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Interannual variability of Danube waters propagation in summer period of 1992–2015 and its influence on the Black Sea ecosystem

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ABSTRACT

The propagation of the Danube River plume has strong interannual variability that impacts the local balance of nutrients and the thermohaline structure in the western Black Sea. In the present study, we use a particle-tracking model based on satellite altimetry measurements and wind reanalysis data, as well as satellite measurements (SeaWiFS, MODIS), to investigate the interannual variability in the Danube plume pathways during the summer from 1993 to 2015. The wind conditions largely define the variability in the Danube water propagation. Relatively low-frequency variability (on periods of a week to months) in the wind stress curl modulates the intensity of the geostrophic Rim Current and related mesoscale eddy dynamics. High-frequency offshore wind-drift currents transport the plume across isobaths and provide an important transport link between shelf and offshore circulation. Inherent plume dynamics play an additional role in the near-mouth transport of the plume and its connection with offshore circulation.

During the years with prevailing northeast winds (~30% of studied cases), which are usually accompanied by increased wind curl over the Black Sea and higher Danube discharge, an alongshore southward current at the NorthWestern Shelf (NWS) is formed near the western Black Sea coast. Advected southward, the Danube waters are entrained in the Rim Current jet, which transports them along the west coast of the basin. The strong Rim Current, fewer eddies and downwelling winds substantially decrease the cross-shelf exchange of nutrients.

During the years with prevailing southeastern winds (~40%), the Rim Current is less intense. Mesoscale eddies effectively trap the Danube waters, transporting them to the deep western part of the basin. The low- and high-frequency southeastern wind-drift currents contribute significantly to cross-isobath plume transport and its connection with offshore circulation. During several years (~15%), the Danube waters moved eastward to the west coast of Crimea. They were transported on the north periphery of the mesoscale anticyclones due to prevailing eastward wind-drift currents. During the years with hot summers, a monsoon effect induced the formation of a strong anticyclonic wind cell over the NorthWestern Shelf (NWS), and the plume moved northward (~15%). Anticyclonic wind circulation leads to the Ekman convergence of brackish surface waters in the centre of the shelf and the formation of a baroclinic geostrophic anticyclone north of the NWS. This anticyclone traps the Danube waters and forces them to remain on the shelf for a long period of time. The impact of the propagation of the plume on the variability in chlorophyll *a* chlorophyll *a* in the NWS and the western Black Sea is analysed in this study based on satellite data.

1. Introduction

The Danube River is the major source of fresh water in the Black Sea Basin. Its discharge is estimated at ~200 km^3/year (6000 m^3/s) (Cociasu and Popa, 2004; Kara et al., 2008), which corresponds to approximately 60% of the total river inflow in the basin. The maximum Danube discharge is observed during late spring (~9000 m^3/s), and the minimum discharge is observed during autumn (~4000 m^3/s) (Tolmazin, 1985; Kara et al., 2008; Ivanov and Belokopytov, 2011). Fresh river water plays the most important role in the Black Sea water and salt balance. An excess of river discharge over evaporation results in strong haline stratification in the basin; the salinity changes from ~18 psu in the upper 20-m layer to ~20 psu at 100 m and > 22 psu below a depth of 500 m. A strong halocline is one of the main reasons for the anoxic and almost lifeless conditions in the deep layers of the Black Sea.

The Danube waters are an important source of nutrients. The Danube provides approximately 200–500 kt/year of dissolved inorganic

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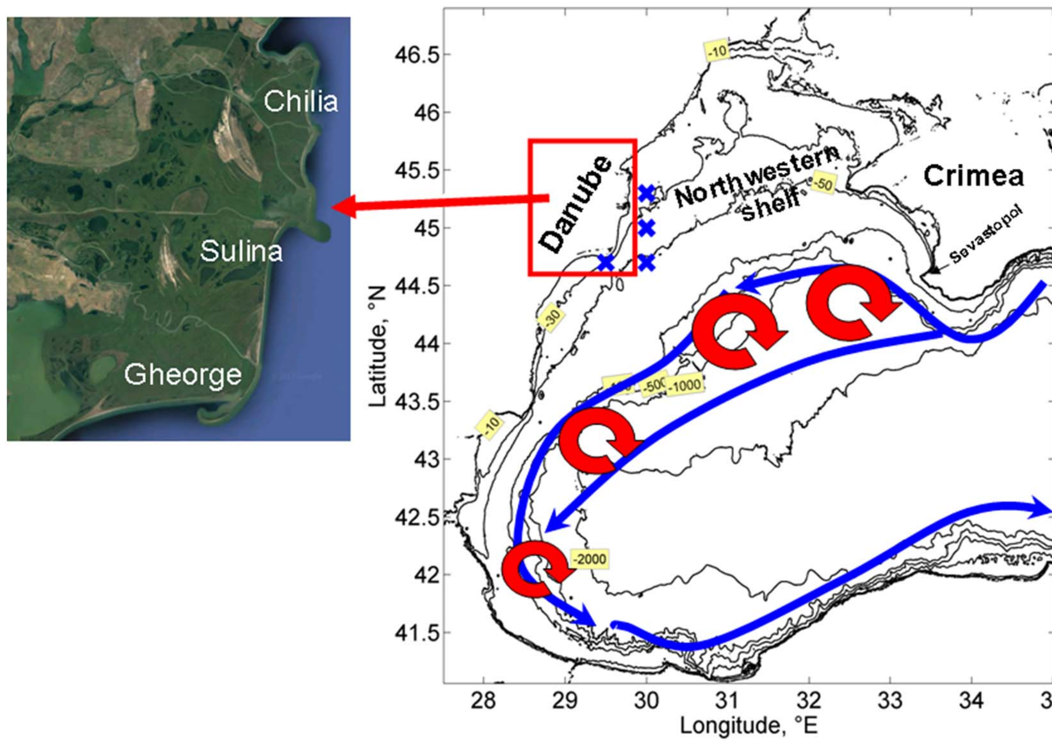

Fig. 1. Schematic presentation of the Black Sea circulation overlaid on the bathymetry contours (black lines). Blue curved arrows show the Rim Current position. Red circles show the usual propagation path of the mesoscale anticyclones. Blue crosses show the positions of the sources of Lagrangian particles. Satellite image in the top-left corner shows the Danube delta (https://www.google.ru/maps). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

nitrogen, ~15–30 kt/year of phosphates, ~200–400 kt/year of silicates (Cociasu and Popa, 2004; Kroiss et al., 2006) and large amounts of biogenic matter (Ragueneau et al., 2002). The Danube waters gradually mix with marine waters and propagate into the Black Sea, significantly changing its chemical composition and affecting both the ecosystem and thermohaline structure of the basin. Mixed waters form a very stable and thin plume that is usually approximately 1–3 m depth (Tolmazin, 1985; Humborg, 1997) but can reach up to ~10 m (Yankovsky et al., 2004; Karageorgis et al., 2014). It is vertically separated from marine waters by a sharp salinity (density) boundary and horizontal fronts. The mixing is accompanied by intense biogeochemical transformations, the sedimentation of fluvial material and high rates of primary production (Humborg, 1997; Ragueneau et al., 2002; Lancelot et al., 2002).

Turbid plume waters rich in suspended, dissolved matter and biota (Burlakova et al., 1997; Mankovskii et al., 2003; Constantin et al., 2016) can be clearly observed using satellite optical imagery (Sur et al., 1994, 1996; Ilyin et al., 1999; Oguz et al., 2002; Karageorgis et al., 2014; Osadchiev and Korshenko, 2017; Stanev and Kandilarov, 2012; Constantin et al., 2017). Because of intense sedimentation processes, high concentrations of suspended matter are mostly observed in the vicinity of the Danube mouth (Dan et al., 2007; Constantin et al., 2017). At the same time, the buoyant brackish shelf waters can transport dissolved matter, nutrients and organics hundreds of kilometres (Özsoy and Ünlüata, 1997; Oguz et al., 2002; Yankovsky et al., 2004; Ilyin et al., 2012). Ocean colour measurements and model calculations show that the Danube plume propagation has strong seasonal and interannual variability (Oguz et al., 2002; Yankovsky et al., 2004; Tsiaras et al., 2008; Constantin et al., 2016). The plume pathways determine the regions that will be supplied by the greatest amount of nutrients or biogenic matter and places where nutrient remineralization processes will occur (Ragueneau et al., 2002; Capet et al., 2016; Zavialov et al., 2014; Sharples et al., 2016). Nutrient changes in the Danube and the variability in plume dynamics impact the ecosystem of the entire Black Sea. Particularly, eutrophication during the 1970s because of the increase in anthropogenic nutrient loads into the Danube was first observed in the northwestern shelf (NWS) and then was transferred to the deep Black Sea, thus affecting the chemical composition and biodiversity of the whole basin (Humborg et al., 1997; Özsoy and Ünlüata, 1997; Konovalov et al., 1999; Konovalov and Murray, 2001; Yunev et al., 2002; Mikaelyan et al., 2013, 2015).

The Danube plume usually occupies several metres near the surface and is related to "surface-advected" plumes (Yankovsky and Chapman, 1997). The main effect of buoyancy-driven plume circulation on the near-mouth circulation is the formation of an anticyclonic bulge in front of the mouth, as well as the generation of an alongshore current directed to the right of the mouth in the Northern Hemisphere related to the baroclinity and Coriolis force (Garvine, 1987; Kourafalou et al., 1996; Yankovsky and Chapman, 1997). Several modeling studies recently discussed (Beckers et al., 2002; Ivanov et al., 1996, 1997, 2004; Kourafalou et al., 2004; Bajo et al., 2014) the formation of an anticyclone near the Danube mouth, which was caused by strong river discharge. At the same time, Korotaev et al. (2003) and Grégoire and Lacroix (2003) attributed the eddy formation in this area to the impact of wind. In the vicinity of the mouth, Danube waters preferably move to the right (southward) (e.g., Tolmazin, 1985; Ivanov et al., 1996, 1997; Giosan et al., 1999; Bajo et al., 2014) in agreement with theory. At a distance of several tens of kilometres from the mouth, the plume significantly dilutes due to wind mixing and horizontal turbulence, and the salinity difference between the plume and adjacent waters becomes relatively small (0.5–2 psu). Thus, the baroclinic effects of inherent plume dynamics at a large distance from the mouth became less significant. At the same time, as the Danube waters contain a large amount of nutrients and organic matter, its impact on nutrient exchange, chlorophyll *a* chlorophyll *a* and primary production in the basin is large even at a distance of hundreds of kilometres from its mouth.

Offshore, in the far-field, the horizontal advection of the Danube plume largely depends on the ambient flow: background geostrophic currents, mesoscale eddies, wind drift, downwelling/upwelling motions and submesoscale processes. The main element of geostrophic