer- which is referenced) discuss sea level rise in the Black Sea and assessing mass addition to the basin as well as steric effects. These are more relevant than a general discussion of what causes global sea level rise.

Answer: We agree with the reviewer. Several references should be added to the introduction to better represent the previous research.

According to Your comments we change the Introduction part completely and significantly extend the reference list.

7. Section 2 data. Need to describe the dataset properly. While there is a paper (Volkov and Landerer, 2015) which argues that the altimetry data set can be used as is in the Black Sea with the imposed DAC for pressure and wind, their argument is based on comparison with tide gauges and their finding that such a correction does not improve the agreement with tide gauges in RMS terms of monthly values. This does not necessarily mean that there are no "trends" is the pressure and wind fields which are artificially and in a spatially coherent manner added as a correction to the se level field through DAC. Thus in, my view, the physical argument that the constraints imposed by the Turkish Straits to water exchange do not permit the use of DAC is the correct one. The argument about RMS change can only partly justify the use of correction and probably not in the context of trends. In addition to the doubts I have in relation to the atmospheric correction it is unclear which other corrections are used and what is their uncertainty. Do the data have a GIA correction and how large it is? While it is not likely to be large it will provide confidence to the data process to express it clearly.

Answer: We should point out that the main purpose of applying the DAC correction to altimetry data is to reduce the aliasing that results from the barotropic response of the ocean to the variable high frequency atmospheric forcing. For this reason, the use of the DAC correction is necessary. The DAC combines the high frequency bands (periods 20 days) from the inverted barometer (IB) correction. We agree with the reviewer that changes in sea level pressure over the Black Sea (including trends) enter the DAC IB correction, and this can introduce spurious sea level changes. However, this is exactly what Volkov and Landerer (2015) addressed by adding the IB correction back to altimetry data and comparing these data to tide gauges. The result shows that adding back the IB correction does not significantly improve the comparison. The RMS differences reported in the paper refer to month-to-month changes as well as to trends. Note that according to a recent study by Volkov et al (2016 – referenced in the manuscript), the constraints imposed by the Turkish Straits are not anymore effective at the interannual and longer time scales, at which the Black Sea level responds to sea level pressure changes in a pure inverted barometer manner. The use of GIA correction would be necessary for tide gauge records, but we did not use tide gauges in our paper. Please note that we use a standard altimetry product that is routinely corrected for instrumental errors and geophysical effects. It is beyond the scope of our manuscript and not necessary for the objectives of the study to present details on the corrections applied to the altimetry product (the details can be found in dedicated literature that is referenced on the AVISO web site).

In the revised version of the manuscript we significantly extend the description of the altimetry dataset, add information about altimetry data processing, near-coast measurements of modern altimeters and its comparison with tide gauges data in the Black Sea.

8. The general uncertainties on the altimetry trends need also to be addressed. While the uncertainty for global trends has been stated to be 0.4-0.6 mm/yr (with one exception of 0.9 mm/yr) several statements about larger uncertainties in regional trends exist. An uncertainty of 1 mm/yr would render some of the suggested spatial variance in trends insignificant though of course there are some strong gradients demonstrated.

Answer: We agree with the reviewer. We will add the estimates of the data uncertainties and trend uncertainties to the revised version of the paper.

We add the estimates of the trend uncertainties in the revised version of the manuscript

9. The same point about uncertainty and trends holds for all the physical parameters used. Trends are stated without much consideration of their significance.

Answer: We agree with the reviewer. We will add the estimates of the trend uncertainties to the revised version of the paper.

We add the estimates of the trend uncertainties in the revised version of the manuscript

10. My understanding of the circulation features of the Black Sea suggests strong seasonality. This paper does not deal with this at all. Are these trends consistent during the year or are they an expression of strengthening of seasonal circulation? This requires extra work.

Answer: The Section 3.2 (Paragraph 1-3) and figure 2 describes the seasonal variability of the Black Sea dynamic sea level. The increase of the cyclonic wind curl on interannual time scale leads to the intensification of the basin cyclonic circulation, as a result sea level rises on periphery and decreases in the basin center. This effect is well seen on the interannual time scales for the time series smoothed with a 365-day moving average (see fig.4 b,d; fig.5 b,c), i.e. this effect is observed for yearly-averaged data. The seasonal variability does not affect the estimates of the average DSL trends.

Due to your comments we decided to add the analysis of the seasonal changes of the DSL trends in the manuscript. These analysis shows that the winter-early spring months are characterized by the maximum coastal vulnerability to the DSL rise, which reaches ~1mm/year. Thank You, we believe it is a valuable result for our studies.

11. The figures should demonstrate the limitations of altimetry by leaving the 30-40 km near the coast blank rather than closing the contouring. This is done for figures 6b,c and d but not for Fig 6a or any other contour plot. With the Black Sea at around 260km at its narrowest having 60-80 km of information lost is a significant percentage of area.

Answer: As we mentioned above, altimetry provides measurements near the coast and the accuracy of these measurements has been improved. A reasonable comparison with tide gauges (Volkov and Landerer, 2015) suggests that the use of near-shore data points in AVISO product is justified. Therefore, we respectfully disagree with the reviewer and decide not to leave the nearshore regions blank. The nearest points of the altimetry along-track measurements is situated at ~ 7 km distance from the coast (see fig.S1). Several studies have shown that the data in the closest point of altimetrytrack is well correlated with the tide gauges measurements (Korotaev et al., 1998 (in Russian); Stanev et al., 2000; Peneva et al., 2001; Goryachkin et al., 2001, 2003 (in russian); Kubryakov et al., 2013; Avsar et al., 2015; Volkov and Landerer, 2015). In this study we use the standard mapped satellite sea level anomaly product without any extrapolation. The resolution of the Black sea mapped regional product is 1/8° or ~12.5 km.

In the revised version of the manuscript we add some information about altimetry data processing and its comparison with tide gauges data

12. The straight lines at Figure, 5 and 7b (trends) are not persuasive. A step change seems also a good alternative.

Answer: We agree that in these figures the linear trends can vary for different periods of time. However, the main task of this study is to understand the spatial variability of the Black sea level trends during the whole investigation period. That is why in figures 5 and 7b we use approximation by linear function to understand the average changes of the investigated parameters.

Impact of basin dynamics on the regional sea level trends in the Black Sea

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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 an increase of sea level in coastal and shelf areas and a decrease in the basin's interior. And second, an extension of the Batumi anticyclone to the west and its intensification resulted in ~1.2 mm/year higher rates of sea level rise in the southwestern part of the sea. Further, we demonstrate that the 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

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 was rising at a stronger 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, 2002, Goryachkin et al., 2003; Vigo et al., 2005; Yildiz et al., 2008), and then it began to decrease 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 (Stanev, 2000; Korotaev, 2001; Kubryakov et al., 2016). In summer, the cyclonic wind curl weakens, Ekman divergence reduces and the water accumulated along the coast flows back into the basin's interior (Zatsepin et al., 2002; Kubryakova, Korotaev, 2016).

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 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. 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 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). 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

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, from which we derived the surface geostrophic currents, was computed as the sum of the mapped SLA and a "synthetic" mean dynamic topography of Kubryakov and Stanichny (2011). 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 meters 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).

3. Results

3.1 Sea level trends

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 1992-1999; then it was decreasing at a rate of -3.0±0.15 mm/year in 2000-2007; and in 2007-2014 it continued to increase 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.

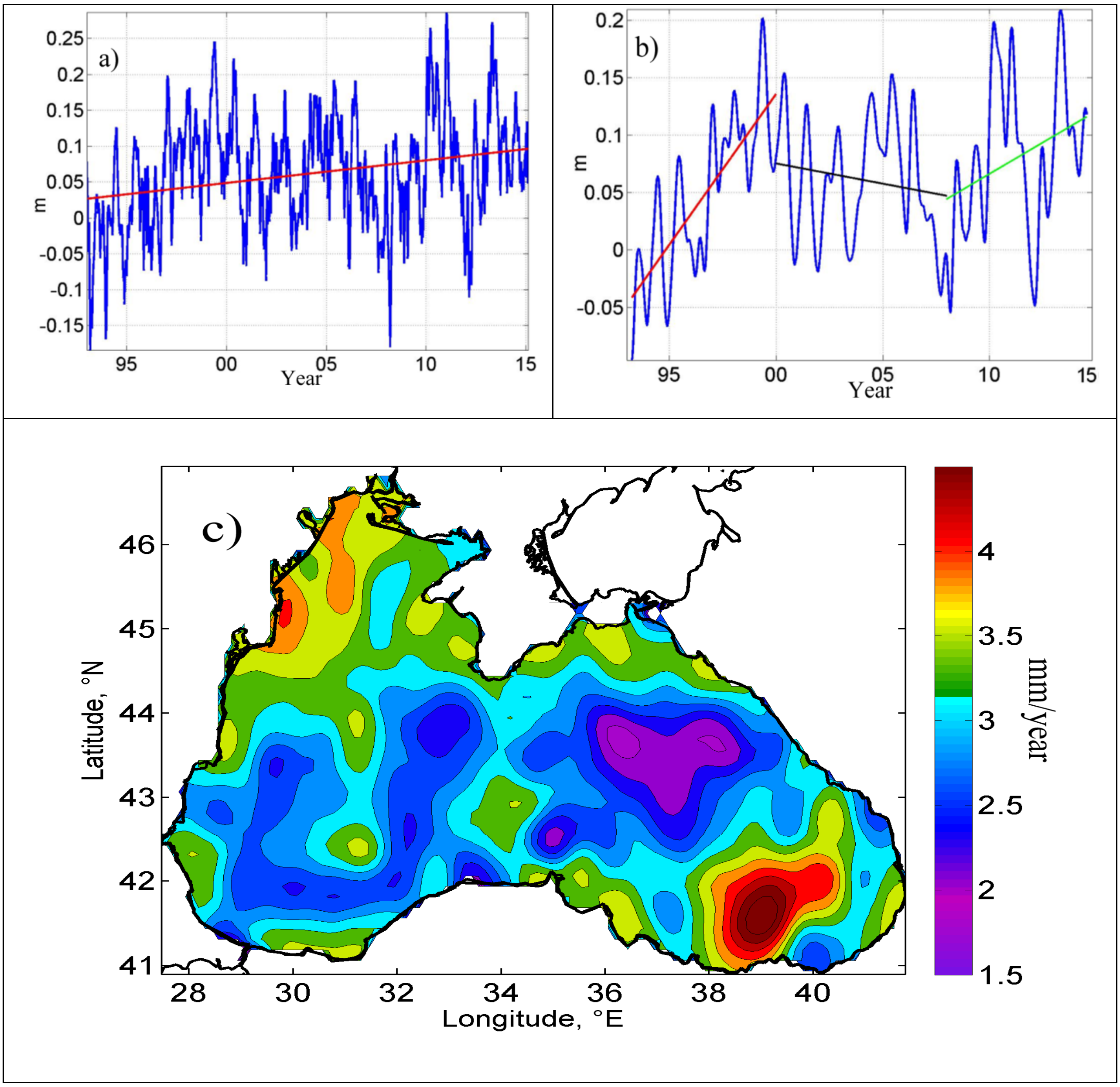

Figure 1: The basin-averaged Black Sea level from satellite altimetry data: a) daily time series (blue curve) and a linear trend for the 1993-2014 time interval; b) time series smoothed with a 90-day moving average and trends for 1993-1999, 2000-2007, 2017-2014; c) spatial distribution of the 1993-2014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

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±0.2 mm/year, which is approximately 1.5-2 times greater than in the center of the basin (1.5-2.5±0.25 mm/year). The largest trend exceeding 5.0±0.25 mm/year is observed in the southwestern part of the basin. The observed spatial differences in the sea level rise are related to the redistribution of water mass within the basin.

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 fall 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).

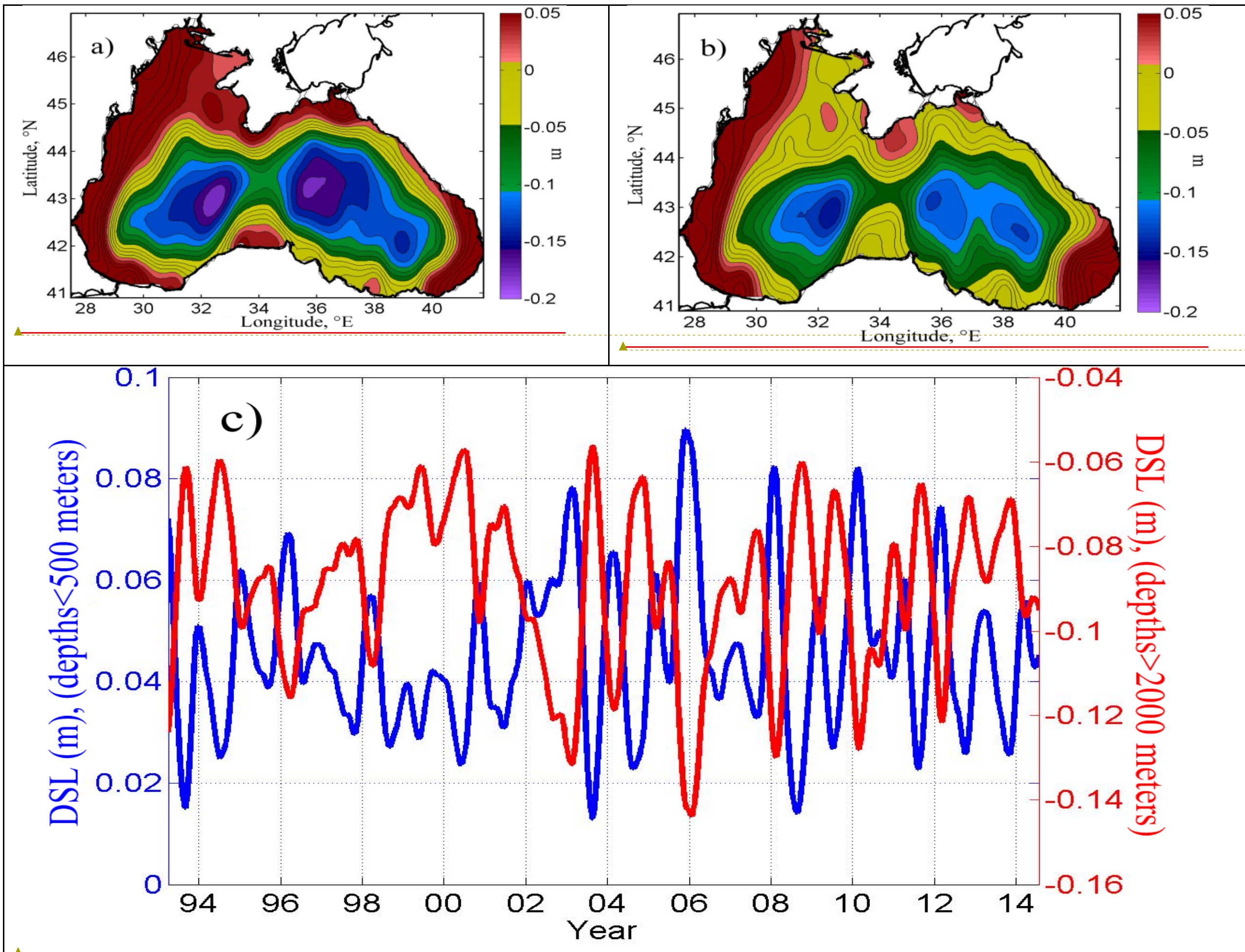

Figure 2: Average DSL distribution in (a) February, (b) July and (c) DSL variability averaged over the central part (depths more than 2000 meters) and along the basin's periphery (depths less than 500 meters). Time series are smoothed by 90-days moving average

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).

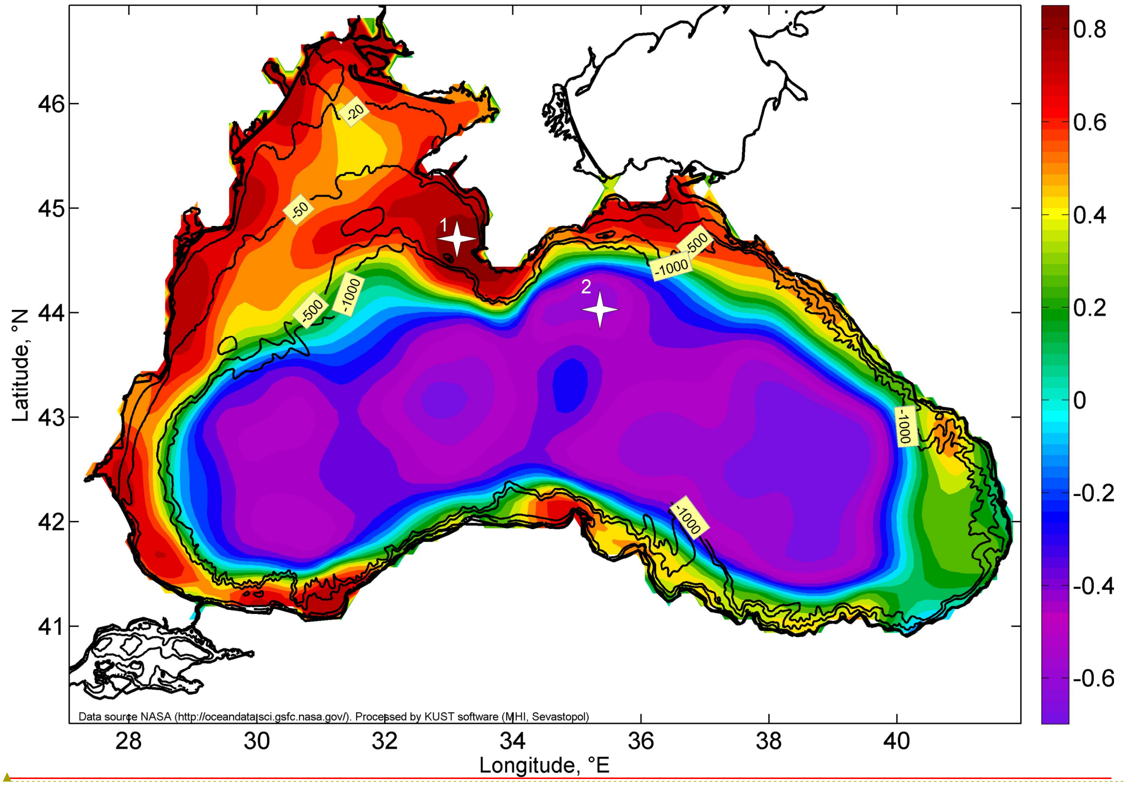

Figure 3: Correlation coefficients between the basin-averaged wind curl and DSL for the time series smoothed with a 365-day moving average (only interannual signals are retained). Solid black lines show izobathes (20, 50, 500, 1000 meters).

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; 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 in the basin (Fig.4 – blue curve) was rising at an approximate rate of 0.5±0.03 cm/s per year, i.e. by 0.3% pee year of the average value.

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. The time lag of about two weeks between the two time series can be interpreted as the time required for water parcels to drift from the central part of the basin to its periphery due to Ekman dynamics (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.

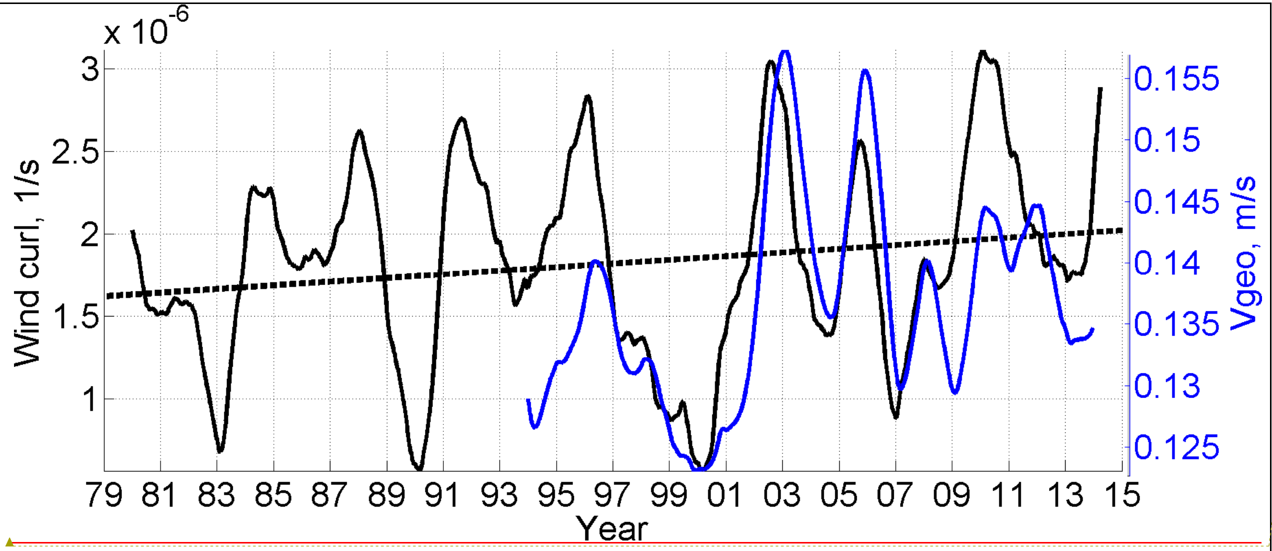

Figure 4: The interannual variability of the basin-averaged wind curl (black curve) in 1980-2014 and the basin-averaged speed of surface geostrophic currents (blue curve) smoothed with a 1-year moving average.

The average range of the interannual oscillations of DSL at the basin periphery is about 5-6 cm, in close agreement with the amplitudes of the DSL averaged over the shallow areas of the Black Sea (Fig.2c). The seasonal amplitudes of DSL reached 10 cm in 2003 and 8 cm in 2006, 2008. Based on tide gauge measurements, the seasonal amplitudes of sea level at most 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 meters) 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 (Kubryakov et al., 2016) (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). Winter-early spring months are characterized by the maximum coastal vulnerability to the DSL rise, which reaches ~1mm/year.

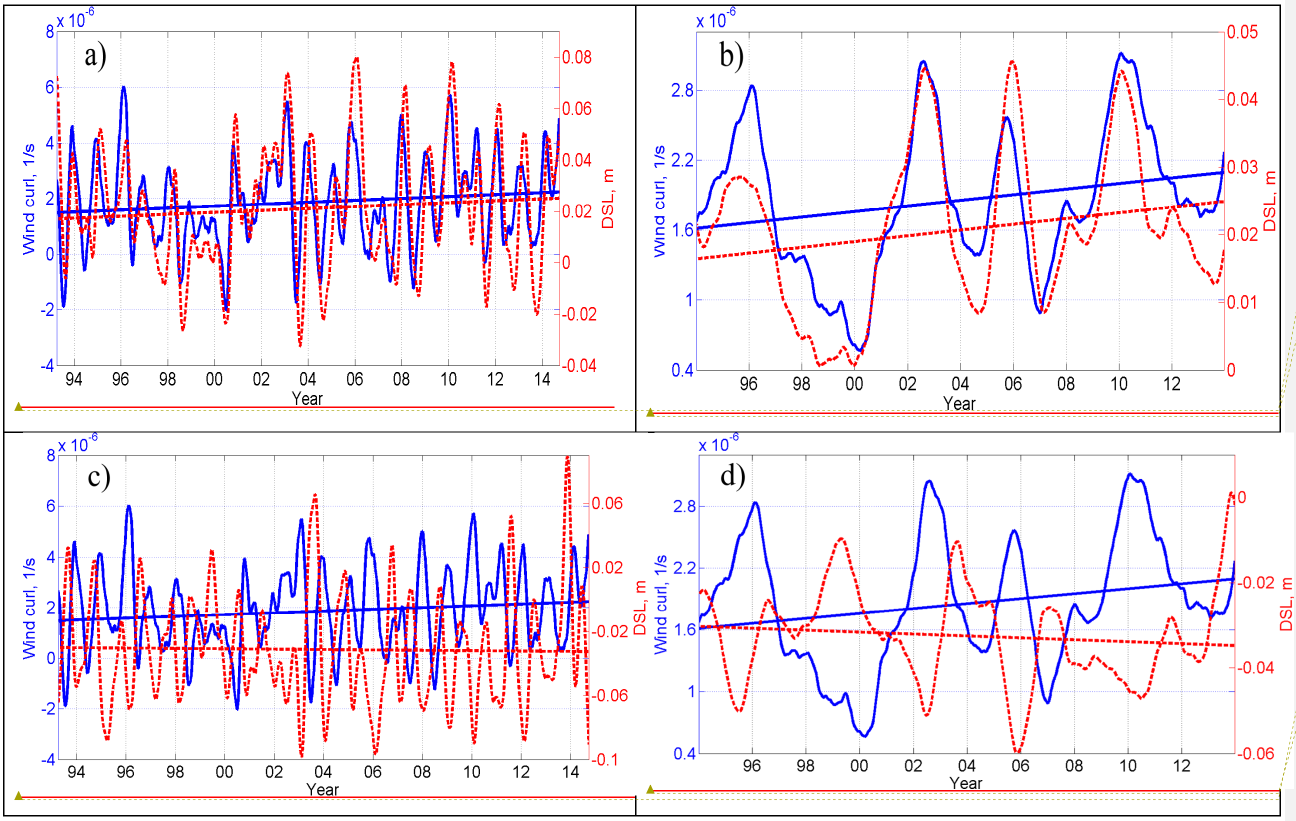

Figure 5: The time series and the linear trend s of DSL (red curves) and the basin-averaged wind curl (blue curves): (a, b) at 33.2°E and 44.8°N (the basin's periphery) and (c, d) at 35.4°E and 44.0°N (center of the basin); the time series are smoothed (a, c) with a 90-day moving average time series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

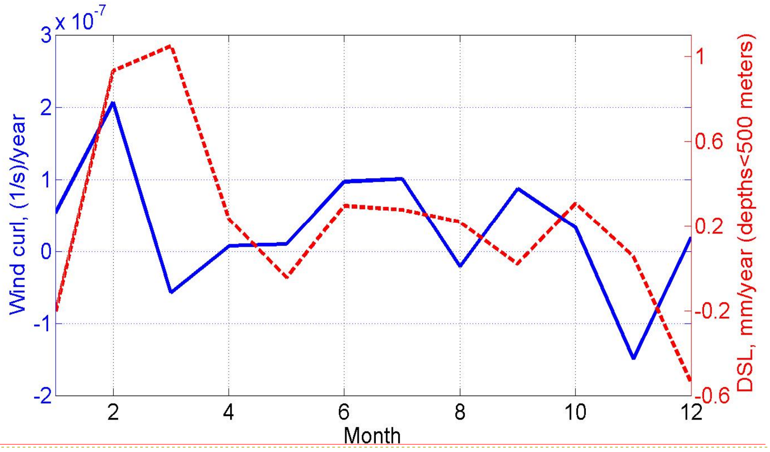

Figure 6: Monthly distribution of the (blue curve) wind curl (1/s per year) and (red curve) DSL trends (mm/year) at the basin periphery

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 total sea level trend at the periphery is S=MSL+DSL, while the total sea level trend in the central part is S=MSL-DSL. The DSL trend (Fig. 6a) is equal to approximately 0-0.5 mm/year at the basin periphery and approximately 1-15 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. The value of the DSL trend constitutes about 15%-50% of the basin-averaged sea level rise and, therefore, plays an important role in sea level rise estimates.

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

Several localized maxima are observed in the spatial distribution of the Black Sea DSL 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 coincidence of the local maximum of sea level trend and the Batumi eddy position suggests that this maximum is related to the 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. A descriptive analysis of eddy characteristics and their seasonal and interannual variability in the Black Sea 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 percentage of the total time when a particular 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)), here we only consider the properties of anticyclones.

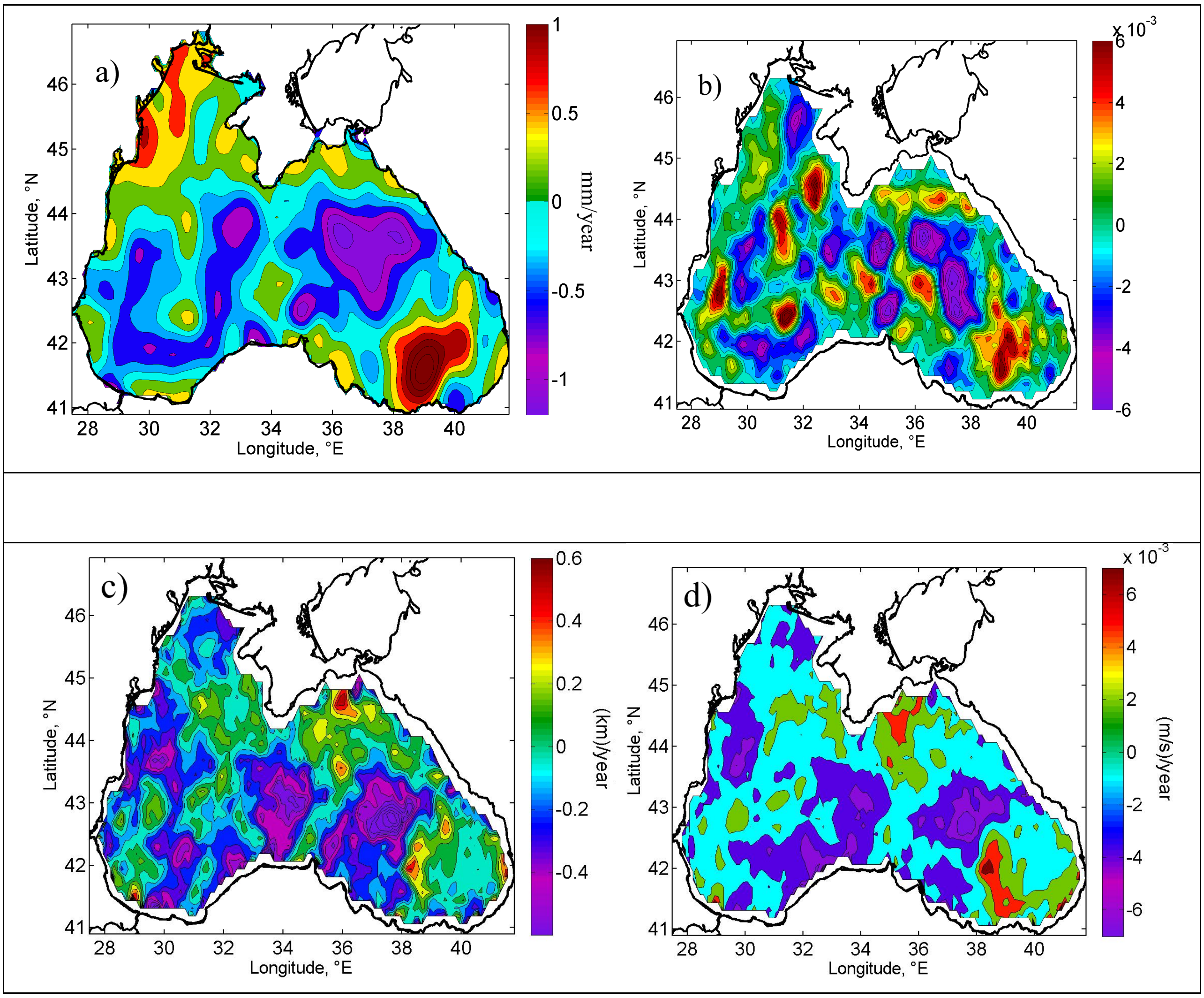

Figure 6: Spatial distribution of a) DSL trends; b) Trends in the frequency of anticyclones in 1993-2014; c) Trends in the radius of anticyclones in 1993-2014; d) Trends in the maximum orbital velocity of anticyclones in 1993-2014;

Displayed in Fig. 7 are the interannual variability of (a) the frequency of anticyclones (% of time) (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).

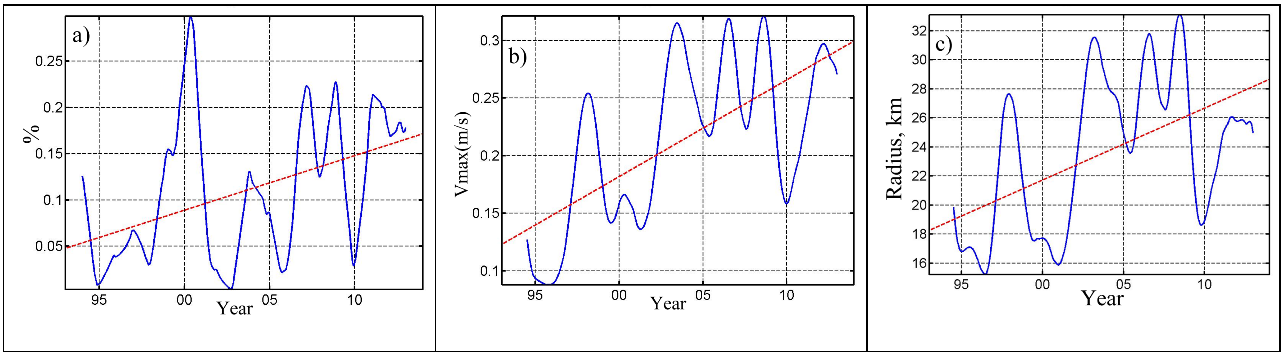

Figure 7: a) Frequency b) the maximum orbital velocity c) radius of anticyclones at 39°E and 41.5°N, derived form altimetry data.

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 - Fig.6d, 7c) and its slight displacement to the west. These changes are illustrated by the trends of frequency, radius and orbital velocity of anticyclones (Fig. 6 b, c, d). Stronger trends of these parameters are observed in the southeastern part of the basin near the western periphery of the Batumi anticyclone (at around 39°E and 42°N).

Based on the observations, we suggest that an 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. 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. 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 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: $DSL=k*W+\varepsilon$ (Fig.8), where ε is the error term.

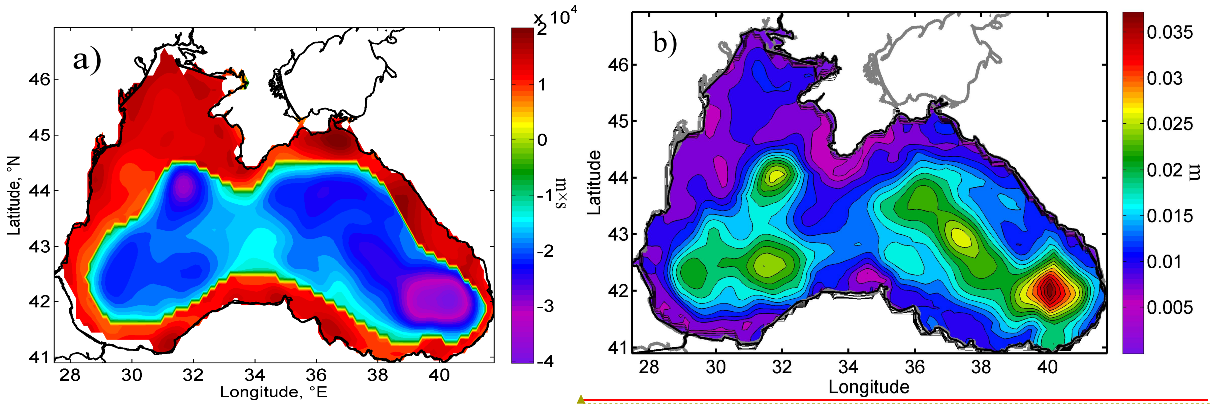

Figure 8: a) Linear regression coefficients (k) between the basin-averaged wind curl and DSL (DSL=k*W+ε); b) Standard deviations of the error term (the difference between the altimetry-derived and reconstructed DSL); time series are smoothed with a 1-year moving average.

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. 8b), generally less that 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. 9 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. 9a) and 365-day (Fig. 9b) 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.

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. 8b).

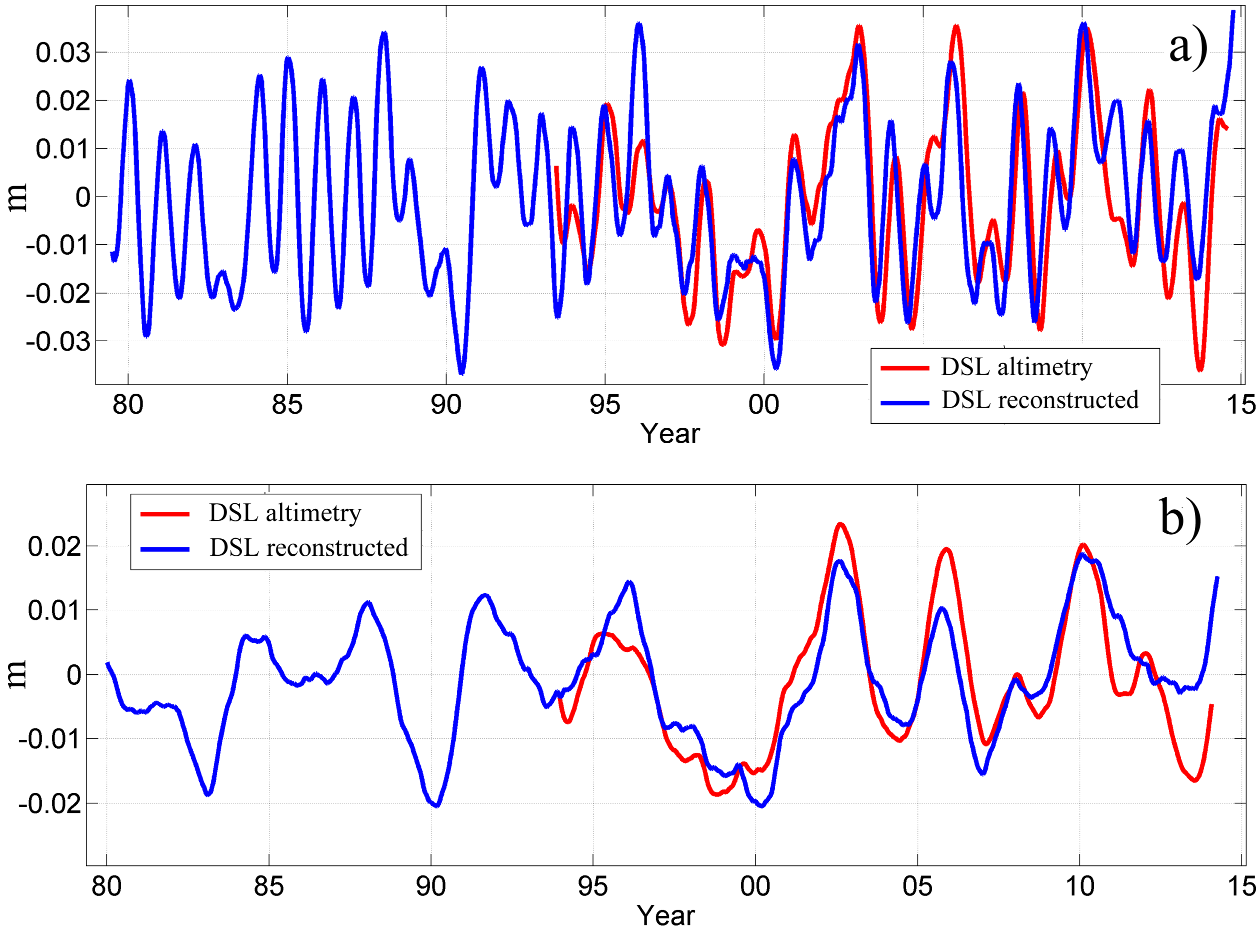

Figure 9: The time series of the altimetry-derived DSL (red curve) and DSL reconstructed from the wind curl (blue curve): the time series are smoothed (a) with a 90-day moving average and (b) with a 365-day moving average.

4 Conclusions

The climatic changes of the large-scale and mesoscale dynamics in the Black Sea significantly impact sea level trends in different parts of the basin. While the basin-averaged sea level has been increasing 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 southwestern 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 an increase of sea level along the Black Sea coast and over the northwestern shelf, and a decrease 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, a westward extension of the Batumi anticyclone 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 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 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.

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