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Analysis of the Spatiotemporal Variability of Pacific Water Propagation in the Sea of Okhotsk Based on the Lagrangian Approach

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Abstract—The eastern Sea of Okhotsk is one of the most important areas of the World Ocean in terms of fisheries. The high productivity of this region is supported, in particular, by the inflow of waters from the Pacific Ocean. The process of inflow and propagation of these waters into the sea is poorly understood. In this paper, altimetry data on current velocities and the Lagrangian approach are used to track the events of the inflow of waters of Pacific origin into the Sea of Okhotsk and to characterize their evolution. Daily values of two types of indices describing propagation of Pacific waters in the Sea of Okhotsk were obtained based on the data on the location and shape of water intrusions. It is shown that in winter such waters are usually located closer to Kamchatka, and in summer, farther from the coast. In 1998, 2003, 2010, 2013, 2017, and 2019, Pacific waters penetrated the farthest distance to the north. Analysis of the morphometric characteristics of the intrusions showed that after reaching the maximum area of the intrusion, its shape quickly becomes more complex. The centroids of the largest intrusions are usually located in the band 152°–154° E. Based on the developed indices it is shown that the inflow of water from the ocean into the sea has increased since 2010.

Keywords: Sea of Okhotsk, current, water transport, seasonality, intrusion

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INTRODUCTION

Accumulation of measurements, including satellite, development of hydrodynamic models of the ocean, and computers in the last few decades have led to the formation of data arrays on the currents of the World Ocean on grids with sufficiently high spatial and temporal resolution, which allows describing small-scale features of circulation. Such arrays, in particular, include data measured using satellite altimetry or mathematical modeling [13]. These arrays initially formed using the Eulerian approach are increasingly used to study the features of water dynamics in the Lagrangian approach.

The use of this approach makes it possible to solve a wide range of fundamental and applied oceanographic problems. In particular, it is used to track the transport of water and suspended matter including pollutants and planktonic organisms in the ocean [8, 25]. In this paper, the Lagrangian approach is used to study the features of the inflow and distribution of Pacific Ocean waters (POW) in the eastern Sea of Okhotsk. The term POW here refers to the waters that have entered the sea from the ocean and have been in the sea for no more than 400 days. The choice of such a threshold for the time of water presence in the sea is discussed below.

The eastern Sea of Okhotsk is one of the most important fishing areas within the exclusive economic zone of Russia. It is characterized by high productivity, apparently associated with its oceanographic features, including the inflow of relatively warm waters from the Pacific Ocean rich in inorganic nutrients [20]. This region has a high nekton biomass and high species diversity [1]. In 2013–2022, only within the two fishing subzones located in this region (Kamchatka-Kuril and West Kamchatka), from 753 to 1163 thousand tonnes of aquatic biological resources were harvested annually. Their contribution to the total catch of Russia amounted to 17–23%. At the same time, the spread of Pacific Ocean waters within the sea can affect the distribution of commercial fish not only through food chains, but also directly. In a recent study, this was shown for the most common species in this region: Walleye Pollock *Gadus chalcogrammus* [15].

Thus, the inflow and distribution of POW in the Sea of Okhotsk can potentially serve as an important indicator of the state of the region's ecosystem as a whole and its commercial part in particular. However, only a few recent works have been devoted to the description of the inflow of waters from the Pacific Ocean into the Sea of Okhotsk and their distribution in the sea. In particular, data from the global model of the World Ocean made it possible to show the regions of the most stable currents in the sea [6]. Long-term mean characteristics of water circulation and analysis of long-term variability of current flow in the region along the western coast of Kamchatka in winter were given based on altimetry in [4]. In [9], the authors used an eddy-resolving regional model and showed the seasonality of the intensity of water inflow from the ocean into the sea and the probability of observing waters transported from the Pacific Ocean into different regions of the sea. In [15], aimed at finding the relation between the location of Walleye Pollock fishery trawling and the location of POW with the time spent at sea up to 1095 days, the complex structure of water circulation in the eastern part of the sea is illustrated, and examples of its interannual variability are given.

It is known that the inflow of water from the ocean into the sea occurs mainly through the northern straits of the Kuril Islands (mainly the Fourth Kuril and Krusenstern, see Fig. 1), and the maximum water inflow is observed generally in January–March [9]. That is, the inflow of water is characterized by intra-annual (seasonal) variability. At the same time, the distribution of Pacific waters into the sea occurs constantly. This allows us to assume that during periods of weakening water inflow in summer–autumn, conditions should be observed for their gradual spreading into the sea, dispersion and mixing with the surrounding waters, as well as for gradual motion to the north. However, the question of identifying individual events of water inflow occurring during periods of its intensification remains open. It is reasonable to assume that during each such event, water enters the sea in a relatively compact form (in portions) and as it flows, it becomes increasingly dispersed throughout the area of study. The features of this process are still poorly understood.

Daily data on Lagrangian indicators characterizing the origin of waters obtained by Budyansky et al. [15] for the Sea of Okhotsk over a long time interval make it possible to describe the process of water inflow from the Pacific Ocean into the sea and to analyze the specific features of their distribution. The main objective of this paper is to provide a general description of the seasonal and interannual variability of the inflow and distribution of waters of Pacific origin in the eastern Sea of Okhotsk based on the Lagrangian approach and spatial analysis.

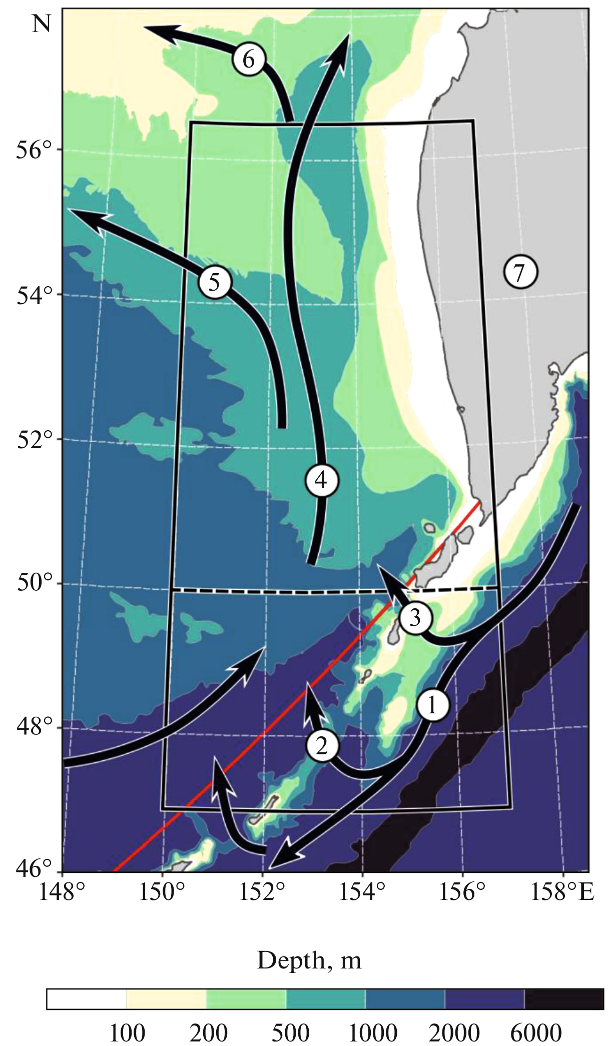

Fig. 1. Bathymetry and general scheme of circulation in the study region. Red line is transect along the Kuril Islands, intersection of which was condition for classifying a water parcel as water of Pacific origin. Black solid line marks region, for which analysis of distribution of waters of Pacific origin was performed. Black dashed line marks southern boundary of region used for general characterization of seasonality of distribution of Pacific waters. Currents are marked with numbers: (1) Kuril Current; (2) inflow of Pacific waters in Krusenstern Strait; (3) inflow of Pacific waters in Fourth Kuril Strait; (4) West Kamchatka Current; (5) Middle Current; (6) North Okhotsk Current (slope branch); (7) Kamchatka Peninsula.

MATERIALS AND METHODS

Calculation of Parcel Trajectories

The study is based on the same simulation data as in [15], but for a slightly longer time interval. In order to determine the coordinates and time of POW penetration into the Sea of Okhotsk, the trajectories of a numerous parcels were calculated for each day in the interval from January 31, 1997 to April 17, 2022. Each parcel motion was tracked back in time using high-resolution current data and a numerical solution to the equations of motion.

The virtual parcels were distributed into the nodes of a regular latitude–longitude grid with the size of 300 × 380 cells in the region of 42.0°–56.5° N, 141°–157° E (114000 nodes, the resolution was approximately 0.038° × 0.054° in latitude and longitude). For each such parcel, the motion was calculated over 1095 days back in time; however, in this paper, only the first 400 days of the calculation were considered, which are sufficient to reconstruct the features of the seasonal variability of the studied process. Parcels whose trajectories touched the coast were excluded from the analysis. Due to the need to perform a very large number of calculations (calculation of more than 10^8 individual trajectories of parcel motion over 1095 days), the calculations were performed on the computer cluster of the Pacific Oceanological Institute, Far Eastern Branch, Russian Academy of Sciences.

Data on currents is derived from the Copernicus Marine Service Information Data Center product [14], which contains current velocity components calculated from altimetry data and, to a first approximation, correspond to the geostrophic current. That is, the work does not take into account short-period wind currents, but takes into account the prevailing steady currents in the study region. The advantage of using this dataset is that it is based on a generalization of all currently available altimetry measurements from various platforms (Jason-3, Sentinel-3A, HY-2A, Saral/AltiKa, Cryosat-2, Jason-2, Jason-1, Topex/Poseidon, ENVISAT, GFO, ERS1/2), and not on the modeling results. At the same time, wind currents can only be taken into account using model calculations, which have additional sources of error. The horizontal resolution of the used product is 0.25° × 0.25° in latitude and longitude, the time resolution is 1 day. To reconstruct the components of the flow velocity at the location of each considered parcel, bicubic spatial interpolation of the data was performed at each calculation step.

The condition of intersection of the line (transect) between Hokkaido Island and the Kamchatka Peninsula was checked for all obtained parcel trajectories. The start point of this conditional transect is 43.0° N, 144.5° E and the end point is 51.75° N, 157.5° E; the transect was constructed in the cylindrical equidistant projection. Parcels whose trajectories crossed this line moving northward were considered as waters of Pacific origin. The longitude of intersection of this line (λ_0, degrees of longitude) was additionally determined for these parcels, and their travel time in the Sea of Okhotsk was calculated: the time interval between the event of intersection of the transect and the moment of observation (T, days).

Thus, as a result of calculations for each day of the selected observation interval, information was obtained on the spatial distribution of parcels that crossed the conventional boundary between the Pacific Ocean and the Sea of Okhotsk during the previous 400 days. Two additional parameters are computed for each such parcel: T and λ_0.

Simplified Analysis of Pacific Ocean Water Distribution

Coordinates of the center of mass (centroid) of the region occupied by POW parcels with T from 30 to 180 days were calculated for each date to get a general characteristic of the seasonality of Pacific Ocean water distribution in the eastern part of the sea. This interval of T was chosen a priori based on the analysis of the obtained water distribution patterns (see, e.g., Fig. 2). This allows one to describe the seasonality of the process under study excluding the influence on the result of waters that entered the sea recently (less than 30 days ago) and are usually concentrated along the boundary of the selected region, and also excluding waters that entered the sea relatively long ago and turned out to be largely dispersed over the region. The choice of other intervals of T (e.g., 20–210 days) gives similar results. However, it should be noted that, due to the general cyclonic circulation in the Sea of Okhotsk, an increase in the upper margin of the interval to 300 days or more leads to the inclusion of water parcels that have re-entered the study area [15], and is therefore redundant. The centroid coordinates were calculated using the spatial data analysis package "sf" of the *R* programming language [22, 23]. The Nadaraya-Watson kernel regression was used to smooth the obtained time series [21, 28]. This version of the analysis was performed for parcels in the region of 50.0°–56.5° N, 150°–157° E. (Fig. 1) in order to reach a result characterizing the distribution of Pacific waters specifically in the eastern part of the sea and to exclude the influence of the waters of the southern part of the sea on the result.

Detection of Intrusions of Pacific Ocean Water

To describe the features of the evolution of POW inflow over time, it is necessary to identify intrusions of such waters on each observation date. In this work, water parcels observed on each individual date (represented by a grid cells) were combined into groups based on their λ_0 and T values using the DBSCAN cluster analysis method [16]. Before grouping, the λ_0 and T values were normalized: shifted by the median and weighted by the interquartile range. The approach for shifted distributions was used to calculate the quartiles [18]. The resulting groups correspond to POW intrusions, and they are displayed on the maps as polygons or multipolygons.

The DBSCAN method requires two parameters to be specified: the minimum number of neighbors and the neighbor search radius (ε). There are no strict rules for selecting the values of these parameters; there are only general recommendations for their selection [27]. At the same time, some objects that are too "far" from others or have a small number of neighbors may be classified as "noise," i.e., not included in any of the clusters.

The minimum number of parcels in a cluster is chosen as 100 to exclude small groups of parcels from the analysis. Reasonable changes in this parameter (e.g., in the range of 80–150) lead to similar results. As a starting point for choosing ε, it is recommended to use a graph of the distance to the kth neighbor, constructed using the data for all grouped objects [17, 27]. Such a graph was analyzed for several randomly selected

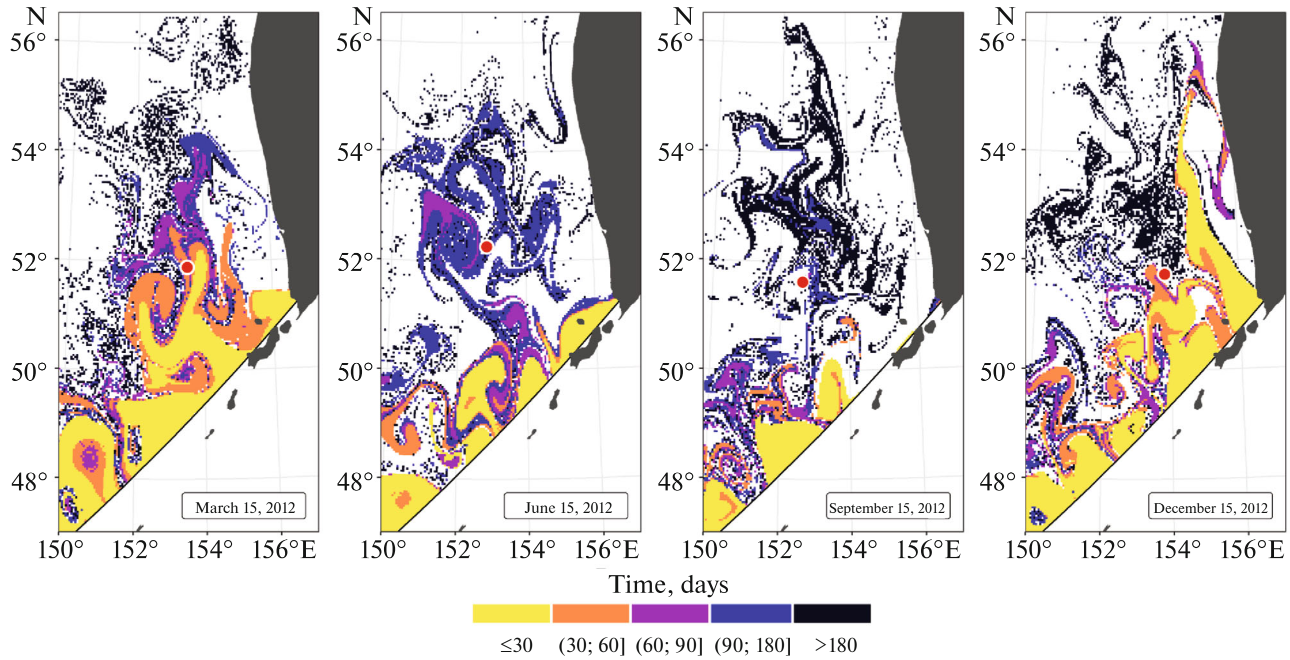

Fig. 2. Examples of distribution of parcels that crossed conventional Kuril transect (black line) during 400 days before observation date. Maps for March 15, June 15, September 15, and December 15, 2012. Color of each cell corresponds to time interval from date of crossing transect to observation date (parcel travel time, T). White color shows waters whose trajectories did not cross transect during 400 days preceding observation date, including those that crossed coast and were excluded from analysis. Centroid of region 50.0°–56.5° N, 150°–157° E occupied by waters with T from 30 to 180 days is marked with red circle.

dates of different seasons. The value 0.05 was chosen as ε (since the data are normalized, this is a dimensionless value).

After grouping, the analysis was continued in geographic space. All cells that fell into one group were combined into a multipolygon (a complex polygon consisting of several polygons); polygons consisting of less than 10 cells were cut off from it. This step allows to indirectly take into account the process of mixing POW with the surrounding waters in the sea and in each case to isolate the main part of the POW patch. Spatial analysis was performed for five such multipolygons having the largest geographic area. This number of groups under consideration is related to the assumption that at any given time there should be a maximum of two large intrusions in the study area: a "younger" and an "older" one formed during the previous cold season. Using the five largest groups allows us to track the appearance of intrusions at an early stage of their life. This type of analysis was performed for parcels in the region: 47.0°–56.5° N, 150°–157° E. This allowed us to track the events of water inflow through the Krusenstern Strait.

To characterize the POW distribution for each of the selected "patches" (multipolygons) several parameters were calculated on each date, including the medians of T and λ_0 of the parcels that constitute the intrusion, the coordinates of the center of mass (centroid) of the intrusion, its perimeter (P_{intr}), maximum linear size (L_{intr}), its area (S_{intr}), and the area of its convex hull (CH, S_{CH}). S_{intr}, as a first approximation, reflects the volume of water corresponding to each inflow event. The ratios S_{intr}/S_{CH} and L_{intr}/P_{intr} serve as options for assessing the convexity of the polygon [31]. The ratio of the logarithm of the polygon area to the logarithm of its perimeter (D_{intr}) is a fractal characteristic [5], one of the options for approximating the fractal dimension of a two-dimensional figure, characterizing the degree of angularity of the figure's boundary.

The analysis was performed in the *R* programming language [26] using the packages "sf" [22, 23], "smoothr" [28], "lwgeom" [24], "robustbase" [19], and "dbscan" [17].

All variants of spatial analysis were performed after converting the coordinates to the Universal Transverse Mercator projection for zone 56N (EPSG:32656). This projection is a conformal equal-area projection, and the selected version leads to minimal distortions in the coordinate range 0°–84° N, 150°–156° E (the central meridian of the projection is 153° E).

Combining Intrusions into Long-Term Water Inflow Events

To characterize the development of water inflow events over time, it is necessary to trace the correspondence of intrusions observed on successive dates to each other. Consideration of the results of cluster analysis showed that with the approach used to unite cells into groups, multiple events of group disintegration and subsequent unification of their parts back into a single whole are possible, which complicates the search for correspondences between water "patches" identified on different dates. Therefore, the search was performed iteratively for intervals of 15 days using the following conditions for attributing intrusions to a single water inflow event: the area of intrusions observed within the date interval should differ from the area of the initial intrusion by no more than 30%, and the median λ_0 should differ by no more than 0.5° of longitude. This approach made it possible to trace the evolution of inflow events in cases where small groups of cells separated from the patches.

After finding long-term water inflow events, Nadaraya–Watson kernel regression with a smoothing bandwidth of 15 days was used to smooth and filter out short-term fluctuations and shifts in the parameters under consideration, associated with the contraction or expansion of the intrusion due to the separation of fragments or merging of smaller groups of cells into larger ones over time [21, 29]. All schematic maps presented in the paper are designed in the *R* programming language using the packages "sf" [22, 23] and "ggplot2" [30] in the universal transverse Mercator projection for zone 56N (EPSG:32656).

RESULTS

Inflow and Distribution of Waters in the Sea on the Example of 2012

In the seasonal aspect, the spatial distribution of POW in the Sea of Okhotsk is characterized by the following features. In summer and autumn, POW with T up to 30 days are concentrated in the southern part of the studied area along the previously considered conditional Kuril transect (Fig. 2, two left panels). At the same time, the waters that entered this part of the sea from the Pacific Ocean earlier, i.e., moved within the sea for a longer period of time (1–6 months), are distributed in the eastern part of the sea in the form of a complex-shaped patch, gradually spreading over the region of interest. In winter and spring, the inflow of waters from the Pacific Ocean increases, and the "freshest" POW can move north by 200–400 km from the conditional transect (Fig. 2, left and right panels). At this time, the "old" POW with T greater than six months are represented mainly by scattered groups of water parcels, dispersed over a vast water area.

In all seasons, the inflow of waters can occur in different parts of the transect considered here: both in the wide Krusenstern Strait and to the northeast (Fig. 3). It is barely possible to visually identify any pattern in the seasonal change in the main region of inflow of Pacific waters into the sea. In general, the waters that entered the sea closer to Kamchatka, e.g., through the Fourth Kuril or First Kuril straits, are regularly located closer to Kamchatka as they flow north. However, the West Kamchatka Current has many meanders and eddies in all seasons; hence, this pattern can often be disturbed.

Variations in the Distribution of Pacific Waters

The centroid of the part of the region 50.0°–56.5° N, 150°–157° E occupied by POW cells with T from 30 to 180 days, was located within 50.2°–52.9° N, 151.4°–154.8° E during the studied time interval. The time series of the latitude of the centroid of this part is characterized by a maximum in the spring-summer period and a minimum in the beginning of winter (Fig. 4). That is, in spring and summer, "newest" POW with T of 1–6 months spread maximally to the north, and in autumn and winter they are usually observed further south. The greatest amplitude of centroid latitude fluctuations was observed in 1998, 2003, 2010, 2013, and 2017. In these years, as well as in 2019, the centroid of this region occupied the northernmost position, that is, Pacific waters extended the farthest to the north. The years with the southernmost maximum location of the centroid of the described region and, accordingly, the smallest spread of these waters in the northern direction are 2001, 2002, 2007, 2008, and 2018.

In the time series of the centroid longitude, the seasonality is less pronounced than in the latitude evolution. During most of the studied years, the maximum of the centroid longitude was in winter. That is, in winter, POW with T of 1–6 months are usually located closer to Kamchatka, and in summer, further from the coast (Figs. 4 and 5). This feature was less pronounced during several winter seasons: 1999/2000, 2007/2008, 2013/2014, 2017/2018, and 2019/2020 (Fig. 4). The POW centroid with T from 30 to 180 days was located closest to the Kamchatka coast in the winter seasons of 1998/1999, 2003/2004, from 2009 to 2013, and also in the winter season of 2016/2017.

An illustrative representation of the POW centroid shifts in the southeastern Sea of Okhotsk is given in Fig. 5. It is seen that in March–May the center of mass of such waters is usually located in the region of 51.5°–53° N, 152.75°–153.5° E. By June–July the center of mass displaces west to 152.25°–152.75° E. The most significant interannual variability of its location is observed from August to November: in different years the centroid was located in the range of latitudes 50.25°–51.25° N and longitudes 151.25°–154.25° E. In December–January it was most often observed in the region 51.0°–52.5° N, 153.75°–154.5° E.

Examples of Distinguishing Intrusions

Grouping water parcels of Pacific origin in the λ_0–T coordinate space using the DBSCAN method with the selected parameters (minimum number of object neighbors for grouping is 100, neighbor search radius is 0.05) allows us to find individual events of water

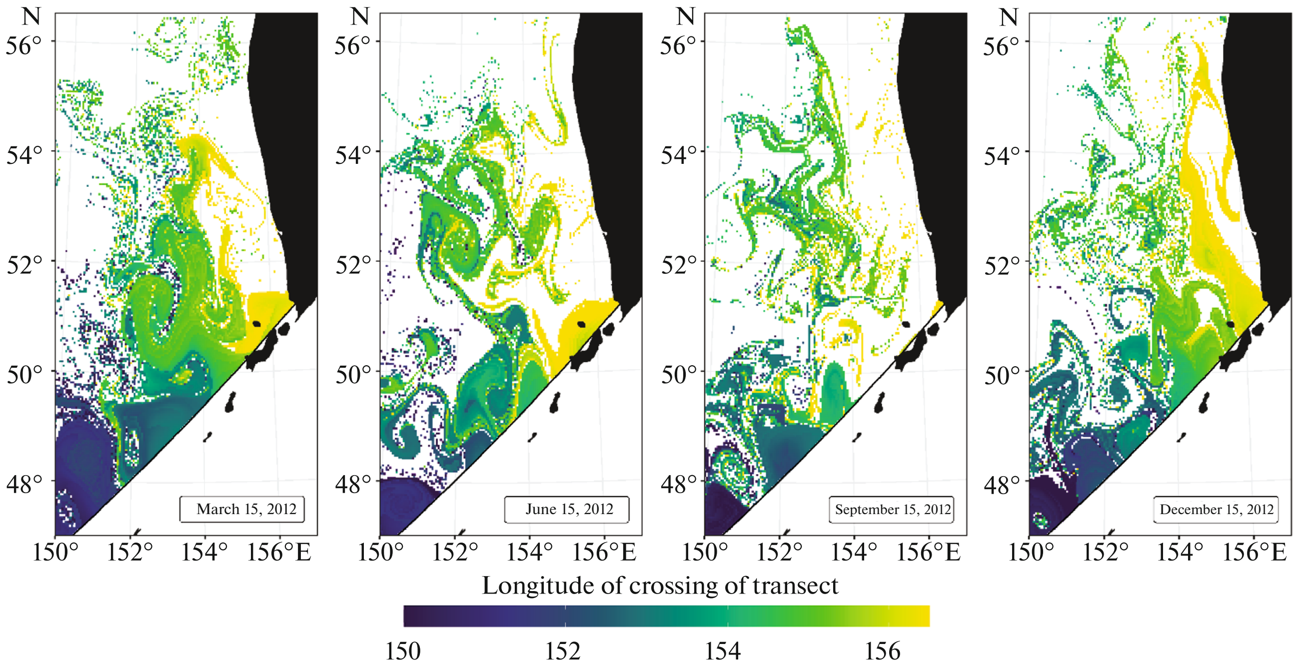

Fig. 3. Examples of distribution of parcels that crossed conventional Kuril transect (black line) during 400 days before observation date. Maps for March 15, June 15, September 15, and December 15, 2012 (dates are same as in Fig. 2). Fill color corresponds to longitude of transect intersection point λ_0. White color shows waters whose trajectories did not cross transect during 400 days preceding observation date, including those that crossed coast and were excluded from analysis.

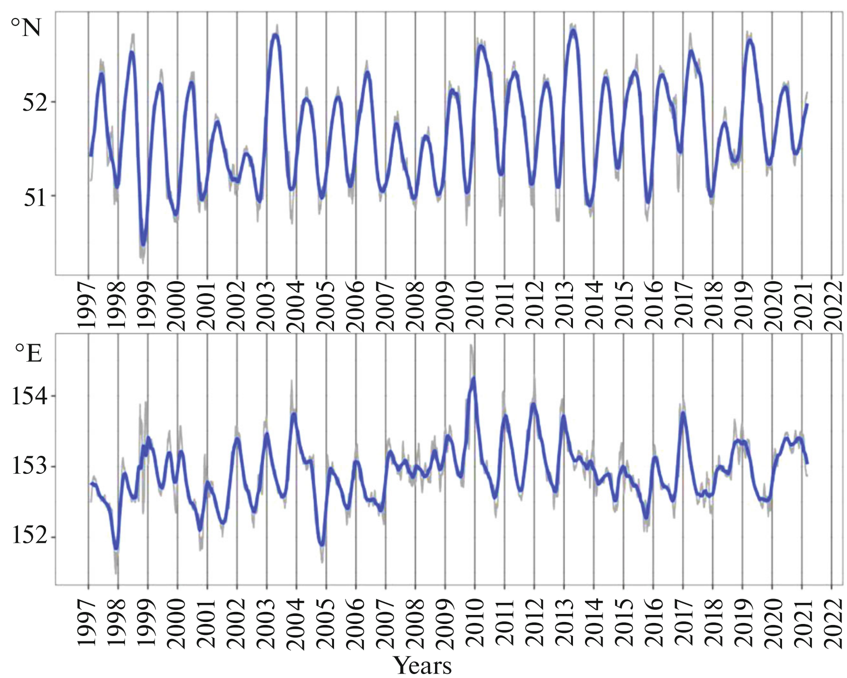

Fig. 4. Latitude and longitude of centroid of waters of Pacific origin in region 50.0°–56.5° N, 150°–157° E with travel time T from 30 to 180 days within Sea of Okhotsk (boundaries of region are shown in Fig. 1). Gray line shows daily values; thick blue line is smoothing of daily data by Nadaraya–Watson kernel regression.

inflow from the ocean to the sea. Figure 6 shows examples of cell groupings on the four dates already considered earlier, conventionally corresponding to the beginning of spring, summer, autumn, and winter of 2012. In March 2012, two main groups of cells were observed: "new" and "older" waters, separated by individual small groups of parcels located in the middle of the figure and classified as noise. In June 2012, one large group of parcels was observed, within which the waters had a wide range of both T and λ_0. The

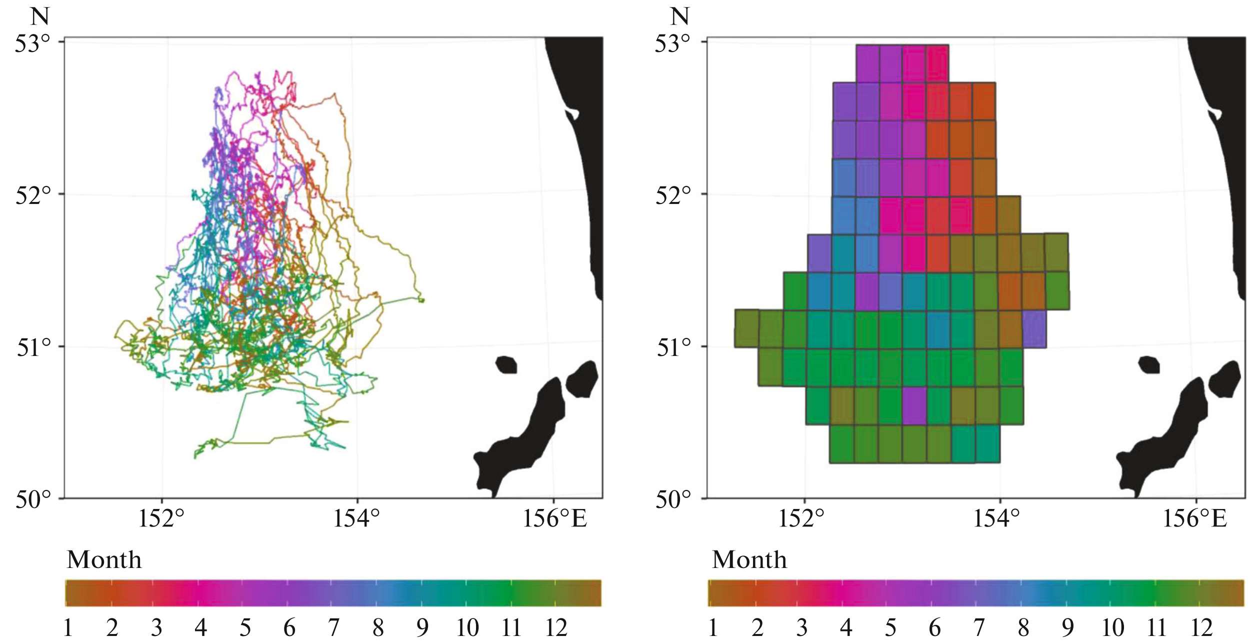

Fig. 5. Variability of centroid of region occupied by waters of Pacific origin with a travel time from 30 to 180 days within Sea of Okhotsk. Color for each observation point represents day of the year (numbers on color scale correspond to months). Daily observations are shown on left; median values for latitude-longitude cells of 0.25° × 0.25° are shown on right.

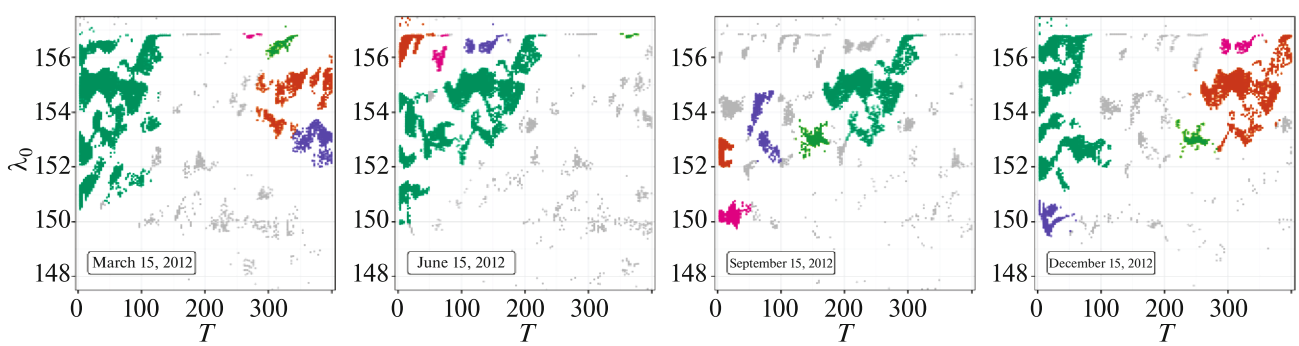

Fig. 6. Grouping of water parcels that crossed conventional Kuril transect during 400 days before observation date, in coordinate space of values of travel time T and longitude of transect crossing λ_0 using DBSCAN method. Figures are given for March 15, June 15, September 15, and December 15, 2012 (same dates as in Figs. 2, 3). Colors show five largest groups for each observation date; gray color is related to small groups and noise (see text for details).

"older" waters observed in March had obviously already moved beyond the region of study by June. In September, the large group of parcels evident in March and June has divided into several smaller groups. The resulting picture is quite consistent with the previously expressed assumption about the gradual destruction of POW intrusions and has a physical meaning. In December 2012, a situation similar to March was observed: all cells were divided into two main groups. Between the "new" and "old" waters, small groups of parcels were again observed, which were excluded from the analysis.

An example of the distribution of water parcel groups identified using cluster analysis in geographic space (on the sea surface) is shown in Fig. 7. The same four dates were used. As in the $\lambda_0 - T$ coordinate space (Fig. 6), two relatively large parcel groups were observed in March 2012. However, the "older" waters located in the northern part of the water area turned out to be represented by small patches, and the intrusion of relatively recently arrived "new" waters occupied a significant area and extended north to 54° N. In June, one main parcel's group was observed, spreading from the Krusenstern Strait across the entire study region to 56° N. Several smaller groups were also notable, some of which formed filaments along the boundary of the largest group of cells.

In September 2012, the main group of cells became isolated not only in the space of coordinates of T and λ_0 values (Fig. 6), but also in geographic space (Fig. 7).

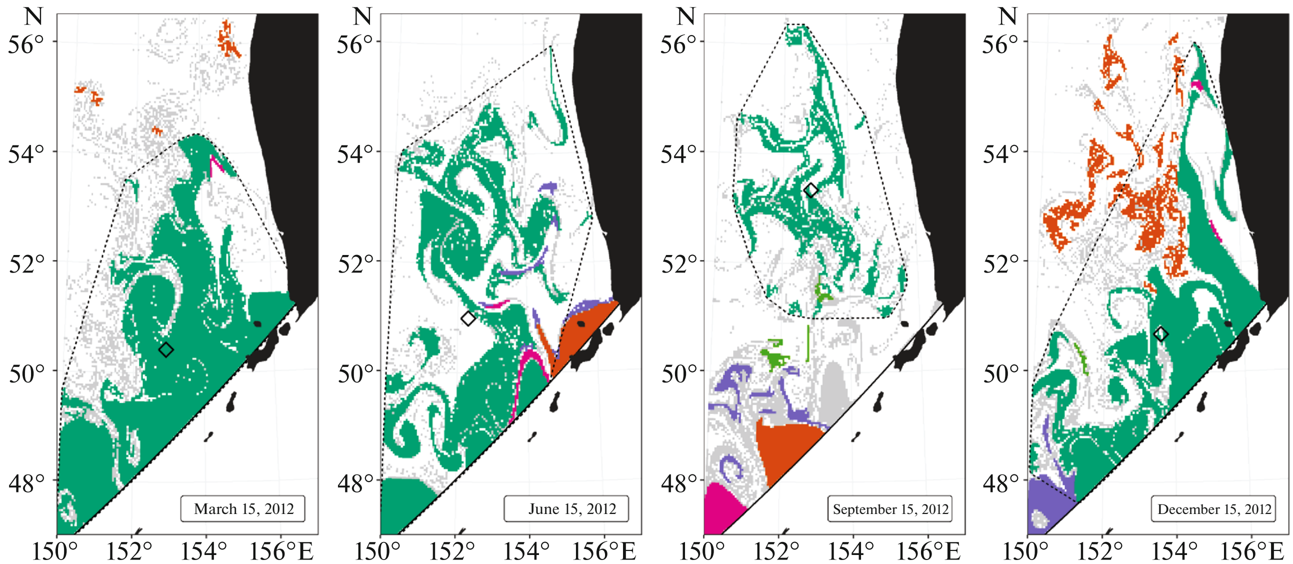

Fig. 7. Examples of grouping of parcels that crossed conventional Kuril transect (black line) during 400 days before observation date. Maps for March 15, June 15, September 15, and December 15, 2012 (same dates as in Figs. 2, 3, and 6). For each date, filling color corresponds to a separate group (groups correspond to Fig. 6, details are in text). Centroid (rhombus) and convex hull (dashed line) are indicated for intrusion with largest area.

Several smaller events of Pacific water inflow were observed in the southern part of the study region. By December, the group of cells observed in September in the north of the study region had lost its structure, and small groups separated from it and were excluded from the analysis. At the same time, a large group of cells of relatively "new" Pacific water formed. This intrusion combined two groups observed on September 15, 2012 and water parcels that entered the study region after September 15. One of the filaments of this intrusion spread north along the Kamchatka coast to 56° N. That is, in certain date intervals, presumably mainly during periods of intensification of the inflow of Pacific waters into the sea, long tongues of POW can be observed, extending far to the north.

Long-term Variations in Water Inflow Events

Analysis of the evolution of Pacific water intrusions identified for each date in the interval from January 31, 1997 to April 17, 2022 was performed. As Figs. 6 and 7 show, the resulting groups of parcels that constitute the POW multipolygon in geographic space can not only shift over time, but also break up into smaller groups or, conversely, merge into larger ones. This makes it impossible to trace the full evolution of inflow events: they are detected only from the moment when the main core of the intrusion is formed, and are often traced not until their complete disappearance, but until the moment of their disintegration into small groups. This is clearly seen in Fig. 8: the largest inflow events could be traced only from the date when their area exceeded 50000 or even 80000 km^2. However, in almost all years of observations, it was possible to combine the largest intrusions observed on individual dates into long-term water inflow events and to follow their evolution over a long time period before and after the moment of maximum development. The exceptions were 2005, 2014, and 2021.

All observed events of Pacific water inflow into the sea reached their maximum development in the first half of the year, then gradually decayed. The exception was 2020, when a large-scale water inflow event was traced until the end of the year, and the maximum area of the formed intrusion occurred on August 14. In other years, the maximum area of the main intrusions was reached in the interval from the end of February to mid-May (on average, on the 94th day of the year, in early April). The most significant water inflow events were observed in 2003, 2010, 2017, and 2020. The maximum area of the main patches of Pacific waters increased in 2010. The average maximum area of tracked POW intrusions in 1997–2010 was 97000 km^2, and in 2010–2022, 141000 km^2. Thus, it can be suggested that the inflow of water from the Pacific Ocean into the Sea of Okhotsk has increased after 2010.

Characteristics of the Evolution of the Shape of Intrusions

Analysis of changes in the fractal dimension $D_{i\mathrm{ntr}}$ and the convexity measure $S_{\mathrm{intr}}/S_{\mathrm{CH}}$ of geometric regions corresponding to intrusions on the sea surface (Fig. 9) showed that at the initial stage of intrusion development, the dimension of $D_{i\mathrm{ntr}}$ fluctuates in the range of 1.2–1.3. At the destruction stage, $D_{i\mathrm{ntr}}$

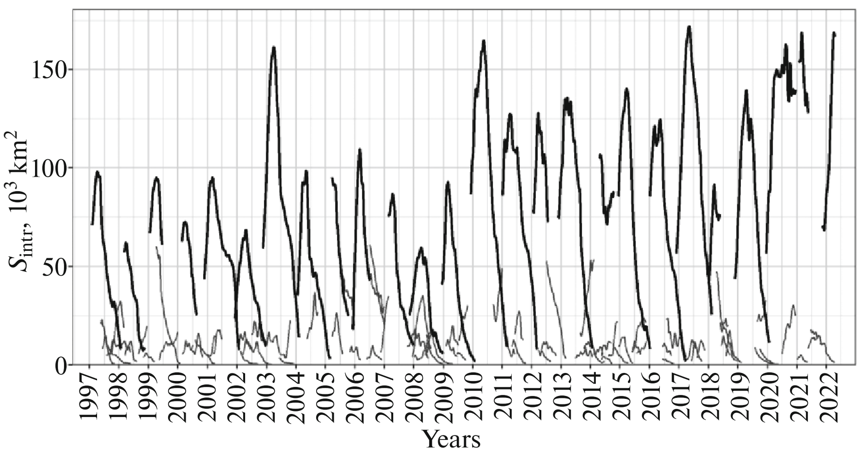

Fig. 8. Variations of area of intrusions (S_{intr}, thousand km^2) of waters of Pacific origin with a traced duration of existence of more than 90 days. Main events of inflow of Pacific waters for each year are shown by bold lines.

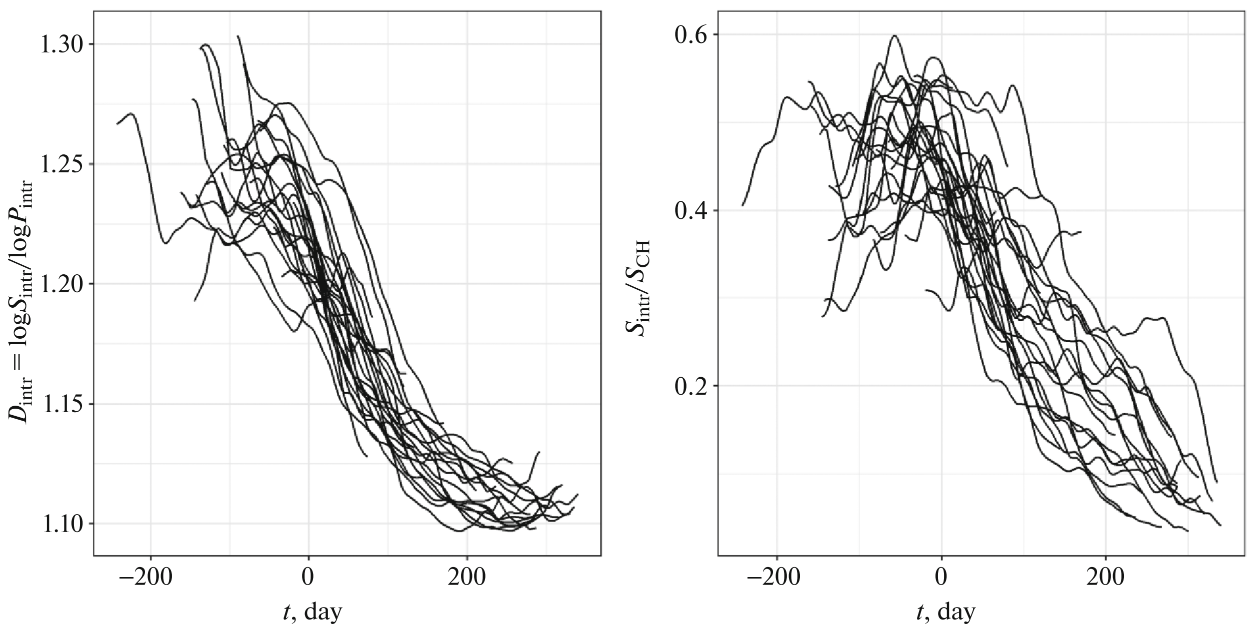

Fig. 9. Characteristics of complication of shape of main intrusions over time t (days) relative to date of reaching maximum area. Change in fractal dimension D_{intr} over time (dimensionless value) (left panel). Change in ratio of intrusion area to area of its convex hull $S_{\text{intr}}/S_{\text{CH}}$ over time (dimensionless value) (right panel).

decreases sharply over 80–120 days, reaching a value of about 1.12 and then remains virtually stable. A value of the fractal dimension $D_{i\text{ntr}}$ close to 1 indicates the proximity of the study region shape to a one-dimensional object (line). This is explained by the elongation of the intrusion shape.

At the stage of intrusion development, the measure of its convexity $S_{\text{intr}}/S_{\text{CH}}$ fluctuates within 0.3–0.6. That is, the study region occupies only about 30–60% of the area of the convex hull set around it. After reaching the maximum area of the intrusion, a sharp decrease in this parameter is observed, reaching a value of about 0.05–0.15 by the time of its breakdown.

Spatial Characteristics of Intrusion Development

The proposed approach allowed us to trace the displacement of intrusions in space. The location of the center of mass (centroid) of the intrusion was chosen as the main spatial parameter. The trajectories of the displacement of the centers of the patches associated with the main annual water inflow events were mainly located in the band of 152°–154° E (Fig. 10a). Most of the intrusions that make up the main water inflow

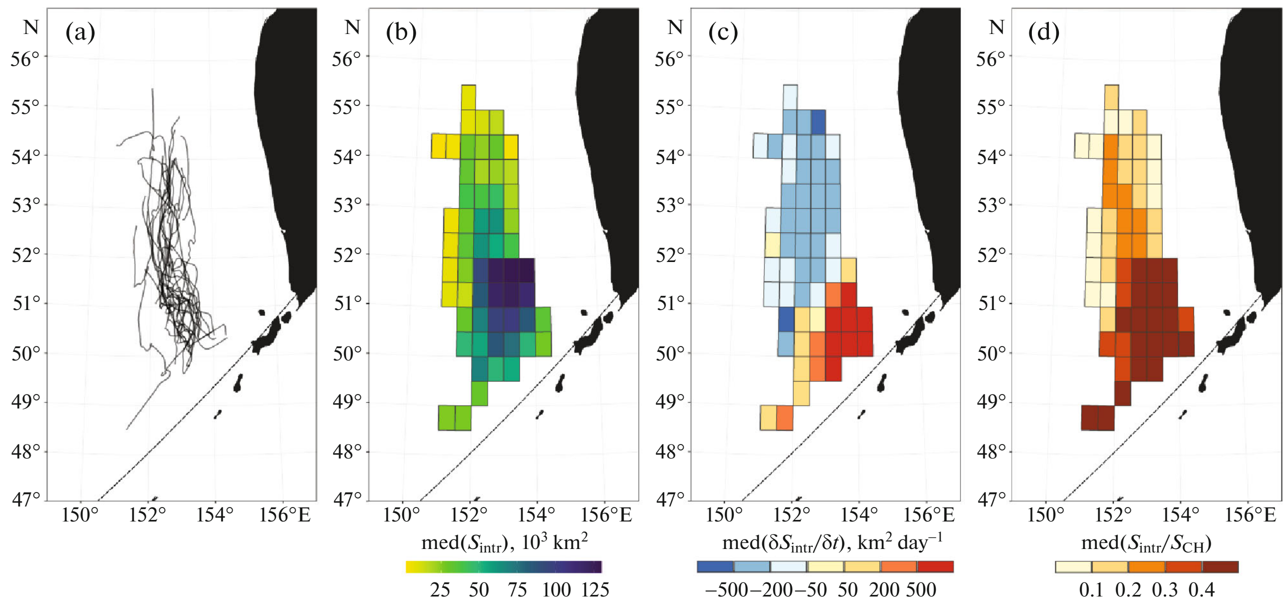

Fig. 10. Spatial characteristics of development of main intrusions of Pacific waters in Sea of Okhotsk: trajectories of intrusion centroids (a); distributions of median area of intrusions (med(S_{intr})), 10^3 km^2 (b), derivative of intrusion area with respect to time (med($\delta S_{intr}/\delta t$)), km^2/day (c), and ratio of intrusion area to area of its convex hull (med(S_{intr}/S_{CH})) (d) corresponding to position of centroids at individual moments of time in 0.5° × 0.5° cells.

events were traced from the moment when their center was near 50° N. The centroids of such patches in most cases reached 53.0°–54.5° N. Spatial analysis of the variability of other parameters of the intrusions was performed with the binning of their centroids into 0.5° × 0.5° cells and the calculation of the median values of each parameter within the cell.

The region in which the centers of the main intrusions passed when they reached their largest area was located within 51°–52° N, 152.5°–154.0° E in the easternmost part of the study region (Fig. 10b). Thus, it can be concluded that the waters corresponding to the largest POW inflow events are confined toward the Kamchatka coast. This is confirmed by the information presented in Fig. 4. Intrusions with an area growth rate of over 500 km^2/day were located in the area northwest of Paramushir Island (Fig. 10c). Probably, the fastest growing intrusions are formed by the simultaneous inflow of water through the Fourth Kuril and Krusenstern straits. With further advancement to the north, after reaching 51.0°–51.5° N, a vast region of decreasing POW patch area elongated in the latitudinal direction was observed.

DISCUSSION

Comparison of the Proposed Methods for Analyzing Pacific Ocean Inflows

In this paper we use two approaches to the analysis of Lagrangian indicators of water parcels in the study region. The simpler and faster of them is associated with the selection of water parcels with a travel time after entering the sea in a certain range and the subsequent determination of the center of mass of the geographic region occupied by these parcels. Despite the simplicity of this approach, it allowed us to characterize the seasonality of the process of POW propagation to and distribution in the Sea of Okhotsk. The second method, associated with the implementation of parcel's grouping for each date using cluster analysis in the space of normalized λ_0–T values using the DBSCAN method, combining water parcels into study regions, removing small individual fragments, and subsequent calculation of several geometric parameters of the resulting study regions, requires much more computer time. However, it allows for a more detailed description of the development of inflow events. At the same time, the results of these two methods are partly comparable. For example, both methods allowed us to conclude that the inflow of Pacific waters was most intense in 2003, 2010, and 2017, and was generally more intense in 2010–2022 than in 1997–2010. Thus, for the tasks that do not require detailed tracking of changes in the shape and location of the area occupied by POW over time, the first analysis option is more suitable.

Disadvantages of the Intrusion Detection Method

The second version of the analysis allows us to describe in detail the evolution of individual intrusions formed by POW, but in the form proposed here it has several disadvantages. The main one is the impossibility of tracing the history of the POW patch from the moment of its appearance at the southern boundary of the study region. This is because clustering by the DBSCAN method in the used version can lead to the disintegration of large groups of parcels into smaller ones or the unification of several small groups into larger ones on successive dates. This is partly due to the use of fixed values of the DBSCAN parameters with constant changes in the distribution features of parcels in the $\lambda_0 - T$ space. One of the possible ways to improve the proposed algorithm can be a dynamic choice of the search radius ε and the minimum number of neighbors depending on the distribution features of λ_0 and T on each date under study.

Comparison of Results with Previous Studies

The results on the seasonal shift of the centroid in the region occupied by POW near the western coast of Kamchatka are in a good agreement with the previous results. For example, it was shown in [10] based on two years of data that the core of the West Kamchatka Current (WKC) is confined to the continental slope in the cold half of the year and moves away from the slope in summer. The advantage of presented analysis is that it characterizes the position of POW on each day for more than 24 years.

The results on the interannual variability of the Pacific Ocean water inflow into the sea are generally in good agreement with the evolution of the WKC water transport in the winter season estimated in [4]. In the years with increased WKC intensity (2010, 2013, 2015, and 2017), we observed a more northern location of the POW centroid with T from 30 to 180 days and intrusions with a larger maximum area. However, there are also discrepancies between our results and the data of Kolomeitsev [4]. For example, the results presented in this paper show that in 2003, an extensive POW intrusion was observed, which is not confirmed by the previously presented values of the intensity of WKC water transport. This may be because the data analysis in [4] is limited to 153° E.

Influence of the Intensity of Pacific Ocean Water Inflow on Biota

Despite the general understanding of the significant role of currents in the study region in the transport of heat, chemical compounds, and zooplankton [2], as well as the relationship between the intensity of the Pacific Ocean inflow and the survival rate of juveniles of the main commercial species [7, 11], this issue has not been studied in detail. In publications concerning changes in the ecosystems of the study region and the Sea of Okhotsk as a whole, the influence of currents on the state of plankton and nekton communities is barely mentioned [3, 12]. This is due, in particular, to the sparseness of in situ observations of currents [3]. Therefore, satellite data on current variability are of extraordinary importance, and the approach to describing the variability of Pacific Ocean water inflow into the Sea of Okhotsk presented in this study can potentially be used in future research of changes in the ecosystems of the eastern Sea of Okhotsk.

CONCLUSIONS

The paper studies the variability of POW propagation and distribution in the Sea of Okhotsk. Annual water inflow events form spatially limited regions of POW (intrusions). On maps, these areas are represented by POW patches, and their digital representations are polygons. The main objectives of this paper are related to the allocation of these polygons, determination of their characteristics and description of their evolution.

The paper is based on altimetry satellite data on currents, with the use of which the trajectories of a numerous virtual water parcels were calculated for 400 days before the observation date on a daily basis for the interval from January 31, 1997, to April 17, 2022. Two approaches to assessing the variability of POW transport in the eastern Sea of Okhotsk are proposed. The indices of variability of the inflow and spread of Pacific waters in the sea obtained with their help are analyzed. It is shown that the spread of POW in the meridional direction has a more pronounced seasonal component than in the zonal direction. “New” Pacific waters spread farthest to the north in 1998, 2003, 2010, 2013, 2017, and 2019. That is, since 2010 there has been a tendency for waters from the Pacific Ocean to move further north into the sea than before 2010.

For each date from the studied time interval, the parcels were grouped using cluster analysis based on the data on the region of entry into the sea (the intersection of the conditional transect) and the time interval between entry into the sea and observation. These groups correspond to POW patches and are represented by polygons on the map. They are differing in terms of the life history of the parcels consisting the group, namely the region and time of entry into the sea. Several parameters were calculated that characterize location, size, and shape features for each such polygon on each observation date. The median travel time of the parcels of POW intrusion remains almost unchanged, as more and more parcels are added to the patch along with the northward transport and aging of some parcels. The shape of the region occupied by POW rapidly becomes more complex after it reaches its maximum area, i.e., after losing its connection with Pacific waters. A gradual shift of the patch centroid in the northward direction is observed, accompanied by a further, but less rapid, complication of its shape. The main area of intrusion motion is in the range 152°–154° E. The largest areas occupied by POW were observed in 2003, 2010, 2017, and 2019. In general, larger POW inflow events were observed in 2010–2022 than in 1997–2010. This suggests that the amount of Pacific Ocean water inflow into the sea was higher in 2010–2022 compared to 1997–2010. This result is consistent with the further northward advance of POW since 2010.

In the region considered in this study, the spread of waters from the Pacific Ocean plays a key role in changing the ecosystem and can potentially determine the state of commercial fish stocks. However, approaches to describing the spread of POW have been previously absent. In this paper, methods for describing the features of POW propagation in the sea are obtained, allowing us to track changes during water inflow and spread with high temporal discreteness. Thus, the quantitative indices of the spread of Pacific waters into the Sea of Okhotsk have a high potential for describing the variability of ecosystems and the causes of fluctuations in commercial fish stocks in the eastern part of the sea.

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ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This work does not contain any studies involving human and animal subjects.

CONFLICT OF INTEREST

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

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