

DYNAMICS OF ANTHROPOGENIC POLLUTANT SPREAD
FROM TAGANROG BAY INTO THE SEA OF AZOVM. V. Budyansky^{1,2}, T. V. Belonenko^{1,*}, V. S. Travkin^{1,3,4},
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Abstract: The Taganrog Bay is the most ecologically vulnerable water area of the Sea of Azov, subjected to significant anthropogenic impact from the ports of Mariupol and Taganrog, as well as the Don River discharge. This paper analyzes the processes of potential pollution transfer from the bay into the Sea of Azov using a three-dimensional Princeton Ocean Model hydrodynamic model and Lagrangian modeling of passive particle trajectories. Model circulation was calculated for 2020 with high spatial resolution, followed by numerical tracking of 7,350,000 virtual particles placed in the main pollution zones. Lagrangian analysis identified key transport pathways, accumulation and retention zones for pollutants, and seasonal variability of water exchange through the Dolzhansky Strait. It is shown that the transfer of potential pollution is determined by a combination of wind forcing, Don discharge, and local circulation. Comparison of model results with MODIS satellite data (2000–2024) confirms the spatial patterns of organic matter distribution and the identified transport directions. The obtained results can be used to assess ecological risks associated with the outflow of pollution into the Sea of Azov and to justify environmental protection measures in the region.

Keywords: anthropogenic pollutants, spread dynamics, Taganrog Bay, Sea of Azov, Lagrangian modeling

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REVIEW

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1. Introduction

Taganrog Bay is one of the most productive and ecologically sensitive areas of the Sea of Azov (Figure 1). As the of the Don River's mouth, the bay accumulates a significant amount of river runoff, the volume of which is comparable to the water body's own volume. The bay's waters are characterized by reduced salinity and a high content of biogenic substances, entering both from river runoff and coastal discharges, including agricultural, industrial, and municipal pollution sources.

Scientific analysis of the ecological status of the Sea of Azov reveals that Taganrog Bay is identified as one of the most polluted areas [Bufetova, 2019; Bufetova and Bufetov, 2019; Kreneva et al., 2008]. The issue of pollutant transfer becomes particularly critical due to increasing anthropogenic pressure on the Don River basin, encompassing agricultural runoff, industrial, and domestic discharges [Kulik et al., 2019]. A key aspect of this challenge is understanding the spatio-temporal organization of water exchange, retention zones, and pollutant migration pathways. Eulerian analysis methods, which examine instantaneous velocity and concentration fields, are often insufficient for accurately describing the transport and accumulation of substances in highly heterogeneous and non-stationary current conditions. Consequently, Lagrangian methods are gaining increasing traction. These methods involve the numerical tracking of passive markers within a flow field, derived from either observational data or hydrodynamic modeling results [Prants et al., 2017].

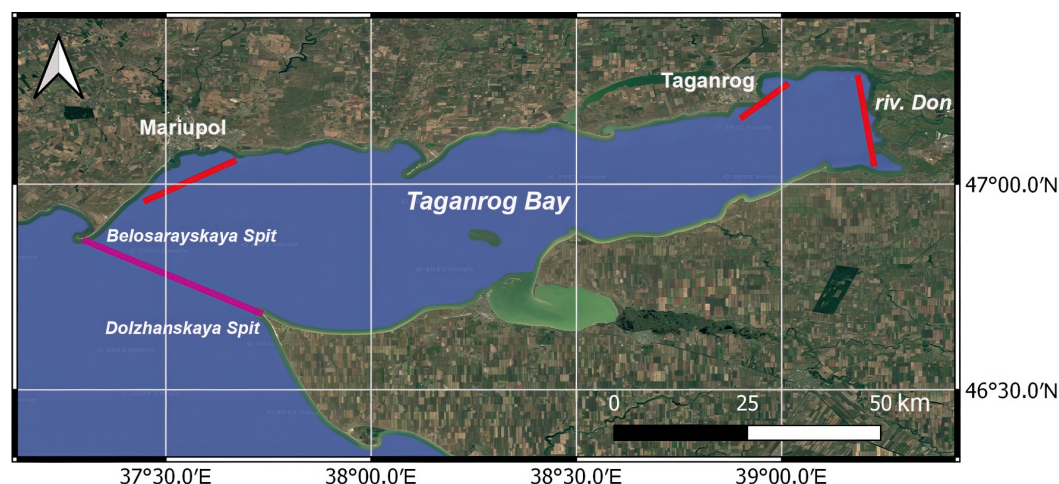


Figure 1. Study area. Red lines indicate the triggering regions for the Lagrangian analysis of passive markers simulating pollution. The purple line marks the imaginary boundary separating Taganrog Bay and the Sea of Azov, running between the Belosarayskaya and Dolzhanskaya spits.

One of the key factors determining the ecological state of the bay is the water exchange with the open waters of the Sea of Azov through the Dolzhansky Strait. This process serves a dual function. On the one hand, the outflow of polluted and eutrophic waters from the bay into the sea contributes to the self-purification of the coastal environment. On the other hand, the influx of more saline seawater into the bay alters hydrochemical conditions, affecting the composition of the biota and, in particular, narrowing the habitat of brackish-water fish species that traditionally dominate the ichthyofauna of the region. Given the high dynamism of water exchange and the complexity of circulation, driven by meteorological and hydrological factors, a detailed quantitative analysis of pollutant transport processes is necessary.

In the work [Simov *et al.*, 2013], estimates of water discharge through the Dolzhansky Strait of Taganrog Bay were obtained. It was shown that the water exchange between Taganrog Bay and the Sea of Azov primarily depends on the intensity of wind-driven surge and drawdown events, and to a lesser extent, on the Don River discharge. The authors demonstrated that the annual values of water outflow from Taganrog Bay into the sea vary from 177 to 212 km³, while inflow from the sea into the bay ranges from 169 to 176 km³. Given that the volume of Taganrog Bay is 24.6 km³, this corresponds to a 5–6-fold renewal of its water masses [Simov *et al.*, 2013].

However, the key significance lies not so much in the magnitude of exchange, but rather in the spatio-temporal nature of pollutant transfer, their potential accumulation in sensitive zones, and advection trajectories depending on hydrometeorological conditions. Even with relatively small circulation volumes, pollution can persist or move along specific directions, forming local hotspots of elevated concentration.

The transport of anthropogenic pollutants from the Taganrog Bay into the Sea of Azov is governed by a complex interplay of hydrodynamic processes, encompassing wind forcing, riverine discharge, and localized water circulation. Primary pollution sources within the coastal zone of Taganrog Bay include the industrial and port areas of Mariupol and Taganrog, as well as the watershed of the Don River estuary, which contributes substantial fluxes of suspended and dissolved matter to the bay. The Mariupol and Taganrog ports, characterized by intensive industrial activity and shipping, act as conduits for heavy metals, petroleum hydrocarbons, and organic pollutants into the territorial waters of Taganrog Bay. These contaminants accumulate in the water column and settle into bottom sediments, imposing a toxic load on the ecosystems. The Don estuary, with its considerable riverine discharge and anthropogenic influences, also constitutes a significant source of pollutants which, through hydrodynamic processes, propagate into Taganrog Bay and subsequently into the Sea of Azov. The impact of riverine discharge is accompanied by the transport of

dissolved and suspended substances, including nutrients, organic matter, and pollutants, thereby influencing the chemical composition and biological status of the sea. Thus, the transport of pollutants from the ports of Mariupol and Taganrog, as well as from the Don estuary, is determined by a combination of seasonal changes in runoff, wind forcing, and the structure of local currents. These processes form a complex and non-stationary water exchange system in which Taganrog Bay plays a key role as the main donor of polluted waters to the Sea of Azov.

It should also be noted that Taganrog Bay of the Sea of Azov is regularly covered with ice during the winter period. Winters in this region are quite cold, with frequent and persistent frosts, which contribute to prolonged ice cover. The average depth of the bay is only about 4.5–5 m, and even shallower in its eastern part. The relatively small water volume cools rapidly and becomes ice-covered. In addition, large rivers (Don, Mius, Yeya) flow into the bay, significantly reducing its salinity. Fresh and low-salinity water freezes at higher temperatures than seawater. Ice usually forms in December and persists until March. The seasonal ice regime may significantly influence water exchange processes in the bay. Winter ice cover can limit circulation and exchange with the open sea, while the spring breakup period may enhance water export [Ogorodov *et al.*, 2020; Yaitskaya and Magaeva, 2018]. These processes are known to affect the seasonal dynamics of the Sea of Azov and should be considered when interpreting pollutant transport patterns.

The aim of this study is a comprehensive Lagrangian analysis of the transport of potential pollution from Taganrog Bay into the Sea of Azov based on a modeled velocity field. Circulation in Taganrog Bay and the adjacent part of the Sea of Azov is simulated using the Princeton Ocean Model (POM) – a three-dimensional, nonlinear, sigma-coordinate hydrodynamic model that has proven effective in studies of coastal dynamics, estuarine, and shelf processes [Blumberg and Mellor, 1987]. Using the resulting velocity fields of the Sea of Azov, a Lagrangian analysis is implemented to identify zones of accumulation and retention of passive markers (potential pollutants), assess the seasonal variability of water exchange processes through the Dolzhansky Strait, and determine the directions and scales of potential pollutant transport.

2. Methods and Data

2.1. Description of the Sea of Azov POM Hydrodynamic Model

The numerical study of water circulation in the Sea of Azov basin is based on the application of the modern three-dimensional nonlinear hydrodynamic model POM (<http://www.ccpo.odu.edu/POMWEB>), developed for calculations in shallow marine basins with complex coastal relief, requiring the use of coordinates unevenly distributed with depth (sigma-coordinates). This model implements the solution of the full system of primitive equations of motion, written under the assumptions of incompressibility, hydrostatics, and Boussinesq, taking into account the Earth's rotation with angular velocity Ω :

$$\nabla \cdot \mathbf{U} + \frac{\partial w}{\partial z} = 0, \quad (1)$$

$$\frac{\partial u}{\partial t} + \mathbf{U} \cdot \nabla u + w \frac{\partial u}{\partial z} - f v = -\frac{1}{\rho_0} \frac{\partial P}{\partial x} + \frac{\partial}{\partial z} \left(K_M \frac{\partial u}{\partial z} \right) + A_x \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right), \quad (2)$$

$$\frac{\partial v}{\partial t} + \mathbf{U} \cdot \nabla v + w \frac{\partial v}{\partial z} - f u = -\frac{1}{\rho_0} \frac{\partial P}{\partial y} + \frac{\partial}{\partial z} \left(K_M \frac{\partial v}{\partial z} \right) + A_y \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right), \quad (3)$$

$$\frac{\partial P}{\partial z} + g\rho = 0. \quad (4)$$

In these equations: z – vertical coordinate along depth; the x -axis is directed eastward, y – northward; t – time; $\mathbf{U} = (u, v, w)$ – velocity; u, v, w – velocity components along the x, y, z axes; $\nabla = \{\partial/\partial x, \partial/\partial y\}$ – vector differential horizontal operator; g – acceleration

due to gravity; ρ – water density; $\rho_0 = \frac{1}{\zeta+H} \int_{-H}^{\zeta} \rho \, dz$ – average water density over depth; $\zeta = \zeta(x, y, t)$ – sea level deviation from the unperturbed state; $f = 2\Omega \sin \varphi$ – Coriolis parameter, φ – geographical latitude; $P(x, y, z, t)$ – pressure at depth z , based on vertical integration of (4): $P(x, y, z, t) = P_{\text{atm}} + g\rho_0(\zeta - z)$, $P_{\text{atm}} = 1013.25$ hPa – normal atmospheric pressure at 0°C at 45° latitude; A_x and A_y – horizontal viscosity in the x and y directions; K_M – coefficient of vertical turbulent viscosity.

The system of equations (1)–(4) is closed by specifying boundary conditions at the free surface, open boundary, and in the bottom layer. During the adaptation of the POM model to the Azov basin, a series of numerical experiments was conducted to assess the applicability of linear approximations and to select optimal spatial and temporal integration steps [Ivanov *et al.*, 2012, 2014]. The calculation of averaged two-dimensional horizontal velocity components and sea level (integration of barotropic mode equations) is performed with a time step of $\Delta t = 18$ s, and deviations from the found averages and the vertical velocity component are calculated with a step of $10\Delta t$. The model domain was obtained by spatial interpolation of the Sea of Azov depth array, taken from navigation charts, onto a bathymetric grid with a horizontal resolution of $\Delta x = \Delta y \approx 1$ km. Vertical discretization with 11 sigma levels adequately describes bottom relief heterogeneities.

The parameterization of vertical viscosity and turbulent diffusion coefficients was performed according to the Mellor–Yamada differential turbulence closure model [Mellor and Yamada, 1982]. The horizontal viscosity coefficient was calculated using the subgrid-scale viscosity model [Smagorinsky, 1963]. Wind stress components were expressed through wind speed values at the standard meteorological height, adjusted by the sea surface aerodynamic drag coefficient [Wannawong *et al.*, 2011]. Boundary conditions at the free surface were updated hourly using data from the SKIRON atmospheric model (<https://forecast.uoa.gr/en>) [Kallos *et al.*, 1998], with interpolation of meteorological fields at 0.1° latitude–longitude resolution onto the model grid of the Sea of Azov within the computational domain.

The results of numerical experiments for model verification, based on comparisons with direct measurement data, are described in detail in several studies [Ivanov *et al.*, 2012, 2014; Ivanov and Shul'ga, 2018; Shul'ga and Suslin, 2018]. These works present the assessment of the impact of spatial ($\Delta x = \Delta y \approx 2$ km) and temporal ($\Delta t = 6$ min) step sizes.

For the present study, POM simulations were performed over a 365-day period from 00:00 on January 1, 2020, to 24:00 on December 31, 2020. The resulting daily velocity component datasets with a horizontal resolution of ~ 1 km were subsequently used for the Lagrangian analysis.

2.2. Lagrangian Modeling

This study employs an integrated approach, combining traditional statistical analysis methods with Lagrangian modeling of substance transport in the marine environment. Lagrangian analysis allows tracking the movement of passive markers within a non-stationary flow field, revealing the main pathways of pollution dispersion. This approach is based on the numerical integration of the equations of motion for passive particles (markers) in a prescribed, time-varying velocity field obtained from a hydrodynamic model. By enabling detailed analysis of individual particle trajectories, this method allows identification of primary transport routes, accumulation and dispersion zones, estimation of temporal characteristics of transport (e.g., the time required for contaminants to reach sensitive areas), and assessment of the influence of seasonal and interannual variability in circulation on pollution patterns [Budyansky *et al.*, 2024, 2015, 2025a,b; Prants *et al.*, 2023, 2017]. The Lagrangian approach is particularly effective for analyzing pollutant transport originating from port areas and river mouths. It enables tracing how local sources of contaminated waters are incorporated into regional circulation, the routes along which they spread, which areas experience the greatest impact, and the time scales over which polluted masses reach distant parts of the sea.

For the implementation of the Lagrangian analysis, 10,000 virtual particles are daily released in the segments near the ports of Taganrog, Mariupol, and the Don estuary, conditionally representing a pollution source. Each particle moves under the influence of the velocity field, and its trajectory is determined by solving the advection equations of the form:

$$\frac{d\lambda}{dt} = u(\lambda, \varphi, t), \quad \frac{d\varphi}{dt} = v(\lambda, \varphi, t), \quad (5)$$

where u and v are the angular zonal and meridional components of the velocity field calculated using the Sea of Azov POM model, and φ and λ are latitude and longitude, respectively. Thus, based on the numerical tracking of the movement of many particles, the directions, speed, and scale of transport are estimated, and areas of possible accumulation or dispersion of matter are determined. This method allows for a quantitative analysis of advection processes, identification of transport barriers, and evaluation of the efficiency of water exchange in the studied system.

The velocity fields required for the calculation of Lagrangian trajectories are defined on a discrete space–time grid and interpolated to obtain values at arbitrary points at each time step. In space (latitude and longitude), bicubic interpolation is used, providing high smoothness and accuracy in reconstructing local velocity gradients and their derivatives. In time, third-order Lagrange polynomial interpolation is applied, which adequately accounts for the non-stationarity of the flows and improves the accuracy of integrating the particle motion equations.

The calculation of Lagrangian trajectories is based on the numerical integration of the advection equations (5) using an explicit fourth-order Runge–Kutta scheme. This scheme provides stability and high accuracy when modeling long trajectories in non-stationary flow fields. The integration time step is fixed at 0.001 days (≈ 86.4 s), which allows for effective accounting of high-frequency variations in the velocity field. Each trajectory is calculated over a period of up to 90 days. This approach allows for the study of the spatial and temporal characteristics of transport and water exchange with high resolution and minimal numerical distortion.

2.3. Data

For the validation of the Lagrangian modeling, satellite data from the MODIS-Aqua and MODIS-Terra missions for the period 2000–2024 were used, available from the NASA Ocean Color portal (<https://oceancolor.gsfc.nasa.gov/>). The data used consist of long-term satellite time series of ocean surface spectral radiance obtained in the visible and near-infrared ranges. Level-3 data with a regular 1 km grid were employed, representing spatially and temporally averaged measurements with prior atmospheric correction and quality control. Monthly and seasonal composites were used in the study to reduce data gaps caused by cloud cover. The 2000–2024 period covers the complete observation cycles of MODIS-Terra (since 2000) and MODIS-Aqua (since 2002), providing a consistent long-term Colored Dissolved Organic Matter (CDOM) dataset for assessing the spatial structure of CDOM fields in both coastal and open-sea areas. MODIS data underwent standard quality flag filtering procedures that exclude pixels affected by clouds, ice cover, high aerosol signals, or errors in atmospheric correction. The selection of a period spanning more than two decades (2000–2024) allows for the assessment of long-term variability in the optical properties of the sea surface layer and the identification of large-scale trends associated with natural variability and external influences.

It is well known that standard NASA Ocean Color data processing algorithms [O'Reilly *et al.*, 1998] inaccurately estimate chlorophyll concentrations in coastal areas and inland seas, such as the Black Sea [Suetin *et al.*, 2002]. In this regard, the optically complex Sea of Azov is no exception, due to its shallow depth and the presence of background effects from shoals, rocks, and bottom sediments. In the present study, the inherent optical properties (IOPs) of the Sea of Azov, including CDOM concentration corresponding to the “Inland seas, estuaries, lakes” (Case-2) category [Gitelson *et al.*, 2009], were obtained using a regional bio-optical model [Suslin *et al.*, 2020], validated against in situ measurements [Churilova *et al.*, 2022].

3. Results

3.1. Lagrangian Analysis of Potential Pollution Transport in the Taganrog Bay

For the Lagrangian modeling of potential pollution areas (the ports of Mariupol and Taganrog, as well as the Don estuary), we define segments (Figure 1), each seeded with 10,000 Lagrangian markers simulating pollution. Particles are released daily from January 1 to September 30, 2020. Each trajectory is tracked over a period of 90 days.

Figure 2a shows the trajectories of passive particles released in the “Taganrog” segment. The color scale represents the number of particles passing through a $0.01^\circ \times 0.01^\circ$ cell in latitude and longitude. The map illustrates the spatial distribution of transport pathways, including the main directions of particle export from Taganrog Bay, dispersion zones in the central part of the Sea of Azov, and areas of increased concentration formed under the influence of local circulation. High particle density in certain areas indicates zones of potential accumulation or flow retardation, whereas widespread distribution demonstrates the influence of marine currents on particle transport. The figure shows that the highest particle accumulation occurs in the northeastern part of the study area, corresponding to the zonal flow direction in this region. Lower trajectory density is observed along the western and southern edges, indicating a lower probability of particle penetration into these areas. The presence of branching trajectories and areas of varying intensity reflects the heterogeneity of hydrodynamic conditions, including the influence of local currents and potential eddy structures.

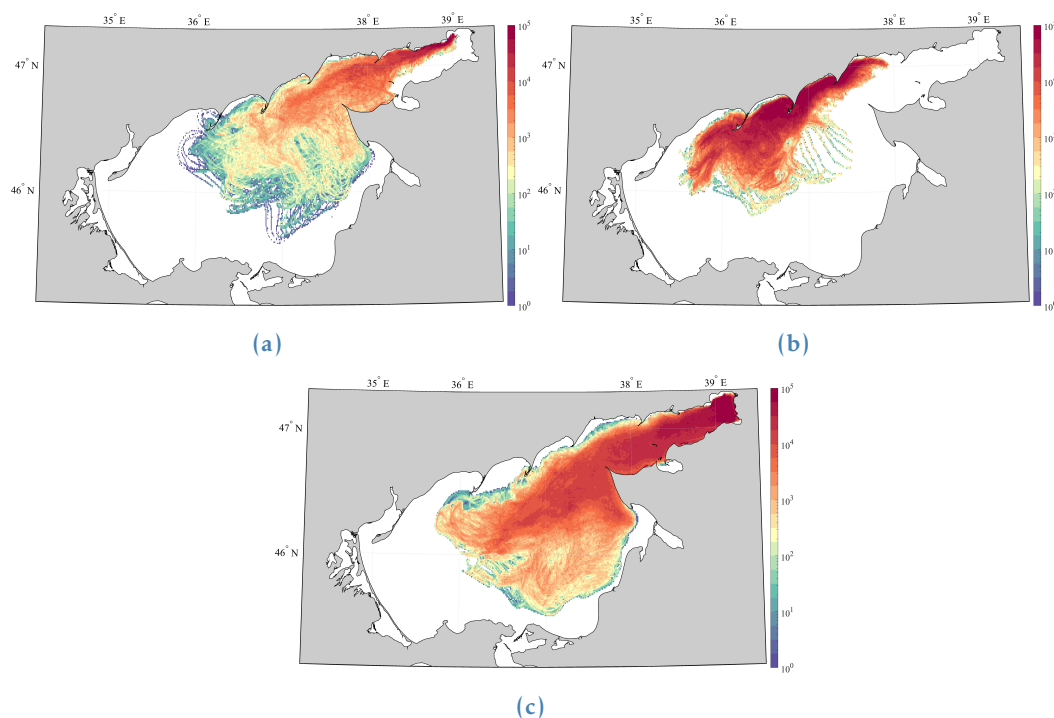


Figure 2. Density of daily trajectories of passive particles released in the “Taganrog” (a), “Mariupol” (b), and “Don” (c) segments. Particles were released daily from January 1 to September 30, 2020. The count is accumulated over a 90-day period. The color scale represents the number of particles passing through a $0.01^\circ \times 0.01^\circ$ grid cell in latitude and longitude. The scale is logarithmic, ranging from 10^0 (1 particle) to 10^5 (100,000 particles).

Figure 2b shows that particles released in the Mariupol area disperse over a considerable area. The highest particle density (dark red regions) is observed near the release site and along the northern coast, extending into the central part of the sea. Less dense particle clusters (lighter colors) spread farther from the initial point. The main particle movement occurs to the west and southwest of Mariupol, which may indicate prevailing currents or winds during this period.

Figure 2c illustrates how particles originating from the Don River are distributed across the sea over an extended period. High particle concentrations in certain areas may indicate zones of slowed water exchange or persistent circulation cells that promote the accumulation of suspended matter or pollutants. The particle distribution also helps to understand the transport pathways of river discharge and associated substances throughout the Sea of Azov. The figure clearly shows a high concentration of particles in the northeastern part of the Sea of Azov, near the Don River delta, which is expected, as the particles were released in this area. Over time (from January to September 2020), the particles spread across most of the Sea of Azov. A pronounced movement of particles is observed to the west and southwest from the Don estuary, as well as along the northern coast. Less intense dispersal occurs in the southern direction. Although particles spread widely, areas of highest concentration remain near the Don estuary and in the eastern/northeastern part of the sea. In the central and western parts, particle concentration decreases, although particles are present throughout the water body.

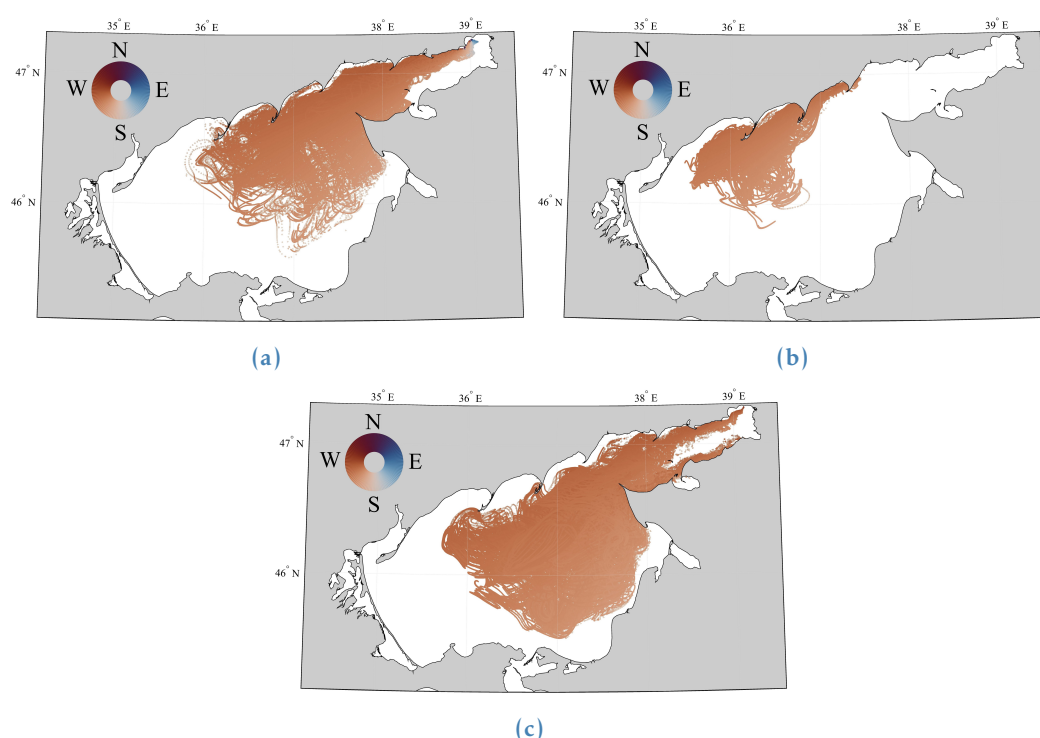


Figure 3. Positions on the final day of the count (December 30, 2020) of all particles released in the “Taganrog” (a), “Mariupol” (b), and “Don” (c) segments. A circular compass is shown in the upper left corner of the map. Its colors indicate the displacement direction of particles from the time of release to the last day of tracking.

Figure 3a shows the final positions (as of December 30, 2020) of all particles released from the “Taganrog” segment. The colors on the map indicate the direction of particle displacement from the moment of release to the last day of tracking. Particles from the Taganrog Bay spread across almost the entire Sea of Azov, reaching its western and southern shores. It is evident that most of the particle trajectories released from the “Taganrog” segment are shaded in red-brown tones. According to the compass, this corresponds to a westward direction of movement. Particles released in the Taganrog Bay primarily move westward, dispersing throughout the Sea of Azov. This indicates the dominant currents or winds facilitating the transport of water masses and suspended matter in that direction. Some trajectories in the central and western parts of the sea show lighter shades (closer to white), which may indicate southward movement in certain areas. However, the prevailing direction is westward.

Figure 3b confirms a significant westward and southwestward transport of water masses in the Sea of Azov originating from the Mariupol area. This is important for understanding the distribution of pollutants entering the sea from this region. The dominance of such transport can affect the Sea of Azov ecosystem, including the distribution of plankton, fish larvae, and other suspended particles across the water body. Comparison with the previous map (Figure 3a, where particles were released from Taganrog Bay) shows a similar overall trend of westward transport, but with different release points and, consequently, areas of highest concentration. Most of the particle trajectories in Figure 3b are shaded in red-brown tones. According to the compass, this corresponds to a westward direction of movement. Particles released in the Mariupol area exhibit pronounced westward and southwestward motion, indicating prevailing currents or winds driving water mass transport in these directions. Some trajectories, particularly at the periphery of the dispersion zone, display lighter shades, reflecting deviations from the main westward direction. Overall, particles from the Mariupol area predominantly spread toward the western and southwestern parts of the Sea of Azov, forming an extensive dispersion area, while a smaller portion moves eastward, remaining closer to the release site.

Figure 3c demonstrates that particles entering from the Don River through Taganrog Bay undergo strong westward transport across the Sea of Azov. This confirms the findings from previous analyses and highlights the importance of the Don River as a pollution source influencing hydrological and ecological processes in the Sea of Azov. The vast majority of particle trajectories are shaded in red-brown tones. According to the compass, this clearly corresponds to a westward direction of movement. Some southward displacement of particles is also observed, visible in the lighter sections of the trajectories, but the dominant direction remains westward.

The following three figures (Figures 4a, 4b, and 4c) essentially represent “probability-of-presence” maps of particles on their final day of integration: the more intense the color, the greater the number of trajectories that ended at that location.

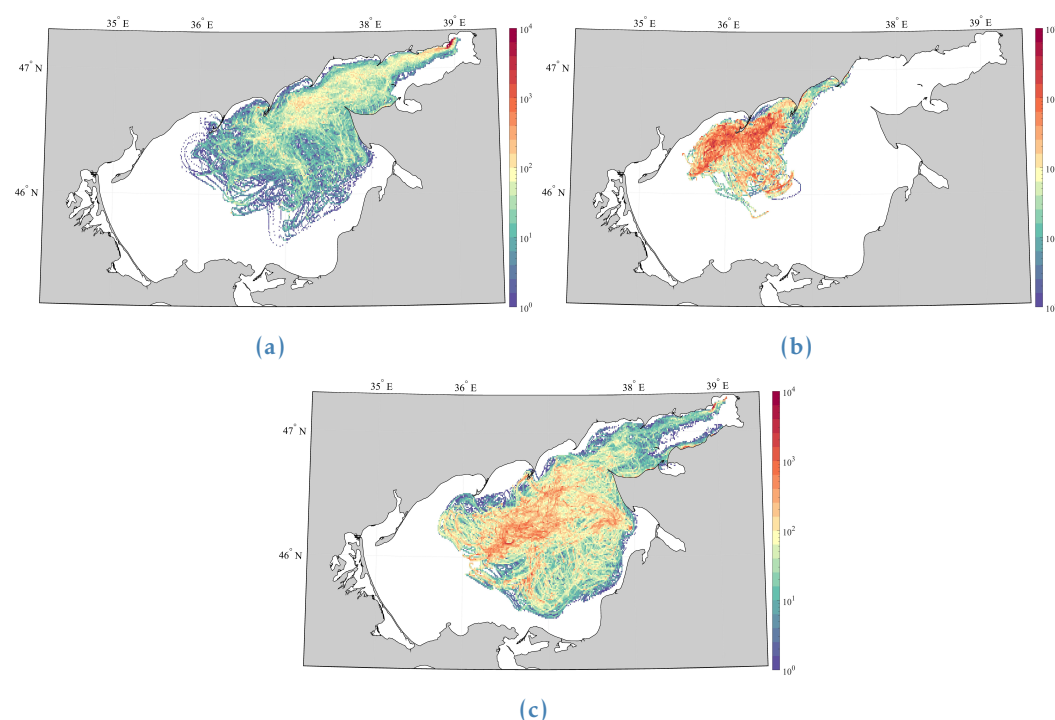


Figure 4. Spatial distribution of the number of particles released in the “Taganrog” (a), “Mariupol” (b), and “Don” (c) segments on the final day of the count (December 30, 2020). Colors indicate the number of particles per $0.01^\circ \times 0.01^\circ$ grid cell in latitude and longitude. The scale is logarithmic.

Figure 4a shows the spatial distribution of particles released in the “Taganrog” area and tracked until December 30, 2020. In other words, this is the result of Lagrangian particle transport modeling, allowing assessment of zones of concentration and dispersion. The particles are widely dispersed across the northern and central parts of the sea, with maximum concentrations along the northern coast, particularly in the northeastern corner. The southern coast, near the exit to the Kerch Strait, exhibits significantly lower particle accumulation. The highest concentration of virtual particles, simulating pollution, occurs in the northeastern part of the sea (red shades, $\sim 10^4$ particles per cell). The central area is shown in yellow-green tones, corresponding to moderate values ($\sim 10^2$ – 10^3 particles). Dark blue and purple regions (low values, ~ 1 – 10 particles) characterize peripheral and distant areas. High-concentration zones coincide with areas likely influenced by small eddies or confined outflows, creating stagnation zones. The central part of the sea demonstrates wide dispersion, indicating active currents and mixing. The northeastern concentration may be related to coastal circulation and the local hydrological configuration.

Figure 4b shows a map of the Sea of Azov with the results of Lagrangian modeling of particle transport, released from the “Mariupol” segment. The color scale represents the number of particles entering each $0.01^\circ \times 0.01^\circ$ grid cell in latitude and longitude (a density mask of daily trajectory traces). It can be seen that the main accumulation of particles is located in the central and northeastern parts of the sea, where the color scale reaches maximum values, indicating the most probable zones of transported material accumulation. The particle trail is elongated roughly in a west–east direction, bending toward the northeast, reflecting the prevailing current/wind drift during the simulation period. Along the southern edge of the sea and near the western coast, particle density is noticeably lower, interpreted as areas that particles from the Mariupol region rarely reach during the considered period. Figure 4b allows assessment of potential accumulation zones of pollutants or floating objects released near Mariupol, as well as the influence of large-scale circulation and wind drift on their transport.

Figure 4c shows a map of the Sea of Azov with the results of Lagrangian modeling of particle transport, released from the “Don” segment. It can be seen that the highest particle density, representing pollution, occurs in the central and northeastern parts of the sea, indicating the main accumulation area of material originating from the Don River estuary. A pronounced elongated tongue of elevated values is visible along the northeastern coast toward the Kerch Strait, reflecting the predominant transport pathway driven by large-scale circulation and wind drift. Along the western and southern coasts, particle density is significantly lower, indicating a lower probability of particles reaching these areas during the considered integration period. The map in Figure 4c effectively represents a probabilistic field of the final positions of Don River discharge particles. The configuration of the accumulation zone highlights the important role of the northeastern current and winter winds, which transport water from the Don estuary into the central sea area and further eastward.

Figure 5a shows a graph of the number of particles that passed from the “Taganrog” area through the segment connecting the Belosarayskaya and Dolzhanskaya spits (the boundary of Taganrog Bay) during the period from January 1 to September 30, 2020. The figure demonstrates that until day 22, the number of particles is close to zero, reflecting the time required for the first trajectories to reach the bay’s boundary. From day 22 onward, a steady increase begins, followed by stepwise growth with fluctuations, reaching approximately 9–11 thousand particles by the end of the period. This indicates that by the end of the simulation, a significant portion of particles released from “Taganrog” reach the Belosarayskaya–Dolzhanskaya line. The observed trend quantitatively characterizes the Lagrangian transport process of passive particles simulating pollution from Taganrog Bay. The modeling results confirm the presence of a time lag between particle release and the onset of their exit beyond the bay’s boundary. The graph also indicates that the fraction of particles leaving the bay daily relative to the total number released is small, emphasizing the cumulative nature of pollution accumulation in Taganrog Bay.

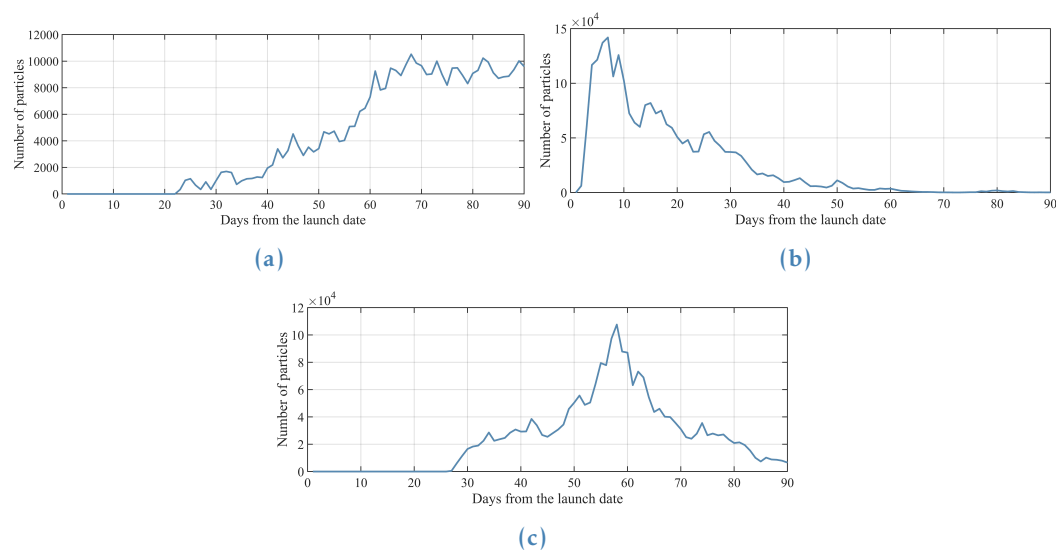


Figure 5. Distribution of the number of particles over travel time from the moment of release (10,000 particles released daily from January 1 to September 30, 2020) from the “Taganrog” (a), “Mariupol” (b), and “Don” (c) segments to the segment connecting the Belosarayskaya and Dolzhanskaya spits (the boundary of Taganrog Bay).

Figure 5b presents the dynamics of the number of particles reaching the conditional line connecting the Belosarayskaya and Dolzhanskaya spits, released daily from January 1 to September 30, 2020, in the “Mariupol” area. The graph shows that the main arrivals of particles at the designated boundary occur within the first 15–20 days after release. During this interval, two pronounced peaks are observed: the first within the first 5–7 days, and the second around days 10–12. This distribution structure indicates the existence of multiple transport mechanisms, likely associated with different wind events, local jet currents, and the circulation of Taganrog Bay. After day 20, the number of particles reaching the boundary sharply decreases, reflecting the decay of the main transport pulse from the source. Between days 20 and 40, only weak episodic arrivals of particles persist, probably linked to slower pathways or retention within local vortex structures. Starting from approximately day 50, the contribution becomes nearly zero, indicating the limited ability of particles released in the Mariupol area to persist in circulation for a long time and reach the outlet of Taganrog Bay.

Figure 5c shows the distribution of the number of particles reaching the line connecting the Belosarayskaya and Dolzhanskaya spits (the boundary of Taganrog Bay), released daily from January 1 to September 30, 2020, at the mouth of the Don River. The blue color indicates the absolute number of particles. The graphs demonstrate a substantially different dynamics compared to particles released in the Mariupol area (see Figure 5b). At the beginning of the time series, up to approximately 25 days after release, the number of particles reaching the boundary is close to zero. This reflects the characteristic hydrodynamic situation in Taganrog Bay, where water entering from the Don estuary is initially retained by the internal circulation and significantly slowed due to shallow depths, weak currents, and the dominant influence of wind forcing. After roughly 30 days, a gradual increase in particle numbers begins, continuing until around 50–55 days. This indicates that particles released in the Don area start leaving the bay only after a long period, passing through regions of complex circulation, including potential stagnation zones and vortex structures in the central part of the bay. The most pronounced peak occurs between 55–60 days, when the maximum number of particles (approximately $1.0\text{--}1.2 \times 10^5$) reaches the boundary. This confirms that the main mass of water transported from the Don estuary exits the bay with a characteristic delay of about two months. The subsequent dynamics is characterized by a gradual decrease in particle numbers with several local secondary maxima, which may reflect changes in wind conditions and seasonal reorganization of the circulation, particularly the strengthening of the autumn current system.

Figure 6 shows the distribution of the normalized percentage of particles reaching the boundary of Taganrog Bay as a function of time elapsed since their release from three regions: Taganrog, Mariupol, and the Don estuary. The graphs reveal pronounced differences in particle transport dynamics, reflecting the characteristics of local circulation and hydrometeorological conditions. For particles released in the Taganrog area, the transport exhibits the smoothest and most inertial behavior. The first arrivals occur around day 22, and the subsequent distribution remains stable without pronounced peaks. Particle arrival continues up to day 90, maintaining a level of about 1.5–2%. This indicates prolonged retention of water masses in Taganrog Bay and the presence of stable but comparatively slow pathways of export. Particles released in the Mariupol area show the fastest and most impulsive response: a pronounced peak (up to 6–7%) is observed already within 5–10 days, indicating the presence of a direct and dynamically active transport corridor in the central part of the Sea of Azov. After this period, the intensity of particle arrivals rapidly decreases and reaches a minimum around days 25–30. This behavior reflects the dominance of short-term export episodes, mainly associated with persistent alongshore currents. For particles released at the Don estuary, transport is characterized by pronounced seasonality. The first arrivals are recorded only after about 25–30 days, reflecting the prolonged retention of water masses in the upper part of the bay and weak winter circulation. The maximum peak (around 2.5–3%) occurs between days 50–60, corresponding to periods of increased Don River discharge and spring circulation reorganization. Subsequent dynamics show a gradual decline, but particles continue to be present throughout the observation period, reflecting the influence of seasonally modulated hydrodynamic processes. Thus, the analysis demonstrates that the three regions differ significantly in the temporal scale and structure of transport: Mariupol is a source of rapid and impulsive input, the Don estuary exhibits seasonally driven transport, and Taganrog shows the slowest but most stable export. These differences reflect the heterogeneity of hydrodynamic conditions across the Sea of Azov and confirm the existence of multiple transport regimes shaped by local circulation, wind dynamics, and river discharge.

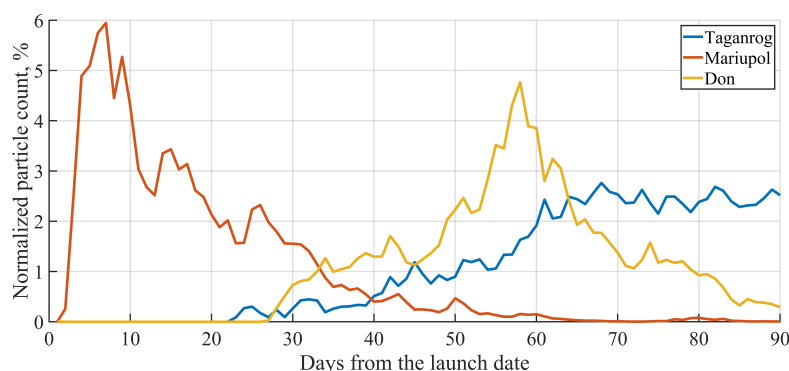


Figure 6. Distribution in % of the number of particles by travel time from their launch (10,000 particles daily from January 1 to September 30, 2020) from the “Taganrog”, “Mariupol”, and “Don” segments to the segment connecting the Belosarayskaya and Dolzhanskaya spits. Normalization is performed based on the total number of particles that reached the border of the Taganrog Bay.

Figure 7a shows the distribution of the number of particles by their arrival dates from the “Taganrog” segment to the boundary of Taganrog Bay (the line connecting the Belosarayskaya and Dolzhanskaya spits). The graph demonstrates pronounced irregularity in particle arrivals, characterized by a series of short-term but intense peaks. The largest peaks occur in the spring (March–April), when the number of particles reaching the boundary reaches its annual maximum. This indicates enhanced water export from Taganrog Bay toward the central part of the Sea of Azov, associated with seasonal changes in circulation, including the spring increase in river discharge and reorganization of wind patterns. The summer months are characterized by more frequent but less pronounced transport events, reflecting the increased role of local wind forcing and strengthening

stratification, which may suppress vertical mixing processes. In autumn, significant peaks reappear, consistent with the intensification of autumn–winter storms and the breakdown of summer stratification, which promotes enhanced transport of water masses. Particle arrivals are concentrated in several clearly defined periods: late March–early April, isolated episodes in May, and the autumn period (September–October). During the winter months (January–February) and summer (June–August), particle export is almost absent. This indicates a strong dependence of particle transport from the Taganrog release segment on seasonal wind conditions and circulation changes in the bay. During winter months (January–February) the export of particles is minimal, while the largest transport events occur in early spring. Such seasonal behavior may also be associated with the regional ice regime of the Sea of Azov. Although ice conditions were not explicitly included in the hydrodynamic model, the winter ice cover typical for Taganrog Bay can substantially limit water exchange, whereas the spring ice breakup may contribute to the release of accumulated water masses. Therefore, the observed spring peaks in particle arrivals are consistent with the known seasonal cycle of ice formation and melting in the region.

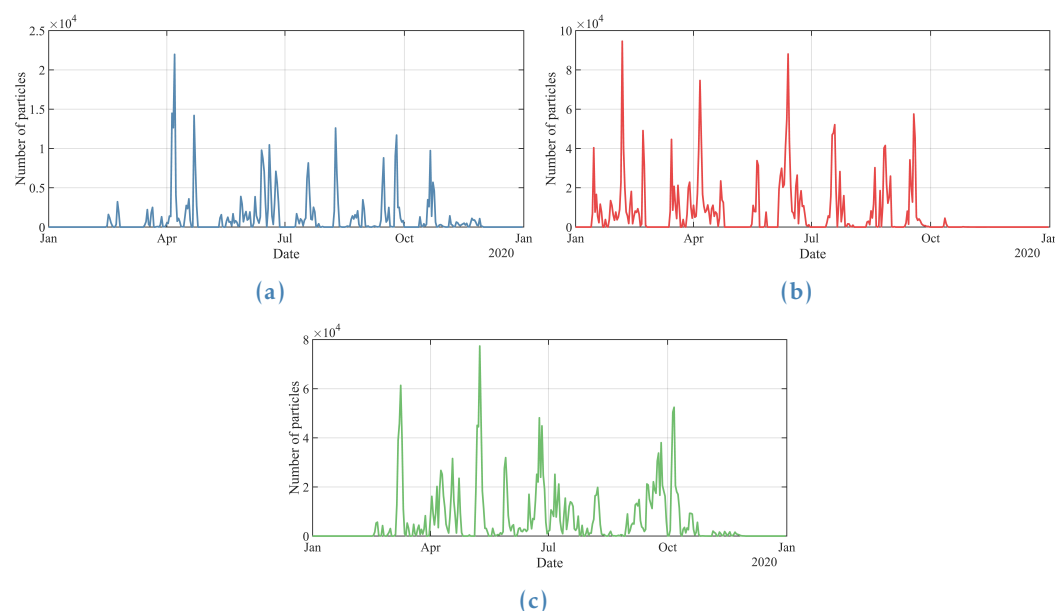


Figure 7. Distribution of the number of particles by arrival dates from the “Taganrog”, “Mariupol”, and “Don” segments to the border of the Taganrog Bay (the segment connecting the Belosarayskaya and Dolzhanskaya spits).

Figure 7b shows the temporal variability of the number of particles arriving at the boundary of Taganrog Bay from the “Mariupol” segment during 2020. The time series is characterized by pronounced episodicity, alternating periods of intense inflow with intervals of almost complete absence. Several major peaks are observed throughout the year, but their intensity and frequency exhibit clear seasonal variation. During winter, only occasional minor peaks occur, indicating a weak contribution of circulation processes to particle transport toward the bay. With the onset of spring (March–April), the volume of incoming particles sharply increases: numerous high-amplitude peaks appear on the graph, associated with intensified wind forcing, reorganization of general circulation in the northeastern part of the Sea of Azov, and increased dynamical activity of water masses. In summer, an even more consistent series of significant peaks is observed, including one of the largest peaks in mid-season. This reflects the high non-stationarity of circulation and the enhanced role of wind forcing, typical for the summer period. In autumn, the amplitude of events remains significant, but their frequency gradually decreases, corresponding to the seasonal weakening of surface currents and changes in stratification structure. The complete cessation of particle arrivals toward winter highlights the seasonal nature of exchange processes between the Mariupol release segment and Taganrog Bay. Overall, the

results indicate that the contribution of this segment to the export of water masses from Taganrog Bay is primarily determined by short-term, intense transport events driven by a combination of wind dynamics, local circulation features, and seasonal reorganization of the hydrological regime in the Sea of Azov.

The graph in Figure 7c illustrates the seasonal variability of particle transport from the Don River outflow beyond Taganrog Bay. The x -axis shows calendar dates in 2020, while the y -axis represents the daily number of particles crossing the bay boundary (the segment connecting the Belosarayskaya and Dolzhanskaya spits). Maximum values reach approximately 8×10^4 particles per day. During winter and early spring, particle flux is low; however, by March–April, the first pronounced peaks appear, likely associated with intensified wind forcing and river discharge. The most intensive transport occurs in April–May and early summer, forming a series of peaks of varying amplitude, indicating the heterogeneous, pulsed nature of the transport. During summer and early autumn, significant variability persists, while toward the end of the year, the daily number of particles gradually decreases to nearly zero. Thus, the distribution of particle arrivals over time demonstrates that the export of water masses associated with the Don River exhibits a pronounced seasonal pattern, alternating periods of enhanced and reduced transport. This highlights the important role of wind variability and Sea of Azov circulation in shaping the temporal structure of river water dispersion and associated pollutants.

Figure 8 illustrates the temporal distribution of the normalized number of particles reaching the boundary of Taganrog Bay (the segment connecting the Belosarayskaya and Dolzhanskaya spits) for three release segments: “Taganrog” (blue), “Mariupol” (red), and “Don” (green). The x -axis shows calendar dates in 2020, while the y -axis represents the percentage of particles arriving on a given day relative to the total number of particles that reached the boundary over the entire integration period. For all three sources, the particle flux to the bay boundary is highly non-stationary and “pulsed”, occurring in discrete episodes with narrow peaks. This structure in the time series is most likely caused by particle interactions with meso- and submesoscale eddy structures, which create quasi-discrete transport corridors and determine the timing of particle arrivals at the bay boundary. The most pronounced transport events generally occur in spring and autumn, when peak daily values may reach 4–6%. Summer peaks are also present and, in some cases, comparable in magnitude. During winter and midsummer, the daily contribution from each source is typically smaller; however, this pattern is partly related to the experimental setup, since markers released from more distant sources (Don and Taganrog) require additional time to reach the bay boundary compared to those originating near Mariupol. The temporal patterns differ between the release areas: particles from “Taganrog” produce earlier and higher-amplitude spring peaks, while “Mariupol” and “Don” contribute more significantly at later dates; periods of enhanced particle arrival from different sources often do not coincide or are partially shifted relative to each other. Thus, Figure 8 demonstrates that the contribution of individual release segments to the particle flux across the bay boundary exhibits pronounced seasonal and episodic variability. It should be noted that the timing of these peaks depends not only on circulation variability but also on the distance between the release segments and the bay boundary, which determines the advection time required for markers to reach the control section. Although all trajectories cross the same monitored boundary, the periods of maximum influence from the Don outflow, the coastal zone near Taganrog, and the Mariupol area do not substantially coincide. This highlights the determining role of short-term changes in wind forcing and local circulation in modulating the direction and intensity of particle transport, including potential anthropogenic pollutants, between the upper and central parts of the Sea of Azov.

3.2. Validation of the Spatiotemporal Distribution of Particles

Figure 9 shows the seasonal variability of CDOM based on MODIS data from 2000 to 2024. Each year in the figure is represented by four separate maps corresponding to winter, spring, summer, and autumn, allowing the spatiotemporal features of CDOM distribution to be tracked across different seasons.

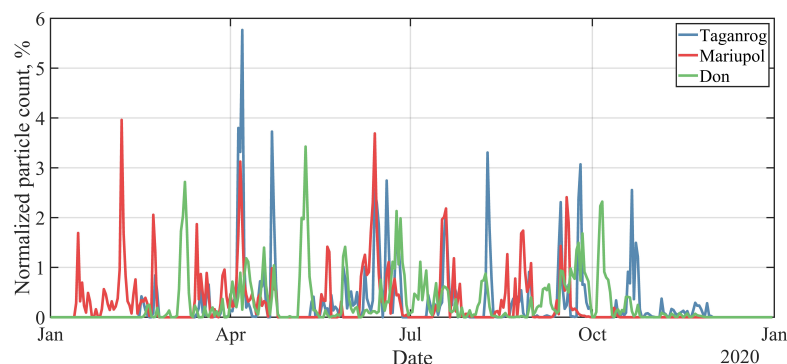


Figure 8. Distribution of the number of particles in % by their arrival dates from the segment during transit since their launch (10,000 particles daily from January 1 to September 30, 2020) from the “Taganrog”, “Mariupol”, and “Don” segments to the segment connecting the Belosarayskaya and Dolzhanskaya spits. Normalization is performed based on the total number of particles that reached the border of the Taganrog Bay.

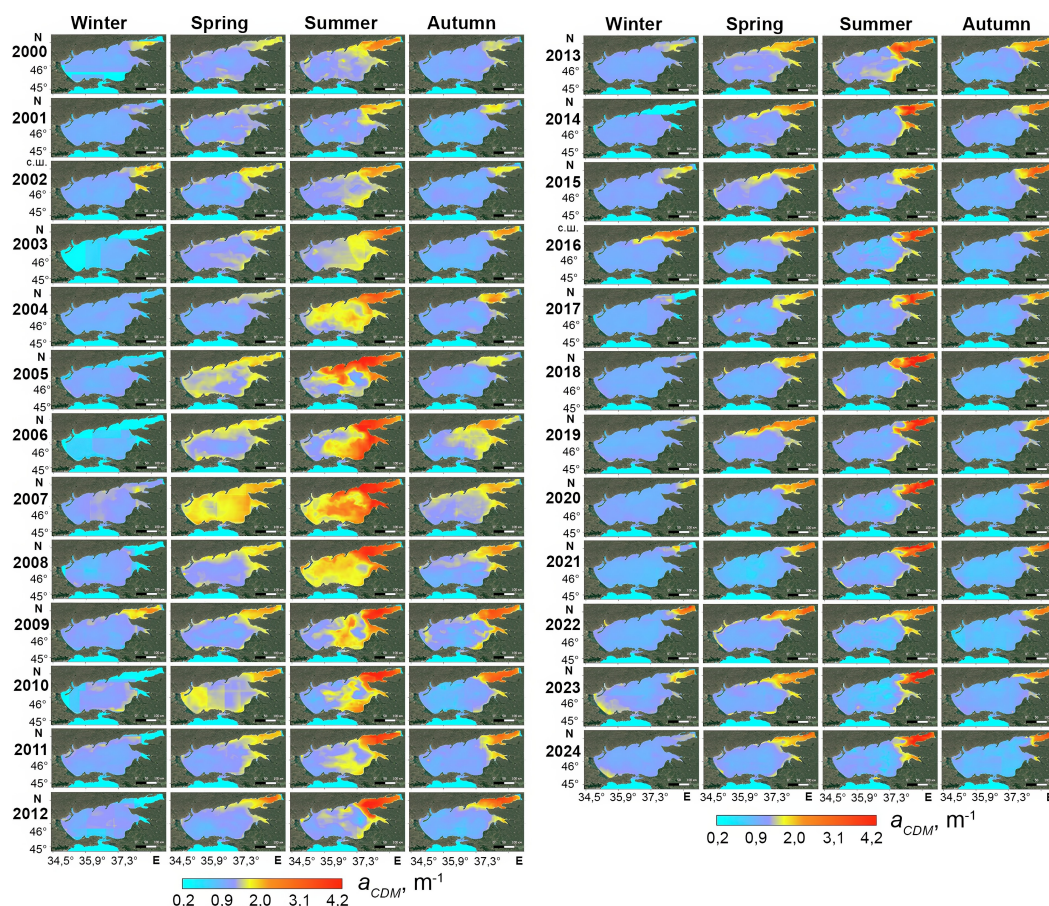


Figure 9. Seasonal maps of CDOM in the surface layer of the Sea of Azov according to MODIS data for the period 2000–2024.

CDOM is a complex of naturally occurring organic compounds dissolved in water, capable of absorbing ultraviolet and visible radiation, giving the water its characteristic coloration. These compounds serve as markers of freshwater input and the decomposition of marine primary production. The spatial distribution of CDOM in coastal and open-sea areas is largely determined by the characteristics of hydrodynamic circulation: currents, frontal zones, and mesoscale eddies. Flows generated by wind and river discharge transport dissolved organic matter from river mouths toward the open sea, where it gradually dilutes

and undergoes photochemical degradation. As a result, a clear relationship is observed between CDOM fields and water mass dynamics – elevated concentrations correspond to zones influenced by river discharge and coastal currents, while lower values are found in regions of intensive exchange and upwelling. As seen in Figure 9, the lowest CDOM concentrations over the entire observation period occur in winter, due to ice cover reducing the input of organic matter.

In the Taganrog Bay and adjacent areas of the Sea of Azov, the spatial distribution of CDOM is closely linked to circulation patterns and the hydrological regime [Prants *et al.*, 2023; Suslin *et al.*, 2020]. The main source of dissolved organic matter is river discharge, primarily from the Don River, which contributes a significant amount of humic compounds. Under the influence of wind-driven circulation and density gradients, outflow currents develop, directed from Taganrog Bay toward the central part of the sea, leading to the spread of elevated CDOM concentrations along the bay axis and into adjacent waters. During periods of persistent east and northeast winds, the export of river waters is enhanced, accompanied by an expansion of the area with high CDOM values. In contrast, under westerly winds, a retention circulation regime forms, promoting the accumulation of organic matter in coastal areas.

The CDOM distribution indicates a pronounced contrast between Taganrog Bay and the central Sea of Azov (Figure 9). These elevated values persist consistently from year to year, with a pronounced gradient between the bay and the open sea: waters of Taganrog Bay are almost always more enriched in colored dissolved organic matter compared to the rest of the Sea of Azov. In the central part of the sea, CDOM levels are relatively low and, on most maps, isolated from Taganrog Bay. This spatial separation confirms that pollution associated with the inflow of colored dissolved substances, primarily from rivers into Taganrog Bay, is largely retained within this water body. Further export of contaminated waters into the open sea is limited, partly due to the characteristics of local currents, circulation in the central Sea of Azov, and restricted exchange through the Dolzhansky Strait. This indicates the isolating role of hydrological processes that prevent the export of pollution beyond Taganrog Bay and emphasizes the importance of this area as a repository for organic matter. The Dolzhansky Strait acts as a hydrodynamic “filter”, limiting the exchange of water masses between the central part of the sea and Taganrog Bay. Thus, the spatial variability of CDOM reflects the dynamics of water exchange between Taganrog Bay and the open Sea of Azov, as well as the seasonal effects of wind and river inputs.

The observed CDOM pattern suggests limited water exchange between Taganrog Bay and the central Sea of Azov. For a more detailed quantitative analysis of transport processes and to assess the degree of isolation of the bay, a Lagrangian analysis of the dispersion of passive markers simulating the behavior of dissolved substances was carried out.

The Lagrangian analysis shows that only a small portion of the particles released in the bay reach the control boundary, confirming its hydrodynamic isolation. Only a fraction of the particles reached the control boundary, mainly from the Don estuary area. For Taganrog, the proportion of markers reaching the boundary was significantly lower, indicating limited water exchange between the inner part of Taganrog Bay and the main Sea of Azov basin.

4. Discussion

The water exchange between Taganrog Bay and the Sea of Azov is highly variable and is predominantly determined by wind conditions. The results obtained in this study are consistent with the findings of [Simov *et al.*, 2013], which demonstrated the dominant role of wind-driven setup and set-down processes in the export of fresh, eutrophic, and polluted waters to the central part of the Sea of Azov. This is also consistent with the studies of [Matishov and Grigorenko, 2020, 2021], in which, on the basis of instrumental measurements, the drift nature of the currents in the Sea of Azov was confirmed. Together, these findings highlight that wind-induced circulation plays a key role in the periodic intrusion of saline waters into Taganrog Bay, thereby influencing its hydrological regime.

Lagrangian analysis revealed pronounced heterogeneity of transport pathways, as well as the presence of stable retention and accumulation zones for pollutants. For particles released to simulate pollution sources in the ports of Taganrog and Mariupol, as well as in the Don River estuary, characteristic migration routes were identified: some markers are rapidly transported to the central part of the sea, while a significant portion circulates within the bay, forming local areas of elevated concentration. These results are consistent with the understanding of high anthropogenic pressure in the Taganrog Bay area [Bufetova, 2019; Bufetova and Bufetov, 2019; Kreneva et al., 2008] and confirm the key role of port areas and river discharge as primary sources of pollution [Kulik et al., 2019].

The most intense export of pollutants occurs during the spring period. The results demonstrate pronounced seasonal pulses of transport, with minimal particle export during winter months and several strong export events in spring. This behavior is primarily related to seasonal changes in circulation and wind forcing. It may also be consistent with the regional ice regime of the Sea of Azov, where winter ice cover can limit water exchange and the spring breakup period may favor the release of accumulated water masses [Kreneva et al., 2008; Kulik et al., 2019; Ogorodov et al., 2020; Yaitskaya and Magaeva, 2018]. However, the ice conditions were not explicitly included in the model and therefore their influence should be considered as a possible explanatory factor rather than a direct modeling result.

The distribution of marker trajectories demonstrates the dependence of transport on local circulation and the characteristics of shallow bathymetry. In the narrow section of the Dolzhansky Strait, zones are formed that limit the export of some particles, whereas under east and northeast wind conditions, rapid and directed transport of pollutants into the central part of the sea occurs. The pronounced episodicity of particle arrival, manifested as narrow, scattered peaks in the time series, indicates that transport from different areas of the water body is primarily controlled by meso- and submesoscale vortex dynamics. Vortical structures, by forming and breaking quasi-discrete transport corridors, determine the moments when particles can be effectively exported to the boundary of Taganrog Bay. As a result, even under a constant background flow, the actual export acquires a pulsed, episodic character, reflecting the uneven interaction of particles with variable vortex formations. This mechanism emphasizes the importance of accounting for vortex activity when analyzing the transport of natural and anthropogenic pollutants in waters with high dynamic heterogeneity [Budyansky et al., 2024, 2025a,b].

Areas with elevated marker density can be considered as potential zones of ecological risk. Their formation is associated with persistent low-velocity currents, orbital circulation structures, and coastal configuration features. These regions can act as local accumulators of pollutants, including heavy metals, petroleum products, and organic compounds. Seasonal variability of circulation determines the temporal scales of transport. During the summer, more stable circulation dominates, ensuring gradual dispersion of pollutants, whereas during periods of storm activity in autumn and winter, the direction and speed of transport can change significantly.

The application of MODIS satellite data (2000–2024) corroborates the correlation between the distribution of dissolved organic matter and key hydrodynamic processes [Shul'ga and Suslin, 2018]. Observed zones of elevated chromophoric dissolved organic matter (CDOM) concentrations correspond to regions where Lagrangian markers exhibit the highest density. During the summer seasons of specific years, the spatial distribution patterns of CDOM fields are in high agreement with the marker transport trajectories derived from Lagrangian modeling. These findings demonstrate the feasibility of employing Lagrangian modeling for the prediction of transport dynamics within the Sea of Azov.

5. Conclusion

This study confirms that Taganrog Bay acts as a key donor of potential pollution to the Sea of Azov. The transport of anthropogenic pollutants is not uniform but is governed by a complex interplay of wind-driven circulation, seasonal variability, and mesoscale vortex dynamics. Using Lagrangian analysis based on the POM model, we identified the main

transport pathways, retention zones, and temporal scales of pollutant export. The most intense export occurs in spring, while winter ice cover (though not explicitly modeled) likely limits exchange. Vortex structures create episodic, pulse-like transport corridors, meaning that even under a steady background flow, pollution reaches the open sea in discrete bursts rather than continuously.

For future research and practice, the developed Lagrangian approach offers a powerful tool for predictive modeling, ecological risk assessment (especially for fishing areas), and emergency response planning. We recommend explicitly incorporating ice dynamics and high-resolution submesoscale processes into future models, as well as validating transport predictions with in situ measurements of heavy metals and organic pollutants. Reducing anthropogenic pressure on the Sea of Azov ecosystem requires targeted monitoring of the identified accumulation zones and pollution sources in the ports of Taganrog, Mariupol, and the Don River estuary.

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References

- Blumberg A. F. and Mellor G. L. A description of a three-dimensional coastal ocean circulation model // Three-Dimensional Coastal Ocean Models. — Washington : American Geophysical Union, 1987. — P. 1–16. — <https://doi.org/10.1029/co004p0001>
- Budyansky M. V., Belonenko T. V., Lebedeva M. A., et al. Surface transport of technical waters from Fukushima NPP to the South Kuril fishing zone // Russian Journal of Earth Sciences. — 2024. — Vol. 24. — ES4002. — <https://doi.org/10.2205/2024es000934>
- Budyansky M. V., Goryachev V. A., Kaplunenko D. D., et al. Role of mesoscale eddies in transport of Fukushima-derived cesium isotopes in the ocean // Deep Sea Research Part I: Oceanographic Research Papers. — 2015. — Vol. 96. — P. 15–27. — <https://doi.org/10.1016/j.dsr.2014.09.007>
- Budyansky M. V., Uleysky M. Y., Fayman P. A., et al. Can contaminated waters from the Fukushima Daiichi NPP penetrate the East China Sea? // Pure and Applied Geophysics. — 2025a. — Vol. 182, no. 4. — P. 1843–1860. — <https://doi.org/10.1007/s00024-025-03688-0>
- Budyansky M. V., Uleysky M. Y., Lebedeva M. A., et al. Potential hazard of radioactive contamination of the marine environment due to possible earthquakes near the Kashiwazaki-Kariwa nuclear power plant // Doklady Earth Sciences. — 2025b. — Vol. 520, no. 1. — <https://doi.org/10.1134/s1028334x24604358>
- Bufetova M. V. Assessment of income and elimination of heavy metals in the Taganrog Bay of the Sea of Azov // Ecological Safety of Coastal and Shelf Zones of Sea. — 2019. — No. 2. — P. 78–85. — <https://doi.org/10.22449/2413-5577-2019-2-78-85> — (In Russian).
- Bufetova M. V. and Bufetov D. O. Assessment of income and elimination of heavy metals in the Taganrog Bay of the Azov Sea // Ecology Economy Informatics. Geoinformation Technologies and Space Monitoring. — 2019. — Vol. 2, no. 4. — P. 192–197. — <https://doi.org/10.23885/2500-123x-2019-2-4-192-197> — (In Russian).

- Churilova T. Ya., Efimova T. V., Moiseeva N. A., et al. Spectral light absorption coefficient of particles and colored dissolved organic matter in the Sea of Azov // *Fundamental and Applied Hydrophysics*. — 2022. — Vol. 15, no. 3. — P. 73–83. — <https://doi.org/10.59887/fpg/ex1p-9vtp-phu8>
- Gitelson A. A., Gurlin D., Moses W. J., et al. A bio-optical algorithm for the remote estimation of the chlorophyll-a concentration in case 2 waters // *Environmental Research Letters*. — 2009. — Vol. 4, no. 4. — P. 045003. — <https://doi.org/10.1088/1748-9326/4/4/045003>
- Ivanov V. A., Cherkesov L. V. and Shul'ga T. Y. Investigation of effects of spatially and temporally variable wind on currents, surges, and admixture spread in the Sea of Azov // *Russian Meteorology and Hydrology*. — 2012. — Vol. 37, no. 8. — P. 553–559. — <https://doi.org/10.3103/s1068373912080079>
- Ivanov V. A., Cherkesov L. V. and Shul'ga T. Y. Dynamic processes and their influence on the transformation of the passive admixture in the sea of Azov // *Oceanology*. — 2014. — Vol. 54, no. 4. — P. 426–434. — <https://doi.org/10.1134/s0001437014030023>
- Ivanov V. A. and Shul'ga T. Ya. Numerical analysis of surge phenomena, currents, and pollution transport in the Sea of Azov // *Doklady Earth Sciences*. — 2018. — Vol. 479, no. 2. — P. 543–546. — <https://doi.org/10.1134/s1028334x18040256>
- Kallos G., Nickovic S., Jovic D., et al. The regional weather forecasting system SKIRON and its capability for forecasting dust up-take and transport // *Proceedings of the WMO conference on dust storms, 1–6 November 1997*. — Damascus, Syria : WMO, 1998. — P. 9–12.
- Kreneva K. V., Svistunova L. D. and Syomin V. L. Evaluation of the ecological state of the Taganrog Bay using a number of characters of microzooplankton and zoobenthos // *The Bulletin of Irkutsk State University. Series Biology. Ecology*. — 2008. — Vol. 1, no. 1. — P. 85–92. — (In Russian).
- Kulik A. K., Vlasenko M. V., Borodichev V. V., et al. Quality assessment of surface waters of the Don River basin for ensuring sustainable functioning of the water industry complex // *PROCEEDINGS of Nizhnevolzhskiy agrouniversity complex science and higher vocational education*. — 2019. — Vol. 2, no. 54. — P. 1–10. — <https://doi.org/10.32786/2071-9485-2019-02-15> — (In Russian).
- Matishov G. G. and Grigorenko K. S. Dynamic Mode of the Azov Sea in Conditions of Salinization // *Doklady Earth Sciences*. — 2020. — Vol. 492, no. 1. — P. 376–381. — <https://doi.org/10.1134/s1028334x20050141>
- Matishov G. G. and Grigorenko K. S. Currents of the Azov Sea during the Don River Low-Water Period // *Oceanology*. — 2021. — Vol. 61, no. 2. — P. 173–182. — <https://doi.org/10.1134/s0001437021020132>
- Mellor G. L. and Yamada T. Development of a turbulence closure model for geophysical fluid problems // *Reviews of Geophysics*. — 1982. — Vol. 20, no. 4. — P. 851–875. — <https://doi.org/10.1029/rg020i004p00851>
- O'Reilly J. E., Maritorena S., Mitchell B. G., et al. Ocean color chlorophyll algorithms for SeaWiFS // *Journal of Geophysical Research: Oceans*. — 1998. — Vol. 103, no. C11. — P. 24937–24953. — <https://doi.org/10.1029/98jc02160>
- Ogorodov S. A., Magaeva A. A., Maznev S. V., et al. Ice features of the Northern Caspian under sea level fluctuations and ice coverage variations // *Geography, Environment, Sustainability*. — 2020. — Vol. 13, no. 3. — P. 129–138. — <https://doi.org/10.24057/2071-9388-2020-77>
- Prants S. V., Budyansky M. V., Fayman P. A., et al. Lagrangian oil spill simulation in Peter the Great Bay (Sea of Japan) with a high-resolution ROMS model // *Pure and Applied Geophysics*. — 2023. — Vol. 180, no. 1. — P. 551–568. — <https://doi.org/10.1007/s00024-022-03197-4>
- Prants S. V., Uleysky M. Yu. and Budyansky M. V. *Lagrangian Oceanography: Large-scale Transport and Mixing in the Ocean*. — Springer International Publishing, 2017. — <https://doi.org/10.1007/978-3-319-53022-2>
- Shul'ga T. Ya. and Suslin V. V. Investigation of the evolution of the suspended solids in the Sea of Azov based on the assimilation of satellite data in a hydrodynamic model // *Fundamental and Applied Hydrophysics*. — 2018. — Vol. 11, no. 3. — P. 73–80. — <https://doi.org/10.7868/s2073667318030097> — (In Russian).
- Simov V. G., Morozov V. I., Fomina I. N., et al. Water exchange between the Taganrog Bay and the Sea of Azov // *Marine Hydrophysical Journal*. — 2013. — No. 4. — P. 73–82. — (In Russian).
- Smagorinsky J. General circulation experiments with the primitive equations: I. The basic experiment // *Monthly Weather Review*. — 1963. — Vol. 91, no. 3. — P. 99–164. — [https://doi.org/10.1175/1520-0493\(1963\)091<0099:gcewtp>2.3.co;2](https://doi.org/10.1175/1520-0493(1963)091<0099:gcewtp>2.3.co;2)
- Suetin V. S., Suslin V. V., Korolev S. N., et al. Analysis of the variability of the optical properties of water in the Black Sea in summer 1998 according to the data of SeaWiFS satellite instrument // *Physical Oceanography*. — 2002. — Vol. 12, no. 6. — P. 331–340. — <https://doi.org/10.1023/a:1021729229168>

- Suslin V. V., Churilova T. Ya., Efimova T. V., et al. Regional bio-optical algorithm for remote estimation of the Sea of Azov's IOPs // 26th International Symposium on Atmospheric and Ocean Optics, Atmospheric Physics. — SPIE, 2020. — P. 34. — <https://doi.org/10.1117/12.2574273>
- Wannawong W., Humphries U. W., Wongwises P., et al. Mathematical modeling of storm surge in three-dimensional primitive equations // International Journal of Computer Mathematics and Sciences. — 2011. — Vol. 5, no. 6. — P. 44–53. — <https://doi.org/10.5281/ZENODO.1062708>
- Yaitskaya N. A. and Magaeva A. A. Dynamics of the ice regime of the Sea of Azov in the XX–XXI centuries // Ice and Snow. — 2018. — Vol. 58, no. 3. — P. 373–386. — <https://doi.org/10.15356/2076-6734-2018-3-373-386> — (In Russian).