

The Study of Pollutants' Pathways in the Caspian Sea by Modeling Lagrangian Trajectories



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Abstract A numerical simulation of 3-D passive tracer trajectories is used to study pollutants pathways in the Caspian Sea. We used the INMOM reanalysis data set representing the state of the Caspian Sea Hydrology to simulate trajectories. We found that upwelling featured to the eastern coast of the Middle Caspian is characterized by vertical particle movement with the order of hundredths mm/s. The vertical motion is modulated with a frequency close to the inertial one. As a result of the passive tracers' trajectories analysis, the features of water exchange in the Middle and Southern Caspian Sea were found. Lagrangian particles move from the western part of the Middle Caspian along the bottom of the Apsheron sill towards the Southern Caspian, rise in the water column and cross the Apsheron sill, and then descend to the deeper layer.

Keywords Lagrangian particle 3-D trajectory modelling · Computational experiment · Inertial waves · Upwelling · The Caspian Sea water exchange

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1 Introduction

The spread of pollutants in the marine environment is an integral part of water exchange processes. Water exchange is a set of physical processes, including advection and mixing of water masses. It leads to the renewal of water masses in an arbitrary sea area. A change in the state of the marine environment in one area of the sea can impact remote areas due to currents influence. This may lead to the transboundary transfer of various pollutants. How the different sea regions are connected and when and along what paths the disturbances propagate are essential questions for many applications. This problem is interdisciplinary and extremely important for water bodies where transboundary impacts are possible.

The chemical composition of the pollutants determines their lifetime in the marine environment. Simultaneously with the spread of the impurity, its physicochemical transformation and biodegradation occur. However, one can consider most marine pollutants as passive impurities. For this reason, the routes of their distribution in the sea are virtually independent of the type of pollutant. One should analyze the possible stable ways of pollutants transport, “rivers” inside the sea, so stable connections between separate sea areas could be specified.

One of the tools for analyzing the transport routes of pollutants in the Caspian Sea on a considerable time scale is the study of Lagrangian trajectories. They were calculated based on reanalysis data of hydrological conditions. In recent decades, modeling of Lagrangian trajectories was used not only at the regional level [6] but also made it possible to determine the connectedness of circulation processes between individual regions of the World Ocean (global conveyor) [7] and even the oceans [8, 9]. The Lagrangian approach makes it possible to trace the “origin” of the water mass, the parameters of which are recorded as a result of observations. A systematized ensemble of the trajectories of tracer particles, plotted on the map, makes it possible to identify the pathways for the transfer of water masses and water exchange between separate areas of the sea.

2 Initial Data and Research Method

We conducted a series of computational experiments to figure out the pathways of pollutants. The initial data for modeling the trajectories of Lagrangian particles were the results of a reanalysis of hydrological fields in the Caspian Sea for 2020, conducted at GOIN with the INMOM model [6]. The CFSR v2 reanalysis data were used for the atmospheric forcing setting [10]. The spatial resolution of the model is 1.5 km, time discreteness of the output array 1 h. The climatic fields of temperature and salinity were used for the model initializing [5]. The experiment consisted in modeling the Lagrangian trajectory of floats of neutral buoyancy, starting their movement at various points of the Caspian Sea. We calculated the trajectories of the floats for two months between May 1 to October 30. For the Lagrangian trajectories

calculation, we used the open-source software OpenDrift, created by the independent research organization SINTEF [7]. The software is designed to calculate Lagrangian trajectories based on hydrological fields and has an advanced visualization system for the resulting data. The authors adapted OpenDrift to use the data fields obtained in the Russian INMOM model. The velocities of Lagrangian particles were found by trilinear interpolation of velocity components from the INMOM model grid to the particle position. We used the implicit Runge–Kutta scheme of the 4th order to integrate the kinematic equation of motion of the tracer particle. The scheme of the experiment involved the calculation of 3-D trajectories of tracer particles, initially located at the nodes of a virtual lattice with dimensions of $5 * 5 * 5$ elements, “immersed” in each of the traditionally distinguished parts of the sea. Figure 1 shows the position of the particles in the projections on the horizontal (a) and vertical (b) projections.

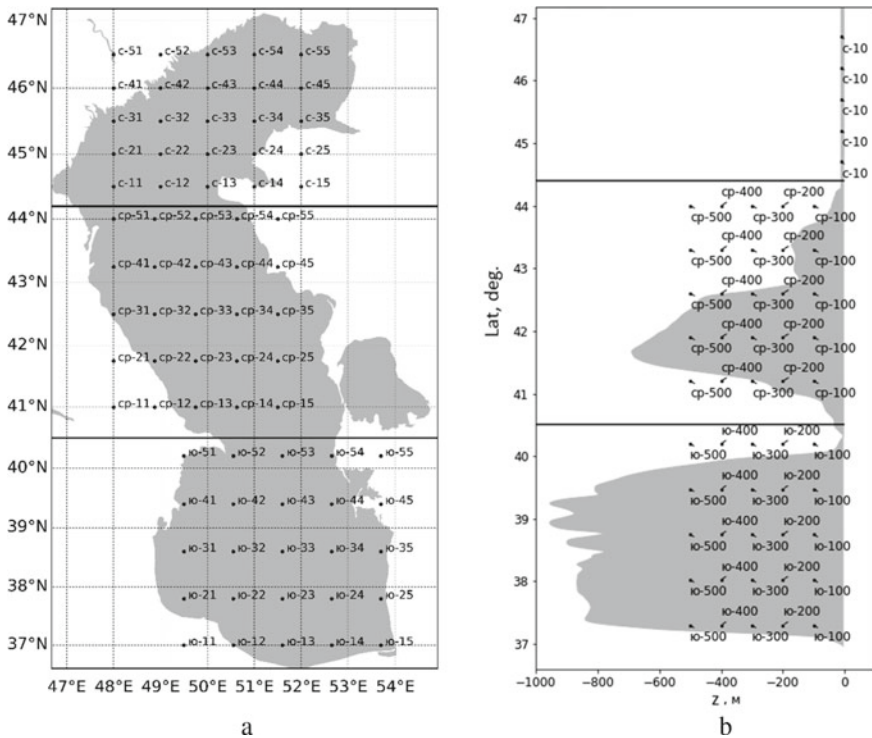


Fig. 1 Diagram of the initial position of particles

3 Results and Discussion

During the implementation of the computational experiment, more than 1000 trajectories of tracer particles were calculated, located in various regions of the Caspian Sea, including deep-water ones in the waters of the Middle and South Caspian. The results obtained in our computational experiments, in general, correspond to the published results of field measurements of deep-water contour currents in the Middle Caspian [1] and calculations using the model of the Hydrometeorological Center of Russia [4] and the results of studying water exchange across the Apsheron threshold [3]. We obtained new results and confirmed the known facts about the circulation in certain parts of the Caspian Sea.

The calculation of the particles' trajectories in the eastern part of the Middle Caspian (Fig. 2) showed that in May–June, deep waters rise from a horizon of 50 m to a horizon of 20 m, which corresponds to the traditional concepts of seasonal upwelling in the eastern part of this sea area. The results of trajectory modeling show that the rise of deep waters occurs at a speed of the order of hundredths of mm/s.

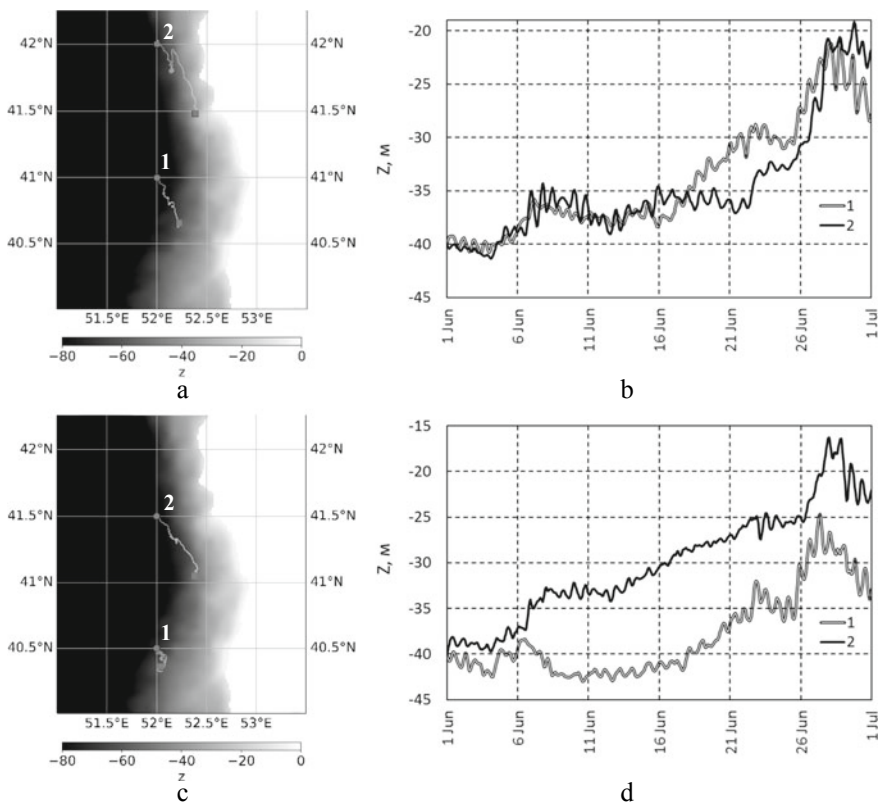


Fig. 2 Trajectories of particles (a, c) and changes in their depth (b, d)

Figure 2b, d shows oscillations of the vertical position of a particle with an amplitude of about 50 cm, the period of which corresponds to the inertial period. Inertial vibrations were noted in the trajectories of tracers released at various depths. The inertial fluctuations, manifested in the change in the value of the vertical coordinate of tracers originating at different depths, were practically in phase, and the value of the correlation coefficient was 0.8.

Another result of our computational experiments is the study of water exchange between the Middle and South Caspian through the Apsheron sill. The book [2] noted the existence of an overflow of the Middle Caspian waters into the South Caspian. The authors associate this phenomenon with the density runoff of cold waters from the northern regions of the sea and the eastern shelf. These waters descend into the bottom layers of the Middle Caspian depression, overflow through the Apsheron sill, and enter the South Caspian depression. As a result of computational experiments, it was found that the transport of tracer particles, starting their movement in the southwestern part of the Middle Caspian at depths of more than 200 m (Fig. 3a), has a direction of propagation in almost all studied periods of the year towards the South Caspian (Fig. 3a, b), with maximal intensity in autumn. As shown in Fig. 3b—the graph of the change in the vertical coordinate versus time—the particles rise as they approach the Apsheron threshold and descend as they move away from it.

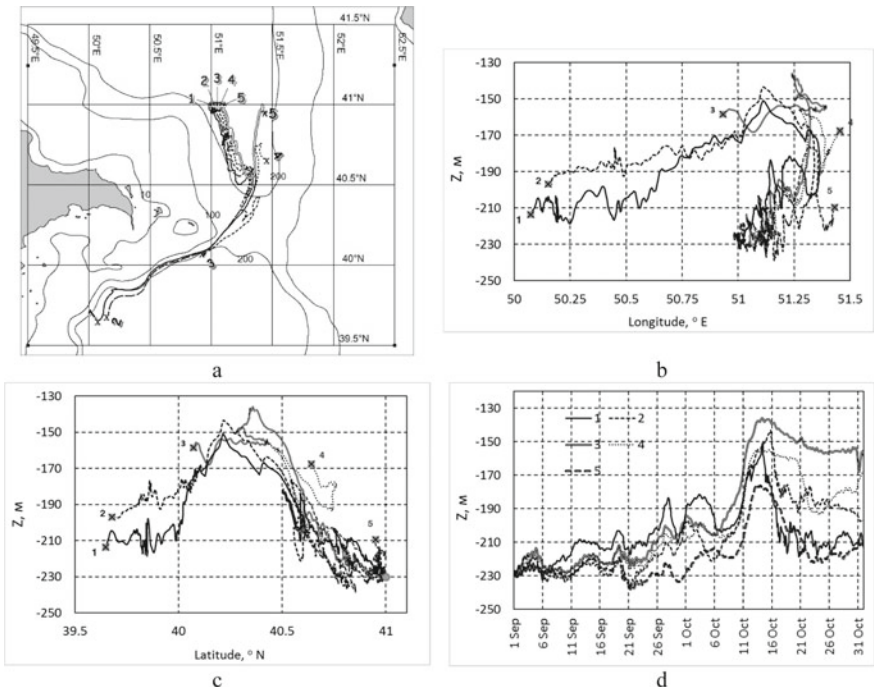


Fig. 3 Trajectories of tracer (a) and time dependence of their coordinates and depth (b, c, d)

The maximum rise of tracers in depth is happening in the area of the Apsheron sill (Fig. 3c, d).

4 Conclusion

Modeling Lagrangian trajectories based on reanalysis of hydrological fields for 2020 made it possible to.

1. estimate the rate of water rise in the upwelling area near the eastern coast of the Middle Caspian,
2. estimate the amplitude of periodic vertical oscillations caused by inertial oscillations,
3. analyze the features of the penetration of deep-water masses of the Middle Caspian into the deep-water part of the South Caspian.

Computational experiments on modeling Lagrangian trajectories were based on calculating the currents of the Caspian Sea with the INMOM model. Any model is a simplified representation of the modeling object. Therefore, the obtained results should be confirmed independently.

The experiments are a part of a planned large-scale project to study the statistical patterns of the distribution of pollutants in the Caspian Sea. We conducted the current study based on a reanalysis of the hydrological fields of the Caspian Sea for a relatively short period, related to a specific 2020 year. In other years, the intensity of hydrometeorological processes may be different, affecting the intensity of transport of deep-water masses. For assessing the interannual variability of the ways of transport of water masses and pollutants, it is necessary to conduct similar studies with preliminary preparation of reanalysis fields of hydrological fields for a representative time interval.

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