

Reply to comments from the reviewers and summary of the major changes made in the revised manuscript OS-2018-2

We strongly appreciate the reviewers' suggestions and comments that served to improve the article. In response to them, first, we added results of numerical modelling that supported the results obtained from analysis of satellite imagery. Second, we clarified methods of detection of surface-advected outflows from the Sea of Azov to the Black Sea and bottom-advected inflows in the opposite direction based on agreement between Chl-a and TSM satellite imagery. Third, we modified the interpretation of influence of wind forcing on inflows from the Black Sea to the Sea of Azov and provided a more thorough physical background based on both satellite data and numerical modelling. Finally, we adopted many specific comments and recommendations from the reviewers, reworked the structure of the manuscript, and improved the quality of English text and figures. The detailed reply to reviewers comments and description of changes made in the manuscript are given below.

1. In this paper, the authors consider the Sea of Azov (SA) as an estuary and investigate a flow exchange between SA and the adjacent Black Sea (BS) by means of remote sensing. As a proxy for the buoyant outflow from SA into BS they use Chl-a, although on page 5 (lines 22-25) they state that SST, Chl-a and TSM “are prone to significant variability and/or do not act as passive tracers, which hinders their direct application for accurate identification” of buoyant outflow from SA.

Response:

Thank you for this valuable comment. SST, Chl-a, and TSM indeed are prone to significant variability and straightforward usage of these individual characteristics for detection of outflow from SA to BS can be misleading. Thus, in the revised version of the manuscript we used more comprehensive joint analysis of SST, Chl-a, and TSM. Inflow events from SA to BS were identified by elevated concentration of Chl-a in the Kerch Strait and the adjacent coastal area of the Black Sea, because Chl-a has the lowest short-term variability among the considered sea surface characteristics and are not affected by wind/wave-induced sediment resuspension. If an inflow event was detected, we analyzed areas of elevated TSM, Chl-a, and elevated (in summer) or reduced (in winter) SST associated with formation of the Azov plume (AP) in the northeastern part of the Black Sea. If general forms and spatial scales of these areas were similar, we defined borders of AP basing on gradient of TSM that is the most stable passive tracer of AP in absence of episodic wind-induced bottom resuspension events. If areas of TSM, Chl-a, and SST anomalies were not consistent with each other, we assumed that areas of elevated TSM and reduced SST (in winter) were modified by wind-induced resuspension and mixing of AP with subjacent sea. In this case we defined borders of AP basing on gradient of Chl-a that is the most stable tracer of AP during intense wind forcing conditions. These issues were described in the text. Also we applied a calibrated hydrodynamic modelling using the BSAS12 model to prove the results obtained from the analysis of satellite imagery. Salinity distributions simulated by BSAS12 in the study region showed good agreement with detection of AP and BP at satellite imagery, that is explicitly described in the revised version

of the manuscript and illustrated by Figures 2, 8, 11. Thus, the applied method of identification of AP and BP and the obtained results are supported by both satellite data and numerical modelling.

2. As a proxy for the BS water inflow into SA, the authors use TSM, which they have discarded as a reliable marker for buoyant water just one page earlier (i.e., page 7, lines 5-8). They have to rely on TSM signal now, because the BS inflow propagates near the bottom and does not produce immediate signature on the surface.

Frankly, I don't think that TSM signal can provide any reliable information about the presence of BS water at the bottom, it just tells us about the wind-induced resuspension of sediments.

10 Response:

TSM is not a reliable marker of SA water in the Black Sea because TSM increases over shallow areas in case of resuspension of bottom sediments. Thus, areas of elevated TSM can be induced by both sediment resuspension and spreading of SA water in the Black Sea. However, spreading of BS water in the Sea of Azov is indicated by reduced values of TSM in the shallow area adjacent to the Kerch Strait. Thus, resuspension of bottom sediments which increases TSM at the study region can not be misleading for detection of SA water indicated by reduced TSM especially at shallow areas. Thus, TSM is not a reliable marker of SA water in the Black Sea, but is a reliable marker of BS water in the Sea of Azov. Moreover, in the revised version we analyzed both TSM and Chl-a, and identified SA water in the Black Sea as areas of reduced TSM and Chl-a. This procedure provides more confidence in detection of SA water, as compared to usage of only TSM. As a result, the scheme of identification of inflow events from the Black Sea to the Sea of Azov and detection of borders of the bottom-advected Black Sea plume (BP) at satellite imagery is relatively straightforward, as compared to identification of inflow events from the Sea of Azov to the Black Sea. However, we assume that BP is not manifested by anomalies of TSM and Chl-a in the surface layer during low wind forcing conditions, while during strong wind forcing conditions resuspension of bottom sediments can induce elevated concentrations of TSM in the surface layer that also hinders identification of BP. As a result, many of BI events are not detected by optical satellite imagery.

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3. The major conclusion of this study is that the buoyant outflow from SA into BS occurs only under the external forcing by northeasterly (NE) winds, while relaxation of NE winds occurs during the relaxation of NE winds (e.g., page 10, line 24) and under any wind conditions. The authors also attempt to quantify "intensity" of the flow exchange through the Kerch Strait by determining the area of the SA plume in BS, and scaling this area against the integral of wind speed when the wind is favorable for the plume formation. In my opinion, there is a major confusion in this conclusion: do the authors imply that NE winds precondition the BS inflow into SA (that is, relaxation of NE winds triggers the BS inflow) or do they mean that the BS inflow occurs always as long as NE winds do not operate? The authors seem to interchange these two very different messages in different parts of their manuscript (e.g., compare lines 24-26 on page 10 and lines 23-26 on page 11).

Response:

Many thanks for this important comment. In the revised version of the manuscript we clarified meaning of “relaxation of NE winds” related to inflow of BS waters into SA. We state that inflow of BS waters into SA occurs after reverse of a barotropic pressure gradient as a result of relaxation of NE winds, i.e. relaxation of NE winds triggers the BS inflow. This result was supported by numerical modelling.

4. I feel strongly that the estuarine exchange flow should occur in both directions, but the authors seem to imply that under light or no wind forcing conditions, it is a one-way traffic: BS water flows in SA in a unidirectional manner.

This is a bold and unsubstantiated claim.

Response:

Many thanks for this important comment. We totally agree that water exchange through the mouth of a positive estuary is typically a two-way process with in- and outflows happening at the same time. However, it is not the case of narrow and shallow central part of the Kerch Strait, which width and depth are equal to 3 km and 3-4 m. In absence of external forcing water exchange through the Kerch Strait indeed is a two-way process. However, due to the dominating role of a barotropic component in the total pressure gradient along the strait (Figure 5 in the revised version of the manuscript), even moderate wind forcing at the study region induces a one-way water exchange in the narrowest part of the strait which defines water exchange between the Azov and Black seas. Numerical simulations show that a two-way water exchange occurred in the Kerch Strait only during weak wind forcing conditions which total annual duration was 34 – 54 days in 1992 – 2010, which is only 9-15% of the whole year (Table 1). Thus, one-way water exchange was observed during the majority of the year. This result is also supported by previous in situ observations (Ivanov, 2011) and numerical modelling (Stanev et al., 2017) of water exchange in the Kerch Strait. The rest of the year a one-way water exchange was observed. This point was described in the text.

5. Apart from this major issue with paper’s conclusions, I have some questions with the analysis. I am not sure why the authors use logarithms of properties compared in Figure 6 (and not the properties themselves). The bottom panel scatterplot does not resemble a linear function, so the linear regression is a poor choice here. This relationship is by no means linear: first, the wind driven transport is proportional to the wind stress (which is quadratic in wind speed). Second, the surface area is not directly proportional to the discharge Q through the Kerch Strait, but rather to Q/h , where h is the sickness of the plume, which is generally unknown but does depend on the wind stress.

Response:

We agree that scatterplots in this figure (Figure 9 in the revised version of the manuscript) do not resemble linear functions, so the linear regression is a poor choice. In the revised version of the manuscript we improved these dependences and their approximations. Alongshore extent and area of AP increase with increase of wind forcing index. However, this increase is not steady, its derivative decreases with increase of wind forcing index. In particular if wind forcing index exceeds 3500 km, alongshore extent and area of AP are almost stable. Thus, the observed forms of dependences between have good approximation by logarithmic functions. We are not aware that logarithmic approximation has any straightforward physical background (despite steady decrease of dependence derivative) due to complex and strongly non-linear dependences between wind speed, discharge through the Kerch Strait, and spatial characteristics of AP. However, the obtained relations are essential for numerical parameterizations of water exchange through the Kerch Strait based on wind data, which are addressed in this study.

6. Regarding the upper panel of Figure 6, I think the alongshore extension of the plume under the downwelling wind forcing primarily depends on the ALONG-SHELF wind stress component (not the wind velocity magnitude).

Response:

We agree with this point. Spatial scales of a buoyant plume in a non-tidal sea are defined mainly by two external forcing parameters, namely, river discharge rate and wind forcing. Thus, alongshore extent of AP depends on discharge rate of SA water through the Kerch Strait and local wind forcing. Inflow of water from SA to BS and formation of AP occurs only under north-easterly wind forcing. As a result, cross-shelf wind component determines discharge rate of SA water through the Kerch Strait and both wind components govern further alongshore extension of AP. In this study, we consider alongshore extension and area of AP only during periods of inflow from SA to BS, i.e., we do not consider AP detached from its source in the Kerch Strait after reverse of flow direction in the strait and cessation of inflow from SA to BS. Thus, we calculate alongshore extension and area of AP only during moderate and strong north-easterly winds that induce inflow from SA to BS. During these periods, alongshore extension of AP indeed shows good relation with variability both cross- shelf and along-shelf wind component. However, the dependence of alongshore extension of AP on wind velocity magnitude is better due to small range of the considered wind directions. This issue was clarified in the text.

7. Throughout the paper, there is unfortunate confusion about the wind direction. In geosciences, wind direction indicates where the wind blows from and it is measured from true north in clockwise direction. Wind direction 210 to 260 degrees (page 6, line 17) means that the wind blows from southwest, and it's not what the authors assume. Likewise, "northeastern" (wind) and "northeastward" have opposite meanings, northeastward denotes a flow from southwest towards northeast, but the authors freely interchange these two terms (e.g., lines 24 and 26 on page 10, and many other instances).

Response:

Thank you for this point, we checked all parts of the manuscript where wind direction was mentioned and corrected the wrong usage of the related words.

- 5 **8. On page 11 (2nd paragraph), the authors compare the SA volume and the annual volume of the freshwater discharge. This is a very strange proposition because a year is not a proper time scale for the exchange processes between AS and BS, according to the authors. In my opinion, the authors should rectify their arguments in this part of the discussion.**

10 Response:

We agree with the reviewer that we should improve arguments in this part of the discussion. In this paragraph we discuss relation between freshwater discharge to river estuary and water exchange between the estuary and open sea, i.e. does signal of river discharge dissipate in the estuary or it influences freshwater outflow from estuary to open sea. This process depends on two main factors, namely, volume of inflowing river discharge and spatial scales of an estuary. If large river inflows to small estuary (e.g., the Amur River and the Amur Liman), variability of river discharge rate strongly affects water outflow from estuary to open sea. On the other hand, discharge of a small river inflowing to a large estuary does not influence and water exchange between the estuary and open sea. The area and volume of the Sea of Azov are large enough; therefore, signals of synoptic and even significant seasonal variability of discharge of the DON and Kuban rivers dissipate in the Sea of Azov and do not influence formation and/or intensity of AI events. It was clarified in the manuscript

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9. Finally, the language should be checked throughout. For instance, it is a “boundary condition”, not a “border condition”. Word “significant” is badly overused. In scientific literature, this word tends to have a statistical context (that is, significant in quantitative, statistical sense). “Substantial” would probably sound better and less irritating for quantitatively minded readers.

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Response:

Thank you for these points, we adopted them.

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Water exchange between the Sea of Azov and the Black Sea through the Kerch Strait

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Abstract. The Sea of Azov is a small, shallow, and freshened sea that receives a large freshwater discharge ~~and, therefore, can be regarded as a large river estuary.~~ Under certain external forcing conditions low-saline waters from the Sea of Azov inflow to the northeastern part of the Black Sea through the narrow Kerch Strait and form a surface-advected buoyant plume. Water flow in the Kerch Strait also regularly occurs in the opposite direction, which results in spreading of a bottom-advected plume of saline and dense waters from the Black Sea in the Sea of Azov. In this study we focus on physical mechanisms that govern water exchange through the Kerch Strait, analyse dependence of its direction and intensity on external forcing conditions. ~~Based on ocean color Analysis of~~ satellite imagery ~~and~~ wind ~~reanalysis~~ data, ~~we show and numerical modelling shows~~ that water ~~transport~~ exchange in the Kerch Strait is governed by a wind-induced barotropic pressure gradient. Water flow through the shallow and narrow Kerch Strait is a one-way process during the majority of the time. Outflow from the Sea of Azov to the Black Sea is induced by moderate and strong ~~northeastern~~ north-easterly winds, while ~~water transport in~~ inflow to the ~~opposite direction~~ Sea of Azov from the Black Sea occurs during wind relaxation periods. ~~Thus,~~ Direction and intensity of water exchange ~~through the Kerch Strait~~ has wind-govern synoptic and seasonal variability, and do not show dependence on the rate of river discharge ~~rate~~ to the Sea of Azov on intra-annual time scale. ~~Finally, we determined numerical~~ The analysed data reveal dependencies between ~~discharge rate from the Sea of Azov to the Black Sea~~ wind forcing conditions and spatial characteristics of the ~~related surface advected~~ buoyant plume ~~informed by the Black outflow from the~~ Sea, ~~on the one hand, and wind forcing conditions, on the other hand of Azov.~~

1 Introduction

The Sea of Azov is an enclosed sea located in ~~the~~ Eastern Europe and is among the smallest and the shallowest seas in the world (Figure 1). Watershed area of the Sea of Azov (586000 km²) is 15 times greater than the sea area (39000 km²) ~~and~~. Therefore, it receives anomalously large river discharge, ~~which the~~ annual volume of which varies in the range of 20 - 54 km³, that is only of one order of magnitude less than the sea volume (290 km³) (Ross, 1977; Ilyin, 2009). 95% of the annual continental discharge is provided by the Don and Kuban rivers that inflow to the northeastern and southeastern parts of the

Sea of Azov, respectively (Ross, 1977; Ilyin, 2009). The southern part of the Sea of Azov is connected to the northeastern part of the Black Sea through the long (45 km) and narrow (4-15 km) Kerch Strait. Hydrological characteristics and the general circulation of the Sea of Azov are governed by the local winds and by the river runoff and water exchange with the Black Sea. Low water salinity (1-12) (Ross, 1977; Goptarev et al., 1991; Ilyin, 2009) caused by large freshwater discharge and limited water exchange with more saline Black Sea (17-18) (Ivanov & Belokopytov, 2011) through the narrow Kerch Strait is one of the main features of the Sea of Azov. Thus, the Sea of Azov is a small, shallow, and freshened water body that can be regarded as a large estuary of the Don and Kuban rivers connected with the Black Sea through the Kerch Strait. Limited water exchange through a narrow strait hinders mixing between connected water bodies which can result in significantsubstantial differences between their physical and chemical characteristics, as well as between their concentrations of dissolved and suspended constituents. Thus, transport of water masses through a strait and their subsequent spreading in adjacent sea areas can significantlygreatly influence many local processes including coastal circulation, primary productivity, water quality, anthropogenic pollution, and deposition of terrigenous material. Impact of water exchange on these processes depend on, first, physical and chemical characteristics of interacting water masses, and, second, variability of water exchange direction, i.e., frequency, duration, and intensity of water exchange periods.

Many previous studies were focused on physical, biological, and geochemical processes related to water exchange between two large water bodies through a narrow strait in different world regions, in particular, the Baltic and North Seas through the Danish straits (Matthäus and Lass, 1995; Sayin and Kraus, 1996; Jacobsen and Trebuchet, 2000; Sellschoppa, 2006; She et al., 2007), the Black and Mediterranean seas through the Bosphorus and Dardanelles straits (Yuce, 1996; Andersen et al., 1997; Gregg et al., 1999; Falina et al., 2017; Sozer and Ozsoy, 2017; Stanev et al., 2017), the Mediterranean Sea and the Atlantic Ocean through the Strait of Gibraltar (Garret, 1996; Sannino et al., 2002; Beranger et al., 2005, Soto-Navarro et al., 2015), the Bering and Chukchi seas through the Bering Strait (Woodgate et al., 2010, 2012; Danielson et al., 2014), the Patos Lagoon and the Atlantic Ocean (Castelao and Moller, 2006; Marques et al., 2009). A number of papers addressed structure and variability of circulation in the Kerch Strait (Simonov & Altman, 1991; Lomakin et al., 2010, 2016, 2017; Sapozhnikov, 2011; Chepyzhenko, 2015) and influence of water inflow from the Sea of Azov on coastal ecosystem in the northeastern part of the Black Sea (Lomakin, 2010; Kolyuchkina et al., 2012; Aleskerova et al., 2017; Izhitsky & Zavialov, 2017; Zavialov et al., 2018). However, many aspects of physical background of water exchange through the Kerch Strait and its dependence on external forcing conditions remain unstudied. Also little attention has been paid to spatial characteristics and temporal variability of sub-mesoscale and mesoscale structures formed in the Black Sea and the Sea of Azov as a result of water exchange between these seas.

In this study, we address physical mechanisms that drive water exchange between the Sea of Azov to the Black Sea, basing our analysis on ocean ~~color~~colour satellite imagery, ~~in-situ and climatic wind~~ reanalysis ~~wind~~ data, ~~and~~ river gauge measurements, and numerical modelling. We reveal dependence of direction and intensity of water exchange through the Kerch Strait on external forcing conditions ~~and analyse temporal variability of these processes from synoptic to intra-annual scales. Also~~. We study dynamics of the surface-advected plume of freshened waters from the Sea of Azov spreading in the

Black Sea, hereafter, referred as AP, and bottom-advected plume of saline waters from the Black Sea spreading in the Sea of Azov, hereafter, referred as BP. We identify ~~their~~ spatial characteristics, ~~their of the AP, its~~ dependence on external forcing conditions, and ~~analyse their~~ analysis of its synoptic variability.

The paper is organized as follows. Section 2 provides detailed information about the study region. Satellite, wind, and river discharge data, as well as the numerical model used for simulation of sea circulation in this study region are described in Section 3. Section 4 focuses on dynamics of inflow and spreading of AP in the Black Sea and BP in the Sea of Azov and addresses dependence of these processes on external forcing conditions on synoptic time scale. The ~~analysis~~ discussion of ~~frequency, duration, and intensity of water exchange through the Kerch Strait on seasonal, annual, and inter-annual time scales is given in section 5,~~ obtained results followed by the conclusions is given in section 6.

2 Study Area

The Sea of Azov is small and shallow, its average and maximal ~~sea~~ depths are 7 and 14.4 m, ~~respectively~~. The 10 m isobath is located at a distance of 20-30 km from the sea shore at the eastern, western, and northern parts of the sea, while the southern coastal area is characterized by a narrow (2-5 km) steep slope to a depth of 10 m (Figure 1). The central part of the Sea of Azov is 10-13 m deep and accounts for less than 50% of the sea area. The southern part of the Sea of Azov is connected with the northeastern part of the Black Sea by the Kerch Strait. The narrowest passages of the Kerch Strait are located at its northern (4-5 km) and central (3 km) parts, while at its southern part its width increases up to 15 km. The central part of the Kerch Strait is very shallow (3-5 m) and steadily deepens to depths of 10 and 20 m at its northern and southern parts, respectively. Bathymetry of the northeastern part of the Black Sea is characterized by the narrow shelf, the distance from the shore to the 100 m isobath varies between 15 and 30 km. Further offshore, the steep continental slope descends to a depth of 1000 m at a distance of 50–80 km from the shore (Figure 1).

Large freshwater discharge ~~significantly~~ strongly influences characteristics of the Sea of Azov. The Don River is the largest river inflowing to the Sea of Azov providing approximately 65% of total freshwater runoff to the sea. The Kuban River, which is the second largest river of the study region, provides another 30% of total freshwater runoff. Volumes of annual discharge of the Don and Kuban rivers vary from 18 to 28 km³ and from 6 to 13 km³, respectively, which is caused by strong climate and anthropogenic influence (Goptarev et al., 1991; Ilyin et al., 2009). Hydrological characteristics of the Don and Kuban rivers are significantly affected by dams and reservoirs constructed at these rivers. Flow regimes of the Don and Kuban rivers are characterized by long spring-summer freshet during March – June and April – July, respectively, however, discharges during these periods are only twice larger than during the rest of the year (Goptarev et al., 1991; Ilyin et al., 2009). Difference between evaporation and precipitation over the Sea of Azov (17 km³) is half less than the mean annual river runoff (35 km³) and shows very low inter-annual variability (Ilyin et al., 2009).

Surface temperature of the Sea of Azov is prone to ~~significant~~ large seasonal variability from 0 °C in winter to 25 °C in summer caused by shallowness and small volume of the sea (Goptarev et al., 1991; Ilyin et al., 2009). Sea ice covers the

northern part of the Sea of Azov every year from December – January to March – April, while its central and southern parts are frozen only during extremely cold winters, which occurred only twice during the last 40 years (Ilyin et al., 2009). Surface salinity in the Sea of Azov varies from 9 to 13 except its more freshened northeastern part, namely, the Taganrog Bay, which receives discharge of the Don River. Large freshwater discharge cause ~~significant~~sharp horizontal thermohaline gradients in the Sea of Azov. On the other hand, wind-induced mixing penetrates to sea bottom due to shallowness of the Sea of Azov which results in low gradients in vertical thermohaline structure of the sea (Goptarev et al., 1991; Ilyin et al., 2009). Temperature in the surface layer in the northeastern part of the Black Sea also varies in a wide range of values from 7 °C in winter to 23 °C in summer, while its salinity is 17-19 during the whole year (Ivanov & Belokopytov, 2011). Large freshwater discharge and intense wind-induced vertical circulation result in high concentration of terrigenous sediments, nutrients, chlorophyll a in the Sea of Azov, which is of one order greater than in the northeastern part of the Black Sea (Ilyin et al., 2009).

Circulation in the shallow Sea of Azov is governed mainly by winds, while ~~baroclinic~~baroclinic forcing is weak (Cherkesov & Shul'ga, 2018). As a result, sea current field ~~shows significant~~and level of the Sea of Azov are prone to large synoptic variability in response due to different intense wind forcing conditions, surges, which amplitudes can exceed 2 m (Ivanov, 2011; Fomin, 2015; 2017). Circulation in the surface layer in the northeastern part of the Black Sea is dominated by a westward current along the continental slope ($0.2\text{--}0.5\text{ m s}^{-1}$), which is a part of the Black Sea Rim Current, and an anticyclonic eddy, which is regularly formed between this current and the coast near the Kerch Strait ($0.05\text{--}0.4\text{ m s}^{-1}$) (Oguz et al., 1993; Ginzburg et al., 2002; Zatsepin et al., 2003; Korotaev et al., 2003). ~~Level of the Sea of Azov is prone to significant intra annual and seasonal variability, which is mainly governed by variability of annual river discharge volume, and has order of tens of centimeters, while intra annual and seasonal variability of the Black Sea level is several centimeters. Synoptic variability of sea level at the coastal areas of the Sea of Azov and the Black Sea, in particular, at the ends of the Kerch Strait is defined by wind surges (Ivanov, 2011; Fomin, 2015; 2017). Tidal amplitudes at the northeastern part of the Black Sea and~~Tidal amplitudes at the northeastern part of the Black Sea and in the Sea of Azov are 2-4 cm; thus, tidal circulation is very low at the study area (Medvedev et al., 2016; Medvedev, 2018).

Water transport through the Kerch Strait is an important part of the water budget of the Sea of Azov, however, its characteristics are ~~susceptible~~prone to ~~significant~~large uncertainty. Volumes of annual water inflow from the Sea of Azov to the Black Sea and from the Black Sea to the Sea of Azov are estimated as 35-64 and 26-44 km³, respectively, which is similar to total continental discharge to the Sea of Azov. Direction and intensity of water exchange through the Kerch Strait is characterized by large synoptic variability (Goptarev et al., 1991; Ilyin et al., 2009). Current velocity in the Kerch Strait generally exceeds 10 cm s⁻¹, ~~in its narrowest part~~ mean current velocities in its narrowest part are 20-30 cm s⁻¹. Barotropic tidal current in the Kerch Strait is less than 5 cm s⁻¹ except the narrowest part of the strait where they are equal to 6-10 cm s⁻¹ during peak flow (Ferrain et al., 2018). However, maximal velocity of 2-days averaged tidal currents in the Kerch Strait ~~are~~is less than 5 cm s⁻¹, ~~therefore, and its flow direction reverses during the role of tide~~tidal cycle. Thus, tidal current does not form persistent residual flow and its role in water exchange between the Black and Azov seas can be regarded as

negligible. ~~Direction and intensity of water exchange through the Kerch Strait is characterized by significant synoptic variability (Goptarev et al., 1991; Ilyin et al., 2009).~~

Large salinity difference between the Azov and Black seas results in ~~significantly~~substantially different spreading and mixing dynamics of waters that inflow from the Sea of Azov ~~into~~ the Black Sea, on the one hand, and waters that inflow from the Black Sea ~~into~~ the Sea of Azov, on the other hand. Inflow of freshened waters from the Sea of Azov to the Black Sea forms a surface-advected AP, which is spreading over wide areas (up to 2000 km³) in the northeastern part of the Black Sea (Aleskerova et al., 2017). Due to elevated concentrations of terrigenous sediments, nutrients, and anthropogenic pollutants in the waters of the Sea of Azov, AP strongly influences physical, biological, and geochemical processes in the areas adjacent to the Kerch Strait in the northeastern part of the Black Sea (Lomakin, 2010; Kolyuchkina et al., 2012; Aleskerova et al., 2017; Izhitsky and Zavialov, 2017; Zavialov et al., 2018). Mesoscale eddies formed in the Black Sea near the Kerch Strait can largely influence spreading and mixing pattern of Sea of Azov waters that inflow to the Black Sea and propagate westward along the southeastern shore of the Crimean Peninsula. Satellite data and numerical modelling reveal that AP are regularly entrained by mesoscale eddies that can significantly intensify cross-shelf transport of freshened water inflowing from the Sea of Azov.

Processes of inflow, spreading, and mixing of Black Sea water in the Sea of Azov, as well as its influence on local ecosystem received much less attention. Saline waters from the Black Sea form a bottom-advected BP, which can affect large areas in the Sea of Azov. However, its characteristics, spatial structure, and temporal variability remain mainly unstudied.

3 Data and methods

3.1 Data used

Satellite data used in this study include ~~EnviSat MERIS~~ satellite imagery from EnviSat MERIS with a spatial resolution of 300 m provided by the European Space Agency (ESA) and from Terra MODIS and Aqua MODIS with a spatial resolution of 250 m provided by the National Aeronautics and Space Administration (NASA). MERIS L1 satellite products were downloaded from the ESA web repository (<http://merisfrs-merci-ds.eo.esa.int/merci>) and used for retrieving maps of sea surface distributions of total suspended matter (TSM) and Chl-a using the MERIS Case-2 Regional water processing module (Doerffer and Schiller, 2008). MODIS L1 satellite products were downloaded from the NASA web repository (<https://ladsweb.modaps.eosdis.nasa.gov/>) and used for retrieving maps of sea surface distributions of TSM and Chl-a using the MSL12 processing module. We analyzed 152 MERIS and 110 MODIS satellite images of the study region taken in 2002–2012 and 2012–2017, respectively.

The Don and Kuban discharge and local wind forcing data were used to study influence of external forcing conditions on water exchange through the Kerch Strait and spreading of AP in the northeastern part of the Black Sea. The Don and Kuban daily discharge data was obtained from the Razdorskaya and Temryuk gauge stations, respectively, while local wind

measurements were performed at the Kerch meteorological station (Figure 1). The atmospheric influence was also examined using wind data obtained from a 6 h NCEP/NCAR reanalysis with a 2.5-degree resolution which showed good accordance with in situ data for the study region (Garmashov et al., 2016). We used zonal and meridional wind components from the only reanalysis grid point located at the study area (44.7611° N, 35.625° E) which were validated against in situ wind measurements.

3.2 Identification of AP and BP by satellite imagery

As it was discussed in Section 3.1, waters of the Azov and Black seas have very different physical and chemical properties. As a result, ~~differentvarious~~ ocean surface characteristics measured by satellite instruments can be used to study spreading of surface-advected AP in the northeastern part of the Black Sea. Previous related studies used sea surface temperature (SST) ~~and~~ concentrations of chlorophyll ~~a~~-(Chl-a) and ~~total suspended matter (TSM)~~ retrieved from optical satellite data (Ivanov & Belokopytov, 2011; Aleskerova et al., 2017). However, all these characteristics ~~are prone to significant variability and/or do not act as passive tracers, which hinders their direct application for accurate identification of borders of AP. cannot be used for straightforward identification of inflow of freshened waters from the Sea of Azov to the Black Sea, hereafter referred as AI, and identification of boundaries of AP due to the following reasons.~~

First, difference in SST between the southern part of the Sea of Azov and the northeastern part of the Black Sea varies from ~~-~~ -4 °C in winter to ± 4 °C in summer (Aleskerova et al., 2017). On the other hand, diurnal variability of SST in the coastal areas of the Sea of Azov and the Black Sea is also equal to several degrees (Ivanov & Belokopytov, 2011; Chepyzhenko, 2015). This fact ~~prevents~~can prevent formation of distinctive frontal zones between AP and the adjacent sea, especially if AP is formed by inflow from the Sea of Azov during several days, i.e. several diurnal temperature cycles of SST. ~~As a result, SST satellite products can be limitedly used for effective detection~~Mean seasonal and diurnal variability of borders of AP. ~~TSM is much lower that difference between mean values of TSM in the Azov and Black seas during the whole year (Lomakin, 2017). Settling time of fine fraction of suspended sediments within the AP is much lower than residence time of AP in the Black Sea, i.e., AP mixes with ambient saline water and dissipates more quickly than fine suspended sediments settle from surface layer to subjacent sea. Thus, TSM provides a clear optical signal of turbid AP in the Black Sea due to large difference in suspended sediment concentration between the Azov and Black seas (Lomakin, 2017). and forms stable gradients at borders of AP, which are distinctly visible in optical satellite imagery.~~ However, wind-induced resuspension of sea bottom sediments, which regularly occurs along the shallow-northeastern coast of the Black Sea, ~~cause~~causes increase of TSM, which can exceed mean TSM values of AP. ~~As a result, usage of TSM for identifying spreading area of AP can be misleading that is illustrated by Fig. 2. Thus, we used (Figure 2a). Chl-a as a stable tracer of AP in the Black Sea, that is consistent with a number of previous studies focused, on tracking~~the opposite to TSM, is characterized by, first, larger seasonal variability of buoyant plumes with satellite ocean color data (e.g., Dzwonkowski et al., 2007; Piola et al., 2008); its difference between the Azov and Black seas during the whole year and, second, larger synoptic variability within the AP

caused by complex biological processes. On the other hand, Chl-a has lower short-term variability, in particular, in response to wind forcing.

As it was shown above, surface distributions of SST, TSM, and Chl-a in the study region are prone to substantial variability defined by various processes apart from mixing between waters from the Black and Azov seas. However, these processes and their temporal scales are different for SST (diurnal cycle of solar radiation), TSM (episodic wind-induced bottom resuspension events), and Chl-a (synoptic and seasonal biological cycles). Thus, joint analysis of SST, TSM, and Chl-a distributions can be used for accurate detection of spreading of AP in the Black Sea. We applied the following scheme of identification of AI events and detection of borders of AP basing on satellite data. Inflow events were identified by elevated concentration of Chl-a in the Kerch Strait and the adjacent coastal area of the Black Sea, because Chl-a has the lowest short-term variability among the considered sea surface characteristics. If an inflow event was detected, we analyzed areas of elevated TSM, Chl-a, and elevated (in summer) or reduced (in winter) SST associated with formation of AP in the northeastern part of the Black Sea. If general forms and spatial scales of these areas were similar, we defined borders of AP basing on gradient of TSM that is the most stable passive tracer of AP in absence of episodic wind-induced bottom resuspension events (Figure 2b). If areas of TSM, Chl-a, and SST anomalies were not consistent with each other, we assumed that areas of elevated TSM and reduced SST (in winter) were modified by wind-induced resuspension and mixing of AP with subjacent sea. In this case we defined borders of AP basing on gradient of Chl-a that is the most stable tracer of AP during intense wind forcing conditions during the whole year.

Inflow of saline waters from the Black Sea to the Sea of Azov, hereafter referred as BI, causes formation of bottom-advected BP that cannot be directly identified at satellite imagery. However, wind-induced mixing, which regularly penetrates to sea bottom at the shallow Sea of Azov, can cause mixing of water of BP with overlaying water of the Sea of Azov. It results in reduced values of TSM and Chl-a in the surface layer above the spreading area of BP, as compared to adjacent areas of the Sea of Azov. Thus, presence of BP in the bottom layer can be identified at satellite imagery as areas of reduced TSM and Chl-a in the Sea of Azov adjacent to the Kerch Strait. The scheme of identification of BI events and detection of borders of BP at satellite imagery is relatively straightforward, as compared to identification of AI events. However, we assume that BP is not manifested by anomalies of TSM and Chl-a in the surface layer during low wind forcing conditions, while during strong wind forcing conditions resuspension of bottom sediments can induce elevated concentrations of TSM in the surface layer that also hinders identification of BP. As a result, many of BI events are not detected by optical satellite imagery.

3.3 Numerical model

In this study we performed numerical simulations using the BSAS12 numerical model to simulate circulation in the Black and Azov seas and study water exchange through the Kerch Strait. BSAS12 is an original regional configuration of the ocean and sea-ice general circulation model NEMO (version 3.6) that covers the Black and Azov seas (Madec, 2016). Horizontal grid resolution of the model is $1/12^\circ$ that is approximately 6.75 km in the study region. The vertical coordinate is represented by 59 vertical z-levels with finest resolution (1 m) in the upper ocean. A partial-step representation of the bottom topography

which adjusts the thickness of the model level adjacent to the bottom to the true ocean depth is used (Barnier et al., 2006). The model domain has an open ocean boundary at the Bosphorus Strait that connects the Black Sea with the Mediterranean Sea. The ocean is driven by the ERA-Interim atmospheric forcing which includes 3-hourly fields of near surface wind velocity, temperature and humidity, and daily fields for incoming long and short wave radiation, total precipitation. Surface fluxes and wind stress are calculated using the CORE bulk formulae (Large and Yeager, 2004) with the sea surface temperature provided by the model. Initial temperature and salinity fields in the Azov and Black seas are obtained from the climatological data given in Goptarev et al. (1991) and Belokopytov (2018). BSAS12 is forced with monthly climatological river runoff to the Black and Azov seas that was set according to the data provided in Jaoshvili (2002), Dai and Trenberth (2002), and gauge data from the Don and Kuban rivers described in Section 3.1. Boundary conditions at the Bosphorus Strait are prescribed according to data provided by Gregg et al. (1999, 2002), Altioek et al. (2012), and Sozer and Ozsoy (2017). The model time step is set to 720 s. The BSAS12 simulation of the circulation of the Black and Azov seas used here covers the period from 1 January 1992 to 31 December 2017. Daily mean values of the model variables were saved every day for the whole period.

In this study we focus on modelling of circulation in the areas of the Black and Azov seas adjacent to the Kerch Strait with emphasis on water exchange through the strait. The main large-scale and mesoscale circulation features of the Black Sea circulation were adequately reproduced by numerical modeling (Figure 3), including the Black Sea Rim Current, quasi-stationary cyclonic gyres at the central divergence zone, and multiple quasi-stationary anticyclonic gyres between the Rim Current and the shoreline near Sebastopol, Batumi, etc. (Oguz et al., 1992; 1993; 1995; Stanev, 1995; Staneva et al., 2001). The model also reproduced seasonal variations of sea surface circulation, in particular, winter–spring intensification of the Rim Current, meandering of the main flow of the Rim Current caused by baroclinic instability, and formation of multiple nearshore anticyclonic eddies during summer at the eastern part of the Black Sea (Oguz et al., 1992; 1993; Titov, 2002; Zatsepin et al., 2003; Enriquez et al., 2005). Mean annual values of water transport through the Kerch Strait during the modelling period (Figure 4) shows good agreement with the reference values of 20 km^3 per year (Stanev, 1990).

4 Results

4.1.1 Water exchange through the Kerch Strait

We used the BSAS12 model to study physical mechanisms that govern water exchange through the Kerch Strait. Based on the simulation outputs, we reconstructed daily averaged baroclinic and barotropic components of pressure gradient force in the Kerch Strait during 1992 – 2017 (Figure 5). They show that the total pressure gradient along the strait is governed by a barotropic component, due to relatively large average difference of water level ($< 0.1 \text{ m}$ during the majority of the year) in the southern and northern ends of the strait. Local wind forcing induces large synoptic variability in magnitude and direction of the barotropic pressure gradient. Stable density gradient that exists along the strait does not exceed 6 kg/m^3 , therefore, the baroclinic pressure gradient is of one order of magnitude smaller than the barotropic pressure gradient, and does not induce a

steady exchange circulation typical for positive estuaries. As a result, circulation through the Kerch Strait is not steady and unidirectional, but has large synoptic variability of intensity and direction governed by episodic wind forcing events. Annual variability of the total pressure gradient in the strait does not show any seasonality. Thus, water exchange through the Kerch Strait has wind-govern synoptic variability, and do not show seasonal dependence on river discharge rate to the Sea of Azov. The role of the barotropic component in the total pressure gradient is the largest in the most shallow (3-4 m) and narrow (3 km) parts of the Kerch Strait. Numerical simulations revealed that even moderate wind forcing at the study region induces a one-way water transport, i.e., only inflow or only outflow, in this part of the strait, which defines water exchange between the Azov and Black seas. Water flow occurs simultaneously in both directions in the shallow part of the strait, i.e., a two-way water transport is formed, only during light winds. Numerical simulations show that a two-way water exchange occurred in the Kerch Strait only during weak wind forcing conditions which total annual duration was 34 – 54 days in 1992 – 2010, that is only 9-15% of the whole year (Table 1). Thus, a one-way water exchange between the Azov and Black seas was observed during the majority of the year, which is not typical for a positive estuary. This result is also supported by previous studies based on in situ observations (Ivanov, 2011) and numerical modelling (Stanev et al., 2017) of water exchange in the Kerch Strait.

4.2 Spreading of AP in the Black Sea

River discharge to the Sea of Azov and wind forcing at the area of the Kerch Strait are the main factors that are believed to govern ~~inflow of freshened waters from the Sea of Azov to the Black Sea, hereafter referred as AI~~ AI events (Goptarev et al., 1991; Simonov & Altman, 1991; Ivanov & Belokopytov, 2011). ~~We analyzed~~ We analysed 48 AI events identified in MERIS and MODIS optical satellite imagery ~~acquired and verified in BSAS12 simulations~~ during 2002-2017 ~~and identified 48 AI events~~. Basing on wind reanalysis data and gauge data of the Don and Kuban rivers we studied dependence of formation of AI events on ~~river discharge and~~ wind forcing conditions ~~and river discharge and~~ on synoptic and seasonal time scales.

First, we ~~analyzed~~ analysed relation between concentration of Chl-a in the Kerch Strait and the adjacent area of the Black Sea retrieved from optical satellite imagery, on the one hand, and direction of wind forcing averaged over 24 hours preceding satellite observations, on the other hand (Figure ~~36~~). Elevated concentrations of Chl-a, which is regarded as the main indicator of an AI event, were observed only if azimuthal angle of wind direction was between ~~240~~30° and ~~260~~80° and wind velocity exceeded 5 m/s. ~~It can be seen that the resulting wind direction range corresponds to the northeastern wind and~~ Thus, formation of an AI event is induced only by moderate and strong northeastern winds. Second, we addressed relation between concentration of Chl-a and discharge rates of the Don and Kuban Rivers (Figure ~~47~~). We obtained that AI events are formed under the whole variety of discharge conditions and do not show any dependence on discharge rate on synoptic time scale. Synoptic variability of river discharge strongly influences water exchange between a river estuary and open sea if volume of an estuary is relatively small as compared to river discharge rate (Officer, 1976; Sheldon & Alber, 2002; Wang et al., 2004). However, ~~the~~ volume of the Sea of Azov, regarded as an estuary of the Don and Kuban rivers, is ~~of~~ one order ~~of~~ magnitude greater than ~~the~~ annual freshwater runoff. As a result, signal of synoptic variability of river discharge dissipates in the Sea of

Azov and does not influence formation of AI events. Thus, we obtain that AI events are induced by wind forcing and do not depend on river discharge conditions on synoptic time scale.

AI event, ~~i.e., inflow of freshened waters from the Sea of Azov to the Black Sea,~~ causes formation of a buoyant AP. Spreading of a buoyant plume in a non-tidal sea is mainly governed by discharge rate ~~and~~, wind forcing and local eddies (Fong et al., 1997; Hallock & Marmorino, 2002; Horner-Devine et al., 2015) and is characterized by strong variability of size, shape, and spreading patterns under different configurations of external forcing conditions (Kourafalou et al., 1996; Xia et al., 2007; Zavialov et al., 2014; Osadchiev, 2015; Osadchiev et al., 2016). However, analysis of satellite imagery and numerical modelling revealed stability of spreading pattern of AP. All satellite images where AI event was detected, showed that AP propagated westward along the southeastern shore of the Crimean Peninsula (Figure 2b), Figure 8). This result is supported by BSAS12 numerical simulations that showed good agreement between modelled distribution of low saline AP and location of AP detected at optical satellite imagery. This freshened alongshore current formed by AP dissipated on a distance of 50-200 km from its source at the Kerch Strait. AP did not spread eastward along the coast of the Taman Peninsula or southward to the open sea ~~at any of the analyzed satellite images. In particular,~~ Elevated values of TSM to the east from the Kerch Strait along the Taman Peninsula, which are regularly observed at satellite imagery, are not accompanied by elevated values of Chl-a and low surface salinity (Figure 2a). This fact indicates that these turbidity features at sea surface layer are induced by bottom resuspension and do not correspond to eastward spreading of AP along the coast of the Taman Peninsula.

Stability of spreading pattern of AP can be explained in the following way. As it was shown above, AI occurs only during northeastern wind and causes formation of AP. Thus, initial spreading of AP from its source at the Kerch Strait is forced by northeastern wind. As a result, the AP forms a quasi-geostrophic coastal current in response to downwelling ~~favorable~~ favourable wind forcing, which was addressed in many previous studies (Garvine, 1987; Yankovsky & Chapman, 1997; Fong and Geyer, 2002), ~~Osadchiev and Zavialov, 2013).~~ Spreading of AP in different direction, e.g., southward or eastward, requires change of direction of wind forcing. However, change of wind direction ~~will also result~~ results in cessation of inflow of freshened water to the Black Sea and ~~cause~~ causes dissipation of the freshened alongshore current.

~~Spatial scales of AP identified at~~ Satellite imagery ~~shows significant synoptic variability. In particular, during an individual AI event~~ and numerical simulations show that AP occupy wide area along the southeastern shore of the Crimean Peninsula in case of stable inflow of freshened waters from the Sea of Azov to the Black Sea during 3-5 days (Figure 8). Alongshore extent and area of AP can increase ~~from 60 to by one order of magnitude and exceed~~ 150 km and ~~from 400 to 1300~~ 2000 km², respectively, during ~~several days (Figure 5). On the other hand~~ an individual AI event. After secession of inflow from the Sea of Azov to the Black Sea, AP dissipates during several days ~~after the end of AI event~~. As it was shown above, intensity of AI, i.e., freshwater discharge rate, depends on local wind, which is, therefore, the only critical external force that governs synoptic variability of spatial scales of AP. Thus, we can reconstruct dependence of spatial characteristics of AP identified at satellite imagery on speed and duration of northeastern wind forcing. For this purpose, we used a wind forcing index $W_t =$

$v_i \cdot t$, [h*km/h] where v_i is the average wind velocity during the time period t when wind direction was between 240° and 260° .

Alongshore extent and area of AP were identified at 48 satellite images obtained during or shortly after northeastern wind forcing conditions. For every registered **APAI event** we calculated values of ~~its~~ alongshore extent (L) and area (S) and of AP and compared them with value of wind forcing index W_i for a period of predominant northeastern wind forcing preceding time of satellite observations. For all these cases W_i exceeded 500 km, therefore, we presume this value as a threshold for formation of an AI event. ~~Figures 6 illustrate~~ Alongshore extent and area of AP increase with increase of wind forcing index. However, this increase is not steady, its derivative decreases with increase of wind forcing index. In particular if wind forcing index exceeds 3500 km, alongshore extent and area of AP are almost stable. Thus, the observed forms of dependences between have good approximation by logarithmic functions. Figure 9 illustrates the obtained ~~linear~~ logarithmic relations between ~~logarithms~~ L and S , on the one hand, and ~~logarithm of~~ W_i , on the other hand: $\lg(L) = 0.4 + 0.53 \cdot \lg(W_i) - 325.1 + 141.5 \cdot \lg(W_i)$; $\lg(S) = 0.53 + 0.77 \cdot \lg(W_i) - 4157.5 + 1640.5 \cdot \lg(W_i)$. The obtained equations reveal that dependences between spatial characteristics of AP and wind forcing index follow a power law: $L = 2.5 \cdot W_i^{0.53}$ (RMSE is about 9 km); $S = 3.4 \cdot W_i^{0.77}$ (RMSE is about 13670 km²).

Finally, we ~~analyzed~~ analysed dependence of seasonal variability of area of AP, which is indicative of intensity of AI, on wind forcing and river discharge conditions. For this purpose we calculated monthly averages of area of AP detected ~~at in~~ optical satellite imagery and compared them with monthly averages of wind forcing index and total discharge rate of the Don and Kuban rivers (Figure 7, 10). Monthly variability of average area of AP shows direct relation with monthly variability of wind forcing index. The obtained graph reveals that both characteristics have similar monthly variations with two distinct peaks in September and December – March and lowest values in May – June. However, the opposite situation is observed for dependence between monthly averages of area of AP and river discharge rate. Several studies showed that variability of the Don and Kuban discharges induces variability of level of the Sea of Azov, thus, presumably influencing formation of AI events on seasonal time scale (Goptarev et al., 1991; Filippov, 2015). Nevertheless, seasonal variability of river discharge characterized by distinct spring freshet and autumn-winter draught showed no relation with intensity of AI events. Thus, we obtain that river discharge does not govern seasonal variability of AI.

4.23 Spreading of BP in the Sea of Azov

Inflow of saline waters from the Black Sea to the Sea of Azov, ~~hereafter referred as BI~~, causes formation of a BP. ~~Density of BP is significantly larger than density of surrounding waters of the Sea of Azov. As a result, dense BP that~~ it is spreading in the bottom layer and cannot be directly identified ~~at in~~ satellite imagery. ~~However, wind induced mixing, which can penetrate to sea bottom at the shallow Sea of Azov, can cause mixing of low turbid water of BP with overlaying water of the Sea of Azov, thus, decreasing surface turbidity above the spreading area of BP. As a result, presence of BP in the bottom layer. As it was described in Section 2.2, BP~~ can be identified at satellite imagery as ~~low turbidity~~ area of reduced TSM and Chl-a in the Sea of Azov adjacent to the Kerch Strait (Figure 8). ~~If these low turbid areas associated with spreading of BP are large~~

enough, they occupy the deepest part of the Sea of Azov and their contours correspond to bathymetric isolines (Figure 9). This fact is presumably caused by spreading dynamics of dense BP, which tends to flow down the slope of the Sea of Azov due to gravity force and accumulate in the central basin of the Sea of Azov.

11). We analyzed MERIS and MODIS optical satellite imagery acquired during 2002-2017 and identified 42 only 8 BI events. The process of formation of BI events does not show dependence on southwestern which were confirmed by salinity distributions obtained from BSAS12 numerical simulations. Thus, we assume that BP is not manifested by anomalies of TSM and Chl-a in the surface layer during low wind forcing, as was revealed for AI events conditions and northeastward winds. On the opposite, many of BI events were not detected during all types of wind forcing except during and shortly after moderate and by optical satellite imagery.

All identified BI events were preceded by strong north-easterly winds, which caused intense outflow from the Sea of Azov to the Black Sea. Numerical simulations showed that formation of BI events was caused by reverse of barotropic pressure gradient along the Kerch Strait as a result of relaxation of strong northeastern winds. Figures 8-9 illustrate wind forcing. Figure 11 illustrates typical cases of formation of BI events in response to local wind forcing. Strong northeasterly wind (up to 15 m/s) observed during 14-21 April 2003 caused formation of AP, which was followed by light and variable wind on 21-27 April 2003 and formation of BP detected at satellite imagery on 27 April 2003 (Figure 8). A large BP occupying approximately 10000 km² in the deep central basin (11a). Formation of the Sea of Azov BP detected at satellite imagery on 12 November 2015 was observed on 23 June 2007. The observation time was also preceded by 14 days of, first, strong north-easterly wind (up to 10 m/s) during 29 October – 1 November 2015 that caused formation of AP and, second, light and variable wind (10-23 July 2007), while on 5-10 June 2007 northeastern wind caused formation of AP observed on 6 July 2007-12 November 2015 (Figure 9 11b).

As it was shown above, northeastern wind causes formation of AI event and prevents formation of BI event. BI event, in its turn, is formed in absence of northeastern wind and area of BP depends on duration of this period. This feature can be explained in the following way. Saline and dense water of the Black Sea tends to form a bottom advected gravity flow to the Sea of Azov through the Kerch Strait. In presence of northeastern wind forcing, wind stress is transferred into a relatively shallow Sea of Azov and induces intense flow of freshened water from the area adjacent to the Kerch Strait to the Black Sea. The Kerch Strait is very shallow, especially at its central part, which is 3-5 m deep. Thus, this wind induced surface flow occupies the whole water column in the Kerch Strait and prevents formation of gravity induced flow in the opposite direction in bottom layer. After the end of a period of northeastern wind forcing and cessation of AI, gravity flow from the Black Sea to the Sea of Azov is restored and BP is formed. As a result, area of BP depends on duration of the period without northeastern wind forcing.

Similar configuration of water exchange between the large Patos Lagoon and the Atlantic Ocean through the narrow strait was described by Castelao and Moller (2006). They revealed formation of a reverse flow of saline ocean water to the lagoon after an outflow of freshened lagoon water induced by wind forcing. This feature is caused by reverse of pressure gradient in the lagoon after end of an outflow favorable wind forcing event. Our results are also supported by direct measurements of

vertical current profiles performed by ADCP instruments in the southern and northern parts of the Kerch Strait during 26-28 September 2011 and reported by Ivanov (2012). These measurements showed that moderate ~~northeastern~~north-easterly winds observed on 26-27 September induced surface-to-bottom ~~northwards~~southward flow in the shallow northern part of the Kerch Strait. ~~However, both wind-induced southward surface flow and gravity-induced northward bottom flow were~~
 5 ~~detected in the deep southern part of the strait.~~ Light western wind observed on 28 September 2011 resulted in termination of southward surface flow ~~in both parts of the strait~~ and formation of a distinct ~~gravity-induced~~surface-to-bottom northward flow.

5 Discussion

~~Analysis of satellite imagery and wind data described in Section 4.1 showed that northeastward wind forcing governs~~
 10 ~~formation of AI events and spreading of AP on synoptic and seasonal time scales. Thus, we can reconstruct dependence of~~
~~intensity of AI, i.e., discharge rate from the Sea of Azov to the Black Sea through the Kerch Strait, on speed and duration of~~
~~local wind forcing. First, we define “AI favorable” wind conditions as a period of predominant northeastern wind forcing,~~
~~which wind forcing index T_* exceeds 500 km. All other periods are prescribed as “BI favorable” wind conditions. Second,~~
~~wind reanalysis for the study region, we identify periods of AI favorable wind events. Finally, we calculate areas of AP~~
 15 ~~formed during these events using the obtained relation between wind forcing index and area of AP. Sum these areas for all~~
~~AI events occurred during a year (S_{AP}) is indicative of total annual volume of water inflow from the Sea of Azov to the Black~~
~~Sea through the Kerch Strait (V_{AI}). Simonov & Altman (1991) estimate mean value of V_{AI} during 1963–1972 as 64.3 km^3 ,~~
~~while we calculated that mean value of S_{AP} during 1963–1972 is equal to 12747 km^2 . We assume that mean depth of AP~~
~~(H_{AP}) does not significantly depend on its spatial scale and is mainly defined by bathymetry of the Kerch Strait. Thus, we~~
 20 ~~obtain that $V_{AI} = H_{AP} \cdot S_{AP}$ and mean annual depth of AP is $H_{AP} = V_{AI} / S_{AP} = 5 \text{ m}$, which is consistent with depth of the Kerch~~
~~Strait (Figure 1). Finally, using the dependence of plume area on wind forcing index and estimation of mean depth of AP we~~
~~obtain the following equation for water inflow volume during an AI event (V): $V = S \cdot H_{AP} = 0.017 \cdot W_t^{0.77}$.~~

~~Basing on the equations described above, we estimated mean monthly and annual frequency, duration, and share of AI-~~
~~favorable and BI favorable wind conditions during the period of 2000–2017 and calculated volume of discharge from the Sea~~
 25 ~~of Azov to the Black Sea (table 1). The most frequent and long AI favorable wind conditions are registered in autumn and~~
~~winter. AI events occur during 36–39% of days in these months except a distinct peak in October, when they account for~~
~~52% of days. Then their frequency decreases from 2.2–3.1 times a month in September–February to 0.9–1.2 times a month~~
~~in May–July that results in decrease of share of AI events to 11–15% of days during the latter period. On the other hand,~~
~~mean monthly duration of AI favorable wind conditions is stable during the year and varies from 91.4 hour in June to 119.1~~
 30 ~~in October. BI favorable wind conditions, on the opposite, are dominating in May–July (85–89% of days) and then their~~
~~share steadily decreases till October (48% of days). Frequency of BI events is the same as frequency of AI events, while~~
~~mean monthly duration of BI events shows significantly greater seasonal variability from 135 hours in October to 718.5 in~~

June. Monthly volumes of discharge from the Sea of Azov to the Black Sea is also stable and varies from 3.54 km^3 in June to 5.68 km^3 in January. Mean annual discharge volume during 2000–2017 is estimated equal to 53.69 km^3 that shows good accordance with previous estimations of this value as 55 km^3 (Goptarev, 1991).

6 Conclusions

5 In this work we studied water exchange between the Sea of Azov to the Black Sea through the Kerch Strait. We revealed that different physical mechanisms govern water transport in southward (from the Sea of Azov to the Black Sea, AI events) and northward (from the Black Sea to the Sea of Azov, BI events) directions. Analysis of satellite imagery, wind data, and numerical model outputs shows that water exchange in the Kerch Strait is governed by a wind-induced barotropic pressure gradient. As a result, water flow through the shallow and narrow Kerch Strait is a one-way process during the majority of the

10 time. Southward AI events are induced by moderate and strong ~~northeastern~~north-easterly wind forcing. In this case, wind stress causes transport of freshened water from shallow southern part of the Sea of Azov through the Kerch Strait ~~that, which~~ results in formation of a buoyant plume in the Black Sea. This surface-advected Azov Sea water plume (AP) is characterized by elevated concentrations of suspended sediments and chlorophyll a and ~~is distinctly visible~~can be detected at optical satellite imagery. AP is spreading off the Kerch Strait as a quasi-geostrophic coastal current along the southeastern shore of

15 the Crimean Peninsula, its area steadily increases during an AI event that last 1–5 days. As a result, AP occupies a large area in the northeastern part of the Black Sea up to 2000 km^2 . However, AP dissipates during 1–5 days after end of AI event. The short-term, but regular process of formation and spreading of AP at the northeastern part of the Black Sea influences many local physical, biochemical, and geological processes, which were addressed in many previous studies.

20 Northward water transport in the Kerch Strait, on the opposite, was registered after relaxation of strong ~~northeastward~~north-easterly winds. ~~Saline that results in reverse of the barotropic pressure gradient along the strait and dense water triggers inflow from the Black Sea propagates through the Kerch Strait and inflows to the freshened-Sea of Azov as a bottom-advected flow that is induced by the gravity force. Strong northeastern. Thus, strong north-easterly~~ wind plays a restricting role for this process, because intense wind-induced southward surface flow of water from the Sea of Azov occupies the whole water column in the shallow ~~central~~northern part of the Kerch Strait. ~~This prevents formation of the gravity induced flow of water from the Black Sea in the opposite direction in the bottom layer.~~

25 Analysis of satellite images did not show any direct dependence of northward water transport in the Kerch Strait on characteristics of local wind forcing. However, this feature can be caused by relatively low number of detected BI events ~~at in~~ satellite imagery, ~~therefore future study of influence.~~ Future studies of wind forcing influence on this process will thus require more specific and detailed in situ measurements and/or numerical modelling in the ~~study~~ region.

30 ~~After water from the Black Sea inflows to the Sea of Azov it forms a bottom-advected BP that tends to spread down the slope due to gravity force and accumulate in the deep central basin of the Sea of Azov. Area of BP depends on duration of the related BI event, i.e., period without northeastern wind forcing that can last up to 13 days. BP exhibits intense mixing~~

~~with overlaying freshened waters caused by frequent wind-induced turbulence that penetrates to sea bottom in the shallow Sea of Azov. This results in formation of area of low turbid water in the surface layer that is visible at optical satellite imagery and indicates location of BP in the Sea of Azov.~~

We determined that wind forcing governs direction and intensity of water transport in the Kerch Strait on inter-annual time scale. River runoff to the Sea of Azov does not show any distinct influence on synoptic and seasonal variability of water exchange through the Kerch Strait ~~which is, i.e., signal of river discharge dissipates in the Sea of Azov and does not influence freshwater outflow from estuary to open sea. This feature is not~~ typical for large river estuaries, ~~including large ones, e.g., the Patos Lagoon (Castelao and Moller, 2006) and the Amur Liman (Osadchiev, 2017). We presume that this feature is caused by large~~ Relation between freshwater discharge to river estuary and water exchange between the estuary and open sea depends on two main factors, namely, the volume of inflowing river discharge and the spatial scales of an estuary. The volume of the Sea of Azov (290 km^3), which is of greater by one order larger of magnitude than the annual continental discharge to the sea ($20 - 54 \text{ km}^3$). As a result, River runoff during flooding period increases the level of the Sea of Azov only by 6-7 ~~centimeters~~ centimetres as compared to draught period. As a result, signal of seasonal discharge variability of the Don and Kuban rivers dissipates in the Sea of Azov and does not influence the intensity of water exchange through the Kerch Strait. The volume of the Patos Lagoon (50 km^3), on the opposite, is of the same order as continental runoff volume (75 km^3), which causes an increase of the lagoon level by 70-80 cm during freshet periods. As a result, stable seaward flow from the Patos Lagoon during the seasonal flood can be reversed only by very strong winds (Moller and Castaing, 1999). The volume of the Amur Liman (20 km^3) is much less than the annual Amur discharge volume (400 km^3); Therefore, water exchange between the Amur Liman and sea is dominated by the river regime during the major part of a year (Osadchiev, 2017). On the other hand, several previous studies reported that inter-annual river discharge variability influence water exchange between the Sea of Azov and the Black Sea (Goptarev, 1991; Ilyin et al., 2009; Ivanov & Belokopytov, 2011). However, detailed analysis of inter-annual variability of water transport in the Kerch Strait and its dependence on external factors is beyond the current article.

~~In this study we revealed wind forcing conditions that cause formation of AI and BI events and analyzed intra-annual variability of their monthly and annual frequency and duration for the period of 2000-2017. BI favorable wind conditions are significantly more frequent than AI favorable conditions and occur during 71% of days in a year with a distinct peak in May-July (85-89% of days). AI events slightly dominate over BI events only in October (58% of days), while during the rest of the year their share is 11-39%. Shifts between AI favorable and BI favorable wind conditions occur relatively rarely, 1-3 times in a month and only 46 times in a year. Thus, AI and BI events generally last for relatively long time periods; their mean annual durations are approximately 4.3 and 13.7 days, respectively. Duration of AI events does not significantly change during a year, while mean monthly duration of BI event varies from 5 to 30 days.~~

~~Basing on satellite and wind reanalysis data we derived numerical equation that define discharge rate from the Sea of Azov to the Black Sea during AI event on speed and duration of northeastern wind. Using this equation, we calculated monthly averages of water transport from the Sea of Azov to the Black Sea during 2000-2017 which showed low seasonal variability.~~

Also we obtained relations between spatial characteristics of AP, namely, alongshore scale and area, on wind forcing conditions during AI event. On the other hand, we did not determine relevant equations for water transport from the Black Sea to the Sea of Azov. It is caused by the fact that spatial characteristics and temporal variability of spreading of BP in the bottom layer of the Sea of Azov is much worse detected at satellite imagery, as compared to surface advected AP. As a result, definition of dependencies for both discharge rate from the Black Sea to the Sea of Azov and spatial characteristics of BP on wind forcing requires specific in-situ measurements which are beyond the current study.

Based on quantitative relations between spatial characteristics of AP and local wind forcing established in Section 4.2 we can reconstruct dependence of discharge rate from the Sea of Azov to the Black Sea through the Kerch Strait based on speed and duration of local wind forcing. First, we define “AI-favorable” wind conditions as a period of predominant north-easterly wind forcing, which wind forcing index T_v exceeds 500 km. Second, using wind reanalysis data we identify periods of AI-favourable wind events. Finally, we calculate areas of AP formed during these events using the obtained relation between wind forcing index and area of AP. The sum of these areas for all AI events occurred during a year (S_{AP}) is indicative of total annual volume of water inflow from the Sea of Azov to the Black Sea through the Kerch Strait (V_{AI}). Simonov & Altman (1991) estimate mean value of V_{AI} during 1963-1972 as 64.3 km^3 , while we calculated that mean value of S_{AP} during 1963-1972 is equal to 12747 km^2 . We assume that mean depth of AP (H_{AP}) does not substantially depend on its spatial scale and is mainly defined by bathymetry of the Kerch Strait. Thus, we obtain that $V_{AI} = H_{AP} \cdot S_{AP}$ and mean annual depth of AP is $H_{AP} = V_{AI} / S_{AP} = 6 \text{ m}$, which is consistent with depth of the Kerch Strait (Figure 1). Finally, using the dependence of the plume area on the wind forcing index and an estimate of the mean depth of AP we obtain the following equation for water inflow volume during an AI event (V): $V = S \cdot H_{AP} = -20.78 + 8.2 \cdot \lg(W_f)$.

Many of the previous studies were focused on numerical modelling of circulation, food webs, water quality, transport and fate of dissolved and suspended matter and other processes in the Black Sea (e.g., Stanev, 1990; Oguz et al., 1995; Stanev & Staneva, 2000; Staneva et al., 2001; Enriquez et al., 2005; Korotenko et al., 2010; Korotenko, 2017, Stanev et al., 2017). Many of these studies did not simulate circulation in the Sea of Azov and the Kerch Strait, but reproduced water exchange through the Kerch Strait as a **borderboundary** condition. However, these works generally applied mean annual or mean seasonal exchange values and neglected the fact that direction and discharge rates of water transport through the Kerch Strait have strongly inhomogeneous temporal distributions and significant inter-annual variability. In particular, we are not aware of any relevant numerical parameterizations of water exchange through the Kerch Strait that reproduce its synoptic variability. Thus, the equations, which define conditions of formation of AI events and dependence of discharge rate during AI event on speed and duration of ~~northeastern~~ north-easterly wind, that were obtained in the current study, hold promise to be useful for numerical modelling of the Black Sea. They can improve existing parameterizations of **borderboundary** conditions at the Kerch Strait and, therefore, increase accuracy of numerical simulation of ~~many~~ physical, geological, and biochemical processes in the Black Sea.

Data availability

The Envisat MERIS satellite data were downloaded from the European Space Agency repository of the Envisat satellite data <http://merisfrs-merci-ds.eo.esa.int/merci> (available after registration). The Terra MODIS and Aqua MODIS satellite data were downloaded from the National Aeronautics and Space Administration repository of LANCE-MODIS satellite data <https://lance3.modaps.eosdis.nasa.gov>. The river discharge and wind data were downloaded from the Federal Service for Hydrometeorology and Environmental Monitoring of Russia repositories <http://gis.vodinfo.ru> (available after registration) and <https://rp5.ru>. The NCEP/NCAR reanalysis data were downloaded from the National Oceanic and Atmospheric Administration website <https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.surface.html>.

Competing interests

10 The authors declare that they have no conflict of interest.

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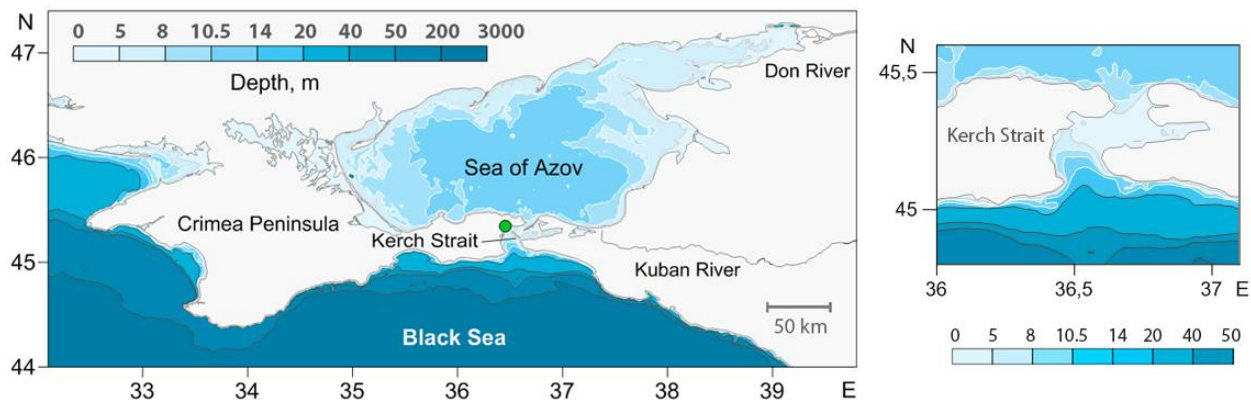


Figure 1: Bathymetry of the Sea of Azov and the northeastern part of the Black Sea (left) and the Kerch Strait (right). Locations of the estuaries of the Don and Kuban rivers and the Kerch meteorological station (green circle).

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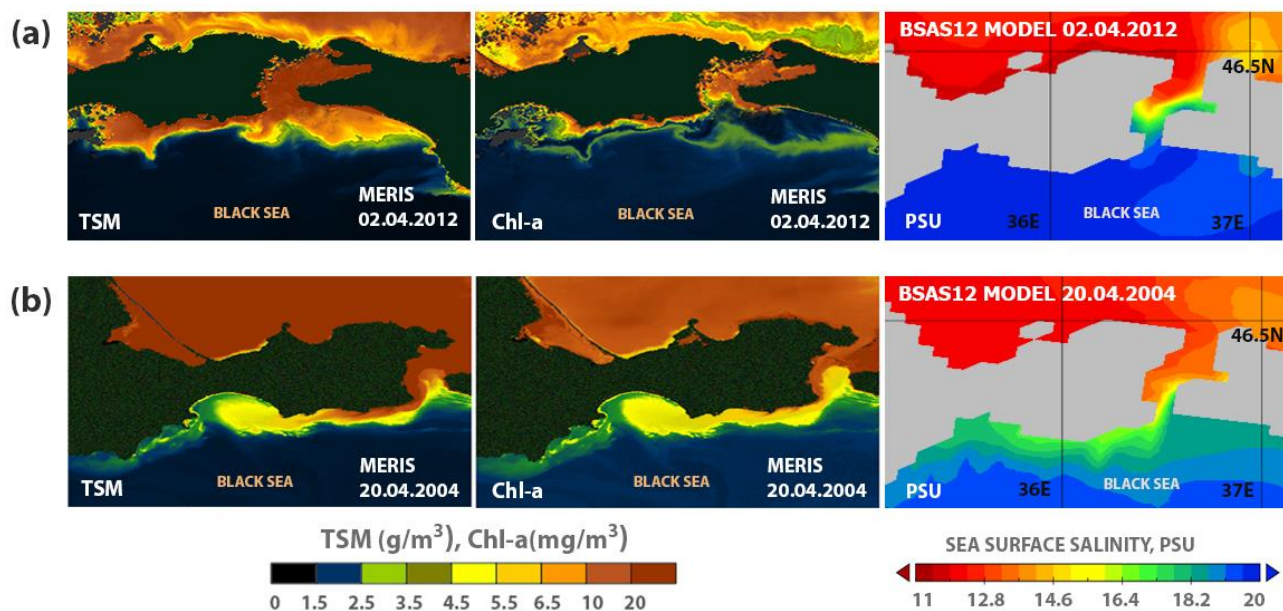


Figure 2: Sea surface distributions of TSM (left) and Chl-a (~~right middle~~) retrieved from MERIS satellite data and sea surface salinity distribution obtained from numerical modelling (right) indicating wind-induced resuspension of sea bottom sediments at the study area on 2 April 2012 (a) and spreading of AP on 20 April 2004 (b).~~2~~

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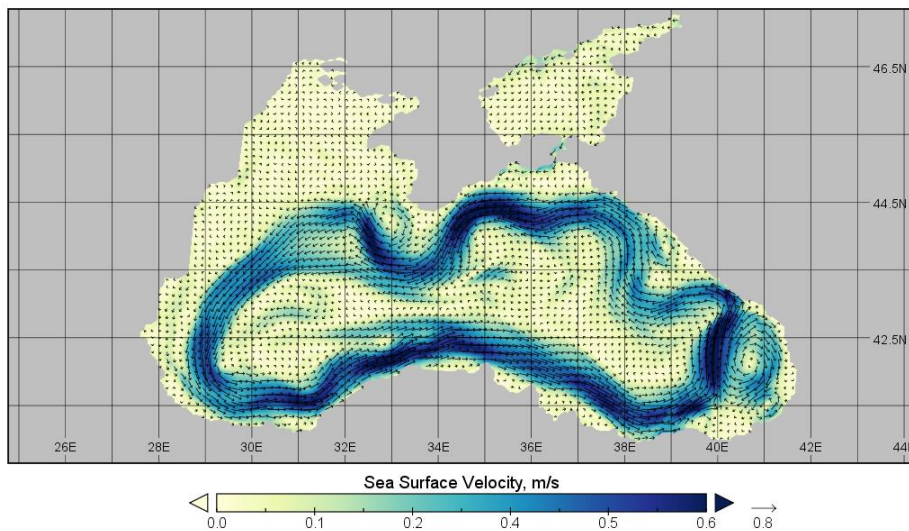
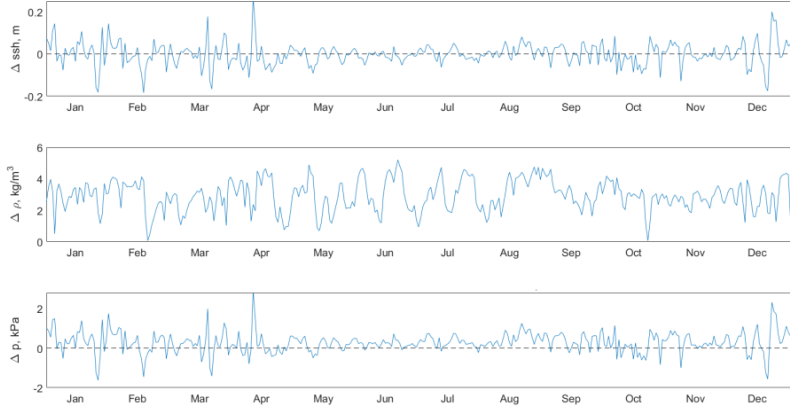


Figure 3: Daily snapshot of surface velocity field on 15 January 1994. It illustrates the cyclonic Rim Current, the quasi-permanent anticyclonic currents - (Batumi, Sochi, Sebastopol), and the westward outflow from the Kerch Strait spreading along the Crimea peninsula.

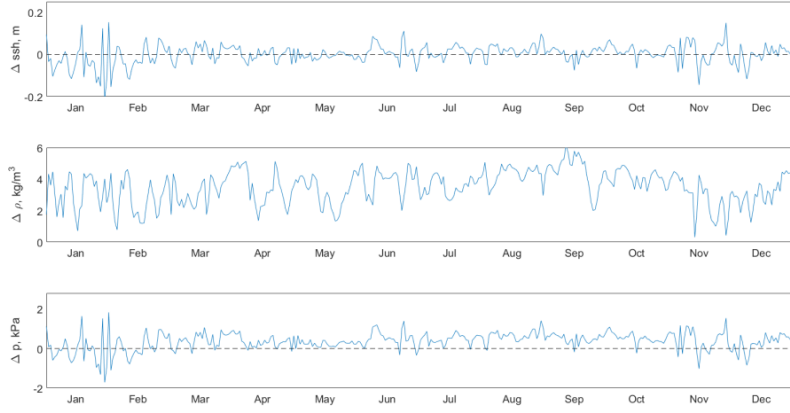


Figure 4: Yearly mean values of total water transport through the Kerch Strait, km³. Dashed line - average yearly transport over the entire period of the experiment.

1997



2007



2017

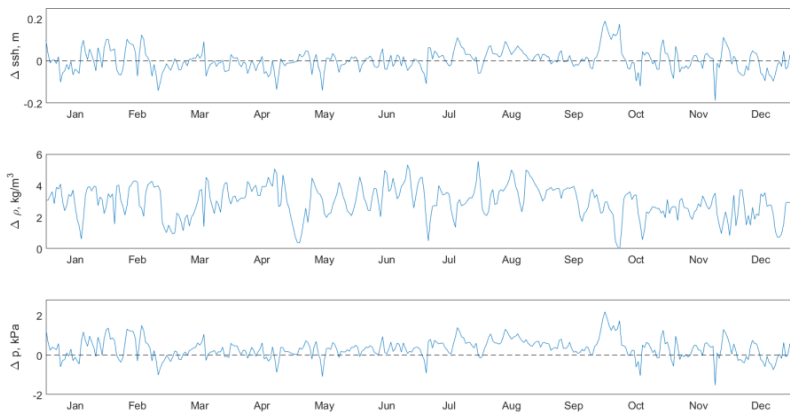


Figure 5: Daily averaged values of sea level gradient (top), density gradient (middle), and total pressure gradient (bottom) between the northern and southern ends of the Kerch Strait reconstructed for the 1997, 2007, and 2017 with the BSAS12 model simulation.

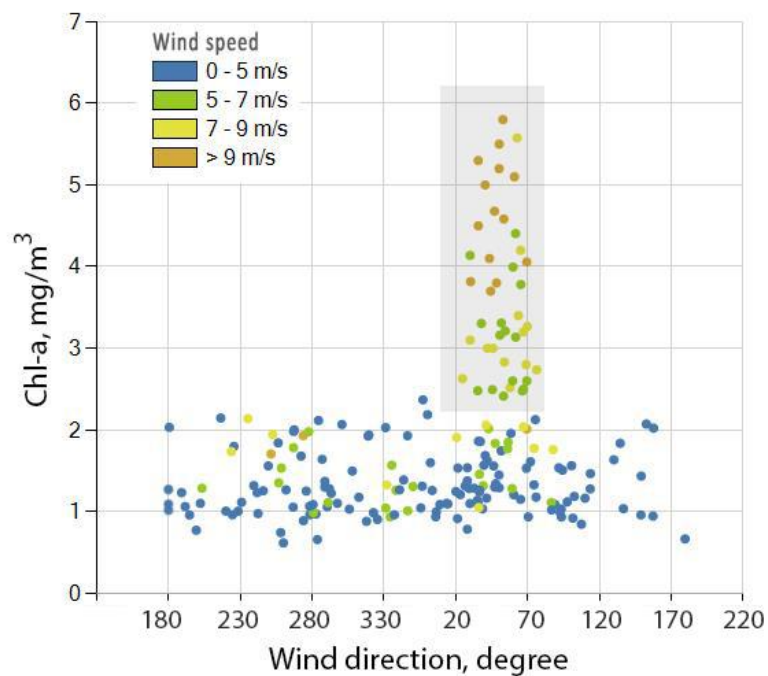


Figure 6: Dependence between concentration of Chl-a in the Kerch Strait and the adjacent area of the Black Sea retrieved from optical satellite imagery, on the one hand, and direction of wind forcing averaged over 24 hours preceding satellite observations, on the other hand

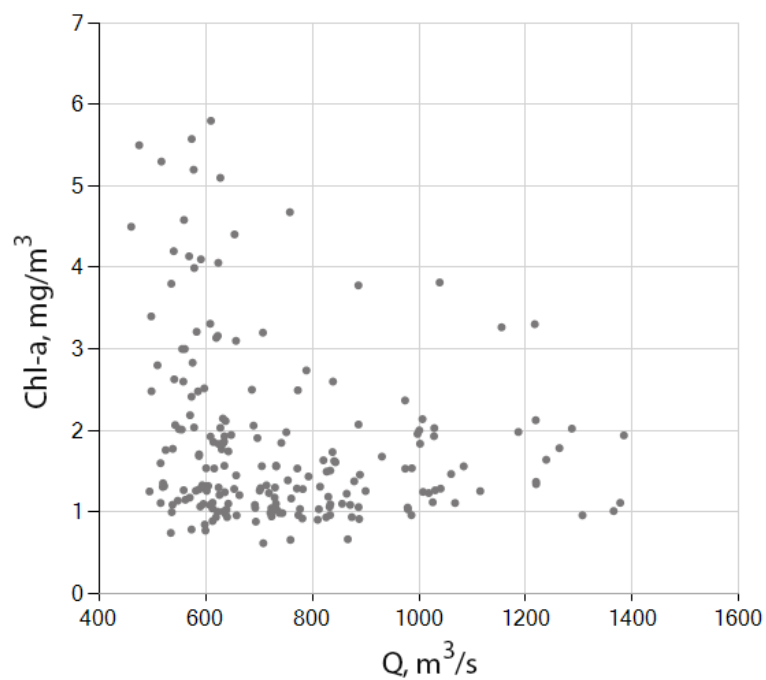


Figure 47: Dependence between concentration of Chl-a in the Kerch Strait and the adjacent area of the Black Sea retrieved from optical satellite imagery, on the one hand, and total discharge of the Don and Kuban rivers, on the other hand.

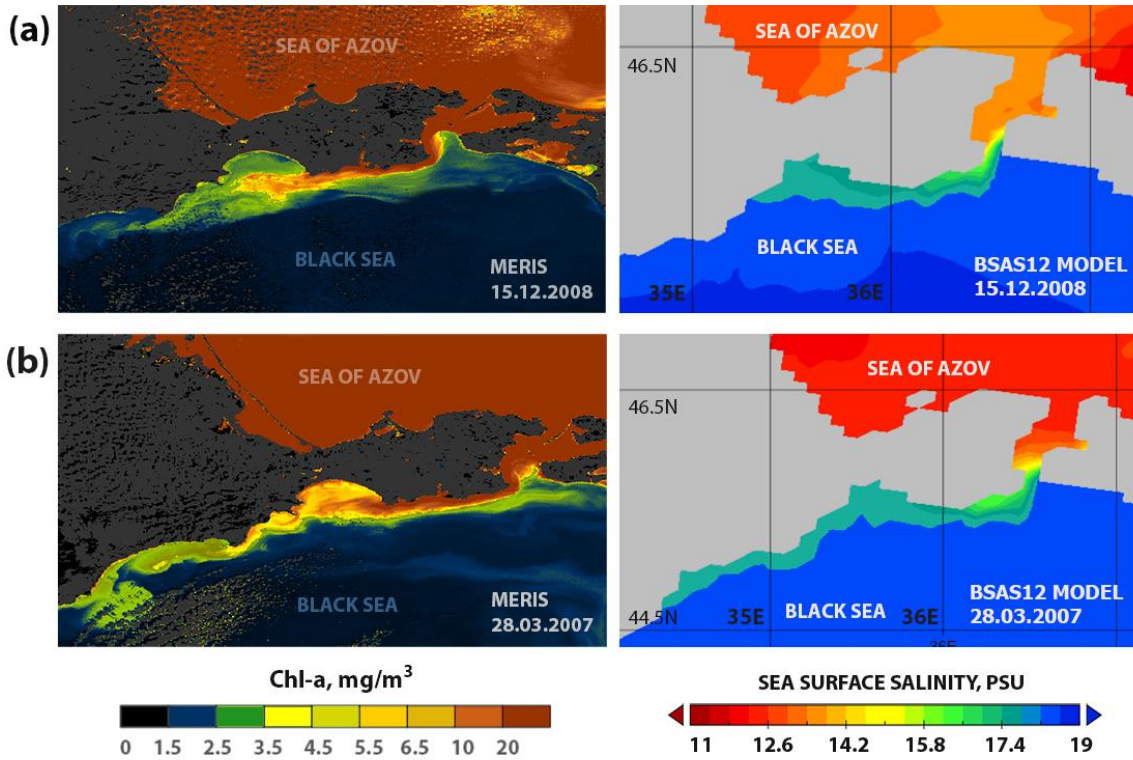


Figure 5: Temporal variability of AP identified at satellite8: Sea surface distributions of TSM on 27, 28, and 30 August 2014; distribution of Chl-a retrieved from MERIS satellite data (left) and sea surface salinity distribution obtained from numerical modelling (right) on 12 December 2008 (a) and 28 March 2007 (b).

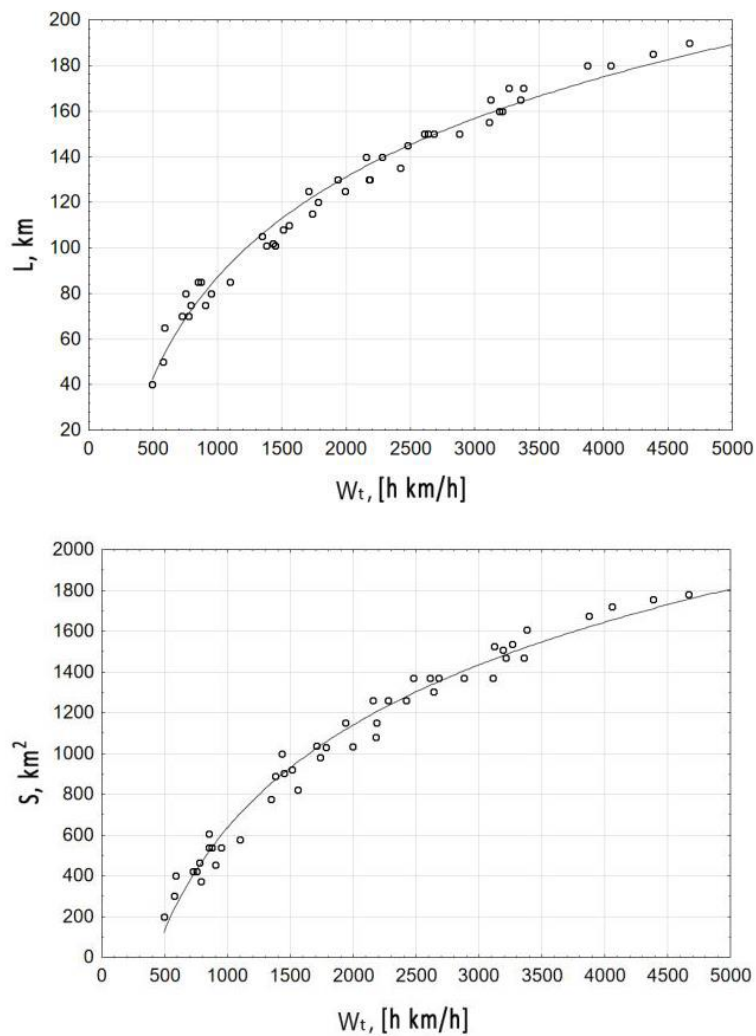


Figure 69: Dependence between alongshore extent of AP (top) and area of AP (bottom) calculated from satellite data, on the one hand, and wind forcing index for the period of predominant northeastern winds preceding time of satellite observations, on the other hand.

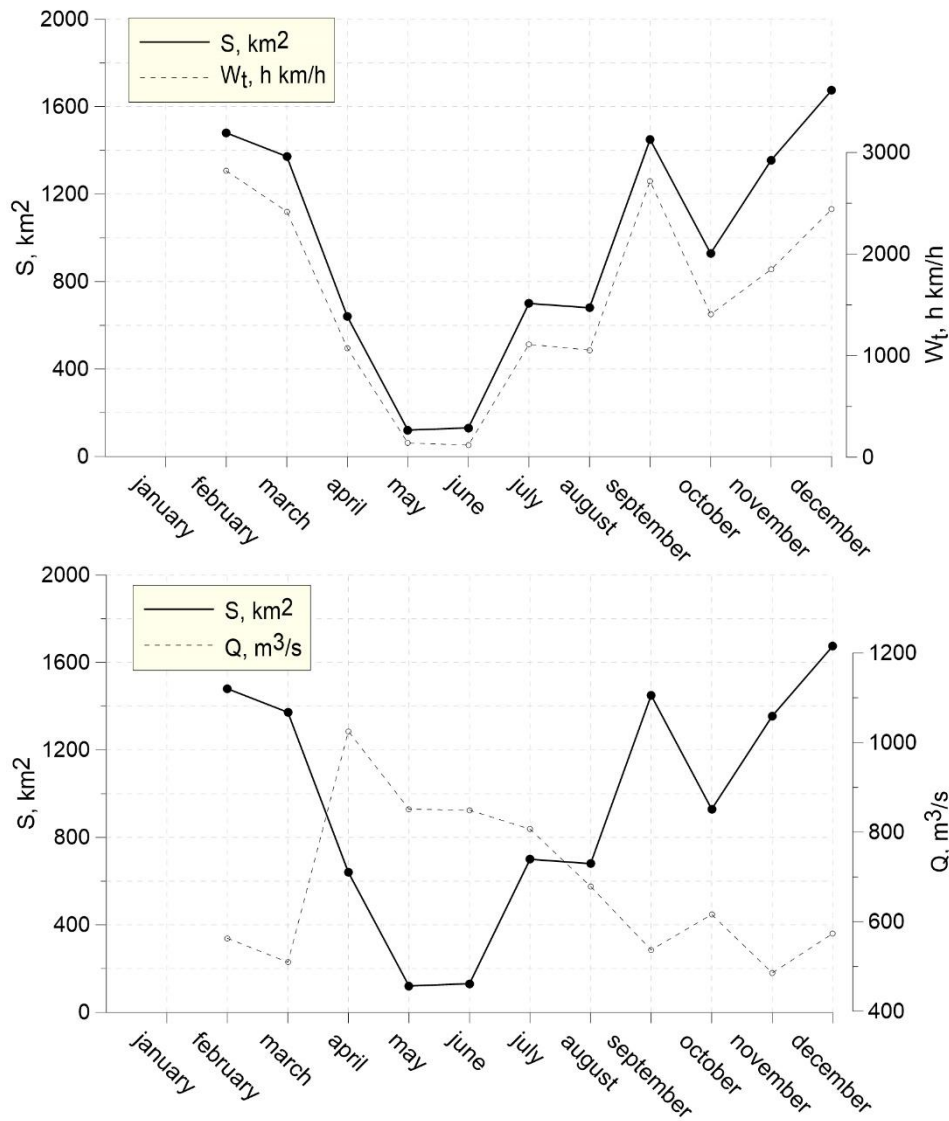


Figure 710: Dependence between monthly averages of wind index (top) and total discharge rate of the Don and Kuban rivers (bottom), on the one hand, and monthly averages of area of AP detected at optical satellite imagery, on the other hand.

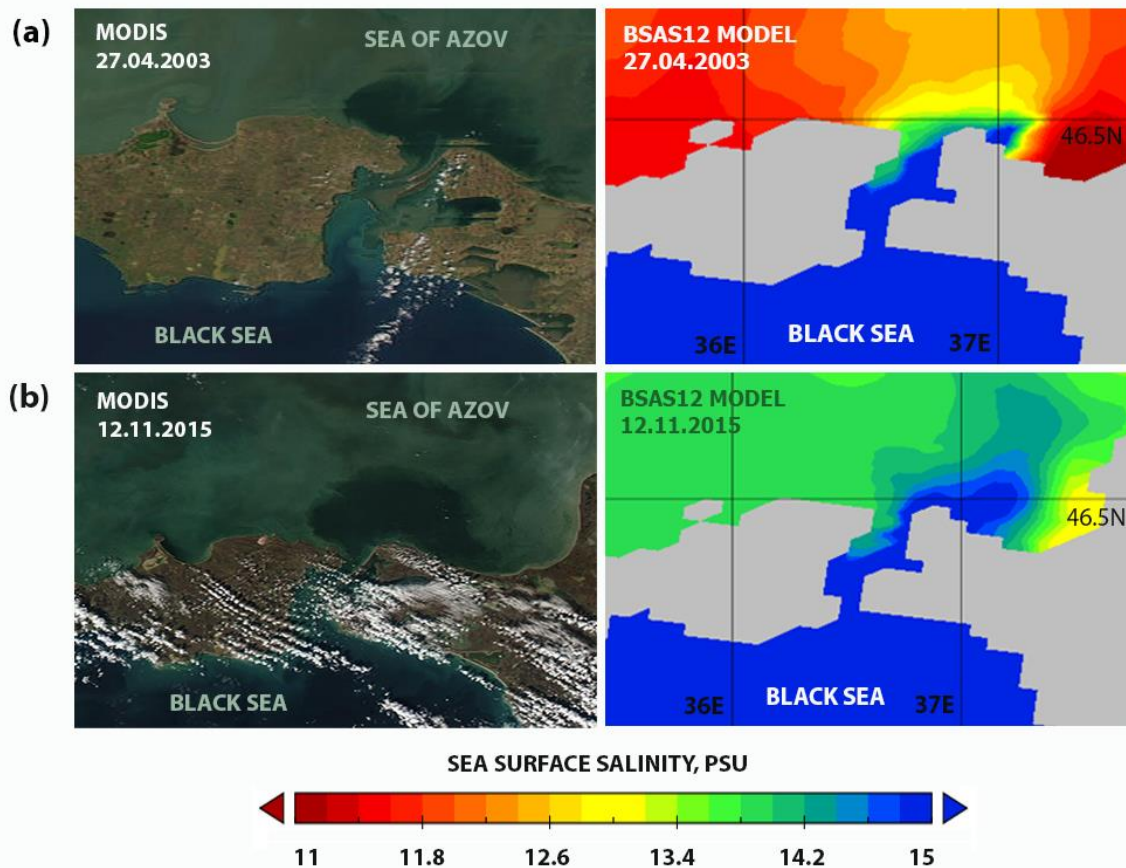


Figure 8-11: Formation of the BP formed during 21-27 April 2003 and AP formed during 14-21 April 2003 identified at satellite surface distributions of TSM after the wind relaxation on 27 April 2003 (a) and 12 November 2015 (b), retrieved from MERIS satellite data (a); local wind forcing with indication of its maximal and average values during 14-21 and 21-27 April 2003 (b).

Table 1: The flow direction statistics in the Kerch Strait for the period from 1992 to 2010, obtained by the BSAS12 numerical model simulation.

| Year | Only into Black sea, days | Only into Sea of Azov, days | In both directions, days |
|------|---------------------------|--------------------------------|--------------------------|
| 1992 | 178 | 145 | 43 |
| 1993 | 177 | 152 | 36 |
| 1994 | 169 | 150 | 46 |
| 1995 | 180 | 150 | 35 |
| 1996 | 171 | 153 | 42 |
| 1997 | 181 | 150 | 34 |
| 1998 | 173 | 146 | 46 |
| 1999 | 171 | 158 | 36 |
| 2000 | 168 | 156 | 42 |
| 2001 | 167 | 150 | 48 |
| 2002 | 170 | 150 | 45 |
| 2003 | 181 | 139 | 45 |
| 2004 | 174 | 152 | 40 |
| 2005 | 172 | 145 | 48 |
| 2006 | 167 | 146 | 52 |
| 2007 | 161 | 154 | 50 |
| 2008 | 176 | 149 | 41 |
| 2009 | 166 | 145 | 54 |
| 2010 | 163 | 157 | 45 |