Original article

DOI: 10.29039/0233-7584-2023-1-20-30

Influence of Upwelling on River Plume Development in the Coastal Zone of the North-Western Black Sea Shelf Based on Numerical Modelling

M. V. Tsyganova *, E. M. Lemeshko, Yu. N. Ryabtsev

Marine Hydrophysical Institute of RAS, Sevastopol, Russia
* *e-mail: m.tsyganova@mhi-ras.ru*

Abstract

In a south wind, coastal upwelling can be observed off the western coast of the Black Sea. In the same area, the hydrological structure of waters is strongly influenced by river runoff, which forms a river plume, and a southward longshore current. The paper studies the evolution of the plume on the northwest shelf of the Black Sea and its interaction with upwelling based on numerical modelling. The impact of upwelling development under the influence of the south wind on plume propagation was studied using a three-dimensional sigma-coordinate numerical model (POM-type) to calculate the circulation in the coastal zone taking into account the river runoff. The calculations were performed for a rectangular region for the cases of both uniform depth and typical water stratification of the northwestern shelf. The last case was sampled for May condition, when, on average, the Danube plume development is maximal. It is obtained that the joint dynamics of upwelling and river plume are closely related to the stratification of coastal waters. In the case of unstratified shelf waters, the thin plume layer enhances upwelling and downwelling on the inshore and offshore sides of the river plume, respectively. The results allowed studying the peculiarities of river water transformation during winds that cause the development of coastal upwelling. Estimates of the time of bottom water rise near the coast under the action of south winds with different wind speeds and shelf water stratification parameters retrieved from numerical modelling data can be used to develop regional upwelling indices based on satellite data on the sea surface temperature and wind speed.

Keywords: Black Sea, river plume, upwelling, numerical modelling, shelf, coastal zone, river runoff

Acknowledgements: The work was performed under state assignment on topic no. FNNN-2021-0005.

For citation: Tsyganova, M.V., Lemeshko, E.M. and Ryabtsev, Yu.N., 2023. Influence of Upwelling on River Plume Development in the Coastal Zone of the North-Western Black Sea Shelf Based on Numerical Modelling. *Ecological Safety of Coastal and Shelf Zones of Sea*, (1), pp. 20–30. doi:10.29039/2413-5577-2023-1-20-30

Влияние апвеллинга на развитие речного плюма в прибрежной зоне северо-западного шельфа Черного моря на основе численного моделирования

М. В. Цыганова *, Е. М. Лемешко, Ю. Н. Рябцев

Морской гидрофизический институт РАН, Севастополь, Россия
* *e-mail: m.tsyganova@mhi-ras.ru*

Аннотация
При южном ветре у западного побережья Черного моря наблюдается проявление прибрежного апвеллинга. В этом же районе сильное влияние на гидрологическую структуру вод оказывают сток рек, который формирует речной плюм, и вдольбереговое течение, направленное на юг. Целью данной работы является изучение эволюции плюма на северо-западном шельфе Черного моря и его взаимодействие с апвеллингом на основе численного моделирования. Влияние развития апвеллинга под действием ветра южных румбов на распространение плюма исследовалось с помощью трехмерной сигма-координатной численной модели *POM*-типа для расчета циркуляции в прибрежной зоне с учетом стока реки. Расчеты проведены для прямоугольной области для случаев как однородной по глубине, так и типичной для мая (когда в среднем наблюдается максимальное развитие плюма Дуная) стратификации вод северо-западного шельфа. Получено, что совместная динамика апвеллинга и речного плюма тесно связана со стратификацией прибрежных вод. В случае нестратифицированных вод шельфа тонкий слой плюма усиливает апвеллинг и даунвеллинг на береговой и морской сторонах речного плюма соответственно. Полученные результаты позволили изучить особенности трансформации речных вод в период действия ветров, вызывающих развитие прибрежного апвеллинга. Оценки времени подъема придонных вод у берега при действии южных ветров с различными скоростями ветра и параметрами стратификации вод шельфа по данным численного моделирования могут быть использованы для разработки региональных индексов апвеллинга на основе спутниковых данных о температуре поверхности моря и скорости ветра.

Ключевые слова: Черное море, речной плюм, апвеллинг, численное моделирование, шельф, прибрежная зона, речной сток

Благодарности: работа выполнена в рамках государственного задания по теме FNNN-2021-0005.

Для цитирования: *Цыганова М. В., Лемешко Е. М., Рябцев Ю. Н.* Влияние апвеллинга на развитие речного плюма в прибрежной зоне северо-западного шельфа Черного моря на основе численного моделирования // Экологическая безопасность прибрежной и шельфовой зон моря. 2023. № 1. С. 20–30. EDN SYKFPE. doi:10.29039/2413-5577-2023-1-20-30

Introduction

The northwestern part of the Black Sea is characterized by a vast shelf and significant river runoff, as well as a variety of morphological types of plumes in the area of the Danube delta and the Dnieper-Bug Estuary [1]. Therefore, the northwestern shelf is a unique testing ground for studying the dynamics of river plumes of various types [2]. The long-term archival hydrological observations of this region make it possible to verify numerical models of river plumes.

With a southerly wind, upwelling is observed along the western coast of the Black Sea. The hydrological structure of the waters in this region is strongly influenced by river runoff, which is a source of nutrients necessary for phytoplankton bloom. In the case of alongshore upwelling in the summer, a decrease in the oxygen content occurs in the coastal zone, which can cause fish to die [3]. Both of these phenomena are closely related to plume dynamics. Therefore, it is necessary to understand how the distribution of river waters changes with the development of coastal upwelling.

The origin and evolution of upwelling in the Black Sea were studied based on the analysis of *in situ* and satellite data [4–9] and numerical simulation [10, 11]. The satellite data make it possible to recognize colder waters [7, 10, 11], but the high variability and transport of river waters in the region of the northwestern shelf significantly complicate the study of processes by such methods [12, 13]. Therefore, it is important to use numerical simulation along with *in situ* and remote sensing data [14].

The development of upwelling near the northwestern Black Sea coast occurs under the influence of southerly winds. The long-term statistics of upwelling formation, obtained based on the analysis of remote sensing data on sea surface temperature, showed that during the extended summer period there are from 3 to 10 intense upwelling events with a total duration of 35 to 65 % of the length of the summer period, respectively [7]. From a comparison of the in-situ and satellite data analyses, it was concluded that the upwelling evolution has a significant effect on the river plume propagation [15].

The coastal upwelling occurrence is compensated by the geostrophic current and the freshwater plume associated with it. The study of the coastal upwelling and river plume dynamic interaction is of particular interest. River waters with low salinity create pressure gradients that cause surface geostrophic currents that arise in the coastal zone in an anticyclonic direction (in the Northern Hemisphere) from the mouth [16]. The river plume can weaken the development of the upwelling if the wind is too weak to disturb the haline stratification. The change in the stratification of shelf waters is an important factor that determines the plume and upwelling dynamics, affecting the plume thickness, the transfer of desalinated water to the inner shelf area, and the bottom transfer of denser bottom waters towards the coast [17].

Therefore, this work is devoted to the study of joint dynamics of the development of upwelling and river plume, identification of patterns of the influence of upwelling on the transformation of river waters on the sea shelf during the development of coastal upwelling.

Materials and methods

The temperature and salinity fields were selected from the MHI hydrological database (http://bod-mhi.ru/) for wind conditions with wind speeds of less than 3 $\mathrm{m \cdot s^{-1}}$. Based on the spatial distribution of temperature and salinity isolines, the river runoff evolution in the Danube Delta region was estimated and the dy-namics of the river plume was studied. The characteristic time during which the plume reaches the southern boundary of the northwestern shelf is about five days, which corresponds to the obtained estimates based on the approach [2].

The effect of upwelling development under the action of southerly winds on plume propagation was studied using numerical modeling based on a three-dimensional POM-type sigma-coordinate numerical model previously adapted and tested for the northwestern shelf of the Black Sea to calculate the circulation in the coastal zone, taking into account the river runoff [18, 19]. The calculations were carried out for a rectangular area for the cases of both uniform in depth and typical for the month of May (when on average the Danube plume develops its maximum) stratification of the waters of the northwestern shelf.

The model parameters were selected in such a way that they corresponded to the area where the Danube inflows into the Black Sea. The model was adapted for a rectangular area and the conditions of the northwestern shelf of the Black Sea. The computational domain coordinates: 28°–31°E и 43°–46°N, the number of grid nodes along the X axis = 51, the number of grid nodes along the Y axis = 171, the grid step is 2 km, the time step is 2 min, the number of sigma horizons is 25. At the initial moment of calculation, the fresh water inflow is included near the mouth of the Danube.

For the first version of the calculations, a homogeneous stratification was set: salinity of the shelf waters was 18 PSU, the temperature was 18 °C, and the salinity of the inflowing water in the area of the Danube mouth was 6 PSU, the water temperature at the mouth was 10 °C, the river discharges corresponded to the climatic values for April–May (8000 $m^3 \cdot s^{-1}$). On the shelf, a steady southward background current was set; its velocity amounted to 5 $cm \cdot s^{-1}$ [19]. For the second version of the calculations, the climatic values of temperature and salinity near the area of the Danube delta for May were used: on the surface, the shelf water temperature was set to 15.75 °C, the salinity was 12 PSU, the temperature at the bottom was 6.5 °C, the salinity was 18.25 PSU [20]. The thermocline was at a depth of 20 m, the halocline was at a depth of 12 m, and the bottom depth was 40 m. The river discharge, temperature, and salinity were the same as in the first version of the calculations.

Results

Under the influence of the south wind at a speed of 5 $m \cdot s^{-1}$ and the flow rate of the river Q equal to 8000 $m^3 \cdot s^{-1}$, the plume is extended from the coast in a north-easterly direction on the 10th day (Fig. 1).

At the same time, the development of coastal upwelling blocks the propagation of the alongshore current of desalinated waters from the plume area to the south. To understand the role of stratification, we compared the results of calculations for the cases without stratification (Fig. 1) and the cases with stratification (Fig. 2). For the case without stratification, the upwelling develops after 3–5 days, but it does not manifest itself in the surface temperature field due to uniformity of its depth distribution (Fig. 1, *b*). Nevertheless, the alongshore current directed to the north develops at a speed of 5–10 $cm \cdot s^{-1}$, which blocks the initial propagation of the plume to the south, and over time, the plume extends into the inner shelf area, which is traced both by salinity (Fig. 1, *a*) and by water surface temperature, since the temperature of river waters is lower than the temperature of shelf waters by 8 °C (Fig. 1, *b*).

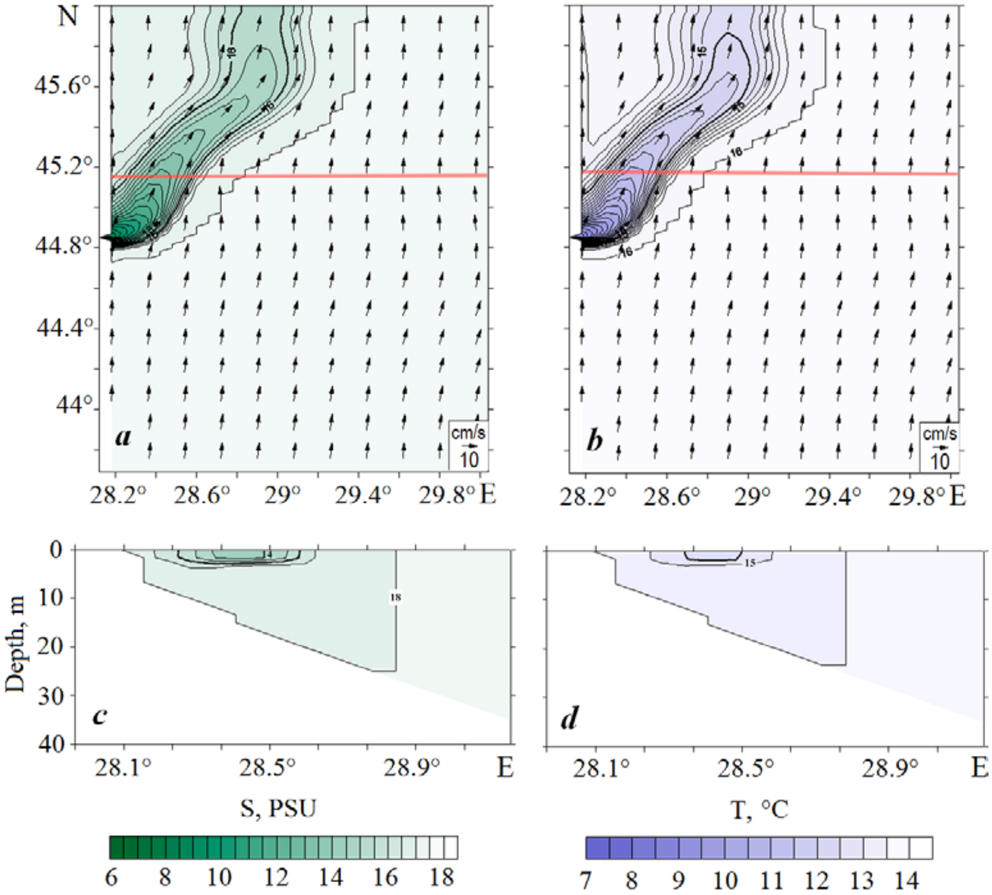


Fig. 1. Surface salinity (*a*) and temperature (*b*) of water from modelling data on the 10th day for uniform stratification influenced by the south wind with a speed of 5 m·s^{-1}. The red line (*a*, *b*) denotes zonal sections of salinity (*c*) and temperature (*d*) fields along 45.18° N latitude

The plume width determined from the position of the 16 PSU isohaline along the transect line at 45.18°N is approximately 25 km; in the temperature field, this corresponds to the plume boundary along the 16 °C isotherm (Fig. 1, *a*, *b*). At the same time, the thickness of the plume is about 5 m, which is seen in the zonal sections of the fields of salinity (Fig. 1, *c*) and temperature (Fig. 1, *d*).

For the case with stratification, the upwelling acquires a well-developed form on the 10th day: the 8 °C isotherm, which characterizes the bottom waters, reaches the surface up to 28.6°E (~ 20 km from the coast), except for the area in the region of the river delta (Fig. 2, *b*).

The upwelling pushes the plume toward the shelf, position of the 10 °C isotherm shifts to the east, and on the 10th day it reaches a longitude of 28.9°E

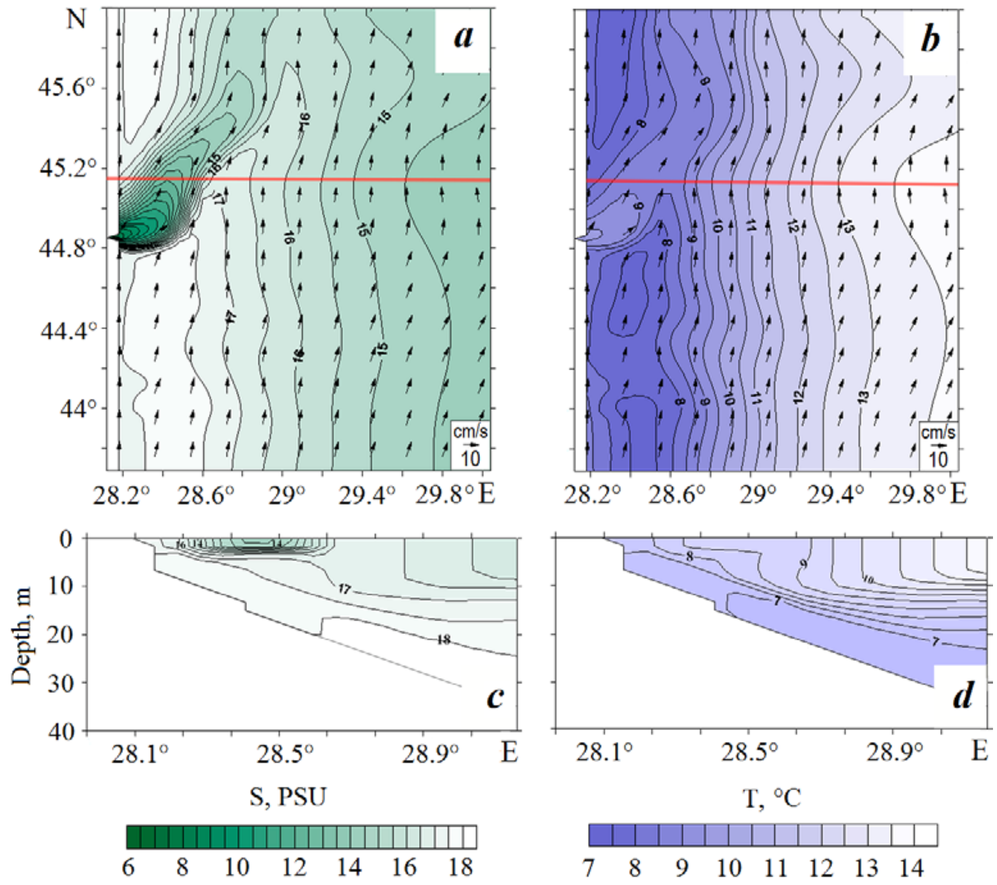
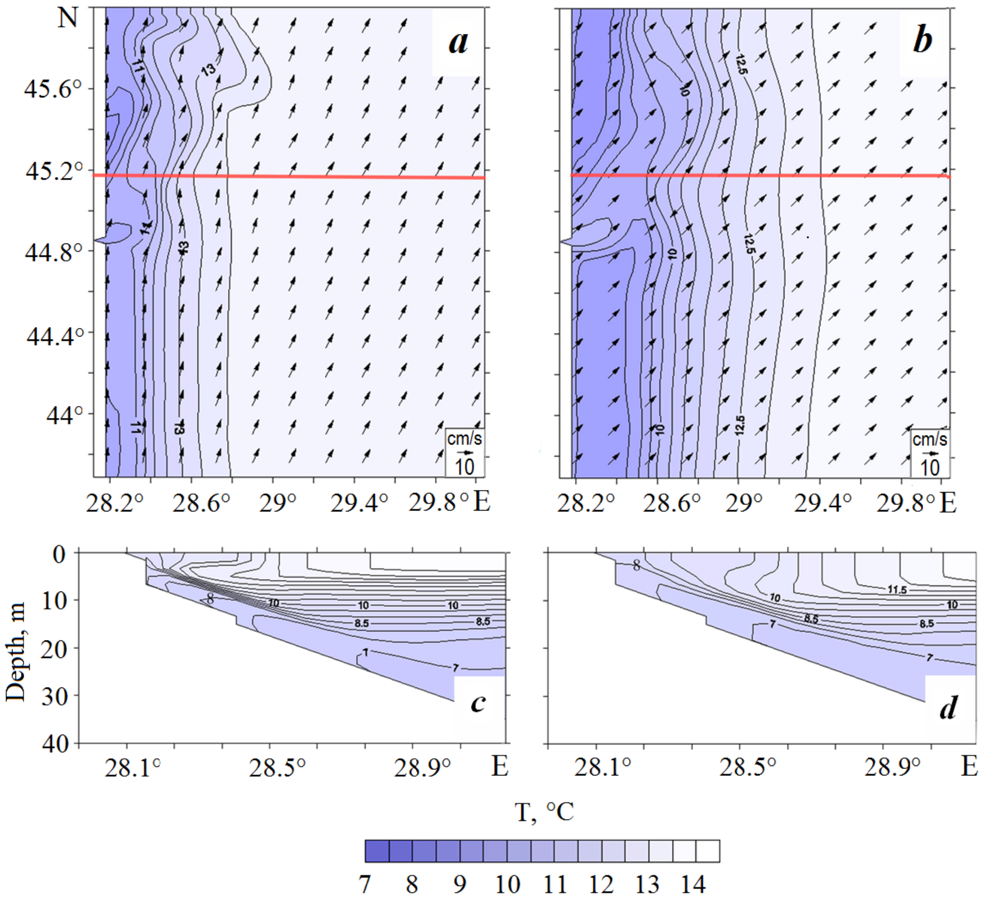


Fig. 2. Surface salinity (*a*) and temperature (*b*) of water from modelling data on the 10th day with shelf water stratification influenced by the south wind with a speed of 5 m·s^{-1}. The red line (*a*, *b*) denotes zonal sections of salinity (*c*) and temperature (*d*) fields along 45.18°N latitude

(Fig. 2, *b*) ~ 55 km from the shore, which in the salinity field corresponds to the position of the 17 PSU isohaline characterizing the bottom waters of the shelf (Fig. 2, *a*). Thus, due to small contrasts between the temperature of the river and the waters of the shelf, the plume identification from satellite data on the sea surface temperature does not contribute to the statistics of upwellings and plumes. When analyzing the results of numerical modelling, the salinity field is used in this case. In addition, unlike the first case without stratification (Fig. 1, *d*), the plume is not distinguished in the temperature field and on the zonal section (Fig. 2, *d*). On the 10th day, the plume elongates to the northeast, and the width of it along the 16 PSU isohaline increases compared to the first case and amounts to 30 km.

On the zonal section along 45.18°N it can be seen that on the 10th day the rise of bottom waters (18 PSU isohaline) reaches a depth of 17 m, the 17 PSU isohaline comes to the surface at a distance of ~ 8 km from the shore (Fig. 2, *c*). In contrast to the plume waters, the position of the bottom waters is clearly distinguished on the zonal sections in the temperature field: the 7 °C isotherm reaches a depth of 10 m, and the 8 °C isotherm comes to the surface at a distance of 8–10 km from the shore (Fig. 2, *d*).

The evolution of coastal upwelling over time is shown in Fig. 3. For calculations with stratification typical for May conditions, the development of coastal upwelling is observed already on the 2nd–3rd day. On the 3rd day, the bottom waters with a temperature of 7–8 °C form a tongue of cold waters, which rises along



F i g . 3 . Surface salinity of water from modelling data with shelf water stratification influenced by the south wind with a speed of 5 m·s^{-1}. The red line (*a*, *b*) denotes zonal sections of temperature fields on the 3d (*c*) and 7th (*d*) day along 45.18°N latitude the slope of the depths and reaches a depth of 10 m (Fig. 3, *c*). On the 7th day, the 8 °C isotherm reaches a depth of 3 m (Fig. 3, *d*), and on the 8th day it comes to the surface. The 10 °C isotherm emerges on the surface near the coast on the 3rd day (Fig. 3, *c*) and masks the position of a plume with a temperature of 10 °C in the temperature field. The waters with a temperature of 10–11 °C occupy the entire alongshore coastal area and are well manifested in the surface temperature field (Fig. 3, *a*). Over time, the 10 °C isotherm shifts to the east and on the 7th day reaches 28.6°E ~ 35 km from the coast (Fig. 3, *b*).

The development of upwelling in time was also analysed based on the variability of the isohaline positions in the zonal section through the plume region along 45.18° N. The rise time of bottom waters, characterized by a salinity of 17 PSU, along the entire coast was on average 5 days for a wind speed of 5 $\mathrm{m \cdot s^{-1}}$. At the same time, the rise of bottom waters occurs along the coastal slope and, after 5 days, their transfer develops in the surface Ekman layer to the shelf area. Based on numerical simulation data, it is possible to obtain detailed estimates of the rate of water rise during the development of coastal upwelling for various values of wind speed, bottom slope angle, and shelf water stratification parameters. The advection time t_{ad} of bottom waters along the shelf slope is directly proportional to the product of the difference between the depths of the pycnocline occurrence H_0 and the depth of the rise of the isopycna (isotherm) H_1 characterizing the bottom waters in the process of upwelling development:

$$t_{\mathrm{ad}} = \frac{\rho \cdot f \cdot d \cdot (H_0 - H_1)}{\alpha \cdot \tau}, \tag{1}$$

where ρ is sea water density; *f* is Coriolis parameter; *d* is bottom layer thickness; α is bottom slope angle; τ is wind stress. The equation (1) gives a theoretical estimate of the advection time as a function of the bottom slope and wind stress. For the parameters characteristic of the northwestern shelf and the wind stress corresponding to a wind speed of 5 $\mathrm{m \cdot s^{-1}}$, we obtain a value of 3 days. If the time of action of the south wind is less than the advection time according to the formula (1), in this case less than 3 days, then cold waters do not have time to reach the surface. Thus, upwelling will not manifest itself in the sea surface temperature field, which must be taken into account when analyzing satellite data.

The advection time t_{ad} is inversely proportional to the wind stress. For the same value of the bottom inclination angle α, numerical calculations were carried out for the case with shelf water stratification and different south wind speeds – 7 $\mathrm{m \cdot s^{-1}}$ and 9 $\mathrm{m \cdot s^{-1}}$. At a wind speed of 7 $\mathrm{m \cdot s^{-1}}$, on the 5th day, the 17 PSU isohaline reaches the surface (Fig. 4, *a*), and the tongue of cold water rises along the slope to a depth of 5 m, according to the position of the 8 °C isotherm (Fig. 4, *b*). For a wind speed of 9 $\mathrm{m \cdot s^{-1}}$ on the 5th day, saline waters (17 PSU) occupy a larger area on the surface (Fig. 4, *c*), and cold waters (less than 8 °C) are on the surface, the width of the upwelling zone along this isotherm is 30 km (Fig. 4, *d*).

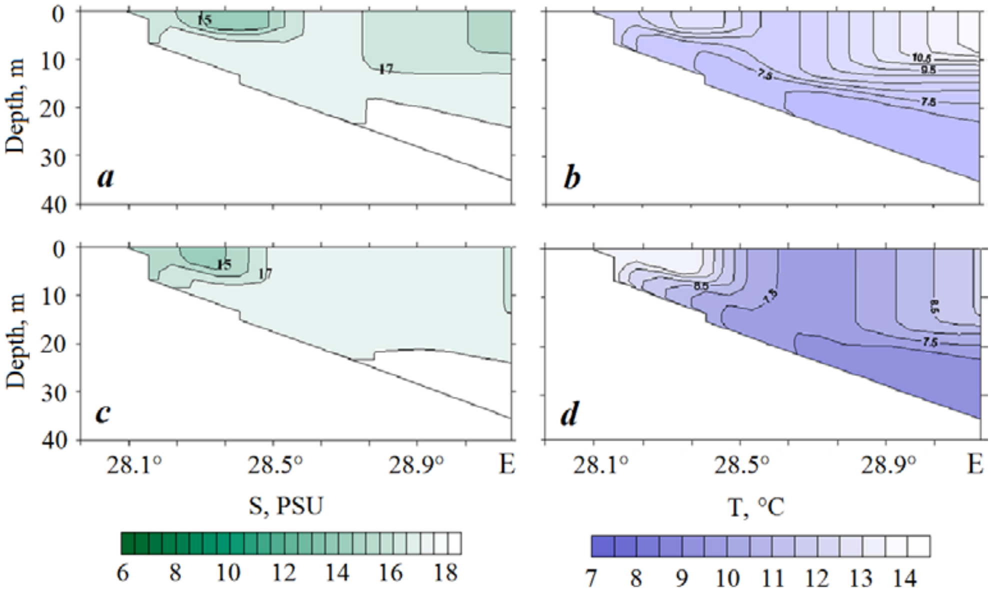


Fig. 4. Zonal sections along 45.18° N latitude: salinity (*a*, *c*) and temperature (*b*, *d*) of water from modelling data with shelf water stratification on the 5th day influenced by the south wind with a speed of 7 $m \cdot s^{-1}$ (*a*, *b*) and 9 $m \cdot s^{-1}$ (c, *d*)

Conclusions

The results obtained made it possible to study the features of the river water transformation during the action of winds that cause the development of coastal upwelling. The plume propagation due to Ekman transport is analyzed depending on the shelf water stratification and wind speed. It was found that the joint upwelling and river plume dynamics is closely related to the stratification of coastal waters. In the case of unstratified shelf waters, a thin layer of plume enhances upwelling and downwelling on the inshore and offshore sides of the river plume, respectively. The upwelling intensity increases when the plume reaches its boundary. In this case, the maximum transport of water towards the shelf is 1.5 times greater than the Ekman transport. After the plume passes through the upwelling region, the water transport is regulated by alongshore density variations.

The regularities of plume dynamics obtained under the conditions of upwelling development manifest themselves in the field of sea surface temperature, which makes it possible to use model estimates of the advection time t_{ad} for interpreting satellite data on sea surface temperature. The estimates of the rise time of bottom waters near the shore under the action of southerly winds with different wind speeds and shelf water stratification parameters based on numerical modelling data can be used to develop regional upwelling indices based on satellite data on sea surface temperature and wind speed.

REFERENCES

1. Horner-Devine, A.R., Hetland, R.D. and MacDonald, D.G., 2015. Mixing and Transport in Coastal River Plumes. *Annual Review of Fluid Mechanics*, 47, pp. 569–594. doi:10.1146/annurev-fluid-010313-141408
2. Lemeshko, E.M. and Tsyganova, M.V., 2021. Investigation of Danube River Plume Formation and Propagation Based on Numerical Modeling. In: MSU, 2021. *InterCarto. InterGIS. GI support of sustainable development of territories: Proceedings of the International conference*. Moscow: MSU, Faculty of Geography, 2021. Vol. 27, part 3, pp. 32–41. doi:10.35595/2414-9179-2021-3-27-32-41 (in Russian).
3. Kondratev, S.I., 2019. Three Typical Hydrological-Hydrochemical Situations near the Danube River Mouth Based on the Marine Hydrophysical Institute Research Expeditions in 1997-2013. *Physical Oceanography*, 26(4), pp. 326–340. doi:10.22449/1573-160X2019-4-326-340
4. Bogdanova, A.K. and Korpachev, L.N., 1959. [Upsurge and Downsurge Circulation and its Role for the Hydrological Regime of the Black Sea]. *Meteorologiya i Gidrologiya*, (4), pp. 26–32 (in Russian).
5. Borovskaya, R.V., Panov, B.N., Spyrydonova, E.O., Leksikova, L.A. and Kyrylova, M.V., 2005. Black Sea Near-Coastal Upwelling and Interannual Variability of Its Intensity. In: MHI, 2005. *Ekologicheskaya Bezopasnost' Pribrezhnoy i Shel'fovoy Zon Morya* [Ecological Safety of Coastal and Shelf Zones and Comprehensive Use of Shelf Resources]. Sevastopol: MHI. Iss. 12, pp. 42–48 (in Russian).
6. Ginzburg, A.I., Kostianoy, A.G., Soloviev, D.M. and Stanichny, S.V., 2000. Coastal Upwelling in the North-West Black Sea. *Earth Observation and Remote Sensing*, 15(6), pp. 933–948.
7. Stanichnaya, R.R. and Stanichny, S.V., 2021. Black Sea Upwellings. *Sovremennye Problemy Distantsionnogo Zondirovaniya Zemli iz Kosmosa*, 18(4), pp. 195–207. doi:10.21046/2070-7401-2021-18-4-195-207
8. Zatsepin, A.G., Silvestrova, K.P., Kuklev, S.B., Piotoukh, V.B. and Podymov, O.I., 2016. Observations of a Cycle of Intense Coastal Upwelling and Downwelling at the Research Site of the Shirshov Institute of Oceanology in the Black Sea. *Oceanology*, 56(2), pp. 188–199. https://doi.org/10.1134/S0001437016020211
9. Silvestrova, K.P., Myslenkov, S.A. and Repkov, D.S., 2022. Wind Upwelling Forecast for the Russian Black Sea Coast. *Hydrometeorological Research and Forecasting*, (1), pp. 89–107. https://doi.org/10.37162/2618-9631-2022-1-89-107
10. Divinsky, B.V., Kuklev, S.B. and Zatsepin, A.G., 2017. Numerical Simulation of an Intensive Upwelling Event in the Northeastern Part of the Black Sea at the IO RAS Hydrophysical Testing Site. *Oceanology*, 57(5), pp. 615–620. https://doi.org/10.1134/S0001437017040038
11. Oguz, T., La Violette, P.E. and Unluata, U., 1992. The Upper Layer Circulation of the Black Sea: Its Variability as Inferred from Hydrographic and Satellite Observations. *Journal of Geophysical Research: Oceans*, 97(C8), pp. 12569–12584. doi:10.1029/92JC00812
12. Mikhailova, E.N., Muzyleva, M.A., Polonskii, A.B., Soloviev, D.M. and Stanichny, S.V., 2009. [Spatial and Temporal Variability of Upwelling Characteristics in the Northwestern Part of the Black Sea and off the Crimean Coast in 2005–2008]. In: MHI, 2009. *Monitoring Systems of Environment*. Sevastopol: ECOSI-Gidrofizika. Issue 12, pp. 318–321 (in Russian).
13. Osadchiev, A.A., 2021. *River Plumes*. Moscow: Scientific World, 285 p.

14. Zavialov, P.O., Makkaveev, P.N., Konovalov, B.V., Osadchiev, A.A., Khlebopashev, P.V., Pelevin, V.V., Grabovskiy, A.B., Izhitskiy, A.S., Goncharenko, I.V., Soloviev, D.M. and Polukhin, A.A., 2014. Hydrophysical and Hydrochemical Characteristics of the Sea Areas Adjacent to the Estuaries of Small Rivers of the Russian Coast of the Black Sea. *Oceanology*, 54(3), pp. 265–280. doi:10.1134/S0001437014030151
15. Kubryakov, A.A., Stanichny, S.V. and Zatsepin, A.G., 2018. Interannual Variability of Danube Waters Propagation in Summer Period of 1992–2015 and Its Influence on the Black Sea Ecosystem. *Journal of Marine Systems*, 179, pp. 10–30. https://doi.org/10.1016/j.jmarsys.2017.11.001
16. Fong, D.A. and Geyer, W.R., 2002. The Alongshore Transport of Freshwater in a Surface-Trapped River Plume. *Journal of Physical Oceanography*, 32(3), pp. 957–972. https://doi.org/10.1175/1520-0485(2002)032<0957:TATOFI>2.0.CO;2
17. Alory, G., Da-Allada, C.Y., Djakouré, S., Dadou, I., Jouanno, J. and Loemba, D.P., 2021. Coastal Upwelling Limitation by Onshore Geostrophic Flow in the Gulf of Guinea Around the Niger River Plume. *Frontiers in Marine Science*, 7, 607216. doi:10.3389/fmars.2020.607216
18. Ivanov, V.A. and Fomin, V.V., 2010. *Mathematical Modeling of Dynamical Processes in the Sea – Land Area*. Kiev: Akademperiodika, 286 p.
19. Tsyganova, M.V., Lemeshko, E.M. and Ryabcev, Yu.N., 2016. Modelling of Hydrofront Forming on the Danube Mouth Area. In: MHI, 2016. *Ecological Safety of Coastal and Shelf Zones of Sea*. Sevastopol: MHI. Iss. 3, pp. 26–31 (in Russian).
20. Ivanov, V.A. and Belokopytov, V.N., 2013. *Oceanography of the Black Sea*. Sevastopol: ECOSI-Gidrofizika, 212 p.

Submitted 20.12.2022; accepted after review 23.01.2023;
revised 1.02.2023; published 24.03.2023

About the authors:

Marina V. Tsyganova, Junior Research Associate, Marine Hydrophysical Institute of RAS (2 Kapitanskaya St., Sevastopol, 299011, Russian Federation), **ORCID ID: 0000-0003-2398-1756, ResearcherID: S-5426-2018, SPIN-code: 2256-0620**, *m.tsyganova@mhi-ras.ru*

Evgeny M. Lemeshko, Senior Research Associate, Marine Hydrophysical Institute of RAS (2 Kapitanskaya St., Sevastopol, 299011, Russian Federation), Ph.D. (Phys.-Math.), **SPIN-code: 3836-5786, ResearcherID: S-7815-2018, Scopus AuthorID: 6508300982**, *eugeny.lemeshko@mhi-ras.ru*

Yuri N. Ryabtsev, Research Associate, Marine Hydrophysical Institute of RAS (2 Kapitanskaya St., Sevastopol, 299011, Russian Federation), **ORCID ID: 0000-0002-9682-9969, SPIN-code: 7853-4597**, *ruab@mail.ru*

Contribution of the authors:

Marina V. Tsyganova – collection, systematization, and analysis of literature, performance of numerical experiments, processing, analysis, and description of the study results, preparation of the text and graphic material for the article

Evgeny M. Lemeshko – problem statement, processing, analysis, and description of the study results, preparation of the article text

Yuri N. Ryabtsev – development of the mathematical model, selection and justification of methods for equation solution, mathematical model correction

All the authors have read and approved the final manuscript.