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GEOECOLOGY

Assessment of Pollution of the Waters in the South Kuril Fishing Zone of Russia by Radioactive Waters from the Fukushima-1 NPP Based on Lagrangian Modeling

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Abstract—The potential hazard arising from the actions taken by the Japanese government regarding the discharge of technical radioactive water from the Fukushima-1 nuclear power plant storage facilities is studied. The contamination of the South Kuril Fishing Zone (SKFZ), which is one of the most promising fishing areas for the Russian Federation, with radioactive particles is considered. Based on the modeling of transport of passive markers simulating radioactive contamination, the pathways and mechanisms of pollution transfer to the SKFZ are analyzed. This research was conducted using altimetric data on the geostrophic speed for the period from August 24, 2022, to August 24, 2023. The transfer of pollution into the SKFZ is determined by a set of conditions related to the current regime of development of the First Kuroshio Meander and the local vortex system of various signs, both near the discharge site and at the SKFZ boundary. A seasonal dependence of the speed and quantity of infiltration of the polluted water toward the shores of the Russian Federation is established. The possibility of rapid advection of pollution into the SKFZ within 13 days is discovered. This speed is determined by the entrainment of contamination by the Kuroshio Meander and its further transport by the mesoscale vortex system to the SKFZ boundaries. The periodicity in the influx of pollution into the SKFZ is revealed. Graphs showing the distribution of the count of "dirty" markers with respect to the times of their release and the arrival of polluted water at the SKFZ boundary are constructed.

Keywords: Fukushima, radiation, contamination, tritium, South Kuril Fishing Zone, SKFZ, fishing, altimetry, vortex advection, currents

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INTRODUCTION

In March 2011, an earthquake and tsunami in Japan caused an accident at the Fukushima-1 nuclear power plant (NPP) that led to the release of radioactive contamination. Radionuclides entered the ocean as a result of the discharge of contaminated water, precipitation onto the sea surface, and leaching of radioactive elements from the soil [1]. By 2023, over 1.25 million tons of technical radioactive water, which was previously used to cool damaged reactors, had accumulated in large tanks near the NPP due to technological processes aimed at restraining further spread of contamination into the environment.

On August 24, 2023, Japan initiated the process of discharging the accumulated technical water from the NPP into the Pacific Ocean. The discharge takes place 1 km offshore through an underwater tunnel. It is planned that by the end of March 2024, approximately 31200 t of liquid will have been released from the nuclear power plant, and the entire process will last for several decades. The Japanese government asserts that the current situation is under control and that the water discharge poses no threat to the environment and human health. To confirm this view, the Japanese authorities refer to the conclusions made by the experts from the International Atomic Energy Agency.

However, on September 1, 2023, international news agencies reported the first detection of the radioactive tritium isotope at the northeastern border of the port since the start of the water discharge from the Fukushima-1 NPP. The concentration of tritium was measured at 10 Bq/L, while the specified value is 0.1 Bq/L. Tritium is a heavy isotope of hydrogen, a beta-emitter, which is transmitted to fish and other

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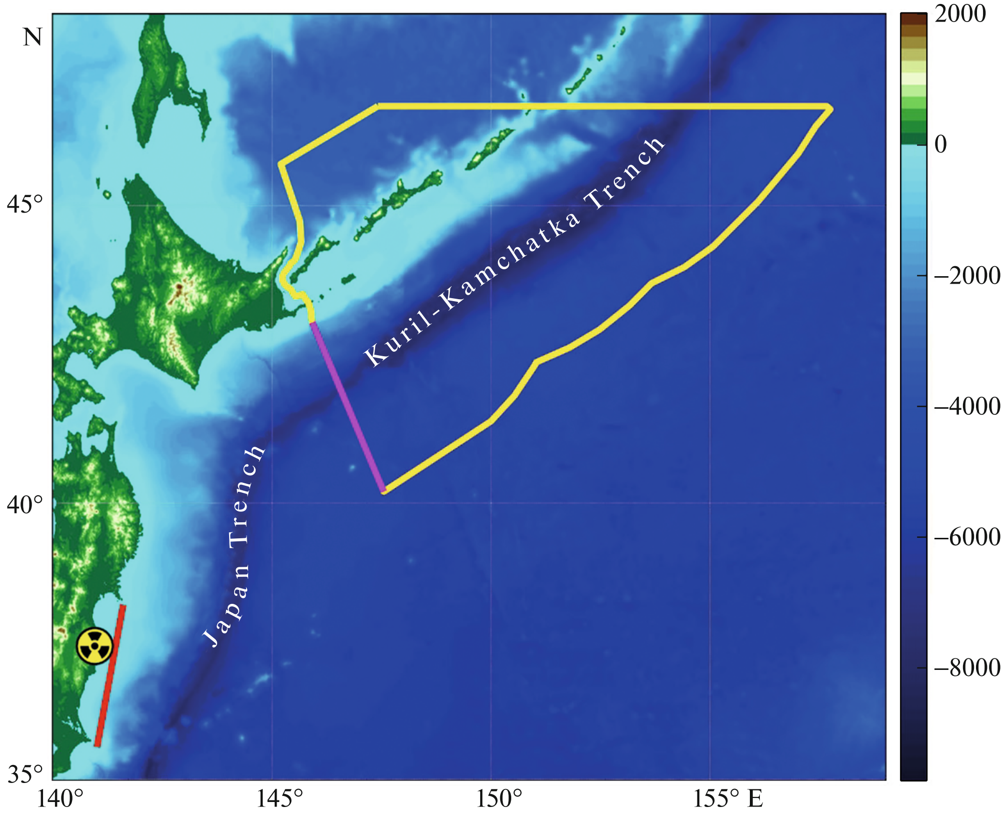

Fig. 1. Study area. The location of the Fukushima-1 NPP (coordinates 37°25′12.0″ N, 141°2′58.0″ E) is indicated by the radiation hazard sign. The yellow line delineates the SKFZ boundaries. The pink segment is the southwestern boundary of the SKFZ. The red segment is the area of release (in Lagrangian analysis in forward time) and entrainment (in Lagrangian analysis in reverse time) of passive markers, simulating pollution. The topography is shown in color. The boundaries of the fishing zone 61.04 (Southern Kuril) are constructed according to Annex no. 1 to the Order of October 21, 2013, no. 385 "On Approval of Fishing Rules for the Far Eastern Fishery Basin."

marine organisms through water contributing to their contamination.

Some experts believe that the discharge of radioactive water from the Fukushima-1 NPP will cause serious consequences for the fishing industry in the Russian Federation, which will result in Russia losing fishing grounds for 150 years.[1] Other scientists state that the contaminated waters will not reach the Russian shores in any case, since the existing system of currents in the region reliably protects the Russian Far East coast from the penetration of radioactive particles.[2] However, these contrary opinions are based on qualitative expert assessments and are not supported by detailed analysis of potential pathways for contaminated particles to reach Russian shores.

To study the issue, we use Lagrangian modeling methods in this work [2–4]. Similar research was conducted immediately after the 2011 accident [1, 5]. It was found that the radioactive water patch spreads eastward of the NPP and is entrained by the Kuroshio current extension. However, the detected effect of entrainment of radionuclides by mesoscale vortices that advect radioactive particles in the Russian coastal waters can be hazardous for living organisms.

In this work, we study the possibility of contamination of the South Kuril Fishing Zone (SKFZ) by the technical water discharged from the Fukushima-1 NPP, which is the aim of this research. The relevance of this study is difficult to overestimate; the SKFZ water area is found within the exclusive economic zone of Russia and is considered to be one of the most promising areas for the fishing industry of the Russian Federation (Fig. 1). This region is rich in diverse marine species, including saury, sardines, mackerel, red cod, flounder, and Pacific salmon, as well as crabs, mollusks, echinoderms, and other marine organisms [6]. Since radioactive particles do not enter instantly into the fishing area from the Fukushima-1 NPP and their entry has a delayed effect, this study focuses on the information about the current system in the region for the year preceding the onset of the dis-

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[1] https://www.gazeta.ru/social/news/2023/09/02/21201482.shtml?updated.

[2] https://www.pnp.ru/in-world/uchenyy-rasskazal-o-posledstviyakh-dlya-rossii-sbrosa-vody-s-fukusimy.html.

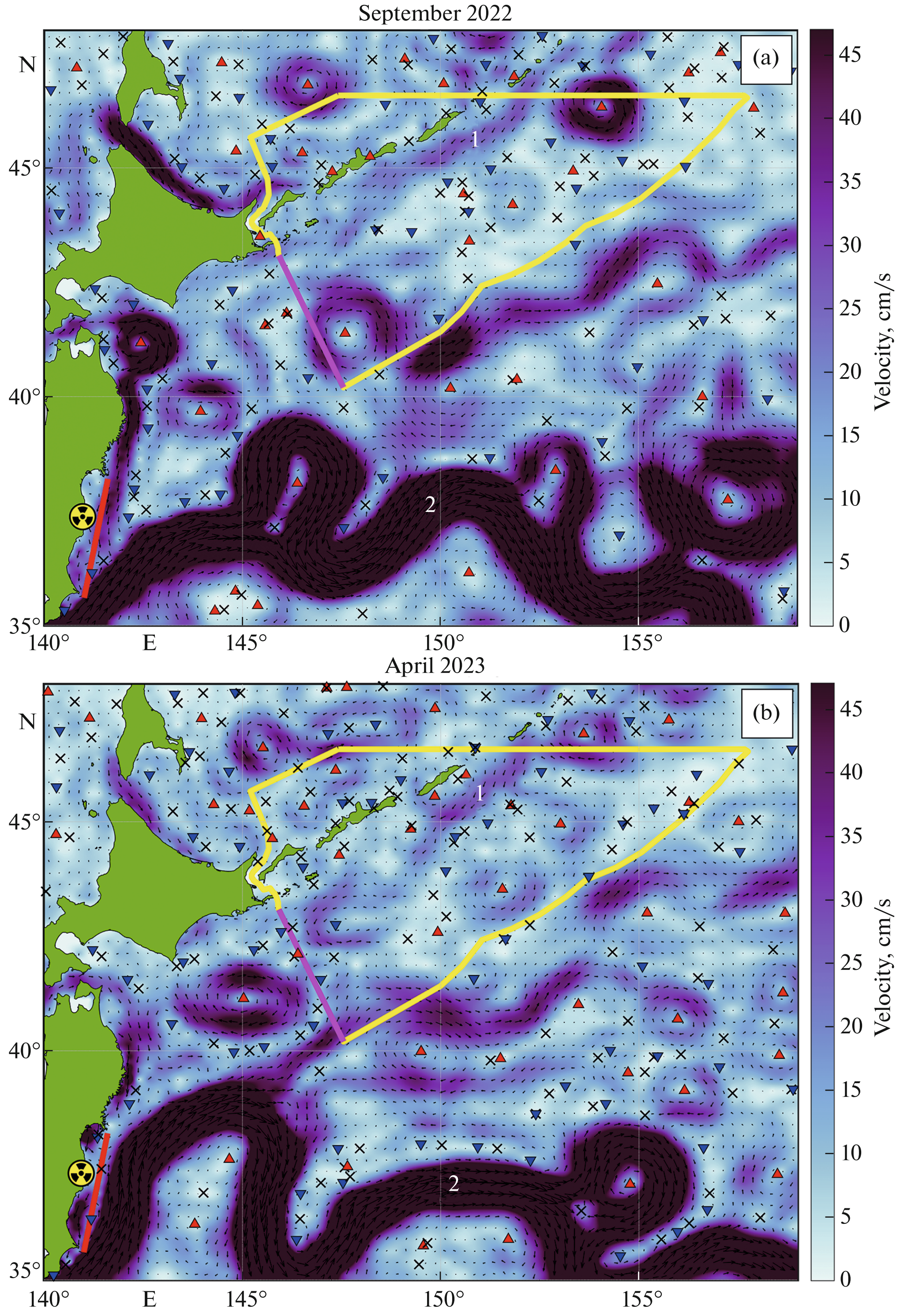
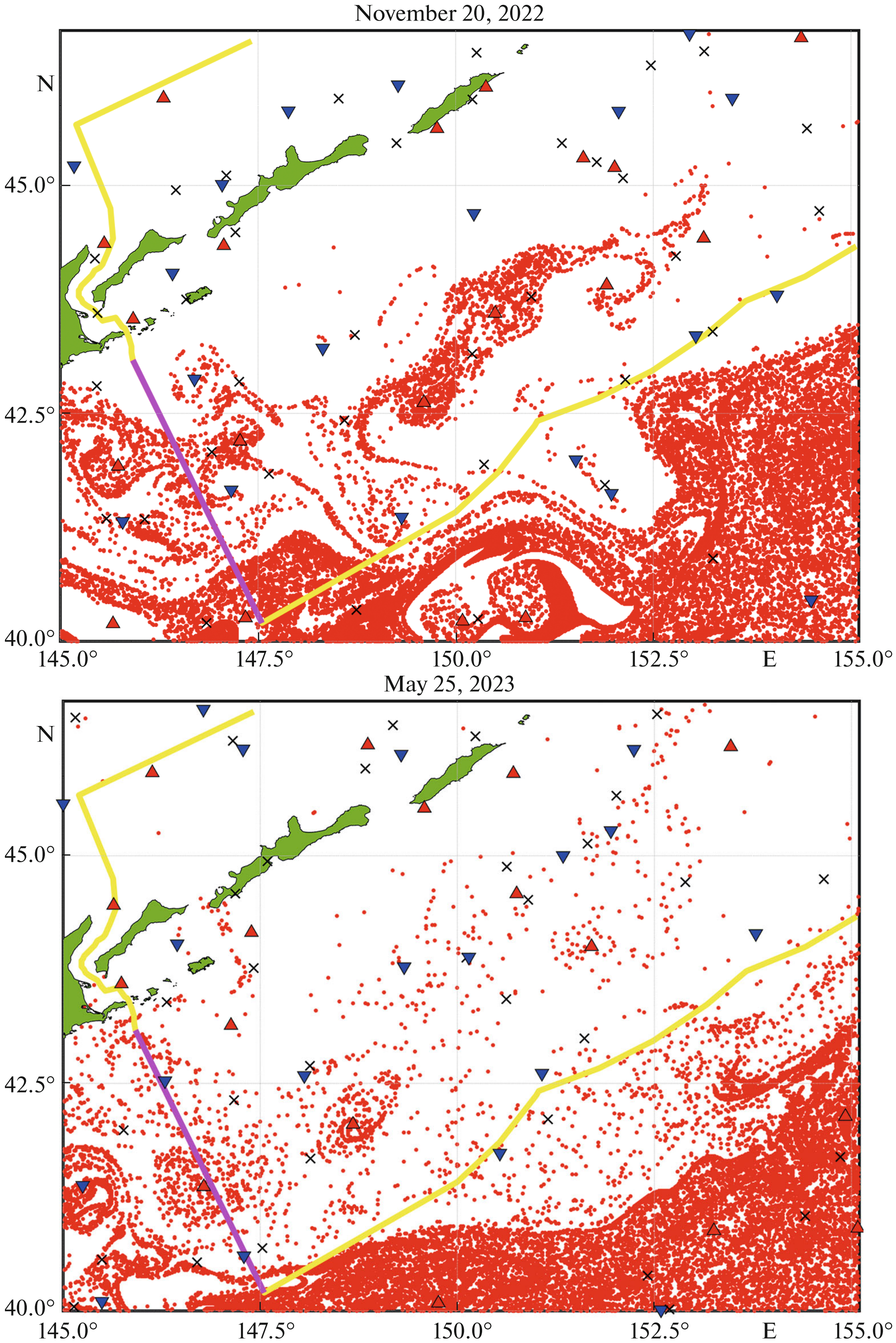


Fig. 2. Geostrophic currents calculated from AVISO altimetric data and averaged for September 2022 and April 2023. Currents: 1, Oyashio; 2, Kuroshio. Arrows mark vectors of the currents, and the color scale corresponds to the velocity modulus. The red segment (35.6° N, 141° E – 38.3° N, 141.6° E) is located near the Fukushima-1 NPP, from where the trajectories of markers are calculated. Red triangles ▲ designate the centers of anticyclones, and blue triangles ▼ denote cyclones. Black crosses indicate hyperbolic points.

charge, i.e., the period from August 24 2022, to August 24, 2023. The proposed approach will make it possible to obtain estimates that in general will be up-to-date for the following years. Although the circulation in the study region exhibits interannual variability, the main current systems remain unchanged.


November 20, 2022

May 25, 2023

Fig. 3. Spatial distribution of “dirty” markers on November 20, 2022, and May 25, 2023. Triangles and crosses denote the same as in Fig. 2.

METHODS AND DATA

To study the transport of radioactive contamination, we use the set of methods developed in [1–5, 7–9].

By Lagrangian modeling, we examine the paths and duration of dispersion of the radioactive substance with a high degree of accuracy and quantify radioactive contamination of the SKFZ, which is located

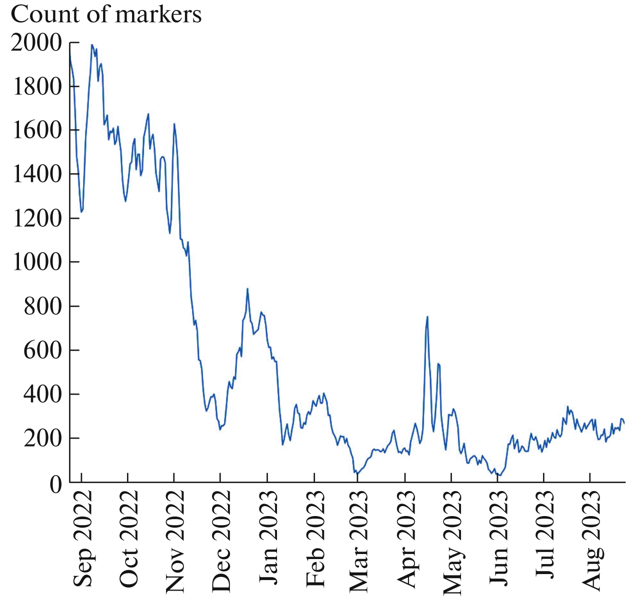


Fig. 4. Temporal variability of the count of "dirty" markers within the SKFZ. The counting was done on a daily basis from August 24, 2022, to August 24, 2023. The trajectory of each marker was calculated in reverse time for a period of one year.

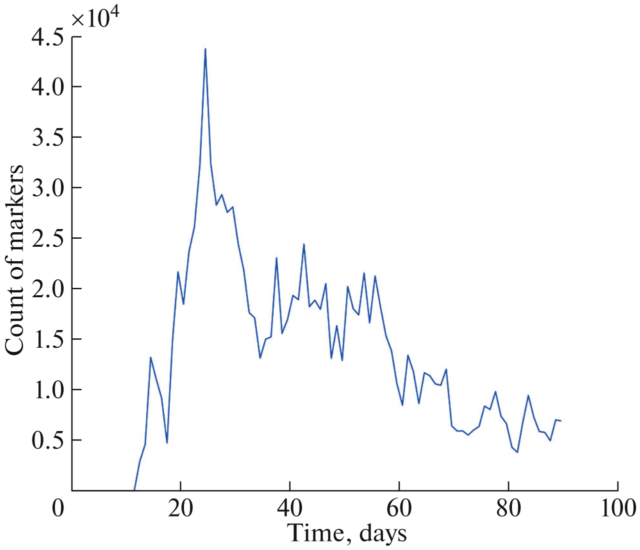


Fig. 5. Distribution of the count of "dirty" markers by time of reaching the SKFZ boundary based on AVISO field data. Only markers that crossed the southern boundary of the SKFZ (pink segment in Fig. 1) are considered.

close to the discharge point of radioactive water from the Fukushima-1 NPP. To study the advection of radioactive contamination, we plan to use the marker-based tracking method, which involves calculating a large number of trajectories of passive tracers simulating contamination.

As information about currents, we use the geostrophic velocities calculated from AVISO satellite altimetric data (with a spatial resolution of 1/4°). These data result from the integration of measurements from all altimetry missions: Jason-3, Sentinel-3A, HY-2A, Saral/AltiKa, Cryosat-2, Jason-2, Jason-1, T/P, ENVISAT, GFO, and ERS1/2 from 1993 to the present. The data are available on the Copernicus Marine Environment Monitoring Service (CMEMS) portal (http://marine.copernicus.eu).

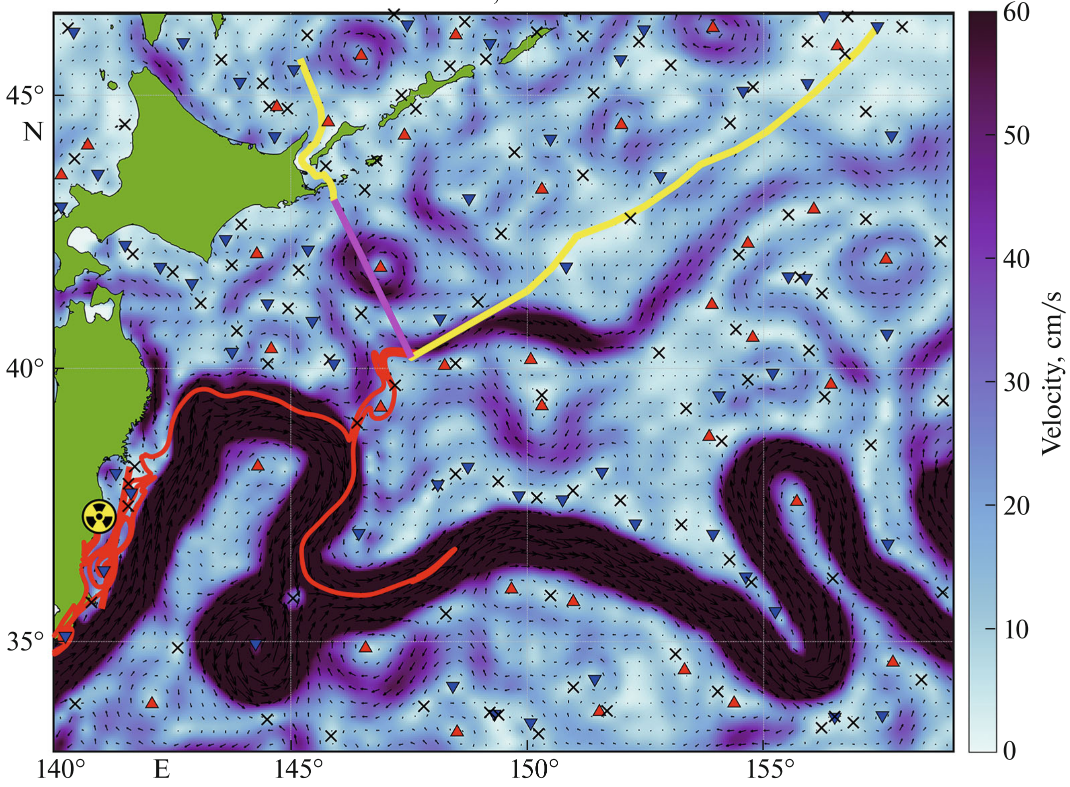
PHYSICAL AND GEOGRAPHYCAL DESCRIPTION

The study area east of Japan is bounded by the meandering warm Kuroshio current and the cold Oyashio current from the south and north. These currents coincide with the corresponding hydrological fronts. The segment of the Kuroshio system from Honshu Island to the Emperor seamounts is referred to as the Kuroshio Extension. At approximately 42°–43° N, the Oyashio current turns eastward (the so-called Second Branch of Oyashio). The region of interaction between the Kuroshio and Oyashio currents is one of the most dynamically active regions in the World Ocean, where oceanological field variability occurs over a wide spatial and temporal range [10]. The observations show that, at certain times, the Kuroshio and Oyashio currents occasionally split into separate branches, i.e., bifurcation of currents occurs [11]. The presence of quasi-stationary Kuroshio meanders leads to the formation of warm anticyclonic vortices on its northern side that are further developed under the influence of topography. Anticyclonic vortices with a scale of about 100 km extend along the Kuril Trench to the northeast [12, 13] and interact with other dynamic structures. Figure 2 shows the meandering Kuroshio current, the Oyashio flow extending southwest along the Kuril Ridge, and the system of mesoscale vortices formed due to the instability of the Kuroshio current. Depending on the season, there are different regimes of development of the Kuroshio current: with the developed First meander extending far north along the Japanese coast (Fig. 2b) and without it (Fig. 2a). The velocities of the Kuroshio current core reach 2.5 m/s. The velocities of the Oyashio current are significantly lower and reach 0.5–1.0 m/s in February, but in summer, the Oyashio current weakens considerably: the velocities do not exceed 0.25–0.35 m/s, which facilitates the penetration of water from the south, mixing of waters of different origins, filament detachment from vortices, and eventually the entry of radioactive particles into the SKFZ waters.

RESULTS OF LAGRANGIAN MODELING

To assess the possibility of contamination of the SKFZ water area by radioactive particles, we con-

June 7, 2023



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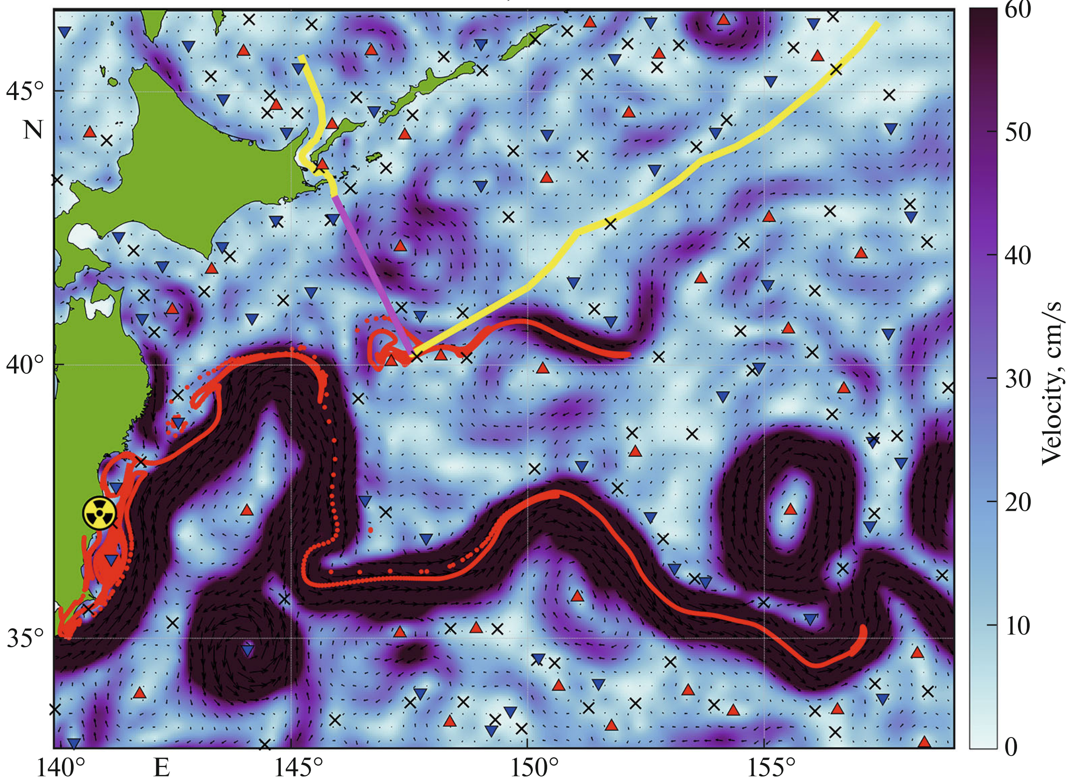

Fig. 6. Velocity field based on the AVISO data with fragments of the evolution of the contamination patch from the coast of Japan at the Fukushima-1 NPP (segment and patch shown in red, see also Fig. 1). The date of release is May 25, 2023. Markers reached the border of the southwestern boundary of the SKFZ (shown in pink) 13 days after being released.

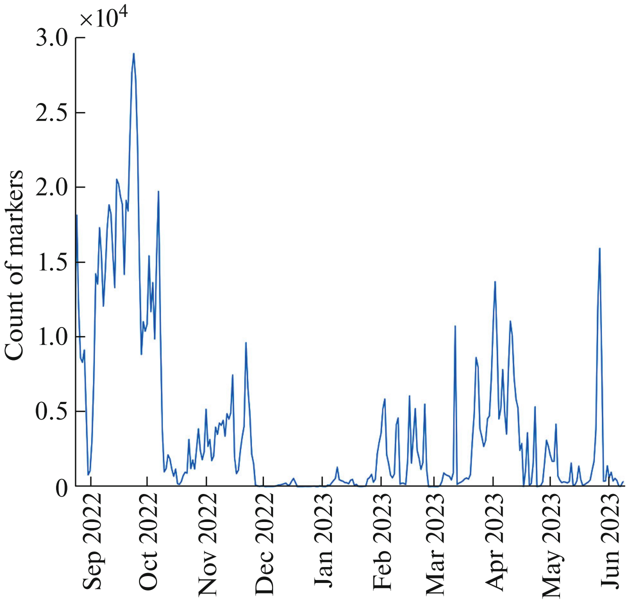

Fig. 7. Distribution of the count of "dirty" markers that reached the SKFZ boundary by the dates of their release from the coast of Japan.

ducted a series of numerical experiments using Lagrangian modeling.

Estimation of Passive Marker Advection Based on AVISO Data

Every day from August 24, 2022, to August 24, 2023, a rectangular area with the coordinates 40°–48.5° N, 145°–159° E, comprising the SKFZ, was seeded with markers on a uniform grid of 500 × 500 nodes. There was a total of 25 × 10^4 markers. Next, for each marker, the advection equations in reverse time over a 365-day interval were solved and the trajectories were calculated. The markers, whose trajectories in the past intersected the segment 35.6° S latitude, 141° E longitude–38.2° S latitude, 141.6° E longitude, located parallel to the coastline near the Fukushima-1 NPP (see Fig. 1), were colored in red. These markers correspond to potentially contaminated water particles from the Fukushima-1 NPP. Although, according to many experts, most contaminated waters are indeed taken and carried away by the Kuroshio current from the shores of Japan into the Pacific Ocean to the east; contaminated particles can be detected near the shores of the Kuril Islands. Figure 3 shows that "dirty" markers reach the SKFZ boundaries and are transported far to the north and are also carried to the Sea of Okhotsk through the Kuril Straits. We note that these markers usually tend to concentrate at the periphery of mesoscale vortices or along meanders, which suggests that vortex advection is one of the mechanisms by which "dirty" markers reach the Russian fishing region.

Figure 4 shows the temporal variability of the count of "dirty" markers in the SKFZ. We considered the period from August 24, 2022, to August 24, 2023, and calculated the marker trajectories in reverse time for a period of one year on a daily basis. The largest count of "dirty" markers that enter the SKFZ through different pathways belongs to the time period from late August to late October. This indicates that this period is potentially the most dangerous for fishing in the SKFZ.

The count of "dirty" markers in the SKFZ (Fig. 4) changes in a jump-like manner throughout the year. The extrema on the graph (particularly in December, February, and May) indicate that "dirty" particles are carried into the SKFZ proportionately. It is evident that this pattern is determined by the features of circulation in the region during the study period.

Estimation of Advection Time of "Dirty" Markers from the Fukushima-1 NPP to the Southwestern Boundary of the SKFZ

The following experiment allows estimating the time that contamination takes to spread from the Fukushima-1 NPP to the southwestern border of the SKFZ (the segment of 40.2° N, 147.55° E–43.084° N, 145.917° E shown in pink in Fig. 1). Each day from August 24, 2022, to June 6, 2023, 50000 passive tracers were released along the segment (35.6° N, 141° E–38.2° N, 141.6° E shown in red in Fig. 1) located along the coastline near the Fukushima-1 NPP and the time required for particles to reach the southwestern border of the SKFZ was calculated. All trajectories were calculated in the forward time for a period of 90 days. Figure 5 shows that as early as 13 days after the release, the first "dirty" markers cross the southern border of the SKFZ; afterward, the count of "dirty" markers increases sharply. Their maximum count, exceeding 4.4 × 10^4, is observed on the 25th day, after which the count of markers decreases by several times, but even on the 90th day after the discharge of radioactive water, their number is still high (around 0.7 × 10^4). We note also that, in this experiment, the estimate of the total number of markers relates to all dates in the study period rather than to a particular date of release.

We managed to capture the startup time of the contamination patch, the particles of which reached the southwestern border of the SKFZ in the shortest time, May 25, 2023. It took the contaminated waters only 13 days to approach the SKFZ boundary. Figure 6 shows the fragments of the evolution of this patch, overlain on the AVISO velocity field. The rapid advection of contamination (from May 25 to June 7) is determined by the entrainment of the patch by an originating Kuroshio meander and the subsequent advection by mesoscale anticyclones (Fig. 6). As the patch passes by hyperbolic points on the periphery of these vortices, it is significantly deformed into folds typical of chaotic advection [2–4]. A week later, on June 15

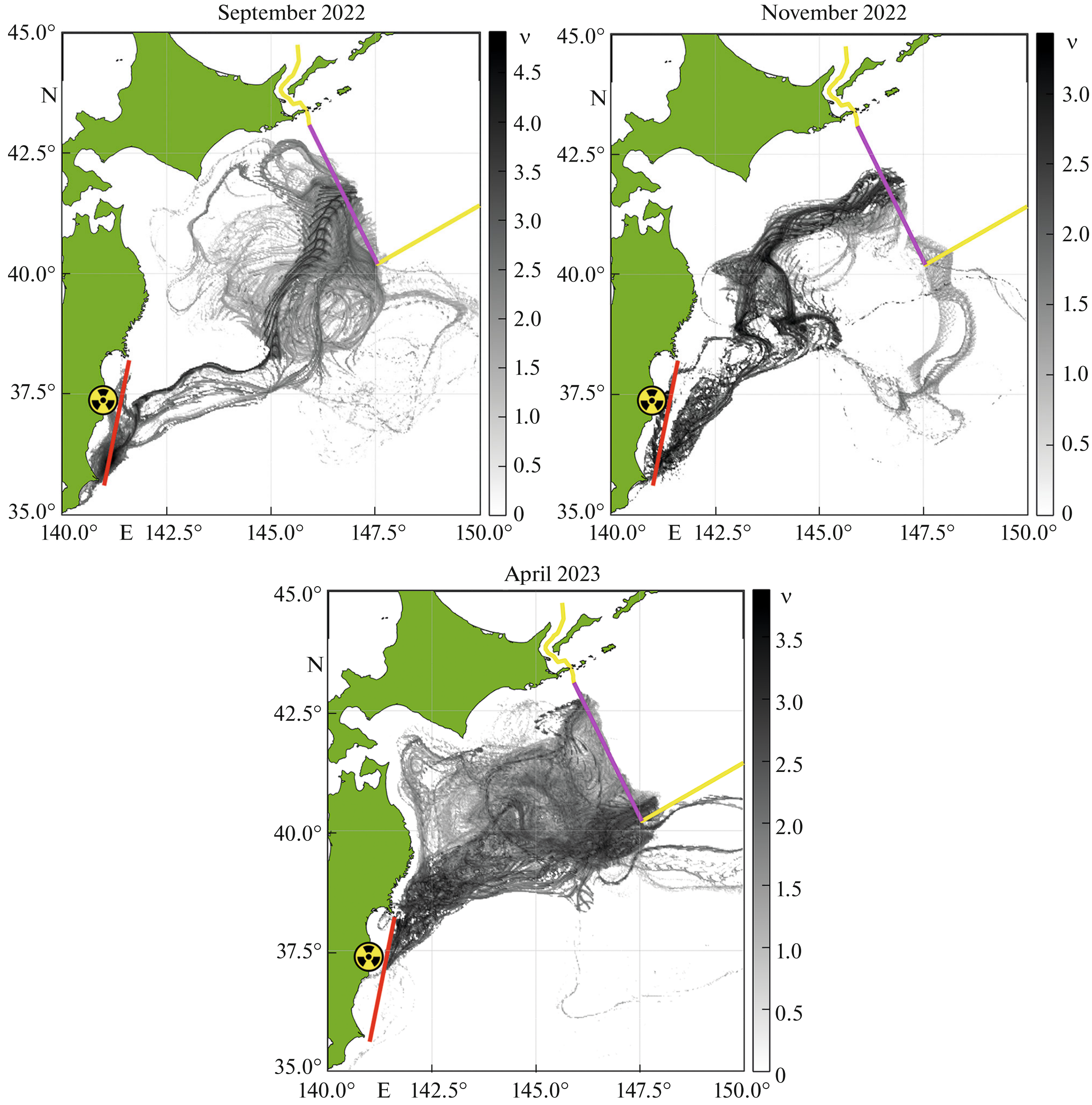

Fig. 8. Dasymetric maps of daily traces of markers released from the Fukushima-1 NPP in September and November 2022 and April 2023 that reached the southwestern boundary of the SKFZ. The tracer density ν is presented on a logarithmic scale.

(Fig. 6), the study patch of "dirty" markers is carried eastward by the Northern Kuril Current branch, crossing the southern part of the SKFZ.

Dasymetric Maps (Density of Tracers)

Figure 7 presents an estimation of the quantities of "dirty" markers that reached the southwestern border of the SKFZ depending on the release date of tracers at the segment near the eastern coast of Japan. In contrast to Fig. 4, where the total number of markers in the SKFZ waters was calculated, Fig. 7 analyzes the input of markers only through the southwestern border. We identify the peaks in October 2022 and April and May 2023, indicating that, if the discharge of contaminated water from the NPP occurred during these periods, it would increase the degree of the SKFZ contamination.

Figure 8 presents the dasymetric maps for September and November 2022 and April 2023, i.e., the maps

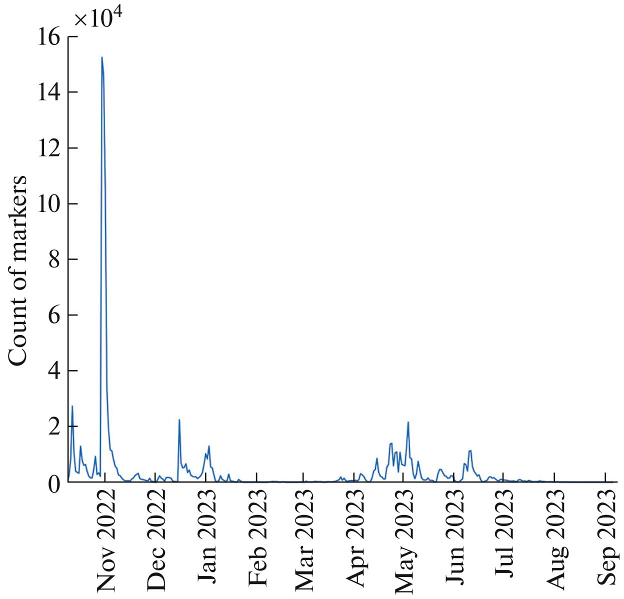

Fig. 9. Distribution of the count of “dirty” markers by the dates of their arrival at the SKFZ boundary from August 24, 2022.

of the density of traces (trajectories) of “dirty” markers released from the NPP at different times. When constructing the trajectories, we first divided the study area of 35°–44° N, 140°–150° E into a uniform grid of 400 × 400 rectangular cells. Then, for each cell, we counted the daily traces left by the trajectories of contaminated markers that were released at a certain time near the coast of Japan (the red segment in Fig. 1) and reached the southwestern border of the SKFZ. This method illustrates the transport pathways for “dirty” markers (released in October 2022 and April and May 2023). These transport pathways have different shapes, as they depend on the field of flows that change with time. However, in all cases, “dirty” markers reach the SKFZ boundary and then enter the area of active fishing.

Figure 9 shows the distribution of the count of “dirty” markers that reached the southwestern border of the SKFZ by dates. The peak in November 2022 is prominent, when the count of markers was 15×10^4, along with the noticeable peaks in November 2022 and January and May 2023. This result implies that if hydrobionts were caught in the SKFZ during these periods, increased attention to dosimetry in this area would be required. One of the possible contamination pathways is determined by the circulation features during this period: the First Kuroshio meander is pressed against the coastline (Fig. 2b), the Oyashio current is weakened, and large-scale vortices in this area entrain and rotationally carry particles into the SKFZ.

CONCLUSIONS

Our analysis shows that Russian coastal waters are facing the real danger of contamination with radioactive water discharged from the Fukushima-1 NPP. Contaminated waters can penetrate the SKFZ, an area of commercial hydrobiont fishing.

This conclusion was made by using Lagrangian modeling of pollution transport, based on the advection of passive markers placed on the sea surface. The numerical calculation of advection equations was performed using the field of AVISO geostrophic velocities found from altimetric data. The modeling period was selected to be one year before the first discharge of technical water on August 24, 2023.

The seasonal dependence of the velocity and amount of contaminated water that penetrated to the shores of the Russian Federation was established.

The transport of pollution to the SKFZ is determined by a set of conditions related to the current development of the First Kuroshio meander, as well as by the local vortex system of different signs both near the discharge site and at the SKFZ boundary.

The possibility of rapid (13 days) advection of contamination to the SKFZ was identified. Such a velocity is related to the entrainment of contaminated particles by the Kuroshio meander and its subsequent transport by the vortex system at the SKFZ boundary.

The inflow of contaminants into the SKFZ occurs proportionately.

Graphs of the distribution of “dirty” markers with respect to the time of their release and arrival at the SKFZ boundary were constructed.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

REFERENCES

1. S. V. Prants, M. Yu. Uleysky, and M. V. Budyansky, Dokl. Earth Sci. **439** (6), 811–814 (2011) [in Russian].
2. S. V. Prants, M. V. Budyansky, V. I. Ponomarev, and M. Yu. Uleysky, Ocean Model. **38** (1-2), 114–125 (2011).
3. S. V. Prants, M. Yu. Uleysky, and M. V. Budyansky, Dokl. Earth Sci. **439** (2), 1179–1182 (2011).
4. S. V. Prants, V. I. Ponomarev, M. V. Budyansky, et al., Izv., Phys. Atmos. Okeana **49** (1), 82–97 (2013).
5. M. V. Budyansky, V. A. Goryachev, D. D. Kaplunenko, V. B. Lobanov, S. V. Prants, A. F. Sergeev, N. V. Shlyk,

and M. Yu. Uleysky, Deep-Sea Res. I **96**, 15–27 (2015). https://doi.org/10.1016/j.dsr.2014.09.007

6. *Bioresources Exploitation in Kuril Archipelago Water: Modern Structure, Dynamics and the Main Elements,* Ed. by A. V. Buslov (Yuzhno-Sakhalinsk, 2013) [in Russian].
7. S. V. Prants, M. Yu. Uleysky, and M. V. Budyansky, Dokl. Earth Sci. **447** (1), 1269–1273 (2012).
8. S. V. Prants, M. V. Budyansky, and M. Yu. Uleysky, Nonlin. Process. Geophys. **21** (1), 279–289 (2014). https://doi.org/10.5194/npg-21-279-2014
9. S. V. Prants, M. V. Budyansky, and M. Yu. Uleysky, Ocean Sci. **13**, 453–463 (2017). https://doi.org/10.5194/os-13-453-2017
10. T. V. Belonenko, V. V. Koldunov, D. K. Staritsyn, V. R. Fuks, and I. O. Shilov, *North-Eastern Part of the Pacific Ocean: Level Variety* (SMIO-PRESS, St. Petersburg, 2009) [in Russian].
11. *Sources of the Oyashio Current,* Ed. by V. R. Fuks and A. N. Michurin (St. Petersburg State Univ., St. Petersburg, 1997) [in Russian].
12. A. Udalov, M. Budyansky, and S. Prants, Deep-Sea Res. Part I: Oceanogr. Pap. **200**, 104129 (2023). https://doi.org/10.1016/j.dsr.2023.104129
13. V. S. Travkin, T. V. Belonenko, and A. V. Kochnev, Sovrem. Probl. Distantsionnogo Zondirovaniya Zemli Kosmosa **19** (5), 222–234 (2022). https://doi.org/10.21046/2070-7401-2022-19-5-222-234