1 Cross-shelf exchange in the northwestern Black Sea

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| 16 | Key points: |
| 17 | • Cross-shelf break transports of volume, heat and salt are quantified |
| 18 | • Exchange mechanisms by mesoscale eddy and wind-driven Ekman drift are |
| 19 | analyzed |
| 20 | • Some exchange events are shown to cause a sharpening of the shelf break density |
| 21 | front |
| 22 | |

23 Abstract: The transports of water, heat and salt between the northwestern shelf and deep interior of the Black Sea are investigated using a high-resolution three-24 dimensional primitive equation model. From April to August, 2005, both onshore and 25 26 offshore cross-shelf break transports in the top 20 m were 0.24 Sv on average, which is equivalent to the replacement of 60% of the volume of surface shelf waters (0 - 20)27 28 m) per month. Two main exchange mechanisms are studied: Ekman transport, and 29 transport by mesoscale eddies and associated meanders of the Rim Current. The 30 Ekman drift causes nearly uniform onshore or offshore flow over a large section of 31 the shelf break, but it is confined to the upper layers. In contrast, eddies and meanders 32 penetrate deep down to the bottom, but they are restricted laterally. During the strong wind events of April 15 – 22 and July 1 – 4, some 0.66×10^{12} and 0.44×10^{12} m³ of 33 34 water were removed from the northwestern shelf respectively. In comparison, the single long-lived Sevastopol Eddy generated a much larger offshore transfer of 35 2.84×10^{12} m³ over the period April 23 to June 30, which is equivalent to 102% of the 36 37 volume of northwestern shelf waters. Over the study period, salt exchanges increased the average density of the shelf waters by 0.67 kg m^{-3} and reduced the density contrast 38 39 between the shelf and deep sea, while lateral heat exchanges reduced the density of the shelf waters by 0.16 kg m^{-3} and sharpened the shelf break front. 40

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42 Keywords: anticyclonic eddy, exchange, Black Sea, shelf water, NEMO_SHELF

43 **1** Introduction

44 Steep bathymetry at the shelf edge inhibits ocean-shelf exchange, as large-scale currents tend to flow along the contours of constant depth [Huthnance, 1995]. 45 However, both theory and observations have demonstrated that the circulation is not 46 47 in geostrophic balance along lateral ocean boundaries, in straits and overflows and in the upper mixed layer [Niiler, 2009]. Hence, ageostrophic features, such as mesoscale 48 49 eddies, turbulent mixing and Ekman transport, become the main agents to provide 50 cross-shelf-edge transport [Houghton et al., 1988; Brink et al., 1992; Sur et al., 1994; 51 Ohlmann et al., 2001; Peliz et al., 2004; Huthnance et al., 2009; Kirincich and Barth, 52 2009].

53 Ocean margin fluxes between productive shelf waters and nutrient-rich deep 54 ocean waters are not only important to carbon and nutrient budgets in the ocean, and 55 thus do matter to global climate change, but are also essential to refresh the highly 56 eutrophic coastal marine ecosystems [Bauer and Druffel, 1998; Pringle, 2001; 57 Huthnance et al., 2002; Biggs et al., 2005]. A variety of physical and biogeochemical 58 processes can modify the properties of shelf waters. Traditionally the focus has been on the effect of river runoff [Caddy and Bakun, 1995]; however, recent studies show 59 60 the significance of exchange with adjacent areas of deep ocean, see e.g., Biggs et al. 61 [2005] and references therein.

62 There have been a number of experiments aiming at estimating the exchange
63 between the shelf and the deep-sea region [*Biscaye et al.*, 1994; *Biscaye and*

Anderson, 1994; *Matsuno et al.*, 2009; *Piola et al.*, 2010]. Direct measurements of
cross-shelf break exchange [*Johnson and Chapman*, 2011] are rare and difficult to
conduct as the cross-shelf current is often much smaller than the along-shelf
counterpart. The use of ocean circulation models proved to be a helpful supplement to *in situ* measurements and satellite observations [*Dinniman et al.*, 2003; *Serra et al.*,
2010; *Zhao and Guo*, 2011].

70 The estimates of exchange fluxes can vary dramatically. According to Biscaye et 71 al. [1994], less than 5% of biogenic particulate matter is exported from the Middle 72 Atlantic Bight of the eastern North America continental shelf. Estimates for the Black 73 Sea based on remotely sensed data are significantly higher; up to 40% of shelf waters 74 could be replenished during the summer season by a single mesoscale eddy [Shapiro 75 et al., 2010]. On the edge of the East China Sea, the cross-shelf volume transport showed significant seasonal variability, ranging from 0.5 Sy (1 Sy= 10^6 m³ s⁻¹) in 76 77 summer to 3.0 Sv in autumn [Guo et al., 2006]. A model study of the Ross Sea shelf 78 showed high values of the individual components of the cross-shelf transport, 79 corresponding to different water masses and different depth ranges [Dinniman et al., 80 2003]. The yearly-averaged onshore surface Ekman transport was 0.3 Sv, while the 81 offshore transport in the bottom Ekman layer was 0.8 Sv, with short-term 82 enhancements of up to 1 - 1.5 Sv. The long-term mean total transport onto the shelf from surface to bottom via a closed boundary was nearly zero (less than 10^{-2} Sv on 83 average) due to mass conservation. 84

As well as in other parts of the ocean, across-shelf exchange in the Black Sea 85 controls the quantities, transformation and fate of materials discharged into the shelf 86 by the rivers. The Black Sea is a unique marine environment, representing the largest 87 88 land-locked basin in the world (Fig. 1). Its general circulation pattern includes the 89 Rim Current - a cyclonic flow located at the seaward side of the shelf break, and two 90 sub-basin cyclonic gyres sometimes called 'Knipovich spectacles' [Bulgakov and Kushnir, 1996]. The drainage area of the Black Sea is about 2,000,000 km², which is 91 92 nearly five times larger than its surface area, and covers almost a third of Europe. This 93 results in a disproportionally large freshwater input making the Black Sea an 94 estuarine-type basin. Large European rivers (the Danube, Dnieper, Southern Bug and 95 Dniester) discharge fresh waters into the northwestern (NW) shelf [Shapiro, 2009]. 96 The rivers bring vast quantities of nutrients, leading to eutrophication of shelf waters and decline of the once flourishing Black Sea ecosystem [GEF-UNDP report, 2006]. 97 98 Exchanges across the NW shelf break provide a mechanism for the self-cleaning of 99 the shelf waters, and hence the quantification of such exchanges is a highly important 100 research topic.

101 The NW shelf and deep areas of the Black Sea differ significantly in terms of a 102 number of characteristics. The concentration of chlorophyll *a* (hereafter Chl-*a*) is as 103 high as $5 - 10 \text{ mg m}^{-3}$ on the shelf, but is as low as $0.2 - 0.5 \text{ mg m}^{-3}$ in the open sea 104 (Fig. 2). The NW shelf is typically colder, fresher and less dense than the open sea in 105 both winter and summer (Fig. 3). Hence, the intensity of across-shelf exchange is 106 instrumental in smoothing, stabilizing or enhancing the gradients of these parameters between the productive NW shelf and oligotrophic deep-sea region. An increase in the 107 108 across-shelf exchange of salt would increase the salinity and density of the shelf 109 waters, reduce the density contrast and decrease the strength of the shelf break front. 110 Reduction of the density front may initiate a positive feedback loop enhancing further 111 across-shelf exchange that may destabilize the density structure of the Black Sea. On 112 the other hand, an increase in the across-shelf exchange of heat would increase the 113 temperature and reduce the density of the shelf waters, hence strengthening the shelf-114 edge density front and initiating a negative feedback loop, thus stabilizing the existing 115 property pattern. The relative strength of the positive and negative feedbacks is difficult to assess based only on reasoning and patchy measurements. It needs 116 117 quantitative estimates of exchanges along the whole NW shelf break for an extended 118 period of time, which can only be achieved by ocean modeling. 119 The role of the anticyclonic eddies in cross-shelf exchange in the Black Sea has

been highlighted in a number of publications [*Blinkov et al.*, 2002; *Zatsepin et al.*, 2003, and references therein]. A long-lived anticyclonic eddy with a nearly 113-km diameter was identified in June 1984 and thought to cause significant transport of water [*Latun*, 1990]. A radiance spectrum from SeaWiFS was used to identify vortex dipoles and diagnose the pattern of the exchange between coastal region and deep basin [*Karabashev et al.*, 2006]. In summers of 1993 and 1998, anticyclonic eddies were traced persistently over the wide and relatively gentle slope; they contributed to 127 cross-shelf exchange particularly between 43°E – 45°N and 29°E – 33°E [*Ginzburg et al.*, 2002]. Anticyclonic eddies are fundamentally recurrent and quasi-stable, and can
129 be reproduced by appropriate modeling [*Korotaev et al.*, 2003].

However, previous research of cross-shelf exchange in the Black Sea was mostly restricted to a qualitative understanding of the underlying processes rather than quantitative estimates, except for Shapiro *et al.* [2010] that gave a quantitative estimate of the horizontal fluxes based on satellite imagery for the year 2005. Due to the nature of the available data, the study was limited in time (cloud-free conditions) and in vertical extent (the surface layer only).

This paper focuses on quantification of cross-shelf-break fluxes in the NW shelf of the Black Sea during the spring – summer period of 2005 when weather condition was more favorable for remotely sensed data, to cover the main period of Chl-*a* bloom. We use a high-resolution numerical model to estimate onshore and offshore fluxes in different depth ranges, with a particular emphasis on the transports in the surface eutrophic layer generated by Ekman drift and mesoscale eddies. We also investigate the locations of these transports and their temporal variability.

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2 Model, Data and Methods

144 The simulation is performed using the 3D Nucleus for European Modeling of the 145 Ocean model [*Madec*, 2008], which was further developed for operational forecast for 146 shelf waters (hereafter NEMO_SHELF) [*O'Dea et al.*, 2012]. The model has been thoroughly tested and validated across the Met Office [*Edwards et al.*, 2012; *O'Neill et al.*, 2012]. The configuration of NEMO_SHELF for the Black Sea has been
optimized to better represent specific features of the Black Sea, for instance, with
limited exchange with the world ocean, and significant river inflow [*Shapiro et al.*,
2013].

152 For this study, the model covers the entire Black Sea (Fig. 1), and is set up with 153 1/24 degree horizontal resolution (approximately 3.3 km in the zonal and 4.6 km in 154 the meridional directions) and a hybrid vertical coordinate system with a total of 33 155 layers. The 18 layers shallower than 100 m are represented by an enveloped s-156 coordinate system [Madec, 2008], which was a further development of the terrainfollowing vertical grid by Song and Haidvogel [1994], and the deeper layers are 157 158 arranged horizontally in a z-coordinate. This configuration will be referred to as NEMO-BLS24. Further details of this configuration and its validation can be found in 159 Shapiro et al. [2013]. The NEMO-BLS24 model was run in a "free" mode, i.e., 160 161 without data assimilation.

The model was initialized to start from January 1, 2005 by interpolating monthly climatological temperature and salinity data for December and January from the Black Sea Atlas [*Suvorov et al.*, 2003] and then generating the matching initial velocities using a "semi-diagnostic adjustment method" [*Sarkisian and Sündermann*, 2009], also known as "diagnostic-prognostic adjustment" [*Ezer and Mellor*, 1994]. After the "diagnostic adjustment" the model was run in a fully prognostic mode, showing that the model adjusts itself to the "wind shock" well within approximately30 days, in a full agreement with the finding by Ezer and Mellor [1994].

Chl-a concentration was obtained from the Level-3 product of Medium 170 171 Resolution Spectrometer (http://oceandata.sci.gsfc.nasa.gov/MERIS/, Imaging 172 MERIS), and from the Moderate Resolution Imaging Spectroradiometer in Aqua 173 satellite (MODISA), which was kindly provided by the National Space Agency of 174 Ukraine (NSAU, http://dvs.net.ua/mp/index.shtml). MODISA incorporates local atmosphere corrections for the Black Sea. Although it is commonly accepted that the 175 176 algorithm for calculating the concentration of Chl-a has difficulties in highly turbid 177 coastal water, we only use Chl-a for qualitative estimates, i.e., as a tracer to identify the border between Chl-a rich shelf waters and oligotrophic waters of the deep basin. 178 179 Sea surface temperature, processed by the NSAU based on data from the National Oceanic and Atmospheric Administration (NOAA) polar-orbiting environmental 180 181 satellites 12 and 15 - 17, is used to compare the eddy position and migration with 182 model results.

The meteorological datasets used to force the model were obtained from the National Center for Environmental Prediction (NCEP). They include 4-times daily datasets on air temperature, relative humidity, wind, precipitation, and downward long- and short-wave radiation. The meteorological data in a few grid boxes that cover both the eastern corner of the Black Sea and the high (more than 5000 m) Caucasus Mountains are highly contaminated by the conditions over the mountains. 189 These data points are replaced by extrapolation from the neighboring "sea-only" grid190 boxes.

191 The simulation includes ten major rivers: the Danube, Dniester, Dnieper, Don, 192 Kamtehiya, Maritza, Kizilirmak, Rioni, Southern Bug, and Sakarya (Fig. 1). 193 Exchange via Bosporus is described as a negative river discharge, representing a 194 balance between the upper (outward) and lower (inward) flows. Daily river discharges 195 into the Black Sea are interpolated from monthly climatological data sets [*Jaoshvili*, 196 2002].

197 The transport of water, salt and heat between the shelf and deep-sea regions was calculated along an enclosed boundary (a "fence") approximating the 200 m isobath 198 199 (Fig. 1, blue squares) plus two short segments connected to the coast (Fig. 1, gray 200 squares). For each day, the total transport was calculated by integrating the individual daily-averaged fluxes through the model grid boxes in the horizontal along the 201 202 "fence" and in the vertical from surface to bottom. Partial transports were also 203 calculated for the surface layer (top 20 m) and the under-surface layer (from 20 m to 204 the bottom). The 20 m level is approximately equal to the Ekman depth in summer 205 [Oguz, 2008]. It is also close to the depth of the biologically active euphotic layer; for instance, the transparency of water in the offshore NW shelf is about 15 - 18 m 206 207 [Zaitsev, 1992].

208 3 Results

209 Following the usual practice [Nezlin et al., 1999; Kopelevich et al., 2002; 210 Shapiro et al., 2010], the satellite charts of Chl-a concentration are used here as a 211 useful tool to identify the front between chlorophyll-rich shelf waters and the deep-sea 212 region, visualizing the meanders of the Rim Current and eddies (Fig. 1). As an 213 example, the MERIS Chl-a distribution on June 30, 2005 (Fig. 4a) shows a strong anticyclonic eddy centered near 31.24°E, 43.86°N with an approximate radius of 214 215 76 km. The location of the eddy center and its propagation from March 6 to July 10 was derived using a set of satellite observed Chl-a and SST charts, and is shown in 216 217 Fig. 4c. The eddy pathway was essentially parallel to the shelf break. During this 218 period, the eddy center was always outside the shelf with a mean separation of 50 km 219 from the shelf break, whilst its mean zonal radius was about 49 km and mean 220 meridional radius was 60 km. Therefore, the eddy impinged onto the shelf to some 221 degree (at least at the surface). The mean travelling speed of the eddy over this period was 1.6 km day⁻¹ (1.9 cm s⁻¹); however, it was nearly stagnant from April 14 to 222 223 June 15.

The model simulation gives the surface horizontal radius of the eddy between 49 km (in the along-shelf direction) and 67 km (in the cross-shelf direction) on Jun 30 (Fig. 4b), in agreement with the satellite observations in terms of eddy's size. However, the eddy in the model displaced farther southwest along the shelf break (centered near 30.25°E, 43.37°N). 229 Consistent with the observations, the model eddy was formed off the Crimean Peninsula in March and then migrated essentially along the same pathway as the 230 231 observed eddy (Fig. 4c, square). Similar to the observations, the larger part of the 232 eddy remained outwards of the shelf. From April on, the model eddy slowly moved to 233 the southwest steered by the shelf slope, impinging onto the shelf most of the time 234 unless occasionally pushed back by wind-driven offshore currents. The lifetime of this 235 model anticyclonic eddy was more than three months, consistent with the eddy in the 236 satellite observations in 2005, which is also close to that observed in 1998, but twice 237 of that in 1993, as given by Ginzburg et al. [2002]. Comparison with satellite 238 observations confirms that the model simulation captures the main features of the eddy in terms of horizontal dimensions, proportion of eddy impinging onto the shelf, 239 240 the eddy's lifetime, and migration path and speed. Some disagreement (time/space 241 lag) does not seem to affect significantly the estimates of the cross-shelf transports 242 integrated along the whole length of the "fence" or local transports around the eddy. 243 The impingement of anticyclonic eddies onto the shelf results in exchange 244 between shelf and deep-sea waters and phytoplankton being carried from the productive shelf region to the deep-sea region. According to Shapiro et al. [2010], 245 246 there were three events in 2005 when noticeable offshore spreading of shelf waters 247 was seen in satellite-derived Chl-a charts. These events occurred on May 5 - 18, June 248 7 to July 14 and August 7 - 17, of which the second event is the most intense, as 249 shown in the Hovmöller diagram [Hovmöller, 1949] in Fig. 5a.

250 A persistent shelf-basin gradient is not only seen in Chl-a concentration (Fig. 2), but also in sea surface salinity (SSS) (Figs. 3c and 3d) due to significant inflows of 251 252 the Danube, Dniester and Dnieper rivers into the NW shelf, making SSS another good 253 tracer of the shelf waters. We use the SSS from the model to check whether these 254 injections of shelf waters can be seen in the salinity field. The Hovmöller diagram in Fig. 5b is obtained by averaging SSS between 30.5°E and 32.0°E to be compatible 255 with the Chl-a distribution in Fig. 5a. It shows that at least the strongest injection 256 257 (June – July) is clearly identifiable in the SSS field by the shape of the isolines 258 between 16.6 and 18.8.

3.1 Volume Transport across the Shelf Break

Due to significant contrasts in Chl-*a* and other biochemical properties between the shelf waters and the Black Sea interior, we start our analysis with the euphotic layer of the sea. Fig. 6a shows the Hovmöller diagram for daily volume transport between the shelf and the deep-sea region in the top 20 m of the water column. The data show depth integrated (0 to 20 m) daily offshore (red for positive value) and onshore (blue for negative value) transports along the shelf break between 43°N and 45°N for the period April 1 to September 1, 2005.

The diagram shows different patterns of the upper layer cross-shelf transport at multiple temporal scales, which are associated with various events. Some periods were characterized by prevailing offshore (positive) movement along the whole shelf 270 break, for instance, during April 15 - 22 (hereafter referred to as Event WA, for wind event A). Other periods were dominated by overall onshore migration (negative), such 271 272 as July 1 - 4 (Event WB, for wind event B). In the period between late April to the 273 end of June, there were sections at the shelf break where the transport was offshore 274 (red bands in Fig. 6a) located next to the sections with the transport in the opposite 275 direction (blue bands), the two timestamps during this event are labeled ES1 (for eddy 276 event stage 1) and ES2 in Fig. 6a. This "double-band" pattern was disrupted in early 277 July but appeared again before decaying in mid-July. This pattern resembles the 278 transports generated by an anticyclonic eddy partly impinging on the shelf.

279 The time series of wind speed averaged over the sea west of 34°E (Fig. 6b) shows correlation with the volume transport diagram in Fig. 6a. During strong 280 281 positive events (offshore transports, red vertical columns in Fig. 6a, related to upwelling of coastal waters), the NW shelf was influenced by southwesterly wind and 282 283 hence the Ekman drift was towards southeast, while the northeasterly wind was prevailing during negative events (onshore transports, related to downwelling of 284 285 coastal waters). During the eddy-dominated event (late April to the end of June), the wind was weak, and both wind speed and direction were highly variable. 286

287 The offshore and onshore volume transports (denoted *VT*) are calculated using288 the equation

$$VT_{z_{1,z_{2}}}^{offshore}(t) = \int_{start}^{end} \int_{z_{1}}^{z_{2}} (\boldsymbol{u} \cdot \boldsymbol{n}) dz dl \qquad \text{when } (\boldsymbol{u} \cdot \boldsymbol{n}) > 0 \qquad (1a)$$

$$VT_{z_{1},z_{2}}^{onshore}(t) = \int_{start}^{end} \int_{z_{1}}^{z_{2}} (\boldsymbol{u} \cdot \boldsymbol{n}) dz dl \qquad \text{when } (\boldsymbol{u} \cdot \boldsymbol{n}) < 0 \qquad (1b)$$

where $VT_{z_{1,z_{2}}}^{onshore}(t)$ and similar $VT_{z_{1,z_{2}}}^{offshore}(t)$ are the volume onshore and offshore 291 292 transports, respectively, at a particular time t integrated across the section of the shelf 293 boundary between the *start* and *end* points on the boundary and between the depth 294 levels z1 and z2; u = u(t, z, l) is the horizontal velocity vector at the boundary; n is 295 the unit vector directed towards the deep-sea region and normal to the shelf boundary; 296 z is depth; l is the length along the shelf boundary. Positive value denotes offshore 297 transport, and negative onshore transport. For analysis of eddy-induced transports, the 298 start and end points confine the section of the shelf break influenced by the eddy, and 299 their locations were calculated daily as the eddy moved southwestward. For all other 300 analyses, the start and end points are the ends of the shelf boundary located at the 301 coast as shown in Fig. 1.

The two main wind events (WA and WB) and the eddy-dominated event (late April to the end of June) are analyzed in more detail in the subsequent subsections.

304 3.1.1 Wind-induced Surface Offshore Transport (Event WA)

Event WA (April 15 – 22) was characterized by prevailing southwesterly wind and offshore water movements over the shelf break in the top 20 m. The wind amplitude peaked on April 19 with the spatial mean 9 m s⁻¹ over the sea west of $34^{\circ}E$ Page 15 of 62

| 308 | (Fig. 7a), which was almost twice the spring-summer mean value. Due to the Ekman |
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| 309 | effect, the wind-generated surface flow in the offshore direction was particularly |
| 310 | strong over the inner and middle shelves. Over the outer shelf, the offshore surface |
| 311 | flow decreased; however, it still dominated the currents at the shelf break. At the |
| 312 | surface, a circular anticyclonic eddy, centered near 31.5°E, 44.0°N with a radius of |
| 313 | 55 km, could be seen from the current field just outside the NW shelf (Fig. 7b). Its |
| 314 | maximum orbital velocity was about 25 cm s ⁻¹ , but it did not impinge onto the shelf. |
| 315 | The Ekman effect decreased quickly in the vertical, and its influence was |
| 316 | confined to the upper 20 m in this study. Below the 20-m depth, the eddy showed a |
| 317 | partial penetration onto the shelf especially at 75 m (Fig. 7c) which is seen in the |
| 318 | meridional velocity transect along 44.29°N (Fig. 7d). This peripheral part of the eddy |
| 319 | contributed to the generation of the northward-flowing (onshore, negative) current |
| 320 | below the surface Ekman layer between 44°N and 44°15'N and eastward (offshore, |
| 321 | positive) current between 44°20'N and 44°30'N. In other words, the upper part of the |
| 322 | eddy was squeezed and pushed away from the shelf break (indicated by blue squares |
| 323 | in Figs. 7b and 7c) by the offshore Ekman flow (Fig. 7d) but the eddy still contributed |
| 324 | to cross-shelf transport at depth. |

The pattern of the combined action of wind-driven current in the surface layer and eddy-generated transport below the Ekman layer can be seen in the profile of volume fluxes along the shelf break (Fig. 7e), plotted along the section of the shelf break shown in Fig, 4c, i.e., excluding the short connecting lines between the shelf 329 break and the coast. The upper layer above 20 m was dominated by the offshore flux330 induced by southwesterly wind over the whole shelf.

331 The offshore transport calculated along the enclosed shelf boundary above 20 m 332 was 0.32 Sv while the onshore transport (mainly between 44.85°N and 44.9°N) was 333 significantly smaller. Below 20 m, the cross-shelf transport was driven by a cyclonic 334 meander of the Rim Current with an associated small anticyclonic eddy (43°N to 43.5°N) and the large anticyclonic Sevastopol Eddy (43.9°N to 44.6°N). The onshore 335 branch of the Sevastopol Eddy below 20 m is fairly diffused and located between 336 337 43.9°N and 44.3°N, whilst its offshore branch is narrow and intense (44.4°N to 338 44.6°N). This pattern is consistent with the existence of a filament of Chl-a enriched waters identified by Shapiro et al. [2010] from remotely sensed data. In the layer 339 340 below 20 m, both the offshore (0.63 Sv) and onshore (-0.93 Sv) transports were 341 higher due to action of the eddy and meander, than that in the upper layer directly 342 affected by the Ekman drift. The overall water balance on the shelf was ensured by 343 the river runoff, and precipitation minus evaporation.

It can been seen in Figs. 7c and 7d that below the Ekman depth, the Sevastopol Eddy was interacting with a smaller cyclonic eddy to the east and an anticyclonic eddy to the southeast that both contributed to its non-axisymmetric shape. The theory of one circular eddy stretched by nearby eddies was developed by McWilliams [1984].

349 **3.1.2 Eddy-induced Transport, Stage One (ES1)**

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350 The Hovmöller diagram in Fig. 6a shows the existence of an eddy-like pattern from April 23 to June 30 when strong localized offshore motion (red band) was 351 accompanied by onshore transport (blue band). The structure, associated with the 352 353 Sevastopol Eddy, moves gradually to the south. At the initial stage of the eddy migration (April 23 to May 10), the onshore transport was represented by a single 354 355 blue band, which subsequently splits into two branches. In this subsection, we analyze 356 the first stage using a snapshot on May 6, 2005, hereafter called event ES1. On that 357 day, the southwesterly wind had relaxed over the NW shelf and adjacent regions of the deep sea, reaching only 2 m s⁻¹ on average (Figs. 6b and 8a), hence making 358 359 Ekman transport a less important contributor to the exchange.

At the surface, the Sevastopol Eddy had an orbital velocity exceeding 30 cm s⁻¹ 360 361 (Fig. 8a). Its penetration onto the shelf was significantly stronger than during wind event WA, and mainly occurred between 43.8°N and 44.5°N (Fig. 8b). The maximum 362 northward component of the current at the shelf break reached 10 cm s^{-1} , thus 363 facilitating the onshore cross-shelf transport (Fig. 8d). In contrast to event WA, the 364 365 vertical axis of the eddy during ES1 was not inclined, and the eddy had its largest horizontal extension at the surface, see the meridional velocity transect along 44.04°N 366 in Fig. 8d. The eddy induced significant cross-shelf transport both onshore and 367 368 offshore over the entire water column, as shown in Fig. 8e. The eddy-induced offshore 369 transport was about 0.31 Sv and was essentially homogeneous from surface to the 370 seabed, accounting for 24% of the overall offshore cross-shelf transport at that day. The eddy-induced onshore transport was -0.51 Sv, larger than the eddy's offshore contribution. This was due to a combined action of the Sevastopol Eddy and the adjacent meander of the Rim Current southwest of the eddy (Figs. 8b and 8c). The offshore transport southwest of the eddy (red band in Fig. 8e between 43.6°N and 43.9°N) was also due to the meandering Rim Current.

376 **3.1.3** Anticyclonic Eddy Enhanced by a Cyclonic Meander (ES2)

The Hovmöller diagram in Fig. 6a shows that after May 10 the blue band representing the offshore transport by the eddy splits and forms a "two-leg" structure, suggesting that an additional factor, apart from the Sevastopol Eddy, contributed to the offshore transport. Next, we analyze the snapshot taken on May 17 (Event ES2).

381 The wind on May 17 was blowing from the east, with a spatial mean amplitude of only 3.6 m s⁻¹ (Fig. 9a), similar to Event ES1. The wind was too weak to generate a 382 383 conspicuous Ekman drift. By May 17, the Sevastopol Eddy, after a slow propagation 384 in the southwest direction, approached an intense cyclonic meander of the Rim 385 Current (Figs. 9b and 9c). The eddy was elongated in the northwest-southeast direction, which facilitated a greater penetration onto the shelf, with farther 386 387 penetration at the surface than at depth (Figs. 9b, 9c and 9d). The eddy was particularly enhanced at its eastern and southern edges by the cyclonic meander. 388 Using a threshold value of 5 cm s⁻¹ of orbital velocity as the eddy's boundary, one can 389 390 see that the east-west semi-axis of the eddy enlarged from 40 km on April 19 to 56 km on May 6 to 72 km on May 17. On May 17, the eddy-induced offshore transport was
0.72 Sv and the onshore transport was -0.50 Sv, accounting for 52% and 35% of the
overall onshore and offshore transports, respectively. In addition, the meander itself
made a considerable contribution to the cross-shelf exchange, which was shown by a
large and diffused blue band between 43.6°N and 43.75°N in Fig. 9e.

396 3.1.4 Wind-induced Surface Onshore Transport (Event WB)

397 As shown by the Hovmöller diagram in Fig. 6a, the near-surface cross-shelf transport during Event WB (July 1 - 4) was directed onshore and opposite to that of 398 Event WA, and was associated with the downwelling of coastal waters. The wind was 399 400 northeasterly and stronger than on April 19, with the maximum amplitude averaged over the sea west of 34°E reaching 11 m s⁻¹ on July 4 (Fig. 10a), generating a 401 significant onshore surface Ekman transport across the shelf break and a southward 402 coastal jet of 10 - 80 cm s⁻¹ and (Fig. 10b). The strong Ekman drift nearly masked the 403 404 surface signature of the Sevastopol Eddy (Fig. 10b). The onshore transport in the top 405 20 m was -0.55 Sv on average over four days, and occupied nearly all the section of the shelf break with the only exception of a small area near Cape Kaliakra (see Fig. 406 407 1), where the strong coastal flow crossed the shelf break generating some offshore 408 transport.

409 Below the upper Ekman layer, the anticyclonic eddy was clearly identifiable with 410 its center near 43.40°N, 30.5°E, (Fig. 10c), which was significantly deformed by the 411 Rim Current meanders both southwest and northeast of the eddy. The eddy in this
412 location is often called the Kaliakra Eddy [*Oguz et al.*, 1993]; however, we can see
413 that it is the displaced Sevastopol Eddy, which has travelled along the shelf break
414 from southwest of the Crimea Peninsula.

415 The effect of the Ekman drift resulted in the top part of the eddy being twisted as 416 its southwest portion (onshore) is enhanced while the northeast portion (offshore) is suppressed. The transect of the meridional velocity along 43.71°N (Fig. 10) shows 417 that the top part of the eddy was displaced onto the shelf (Fig. 10d) while the highest 418 419 orbital velocity was achieved below the Ekman layer at depth from 75 m to 150 m. The horizontal extension of the eddy was smaller than that during Events WA, ES1 420 and ES2; however, its maximum orbital velocity, achieved at 100 m, increased to 421 45 cm s^{-1} at its southwest portion. The eddy contributed -0.35 Sv to the onshore flux, 422 423 but it has to be noted that a significant part of it was in the upper layer where the 424 effects of the eddy and the strong wind were combined (Fig. 10e). The offshore 425 transport was generated by the eddy only below the top 20 m at the rate of 0.24 Sv. 426 The meander of the Rim Current northeast of the eddy was relatively weak, while the meander southwest of the eddy was enhanced leading to significant offshore transport 427 428 (Fig. 10c).

The transports associated with wind and eddy events and averaged over the respective periods are summarized in the Table 1. The numbers in the brackets show the total volume (in units of 10^{12} m³) of water transported across the shelf break over

Table 1. Average offshore and onshore cross fence (shelf break plus the two segments connected with the coast) transports (in Sv) and associated volumes of transferred waters (10¹² m³, in brackets) for the three events in spring-summer 2005 compared to the entire study period

| 4 | 3 | 8 |
|---|---------------|---|
| т | \mathcal{I} | υ |

_

| | Event WA | Eddy | Event WB | Whole period |
|----------------------------|---------------|-----------------|---------------|----------------|
| | Apr 15 – 22 | Apr 23 – Jun 30 | Jul 1 – 4 | Apr 1 – Aug 31 |
| $VT_{0,20}^{offshore}$ | 0.32 (0.22) | 0.06 (0.35) | 0.19 (0.07) | 0.237 (3.13) |
| $VT_{0,20}^{onshore}$ | -0.13 (-0.09) | -0.05 (-0.31) | -0.55 (-0.19) | -0.243 (-3.21) |
| $VT_{0,bottom}^{offshore}$ | 0.95 (0.66) | 0.48 (2.84) | 1.28 (0.44) | 1.14 (15.1) |
| $VT_{0,bottom}^{onshore}$ | -1.06 (-0.73) | -0.40 (-2.41) | -1.33 (-0.46) | -1.18 (15.6) |

439

In order to assess the sensitivity of the cross-shelf-break transports to the exact location of the "fence", the computations were also performed for the "fences" located at 170 m and 230 m depth contours. The results are very close due to the steep continental slope, where the horizontal separation between 170 m , 200 m and 230 m isobaths is very small, and hence the 'fence' crossed mainly the same model grid boxes.

446 3.2 Maintenance of the Shelf Break Front

447 Due to the gradient in salinity and temperature between the shelf and the deep-448 sea region, the currents crossing the shelf break contribute to the transport of salt and Page 22 of 62 449 heat on and off the shelf.

450 The instantaneous transports of salt and heat in the top 20 m across the shelf 451 break were calculated using the equations

452

$$ST_{0,20}(t) = \int_{start}^{end} \int_{0}^{20} S\rho(\boldsymbol{u} \cdot \boldsymbol{n}) dz dl$$
⁽²⁾

$$HT_{0,20}(t) = \int_{start}^{end} \int_{0}^{20} C_p \rho T(\boldsymbol{u} \cdot \boldsymbol{n}) dz dl$$
(3)

453

454 where $ST_{0,20}(t)$ (kg s⁻¹) is the salt transport in the top 20 m, S (psu) is the salinity of 455 water flowing in or out the shelf, ρ (kg m⁻³) is the density of water, $HT_{0,20}(t)$ (J s⁻¹) is 456 the heat transport in the top 20 m, $C_p = 4.0 \times 10^3$ J kg⁻¹ K⁻¹ is the specific heat capacity 457 of seawater; *start* and *end* represent the coastal endpoints of the shelf boundary. 458 Similar equations are used for other depth ranges.

459 The amounts of salt and heat crossing the shelf break during the Events WA (April 15 – 22), WB (July 1 – 4) and by the eddy action (April 23 – June 30) are 460 shown in Table 2. The values corresponding to the wind events were calculated along 461 the whole section of the "fence" shown in Fig. 1, while the values related to the eddy 462 action were calculated only for a segment of the shelf break influenced by the eddy. 463 The location of this segment changed with time as the eddy migrated southwestward. 464 465 Table 2. Amounts of heat (10^{18} J) and salt (10^{12} kg) crossing the shelf break during the three 466 events. Note that the number above the fraction is related to offshore transfer, and that below is 467

468 related to the onshore transfer.

| | Event WA | Eddy | Event WB |
|---------------------------|----------------------|--|----------------------|
| | Apr 15 – 22 | Apr 23 – Jun 30 | Jul 1 – 4 |
| HT _{0,20} | $\frac{8.04}{-3.38}$ | $\frac{16.82 + 6.39 = 23.2}{-3.20 - 16.04 = -19.2}$ | 5.53 -16.2 |
| HT _{0,bottom} | $\frac{22.6}{-24.7}$ | $\frac{71.09 + 42.19 = 113.3}{-17.81 - 76.53 = -94.3}$ | $\frac{20.7}{-26.5}$ |
| <i>ST</i> _{0,20} | $\frac{4.01}{-1.73}$ | $\frac{4.76 + 1.82 = 6.58}{-0.88 - 5.07 = -5.95}$ | $\frac{1.23}{-3.55}$ |
| ST _{0,bottom} | $\frac{12.7}{-14.4}$ | $\frac{33.95 + 22.06 = 56.0}{-8.77 - 39.09 = -47.9}$ | 8.67 -8.92 |

The heat and salt transports contribute to the variation of density of the shelf waters and hence to the density gradient across the shelf break and the maintenance of the density front along the shelf break. In order to calculate the "exchange transports", let us apply the equations similar to those used in turbulence theory to assess, say turbulent viscosity and diffusivity. At any moment in time let us split cross-shelf velocity, temperature, salinity and density into the mean values, i.e., averaged along the length and the depth of the "fence", and their fluctuations about the mean:

$$S = S_0(t) + S'(t, l, z)$$

$$T = T_0(t) + T'(t, l, z)$$

$$\rho = \rho_0(t) + \rho'(t, l, z)$$

$$u = u_0(t) + u'(t, l, z)$$
(4)

477 Where the subscript zero indicates the mean value calculated as follows for salt,

$$S_0(t) = \frac{\int_{bottom}^{surface} \int_{start}^{end} S(l, z, t) dldz}{\int_{bottom}^{surface} \int_{start}^{end} dldz}$$
(5)

478 and similar for other variables. The mass flux, MF (i.e., transport through a 1 m^2 area)

479 is:

$$MF(t, l, z) = \rho(t, l, z) * u(t, l, z) = \rho_0 u_0 + \rho_0 u' + \rho' u_0 + \rho' u'$$
(6)

480 and the mass transport, *MT*, equals to the mass flux integrated over the entire "fence"

481 as follows,

$$MT(t) = \int_{bottom}^{surface} \int_{start}^{end} \rho(t, l, z) * (u(l, z, t) \cdot n) dldz =$$

$$\rho_0 u_0 * A + \int_{bottom}^{surface} \int_{start}^{end} \rho'(t, l, z) * (u'(l, z, t) \cdot n) dldz$$
(7)

482 where *A* is the area of the "fence" (depth×length), and the average of the fluctuations483 is equal to zero by design.

In this section we are only interested in the "turbulent" component of the mass flux (second term on the right hand side in Eq. (7)), generated by the non-linear term $\rho' \times u'$. This term controls the dissolution of the front, not the mean advection of the front, i.e., the first term on the right hand side in Eq. (7). Hereafter, we call this "turbulent" component the "exchange transport", as it is physically associated with swapping of water parcels of identical volume between the shelf and the deep-sea region.

491 As variations in temperature and salinity along the "fence" are relatively small, 492 we can use the linearized equation of state to link salinity/heat transports with the 493 mass transport across the shelf break and split the mass transport exchange into two 494 components -- related to the salt (EXM_s) and heat (EXM_T) transports, respectively.

$$EXM_{S}(t) = \rho_{0}(t) \int_{bottom}^{surface} \int_{start}^{end} \beta(t, l, z) * S'(t, l, z) * (\boldsymbol{u}'(l, z, t) \cdot \boldsymbol{n}) dldz$$
(8)

$$EXM_{T}(t) = -\rho_{0}(t) \int_{bottom}^{surface} \int_{start}^{end} \alpha(t, l, z) * T'(t, l, z) * (\boldsymbol{u}'(l, z, t) \cdot \boldsymbol{n}) dldz$$
⁽⁹⁾

Based on the mass conservation, a corresponding gain of mass (ΔM) and change of average density ($\Delta \rho$) of shelf waters due to salt and heat exchanges can be calculated using the following equations and corresponding integrals for average density.

$$\Delta M_{S} = -\int_{1 \ April}^{31 \ August} EXM_{S}(t)dt \tag{10}$$

$$\Delta M_T = -\int_{1 \, April}^{31 \, August} EXM_T(t)dt \tag{11}$$

500 As we can see from Table 3, the exchanges of saline and warmer deep-sea waters 501 with fresher and colder shelf waters result in an overall increase in average shelf water density (+0.51 kg m⁻³), and hence reduction in the density contrast between the shelf 502 503 and deep sea. This change is the sum of density increase due to salt exchange (+0.67 kg m⁻³) and a density decrease due to heat exchange (-0.16 kg m⁻³). In other words, 504 505 while the salt exchanges smooth out the density contrast, the heat exchanges enhance the density gradient and contribute to the maintenance of the density front along the 506 507 shelf break.

TABLE 3. Gain (+) and loss (-) of mass and average density of the shelf waters due to salt and
 heat exchanges with the deep-sea region.

| ΔM_S | ΔM_T | Δho_S | Δho_T |
|---------------------------|---------------------------|-------------------------|-------------------------|
| +1.88*10 ¹² kg | -0.44*10 ¹² kg | +0.67 kg/m ³ | -0.16 kg/m ³ |

512 4 Discussion

513 The cross-shelf filaments, mesoscale eddies and meanders of the Rim Current 514 have long been considered an important mechanism for the cross-shelf break 515 exchange in the Black Sea [Sur et al., 1996; Zatsepin et al., 2003]. However, quantitative estimates have been few (see Shapiro et al. [2010]). In this paper, we use 516 517 a 3D high-resolution ocean model to provide a quantitative estimate of cross-shelf break transports in the NW Black Sea with a focus on the quantification of two 518 519 exchange mechanisms, one related to Ekman drift in the surface layer and the other one related to a slowly-moving long-lived anticyclonic eddy and associated meanders 520 521 of the Rim Current.

The two mechanisms are different not only in terms of underlying physics (frictional effects in the Ekman flows vs. quasi-geostrophic flows in the eddy/meanders) but also in terms of their geometric patterns. Ekman drift causes nearly uniform onshore or offshore flow along a large section of the shelf break, but it is confined to only the top layer of approximately 20 m. Eddies and meanders penetrate toward the bottom at the shelf break, but they are restricted laterally by the size of the eddy or meander.

529 The strong wind-driven currents occurred during Event WA (April 15 – 22, 530 2005) generated a net offshore near-surface transport of 0.19 Sv (which was the balance of 0.32 Sv offshore and -0.13 Sv onshore transports; see Table 1), corresponding to the upwelling of coastal waters and a compensating onshore flow below the Ekman depth. During this event, 0.66×10^{12} m³ of shelf water was transported into the deep-sea region when at all depth levels were combined, which is approximately equal to 23% of the overall volume of the shelf waters (2.78×10¹² m³; see Fig. 11a-c).

The second wind event WB (July 1 – 4, 2005) featured higher wind speeds up to 11 m s⁻¹ and generated a net onshore near-surface transport of -0.36 Sv. During this event, the total amount of 0.46×10^{12} m³ (at all depths) of deep sea waters entered the shelf, which equates to 17% of the overall shelf water volume. A similar amount moved in the opposite direction.

542 Strong wind events in the spring-summer-early autumn period are rare and 543 normally do not last more than one week. Apart from these significant events, the 544 contribution of wind-driven current to the cross-shelf break transport was small.

545 Both upwelling and downwelling wind events replaced surface waters with 546 subsurface (below Ekman depth) ones, which are different not only by their physical 547 but also by biochemical properties. However, the analysis of the latter is beyond the 548 scope of this paper.

549 The eddy-induced exchange is different from that induced by the Ekman drift, as 550 the eddy mainly replaces surface water and sub-surface water with the same layer 551 water, and hence contributes to the self-cleaning of eutrophied surface shelf waters with oligotrophic surface waters of the deep-sea region. Despite occupying a smaller
area, the eddy acts as a cross-boundary agent for a relatively long time scale – in 2005
the eddy-induced transport is clearly detectable from April 23 to June 30 (see Fig. 6a).
Below the Ekman depth, the eddy-induced transport is detectable even during strong
wind events (see Figs. 7e and 10e).

557 During the 69 days from April 23 to June 30 in 2005, the anticyclonic Sevastopol Eddy transferred shelf water offshore across the shelf break at an average rate of 558 0.48 Sy, with a total volume of 2.84×10^{12} m³, which is comparable with the total 559 volume of the shelf waters over the NW shelf of 2.78×10^{12} m³. The offshore (onshore) 560 transport confined within the top 100 m was on average 0.32 Sv (-0.28 Sv). This 561 estimate, which is based on the model simulations, is close with that obtained from 562 563 observations, namely, 0.3 Sv for the offshore transport by the eddy in the top 100 m 564 [Shapiro et al., 2010]. The total volume of water transported out of the shelf in the top 100 m estimated from observations was quoted as 1×10^{12} m³, similar to the figure of 565 $1.1 \times 10^{12} \text{ m}^3$ obtained here from the model simulation. The long-term net transport 566 567 induced by the eddy is small as the onshore- and offshore- components nearly balance each other. However, it is important to quantify in- and out- fluxes separately, as they 568 move different waters, as can be seen from the fact that even though the net 569 volumetric transport is close to zero, the net heat and salt transports are not (see Fig. 570 571 11a-i and Table 3). The 'in' branch of the eddy brings deep sea water (with low Chl-a 572 content) onto the shelf, this water mixes with the native shelf waters, and the 'out'

573 branch of the same eddy exports the water of a similar volume but with different 574 properties (e.g. high Chl-*a* content). This process is clearly seen in the satellite image 575 in Fig. 2.

576 For comparison, the two wind events generated the transports in the top 20 m of 0.32 Sv (offshore, Event WA) and -0.55 Sv (onshore, Event WB), which were similar 577 578 or even higher than the eddy-induced transport (see Table 1). It should be noted that these figures also include a small contribution from the eddy- and meander- induced 579 580 transports in the top 20 m (see Fig. 6a). However, due to the short duration, the two wind events transported only 0.22×10^{12} m³ of the shelf water to the deep-sea region 581 (Event WA, top 20 m) and 0.19×10^{12} m³ of the deep-sea water onto the shelf (Event 582 583 WB, top 20 m), which is only about 7% of that of the Sevastopol Eddy (which 584 transported at all depths).

In an addition to the anticyclonic eddy, there were other dynamic features 585 586 affecting the across-shelf exchange. First, the meandering Rim Current could facilitate 587 the exchange, not only by impinging onto the shelf break but also by enhancing the anticyclonic eddy when it strengthens the eddy orbital velocity (for example in the 588 snapshot ES2; Fig. 9b-c). The maximum orbital velocity in the southwestern 589 periphery of the eddy (influenced by the meander) was 50 cm s⁻¹, as compared to 40 590 $cm s^{-1}$ in the northeastern periphery. Hence, the eddy-induced onshore transport was 591 facilitated by the meander (see section 3.1.3). As in all other cases, the localized 592 593 imbalance between onshore and offshore transports generated by the eddy during the

event ES2 was compensated at other segments of the boundary (see Fig. 9e), so that 594 the net transport across the whole boundary (shown in white in Fig. 11a) is 595 significantly smaller than onshore (shown in blue) and offshore (shown in red) 596 597 transports on their own. The impinging of the Rim Current meander onto the shelf is 598 clearly seen in the velocity maps on May 17 (Figs. 9b-c). Some smaller, sub-599 mesoscale eddies also contributed to the cross-shelf exchange (see Fig. 10c); however, their contribution was much smaller compared to the Sevastopol Eddy, due 600 to their small horizontal and temporal scales and weak orbital velocities. In addition, 601 602 there is a coastal current contributing to the exchange between the NW shelf and the rest of the sea in the areas where the shelf becomes narrow, i.e. near the Crimean 603 peninsula and the cape Kaliakra (Fig. 1), This current is evident during the strong 604 605 wind events and is much weaker during the periods of calm weather. The coastal 606 current is flowing northeastward during the event WA and in the opposite direction 607 during the event WB. The effect of the coastal current on shelf-deep sea exchange is seen in Fig. 6a as small red (outward flowing) patches at 44.7°N on April 19 and 608 43.2°N on July 4. 609

As expected, the various cross-shelf break transport processes resulted in a nearly zero balance of volume entering/leaving the shelf across the enclosed boundary (shelf break plus the two short segments connecting the shelf break and the coast). The average total offshore transport across the shelf boundary for the period April 1 to August 31 was 1.14 Sv, with a small imbalance with the onshore transport of only 615 3.4%, which was caused by river discharges, precipitation minus evaporation and616 computational noise.

As the long-lived anticyclonic mesoscale eddies are an ubiquitous feature of the Black Sea circulation [*Sur and Ilyin*, 1997; *Ginzburg et al.*, 2002; *Karabashev et al.*, 2006; *Stanev and Kandilarov*, 2012], one could expect that the eddy-induced transport plays a significant role in shaping the properties of the shelf waters in the Black Sea in general and is not specific to the year 2005.

The time line of cross-shelf exchanges for the whole warm season (April 1 to August 31) is shown in Fig. 11, separately for the upper 20 m, the subsurface layer (20 m to bottom) and the for the entire water column from surface to bottom. The graphs are obtained by integrating volume, heat and salt fluxes along the enclosed boundary. The graphs show incoming and outgoing transports separately as well as the balance between them.

The volume transport integrated from the entire water column varies gently over the warm period (Fig. 11a). Five periods have persistently strong (higher than 0.9 Sv) daily-mean transport: April 1 – 3, May 5 – 13, June 19 – 26, July 3 – 5 and July 10 – 16. The period of enhanced transports (beginning of May to mid-July) correspond to the periods of greater eddy activity and Rim Current meandering. The transports at the end of April and after July 20 are relatively small.

634 The wind events WA and WB are clearly seen in Fig. 11b, that shows the635 transports in the upper 20 m of the water. Figs. 11b and 11c show that variability of

transports in the upper layer and below are different in terms of both their values and
the pattern. As primary production is mostly concentrated in the top 20 m, the volume
transport in the upper layer may have a greater significance on the assessment of the
state of the ecosystem, than the overall transports.

The across-shelf exchanges contribute to the variation of heat (Figs. 11d-f) and salt (Figs. 11g-i) content on the shelf. Coherent patterns of variability in the top 20 m and the lower layer correspond to eddy-meander activities (see snapshots ES1 and ES2) while the wind dominated events tend to produce an anti-symmetric picture due to variation in the flow within the Ekman layer and below. The most significant heat and salt transports take place in the layer below 20 m, due to its greater thickness compared to the top Ekman layer.

647 The exchange of mass (as defined in section 3.2) due to heat and salt transport is shown in Fig. 12 as a function of time. The timeline of mass transport is different 648 649 from the volume transport discussed above due to variations of seawater density. Climatological data [Suvorov et al., 2003] show that throughout the year shelf waters 650 651 are less dense than deep-sea waters. While exchanges of waters with different density across the shelf break generally contribute to dissolution of the density gradient 652 653 between the shelf and deep-sea, in some cases they result in the enhancement of this 654 gradient. This conclusion looks paradoxical, but it has a straightforward explanation. 655 The shelf is generally colder, less saline, and less dense than the deep Black Sea. Heat exchanges reduce the temperature gradients and make the shelf warmer, and hence 656

less dense. The reduction in shelf water density (which on average is already lower 657 than the deep sea, see Fig. 3e-f) makes the density contrast stronger. On the other 658 hand, mixing of salinity makes the shelf waters more saline and hence more dense, 659 thus reducing the density contrast. Integrated over the whole period (April 1 to August 660 31) the heat transport reduces the average shelf water density by 0.16 kg m^{-3} , while 661 salinity transport increases it by 0.67 kg m⁻³ (Table 3). However, there are periods 662 663 (e.g. July 21-23 or August 3-5) when the heat transport dominates over the salt transport resulting in the net reduction of shelf water density, i.e. enhancement of 664 665 density contrast (Fig. 12).

During the wind event WA (upwelling) the mass transport was negative, i.e. in 666 the onshore direction, and the major contribution to density transport was due to 667 668 salinity (blue bars in Fig. 12). The physical mechanism behind this is that fresher surface waters were replaced by more saline deeper waters that were carried in by the 669 670 compensating flow. The temperature difference across the shelf break in April was not large, so the heat exchange was relatively small. The situation was dramatically 671 672 different during the downwelling wind event WB (July 1 - 4). In this case, warmer surface waters off of the shelf break was brought onto the shelf, making the shelf 673 water less dense and hence enhancing rather than reducing the density gradient 674 675 between the shelf and the deep-sea region. We see that the complex nature of across-676 shelf exchange in the Black Sea includes a less intuitive process of enhancing the 677 density gradient and hence contributing to sustaining the shelf break front. During Event WB, the exchanges of salinity also strengthened the gradient (via reducing the density of the shelf waters) as the salinity of incoming surface waters off of the shelf break was lower than the salinity of deeper (below 20 m) shelf waters if they were transported out across the shelf break. Fig. 12 shows that between April 1 and June 30 the cross-shelf break exchange mainly weakened the gradient between the shelf and the deep-sea region, while the exchange between July 1 and August 31 mainly enhanced the density gradient by making the shelf waters less dense.

685 Our results show that the exchange across the shelf break during the biologically 686 productive season April to September are quite significant and hence are vital for the health of the NW shelf ecosystem. The degradation of the NW shelf ecosystem in the 687 Black Sea in recent decades has been largely attributed to the supply of nutrients and 688 689 contaminants by the rivers and coastal activities [Mee, 1992; Cociasu et al., 1996; Mee et al., 2005; Yunev et al., 2007]. The renewal of shelf water across the shelf 690 691 break not only leads to the reduction of eutrophication on the NW shelf, but also may 692 modify the ratio of different nutrients there as the utilization of nutrients occurs 693 mainly in the euphotic zone.

The cumulative effect of the offshore transport in the biologically active top 20 m layer for one month $(0.62 \times 10^{12} \text{ m}^3)$ is approximately equivalent to 60% of the total volume of the top 20 m over the whole NW shelf (see Fig. 13). Over the entire warm period (April 1 to August 31), the transferred volume of water in the top 20 m is equivalent to three times of the volume of the shelf waters in the same layer. The wind strength over the NW shelf decreases from April – May to June – July; however, the trend in shelf water renewal is nearly linear (see Fig. 13). This result supports the argument that the most efficient mechanism of cross-shelf exchange is related to the mesoscale dynamics in the Black Sea, namely, eddies and meanders. The practical consequence of this is that only eddy-resolving ocean models could adequately model the shelf waters.

705 From the beginning of April to mid-May (which approximately corresponds to 706 the period of the spring phytoplankton bloom), the amount of water entered the shelf 707 from the deep-sea region within the depth range of 0 - 20 m was equivalent to 100% 708 of the total volume of shelf waters in the same depth range (Fig. 13), manifesting 709 quick renewal of biologically productive waters. This estimate is consistent with the 710 previous study of phytoplankton variability suggested by McQuatters-Gollop et al. 711 [2008], who showed that a strong lag correlation of Chl-a distribution on the shelf 712 does not exceed one month.

713 **5 Conclusion**

This study analyzes the physical mechanisms and quantifies the transport of water, heat and salt across the NW Black Sea shelf break using a 3D eddy-resolving ocean circulation model over the period of April 1 to August 31 2005. Despite the inhibiting action of the steep continental slope, the exchanges across the NW shelf break contribute to fast renewal of shelf waters and to transport of eutrophied surface water masses into the deep-sea region. Two physical processes – a long-lived
anticyclonic eddy together with menders associated the Rim Current and wind-driven
Ekman transport – are shown to be the major contributing factors to the across-shelf
exchange.

723 Due to the high intensity of cross-shelf exchanges, the average renewal time for 724 the vast NW shelf in the Black Sea was only 28 days. During the short but intensive wind events of April 15 - 22 and July 1 - 4, 23% and 16% of shelf waters, were 725 726 moved into the deep-sea region, respectively. However, a much larger cross-shelf 727 transport was generated by a long-lived anticyclonic eddy impinging on the shelf, 728 sometimes assisted by a cyclonic meander of the Rim Current. Over 69 days between April 23 and June 30, 2.84×10^{12} m³ of water (102% of the entire volume of the shelf 729 730 waters) was transported out of the shelf and a similar amount onto the shelf.

731 Cross-shelf break exchange can influence the density gradient between the shelf 732 (typically less dense) and the deep-sea region. From April 1 to the end of June, the 733 exchange smoothed the gradient, as one would expect from the "turbulent" exchange 734 processes. What is less intuitive is that the exchange sharpened the gradient between 735 the shelf and the deep-sea region in July – August. This was mostly due to a complex 736 interplay of 3D circulation and stratification of the water column: the warmer (and 737 less dense) deep-sea surface water was transported onto the shelf, while higher 738 salinity (and hence denser) subsurface water left the shelf for the deep-sea region. 739 Over the whole study period, salt exchange increased the average density of the shelf

| 740 | waters by 0.67 kg m^{-3} | while heat | exchange | decreased | the | average | density | over | the |
|-----|----------------------------|------------|----------|-----------|-----|---------|---------|------|-----|
| | | | | | | | | | |

741 shelf by 0.16 kg m^{-3} .

| 742 | As the mesoscale features significantly contribute to the across-shelf exchange |
|-----|--|
| 743 | in the biologically active euphotic layer, mesoscale dynamics should be taken into |
| 744 | account in assessing the state of the NW shelf ecosystem in the Black Sea. |
| 745 | |
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Figure 1. Geographic setting, main rivers and topographic features of the Black Sea 948 949 with solid contours representing bathymetry. The annual mean runoffs of the main 950 rivers and discharges via the Kerch and Bosporus straits are shown in the parenthesis (units: m^3/s). The boundary enclosing the northwestern shelf (the "fence") is 951 952 composed of the shelf break following the 200-m isobath (line of blue squares) and two short segments connecting to the coast (gray squares) at the two ends of the line 953 formed by blue squares. Schematic of the Rim Current, main gyres and anticyclonic 954 eddies are indicated by arrows, modified from that of Oguz et al.[1993]. 955 956



Figure 2. Satellite observed Chl-*a* concentration in the Black Sea in June 2005. An
anticyclonic eddy centered around 44°N, 31.5°E is seen to draw waters with high
concentrations of Chl-*a* from the biologically productive shelf into the deep Black Sea
basin.



Figure 3. Climatological sea surface temperature (T), salinity (S) and density (Sigmat). (a), (c) and (e) Winter (Feb). (b), (d) and (f) Summer (Aug). Note that the color
bars are different for summer and winter charts. Redrawn after Suvorov *et al.* [2003].



Figure 4. Comparison of the properties of the anticyclonic eddy identified from the 971 972 satellite observations and simulated by the model. (a) Chl-a concentration from 973 MERIS, with the eddy schematically marked by the purple dotted line. (b) Modeled surface currents showing an eddy of comparable radius as in (a) in a location close to 974 the observed eddy (reproduced); the modeled eddy is schematically marked by the 975 976 blue ellipse. (c) Positions of the eddy derived from the satellite observations (gray 977 circles) and model (squares) in 2005. The plotted current vectors are averaged using nine neighboring grid points. The NW shelf is indicated the same way as in Fig. 1. 978



980

(b)

Jun

42

May

Figure 5. Upper panel: Hovmöller diagram showing penetration of Chl-*a* from
SeaWiFS (Redrawn of Fig. 3 in Shapiro *et al.* [2010]) from the NW shelf into the
deep-sea region. The Chl-*a* was averaged between 30.5°E and 32.0°E. Lower panel:
Low surface salinity waters in the model, also averaged between 30.5°E and 32.0°E.

Jul

Aug

16.5

16



Figure 6. (a) Hovmöller diagram of the cross-shelf volume transport integrated from the sea surface to 20 m and calculated along the shelf edge as shown in Fig. 1. The positive value is for offshore transport, and the units are Sv per 1° latitude. (b) Wind components averaged west of 34°E over the water for the same period as (a). The events labeled as WA, ES1, ES2, and WB represent different mechanisms of crossshelf exchange.









Figure 7. (a) Strong southwesterly wind on April 19. (b) Prevailing offshore transport in the upper layer (model surface currents). (c) Model currents at 75 m. (d) Meridional velocity at the transect along 44.29°N indicated by the red dotted line in (b) and (c). (e) Volume flux across the shelf break indicated by the blue squares in (b) and (c). In this case, the wind-driven currents dominated at the surface, but the anticyclonic eddy was the major contributor to the exchange below 20 m. The current vectors in (b) and (c) are the average of four neighboring grid points.





Figure 8. (a) NCEP wind field. (b) Model surface currents. (c) Model currents at 50 m. (d) Meridional velocity at the zonal cross section along 44.04°N indicated by the red dotted line in (b) and (c). (e) Volume flux across the shelf break. In this case, the wind was weak on May 6; the cross-shelf transport was associated with an anticyclonic eddy seen in both (b) and (c).







Figure 9. (a) NCEP wind field. (b) Model surface currents. (c) Model currents at 75 m. (d) Meridional velocity at the zonal transect along 43.79°N indicated by the red dotted line in (b) and (c). (e) Volume flux across the shelf break. In this case, the wind is rather weak; the onshore transport was induced by the eddy and enhanced by a neighboring cyclonic meander of the Rim Current south of the eddy on May 17.







Figure 10. (a) The northeasterly wind on July 4. (b) Prevailing offshore transport in the surface layer (model surface currents). (c) Model currents at 75 m. (d) Meridional velocity at the transect along 43.71°N indicated by the dotted line in (b) and (c). (e) Volume flux across the shelf break. In this case, the wind-driven currents dominated at the surface, but the anticyclonic eddy is the major contributor to the exchange below 20 m.







Figure 11. Volume transport (a-c), heat transport (d-f) and salt transport (g-i) across the shelf break in 2005 from the model. The transport is vertically integrated: (a, d and g) from surface to seabed; (b, e and h) from surface to 20 m; and (c, f and i) from 20 m to the seabed. The critical cases discussed in the text are labeled as WA, ES1, ES2 and WB.





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Figure 12. Contribution to mass exchange (EXM) across the shelf break (positive for offshore) by salinity (EXM_S) and temperature (EXM_T) . Values are integrated over the enclosed boundary encircling the shelf and over the entire water column. The letter labels mark the dates of the four events discussed individually in section 3.1.



1071 Figure 13. Renewal rate of the NW shelf water in the upper layer (surface to 20 m)

1072 caused by the exchange across the enclosed boundary.

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