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HYDROPHYSICAL PROCESSES

On Water Circulation in Tatar Strait[1]

V. M. Pishchal'nik[a], V. S. Arkhipkin[b], and A. V. Leonov[c]

[a] *Sakhalin State University, ul. Lenina 290, Yuzhno-Sakhalinsk, 693008 Russia*
[b] *Moscow State University, Leninskie gory, GSP-1, Moscow, 119991 Russia*
[c] *Institute of Oceanology, Russian Academy of Sciences, Nakhimovskii prosp. 36, Moscow, 117997 Russia*

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Abstract—Numerical modeling with the help of an oceanic model developed in the Bergen University and with mean annual data was used to carry out monthly calculations of water circulation fields in Tatar Strait, to calculate the vertical velocities and horizontal transfer rates between three areas identified within the strait and on its external boundaries. Analysis of calculation results revealed new features in water circulation in the strait (in particular, in winter) and made it possible, for the first time, to jointly evaluate water exchange components on the external boundaries and within the strait.

Keywords: numerical modeling, horizontal and vertical water circulation, seasonal variations, water flow rates on strait boundaries.

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INTRODUCTION

In the context of development of shelf oil-and-gas projects, studying water circulation near Sakhalin coast has received considerable attention in the recent decade. As regards Tatar Strait, this is mostly due to the need to evaluate the propagation of possible emergency oil spills with the aim to prevent environmental catastrophes (year-round oil transportation by supertankers has been carried out from De-Kastri seaport since December 2006). Moreover, quantitative characteristics of water circulation are required for modeling many processes taking place in the marine environment and solving various applied problems. To do this, one needs to know the details of seasonal rearrangement of water circulation in the strait.

Most studies of water circulation in Tatar Strait give results mostly based on mathematical modeling [2, 3, 7, 14, 18, 20, 25]. This is due to the extremely small amount of instrumental observations of currents in the strait. Analysis of the modern literary sources allows the seasonal variations of the general water circulation scheme in Tatar Strait to be described as follows.

Warm waters of the northern branch of Tsushima Current enter the eastern part of the strait from the south all year round. The core of the main water flow, whose intensity varies within the year in accordance with the general velocity variations in the current as a whole, is located at the depth of 50 m. The current moves northward along 141°N. Upon reaching the latitude of Moneron Island, the current bifurcates: its smaller part runs around the island and returns into La Perouse Strait, while its major portion moves northeastward and, reaching the abrupt denting near Slepikovskogo Cape (Fig. 1), turns westward. After the turn, the major water flow bifurcates again. Its smaller branch, deviating to the right, moves away from the continental slope into the northern part of the strait (along the slope of a deep trough). The major portion of this flow continues moving westward and southwestward and, reaching the continental coast gives rise to the Primorskoe Current.

Velocity estimates of the Primorskoe Current based on diagnostic calculation data show them to be minimal in the surface layer in summer (1–3 cm/s). The current can be seen as a single flow, (with velocities of 10–15 cm/s) running along the outer boundary of the continental shelf, only below the horizon of 75 m. In autumn, the velocity in its surface layer increases to 10 cm/s, and maximal velocities are recorded in winter, when they reach 30–40 cm/s [3, 14].

Some authors also identify in all seasons the cold West Sakhalin current along west coast of Sakhalin Island to the south of Lamanon Cape down to depths of ~100 m, with maximal velocities from 20 (in winter) to 40 cm/s (in summer) [3, 16].

Thus, the main feature of general water circulation in the southern deep-water part of the strait in all seasons is the motion with cyclonic direction and a quasi-steady anticyclonic vortex (with a characteristic diameter of 40–50 miles) around Moneron Island. The maximal current velocities in the northern branch of the Tsushima Current on the surface are recorded in June–August. The calculated current velocities also vary within wide limits—from 20–25 [14] to 60–75 cm/s (sometimes, >100 cm/s) [3].

[1] The translation of this paper was edited by the authors.

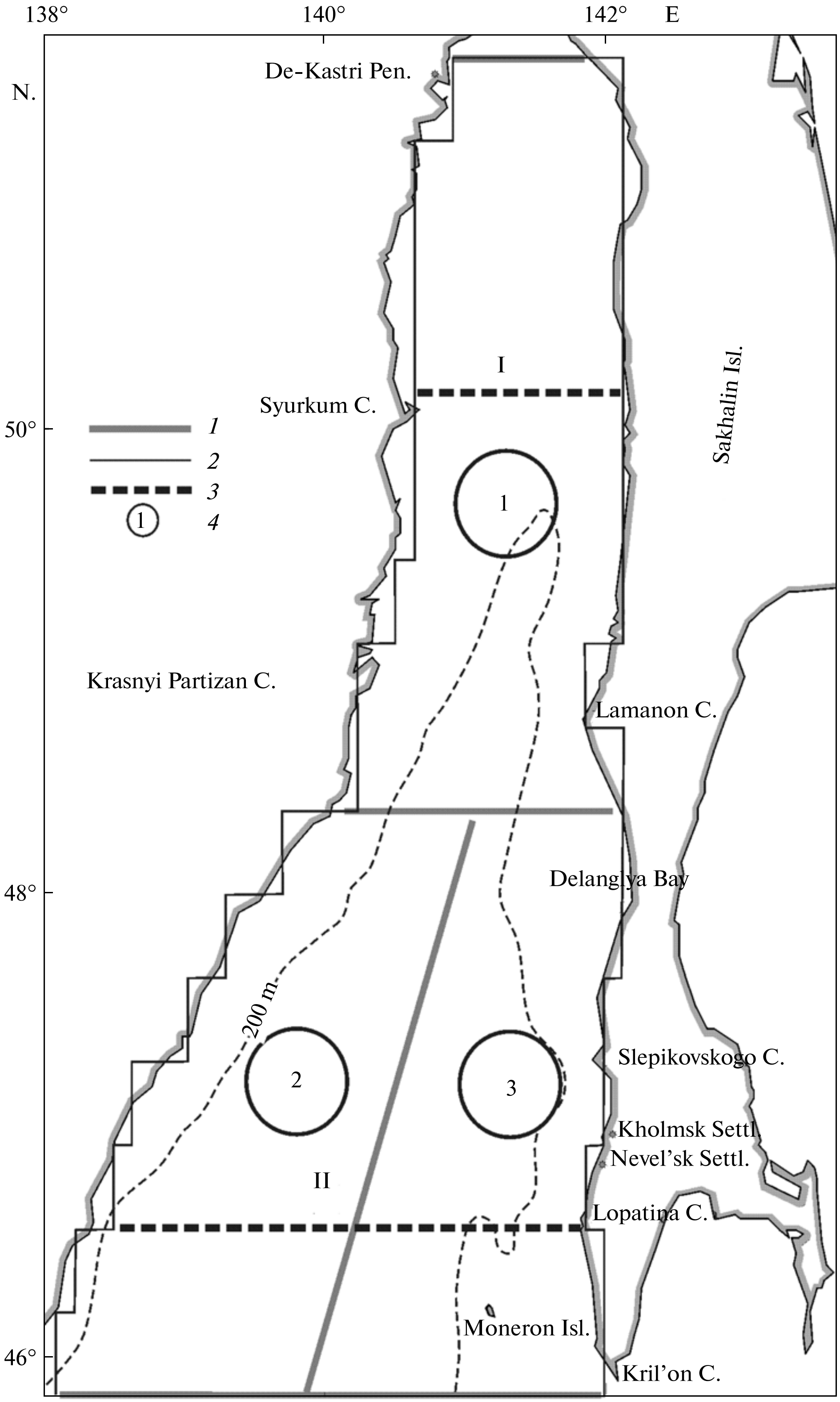

Fig. 1. Areas 1–3, boundaries of the grid domain and the layout of cross-sections in (I) the northern (along 50.158°N) and (II) southern (along 46.544°N) part of Tatar Strait. (*1*) Boundaries of areas, (*2*) boundaries of model grid, (*3*) cross-sections, (*4*) numbers of areas.

Water circulation with predominantly cyclonic direction forms in the shallow northern part of Tatar Strait (north of 49°N). The western branch of this circulation is more distinct than that near Sakhalin shore. The Russian researcher L.I. Schrenk was the first to describe the current near the northwestern shore of the strait (1874). He called it the Limanskoe Current. According to the results of diagnostic calculations [14], the velocity of this current (which was later rightly called the Schrenk Current [20]) increases from the spring to the summer from 5–7 to 7–9 cm/s and further drops to 4–5 cm/s by the autumn.

Radical changes in the general water circulation in the northern part of Tatar Strait take place in autumn, when the inflow of fresh water from the Amur through Nevel'skogo Strait increases many times. Calculations show [14] that in late October–early November, a mesoscale anticyclonic vortex forms north of 50°N with a flow of freshened water on its eastern margins moving to the south direction along west coast of Sakhalin Island with a velocity of up to 20 cm/s between the surface and the depth of 20–30 m. At the latitude of Lamanon Cape, this flow diverges southwestward and, crossing the strait, empties into the Primorskoe Current, appreciably reducing its water salinity in the surface layers.

Current velocities gradually decrease with depth. An additional feature, characteristic of shallow areas (with depths up to 50 m) is the restructuring of current fields accompanied by changes in the direction of water movement [24].

In conclusion, we note that no detailed studies of water circulation in Tatar Strait have been carried out in winter, and the data on current available now, which have been obtained with the use of drifting buoys, cause growing doubts in researchers regarding the reliability of the results of water circulation model calculations made using many-year hydrological information [7, 19].

This study is a logical continuation of a series of publications involving the application of the systems approach and up-to-date models to a comprehensive analysis of the state of marine environment in Tatar Strait based on expedition data collected in the past 50 years. Numerical modeling of water circulation was carried out for each month with the use of the Bergen University Oceanic Model (BOM) based on mean monthly thermohaline fields [13]. Considering the current knowledge of the hydrophysical and hydrobiological processes taking place in the Sea of Japan as the whole [4–6], Tatar Strait was divided into three areas ((1) northern area, (2) southwestern area, and (3) southeastern area). Horizontal water transfer rates (water flow rates) between the areas within the strait and through its external boundaries were calculated for two layers, whose bottom boundary depths were evaluated separately for each month [11, 13].

This paper gives and analyzes modeling data characterizing the seasonal distribution of water circulation in winter (February 26), spring (June 26), summer (August 26), and autumn (November 26), as well as the vertical distribution of meridional components of current velocities at two cross-sections, which best characterize the flows in the shallow northern and deep-water southern parts of the strait (cross-sections I and II, respectively, Fig. 1).

MATERIALS AND METHODS

The input data for the reconstruction of thermohaline fields were taken from observations on a network of standard oceanographic cross-sections carried out with a frequency of 2–3 to 6–8 times per year since the late 1940s to the mid-1990s. The total number of deep-sea hydrological stations made in this period in the strait at seven latitudinal cross-sections spaced 30–60 miles apart is ~7000 [13, 15]. Statistical methods were used to calculate, for each station at all standard horizons (from the surface to the bed), long-term monthly means of water temperature and salinity, which were next used to reconstruct these characteristics in the nodes of a regular grid with the help of numerical modeling. Three-dimensional, nonsteady-state, nonlinear, numerical oceanic model BOM in σ-coordinates was used for this purpose. The atmospheric pressure, wind stress, and the fluxes of heat and salts were not specified in the modeling. The Neumann condition was specified at the liquid boundaries for current velocities, temperature, and salinity. The steps on calculated grid along the x and y axes were 10 and 40 km, respectively. Thirty-two σ-horizons were specified in the vertical between the surface and the bed.

The major advantage of this approach is that water temperature and salinity at individual oceanographic stations remain constant at each calculation step. In the nodes of the regular grid not coinciding with stations, those characteristics are evaluated taking into account the specified values at the stations and the water circulation calculated at the same step taking into account the bed topography and basin configuration. The calculations will be ceased when the values of sea level and currents became stationary in all nodes of the regular grid.

WATER EXCHANGE THROUGH THE NORTHERN BOUNDARY OF TATAR STRAIT

Water transfer through the northern boundary of Tatar Strait is largely determined by the hydrological regime of Amur mouth area. Therefore, it is of use to consider the specific features of its functioning with the aim to elucidate the causes of difference between the available estimates in water flow rates through this boundary (Table 1).

Amur mouth area at the river's emptying into the sea is divided into the mouth area of the river, the submarine delta, and the nearshore area. The upper

Table 1. Mean monthly values of water flow rates, km^3, at the Amur Liman–Tatar Strait interface evaluated by mean annual data in [26, 11] (minus means flow direction from north to south)

Total water flow according to	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
[26]*	–7.0	–5.3	–3.7	–2.5	–7.9	15.6	15.6	3.8	10.8	–0.9	–13.4	–10.4	–5.3
[11]	–0.7	–0.3	–0.2	–0.1	–46.9	–70.5	–97.3	–128.1	–27.3	–13.6	–14.5	–12.7	–412.2

* calculations were carried out by balance method taking into account salinity difference between the Amur Liman and Tatar Strait.

boundary of the mouth area of the river is identified by the tide propagation distance in it and is conventionally taken to be bounded by the cross-section in Mariinskoe Village; in the lower part, this is the cross-section of Gilyak Cape–Bol'shoi Chkhil Cape. The submarine Amur delta is a network of large and small water streams–fairways of both the delta itself and the Amur Liman. The most considerable water streams in the submarine Amur delta are the fairways Southern, Nevel'skogo, Eastern, Gavrilovskii, Nerpichii, and Khussinskii. The nearshore includes the Sakhalin fairway of the Amur liman (with shallows between the Sakhalin Fairway and Sakhalin Island shore) and areas of the Sea of Okhotsk (with the northern boundary of the nearshore area running from the base of Petrovskaya Spit in the northeastern direction to the 20-m isobath, next eastward and southeastward along this isobath toward Ush Island in Sakhalin Bay) and the Sea of Japan (with the southern boundary of the nearshore area along the line from Yuzhnyi Cape to Tyk Cape in Tatar Strait), adjacent to Amur Liman [10].

The river's mouth area is 250 km in length. A short distance upstream of the mouth cross-section, the main branch of the river separates into two branches—the Northern and the Southern—which empty into the Amur Liman separately [9]. The Amur is 15 km in width in the mouth area between Tabakh Cape in the north and Pronge Cape in the south [22]. In the mouth area (near Tabakh Cape) the Northern Branch separates into three fairways, two of which (Nevel'skogo and Nerpichii) carry out water to the north into the Amur Liman, while the third (Gavrilovskii) fairway flows southward within the mouth area. Abeam Pronge Cape, water from the Gavrilovskii fairway merge with water from the Eastern fairway and flows into the Amur Liman. Water of the Southern Branch downstream of Pronge Cape flows into the Amur Liman via the Southern fairway and next flows southward [9].

The Amur Liman in the mouth area of the Amur is a separate geographic feature. This is a vast basin (between the continent and the western shore of Sakhalin), connecting the Sea of Okhotsk and the Sea of Japan. The total length of the Amur Liman, elongated in the meridional direction is ~180 km, and its maximal width is ~50 km. According to zoning of the Amur mouth area, the Amur Liman includes part of the submarine delta and part of the river's nearshore area. The major portion of the Amur Liman is shallow, filled with banks and shallows, between which the narrow and sinuous fairways of Southern, Sakhalinskii, Nevelskogo, Nerpichii, Eastern, and Khussinskii are flowing. In the liman, these fairways serve as continuations of the Amur submarine delta [9, 10].

In the summer, ~91% of river runoff enter the Amur Liman through the deep branches of the Amur (Northern and Southern), while 9% of runoff flows through shallows. The total runoff into the liman through the fairways of Nevel'skogo, Nerpichii, Eastern, and Southern accounts for 81% (18, 8, 40, and 34%, respectively), while 19% are due to the flow through shallows. The distribution of runoff through the same fairways in winter is 24, 16, 18, and 42%, respectively. However, the winter river runoff into the liman is ~15 times less than that in the summer [22]. Thus, the maximal total runoff in both summer and winter flows through the Eastern and Southern fairways (74 and 60%, respectively).

A characteristic feature of the Amur's mouth area is that it is functioning as a whole system, whose water mass dynamics is governed by several input parameters (river runoff volume, the differentials between water levels and densities at the offshore boundaries of the mouth area, wind velocity and direction, the presence of ice cover, bed roughness, the magnitude and phase of tides at the offshore boundaries of the Amur Liman). A change in one or several out of these parameters leads to changes in the properties of the entire system, considerable rearrangement of its water dynamics, and, through this dynamics, to changes and development of channel processes as a whole [10].

It is sufficient to mention that water runoff in the head of the river mouth area, which determines some other important characteristics (sediment runoff, water surface slopes, and water levels), may change by a factor of several tens! The hydrological phases that can be isolated in it are as follows: winter low-water period, spring–summer flood, summer low-water period (only in dry years), and summer–autumn flood. The open-channel period (May–October) accounts for 86.8% of river runoff, while the runoff in the under-ice period (December–March) is insignificant [10].

The characteristic width of the Amur Liman in the north (35–40 km) and the south (7–8 km in Nevel'skogo Strait) largely determines the resulting water transfer in the liman in the summer from the south to the north, the river runoff inflow in the northern part of the liman (through the Nevel'skii and Nerpichii fairways) and in its southern part (through the Southern fairway) being the same [10]. The narrow and shallow (~7 m) Nevel'skogo Strait is incapable of passing the entire volume of summer river runoff; therefore, its considerable portion spreads from the Amur Liman into Sakhalin Bay and moves to the northern extremity of Sakhalin Island along its northwestern coast [17].

The existing opinions about water exchange between the seas of Okhotsk and Japan, in particular, about the directions of water motion in the Amur Liman, are contradictory, because different researchers take into consideration different factors.

Analysis of observations of the winter of 1970 an the summer of 1973 (at 15 buoy stations in Nevel'skogo Strait and at the northern boundary of the Amur Liman with continuous runoff series no less than 7 days in duration, as well and mean daily winter and summer measurements of Amur water runoff at the gage near Bogorodskoe Village) were used to calculate the nonperiodic components of water transfer through the northern and southern boundaries of the liman. It was found that water flow near the continental coast is steadily directed southward, while that near Sakhalin is directed northward. The zone of southward water flow in Nevel'skogo Strait persisted in the summer, though with a smaller area. However, under southern winds, water transfer in the summer from the south to the north in Nevel'skogo Strait can increase 10–15 times [21].

Balance calculations based on the water salinity difference between the Amur Liman and Tatar Strait showed that the water transfer in Nevel'skogo Strait was directed from the north to the south in January–May and October–December and from south to the north in June–September [26]. Calculations carried out in this study showed the resulting direction of water transfer through the north boundary of the grid area, located ~30 miles to the south from the center of Nevel'skogo Strait (Fig. 1), remains unchanged during the year—from the north to the south—with water runoff ranging within 0.1–12.7 (with a mean of 6.4) in December–March and within 27.3–128.1 (77.7) km^3/month (with the ratio of 12 on the average) in May–September (Table 1).

The estimates of water flow rates through the northern boundary of Tatar Strait obtained by different methods for the winter have the same direction but somewhat differ in their magnitudes, while those for the summer are completely different (in both the direction and the rate of transfer). The different factors used in the procedures applied to estimating water flow rates determine the difference in estimates of these characteristics for the summer period, when the impact of different factors on water transport in Amur mouth area is especially significant (e.g., the effect of higher river runoff).

It is worth mentioning that Amur mouth area and its parts near the boundaries with nearby marine zones are areas with nonsteady currents (with large differentials in the directions, velocities, and water chlorinity/salinity), whose formation is especially typical of the summer period under the joint impact of all identified factors. An example is a series of observations in the southern part of Amur Liman (Nevel'skogo Strait) in June–September 1968–1970 (9 series in total) at horizons of 0, 2, 5, 10, 15, and 19–21 m, at which differently directed transfer of seawater or mixed (river and sea) water was recorded (Table 2) [12].

In six series out of the nine, water transport in the water column had the same vertical direction: three cases with a southern (to *S-SSW*) and three cases with a northern (*NNE–NNW*) direction, and three series with different directions at individual horizons (sometimes, opposite). The averaging of data over the same directions have shown the velocities of flows with southern directions at different horizons to vary between 29 and 129 (with a mean of 65) cm/s, and water chlorinity, from 3.59 to 18.11 (14.39)‰. The respective values of flows with near-northern direction were 18–106 (62) cm/s and 10.84–18.35 (15.50)‰. These data show that, even with the steady vertical transfer, the values of other characteristics (in this case, the velocity and chlorinity) at individual horizons may vary widely. That is why, the motion and transfer of water masses in the strait cannot be characterized based on a single characteristic.

The analysis of data presented above allows the following conclusion to be made: when water flow rate in the head of Amur mouth area is large in the summer, the entire water mass of the Amur cannot pass through the narrow Nevel'skogo Strait, and part of it flows through the wider part of the Amur Liman into Sakhalin Bay. Many authors use the term *resulting transfer*, assuming that water transfer in the liman is mostly directed northward, seemingly ignoring that its considerable portion also moves southward. The opinion that the resulting water transfer in the liman is northward in the summer was formulated by L.P. Yakunin in the 1980s and was repeated later in other publications. However, it is clearly stated in the most recent generalizing study of the hydrology of the Sea of Japan [7] that water transfer in summer is directed southward from the Amur Liman to the Sea of Japan to Nevel'skogo Strait. This opinion appears quite justified, as can also be seen from the authors' calculations (Table 1).

ANALYSIS OF THE RESULTS OF MODELING SEASONAL WATER CIRCULATION IN TATAR STRAIT

Analysis of calculation results shows that there is almost no vertical stratification of water temperature

Table 2. Parameters of transfer and mixing of sea and river waters in the southern part of Amur Liman (Nevel'skogo Strait) (dash means no data available) [12]

Date	Parameter	Horizon, m						Note
		0	2	5	10	15	19–21	
June 22, 1968	Time of day	12.28	12.28	12.33	12.37	12.43	12.50	Laminated structure, differently directed transfer: 0–5 m, to *NNW–N*; 10–15 m, to *S*; 19–21 m, to *NW*
	Direction, grad	–	322	7	177	177	307	
	Velocity, cm/s	–	26	16	14	10	10	
	Cl, ‰	17.70	17.21	17.26	17.36	17.41	17.86	
July 12, 1969	Time of day	12.14	12.18	12.21	12.25	12.30	12.35	In layer 0–15 m, transfer to *N–NW*; at the bed, to *N*
	Direction, grad	20	4	25	7	7	352	
	Velocity, cm/s	77	82	71	76	67	44	
	Cl, ‰	16.95	16.99	17.05	17.05	17.09	17.10	
Aug. 1, 1968	Time of day	14.16	14.16	14.19	14.22	–	14.26	In layer 0–2 m, transfer to *NW*; in layer 5–21 m, to *NNE*
	Direction, grad	–	297	49	37	–	27	
	Velocity, cm/s	–	35	49	38	–	18	
	Cl, ‰	18.17	18.35	18.30	18.25	–	18.26	
Aug. 16, 1968	Time of day	11.08	11.08	11.11	11.14	11.17	11.20	In water column, transfer in one direction to *SSW*
	Direction, grad	–	197	197	195	194	195	
	Velocity, cm/s	–	54	52	44	40	33	
	Cl, ‰	18.02	18.00	18.05	17.90	18.05	18.05	
Sep. 25, 1969	Time of day	16.18	–	16.21	16.25	16.32	16.38	In layer 0–5 m, transfer to *E*; in layer 10–21 m, to *SSW*
	Direction, grad	87	–	92	217	206	199	
	Velocity, cm/s	16	–	12	7	10	14	
	Cl, ‰	4.15	–	4.25	4.90	4.35	4.40	
Aug. 13, 1968	Time of day	15.25	15.28	15.34	15.39	–	15.54	In water column, transfer in one direction to *S–SSW*
	Direction, grad	193	189	205	204	–	174	
	Velocity, cm/s	56	69	57	47	–	29	
	Cl, ‰	–	3.59	4.04	4.54	–	5.28	
June 27, 1970	Time of day	04.50	04.55	04.57	05.03	05.06	05.11	In water column, transfer in one direction to *N*
	Direction, grad	357	2	357	355	357	352	
	Velocity, cm/s	62	79	106	79	75	34	
	Cl, ‰	10.84	11.40	12.66	12.17	11.95	11.79	
July 22, 1970	Time of day	21.20	21.16	21.12	21.08	21.05	21.00	In water column, transfer in one direction to *S–SSW*
	Direction, grad	187	197	180	199	189	185	
	Velocity, cm/s	96	90	96	81	74	129	
	Cl, ‰	17.36	17.24	17.24	17.43	17.29	18.11	
Aug. 14, 1970	Time of day	10.28	10.25	10.20	10.15	10.11	10.08	In layer 0–10 m, transfer to *S*; at 15 m, to *SW*; at 19–21 m, to *NW–W*
	Direction, grad	187	187	187	177	237	290	
	Velocity, cm/s	69	46	39	16	15	29	
	Cl, ‰	14.69	14.99	15.33	15.97	16.36	16.31	

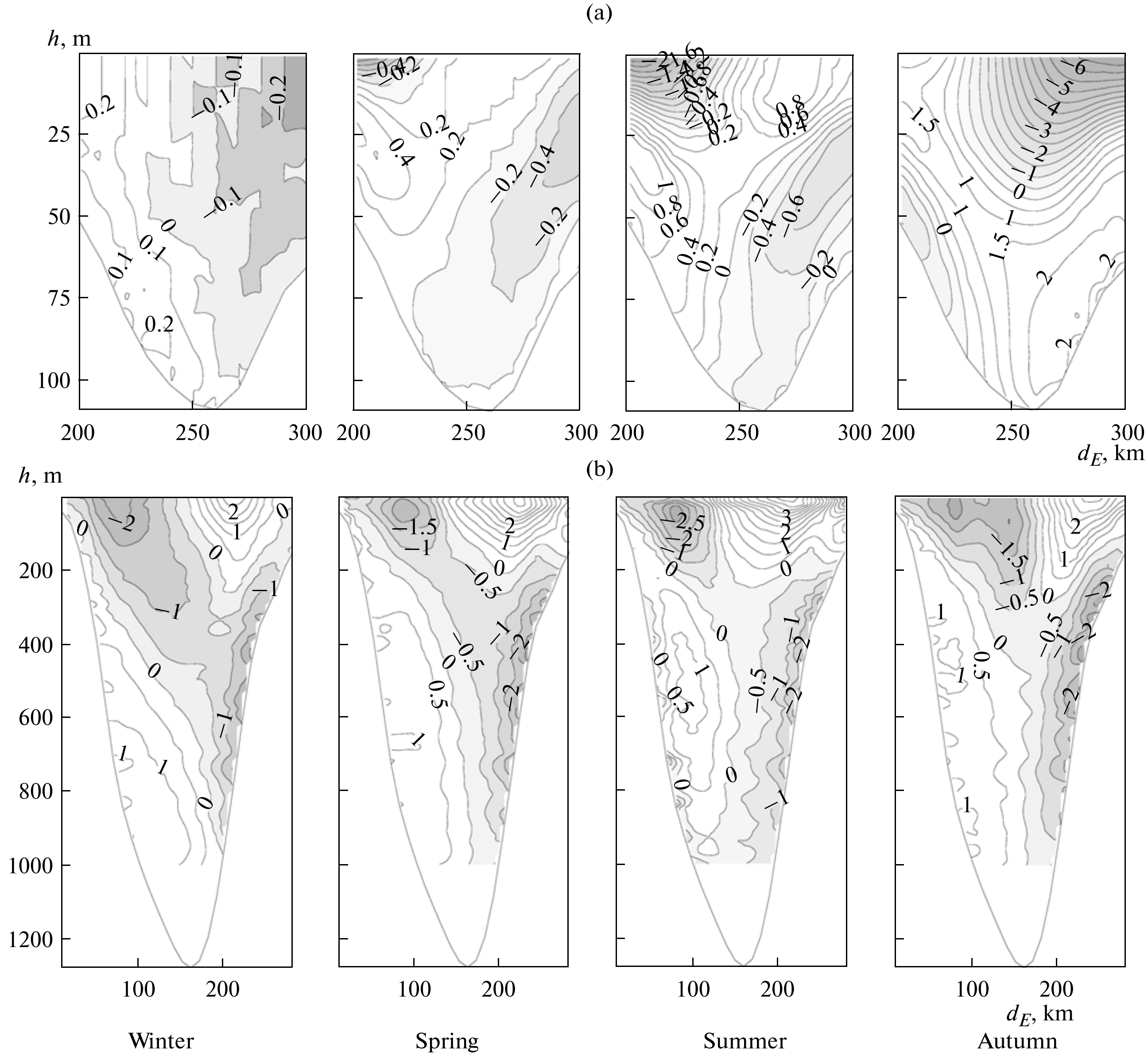

Fig. 2. Distribution of meridional component of flow velocity, cm/s, in cross-sections (a) I and (b) II over seasons. Shaded domains are for southward water movement (here and in Fig. 3, winter means February 26, spring means June 26, summer means August 26, and autumn means November 26; h is depth, m; d_N, d_E are the distances from the initial node of the calculation grid to the north and east, respectively, km).

and salinity in the northern, shallow part of Tatar Strait in mid-winter because the convective mixing here spreads down to the bed. At the same time, a weak anticyclonic water vortex with the meridional components of flow velocity of ~0.1–0.2 cm/s exists throughout the water depth to the north of 49°30′N in the presence of ice cover (Fig. 2a).

In the spring, with the formation of vertical water stratification and a change in monsoon circulation, mostly cyclonic vortex forms in the surface layer of the northern part of the strait and an anticyclonic vortex forms in the lower water layer. At the same time, a jet of the Schrenk Current can be clearly seen along the continental shore at a distance of up to 30 km and a depth up to 20 m (Fig. 2a).

From the spring to the summer, the intensity of the upper water vortex increases more than twice (the meridional components of velocities in the Schrenk Current increase from 1.0 to 2.2 cm/s with a simultaneous increase in the width of its major jet up to 50 km and depth to 30 m). In the summer, the northward flow comes to Sakhalin coast and the meridional velocity components in it also increase twice (from 0.4 to 0.8–0.9 cm/s). At the same time, almost no changes take place in the rates of currents within the antiсyclonic water anticyclonic water vortex in the lower layer in this period (Fig. 2a).

Radical rearrangement of the general circulation takes place in autumn in the extreme northern part of Tatar Strait because of the inflow of a large amount of Amur water—the directions of water motion in the upper and lower layers change to the opposite [14, 15]. In November, the meridional velocity component of water flow moving southward along Sakhalin coast attains its absolute annual maximum (6.5 cm/s). At the same time, a current with the opposite direction and the meridional velocities of ~2.0 cm/s moves along the continental shore (Fig. 2a). Water outflow from the upper layer is compensated for by the intensified inflow of transformed water of the Tsushima Current with the maximal meridional components of flow velocities (up to 2.0 cm/s) into the lower layer along Sakhalin coast in the northern part of the strait. This is the major cause of the change from anticyclonic to cyclonic direction of water motion.

In December, the autumn flood in the Amur comes to an end and ice cover starts forming; Amur water flow through Nevel'skogo Strait drops almost 20 times, causing an abrupt drop in the intensity of the southern water flow along Sakhalin coast in the surface horizons. Against the background of the seasonal decrease in the general intensity of the Tsushima Current, the compensating inflow of Tsushima water in the bottom horizons into the northern part of the strait first declines and next stops completely. Hence, no cyclonic water circulation forms in the bottom horizons any more. Therefore, weak water circulation with anticyclonic direction forms in winter from the surface to the bed and persists until the complete destruction of ice cover and the beginning of summer monsoon development (late March–early April).

Calculation results show that, unlike the shallow part of the strait, a two-layer water circulation system exists in all seasons in the southern, deep-water part of Tatar Strait (up to ~48°30′N) (Figs. 2a, 2b)—the circulation in the active layer is cyclonic, while that in the lower layer, anticyclonic. Only changes in the intensity and configuration of water flows themselves take place from month to month.

In cross-section II in the southeastern part of the strait, in all seasons, down to the depths of 200–250 m, a jet of the Tsushima Current water can be clearly observed (Fig. 2b), moving northward, as it will be shown below. The width of the current is minimal in the autumn and winter (~120 km) and maximal in the spring (~170 km). In warm seasons, the flow intensity is maximal in surface horizons (0–100 m). The largest values of meridional velocity components in the currents were observed in August and the least in February (up to 5.5 and 2.8 cm/s, respectively). It is worth noting that, with an increase in the intensity of the main flow in the Tsushima Current near Slepikovskogo Cape, the vertical velocities of water sinking increase as the compensation for the growing backwater effect and the flow rate in the jet, which deviates to the right and forms a distinct alongshore southward current. In May, it can be detected first in subsurface horizons (at depths of 40–50 m), and in the period of its maximal development, in the entire surface layer. Its width is ~15 km, and the meridional velocity component is >1.0 cm/s.

The joint analysis of the distribution of meridional velocity components of currents on the latitudinal cross-section along 48°30′N and water circulation at horizons 0 and 50 m (Figs. 3a and 3b) allows us to conclude that in winter, water mostly flows from the northern to the southern part of the strait all over the latitudinal cross-section from the surface to the depth of 50 m near coasts and to 200 m in the center. A compensation inflow of Tsushima water with higher salinity takes place in the lower layer. The maximal northward flow velocities are observed at depths >100 m along both slopes of the deep-sea trough (the values of the meridional velocity component vary from 1.4 to 1.6 cm/s). The maximum of the southern flow with the meridional velocity component >2.5 cm/s tends to the surface and lies above the boundary of the insular shelf, where it forms local compensation vortices with cyclonic rotation and water rise in their centers.

The stable mesoscale anticyclonic vortex in the spring in the upper layer near Delanglya Bay forms a southward current along Sakhalin coast up to 40 km in width, manifesting itself down to the depth of ~100 m. Water motion in the central, deep-sea part of the cross-section (Fig. 3a) is northward in this period. The meridional velocity components of both flows are comparable and reach 1.2 cm/s in their maximums. A southwestward current persists along the continental coast.

Water motion in the summer above the deep-sea trough down to the depth of 200 m is mostly northward. The main jet of this flow is deep, and the maximal components of meridional velocity (>1.6 cm/s) are observed at 100-m horizon (Fig. 3a).

A winter type of water circulation forms in the autumn: a southward water flow with the maximal meridional velocity components in surface horizons >3.0 cm/s is observed throughout the latitudinal cross-section from the surface to depths of 40–80 m. Next, the lower boundary of this flow sinks to 200 m with a simultaneous decrease in the meridional flow velocity component to 2.5 cm/s (Fig. 3a).

No southward flow takes place in cross-sections south of 48°N in the eastern part of the strait in the layer down to 200–300 m. This means that the West Sakhalin Current, identified by some authors [3, 16] does not exist as a single flow along the western Sakhalin coast (from Lamanon Cape to Kril'on Cape). It manifests itself in individual areas in different months either as the result of formation of sufficiently stable mesoscale vortices (e.g., in the spring in Delanglya Bay), or as the formation of compensation flows 30–

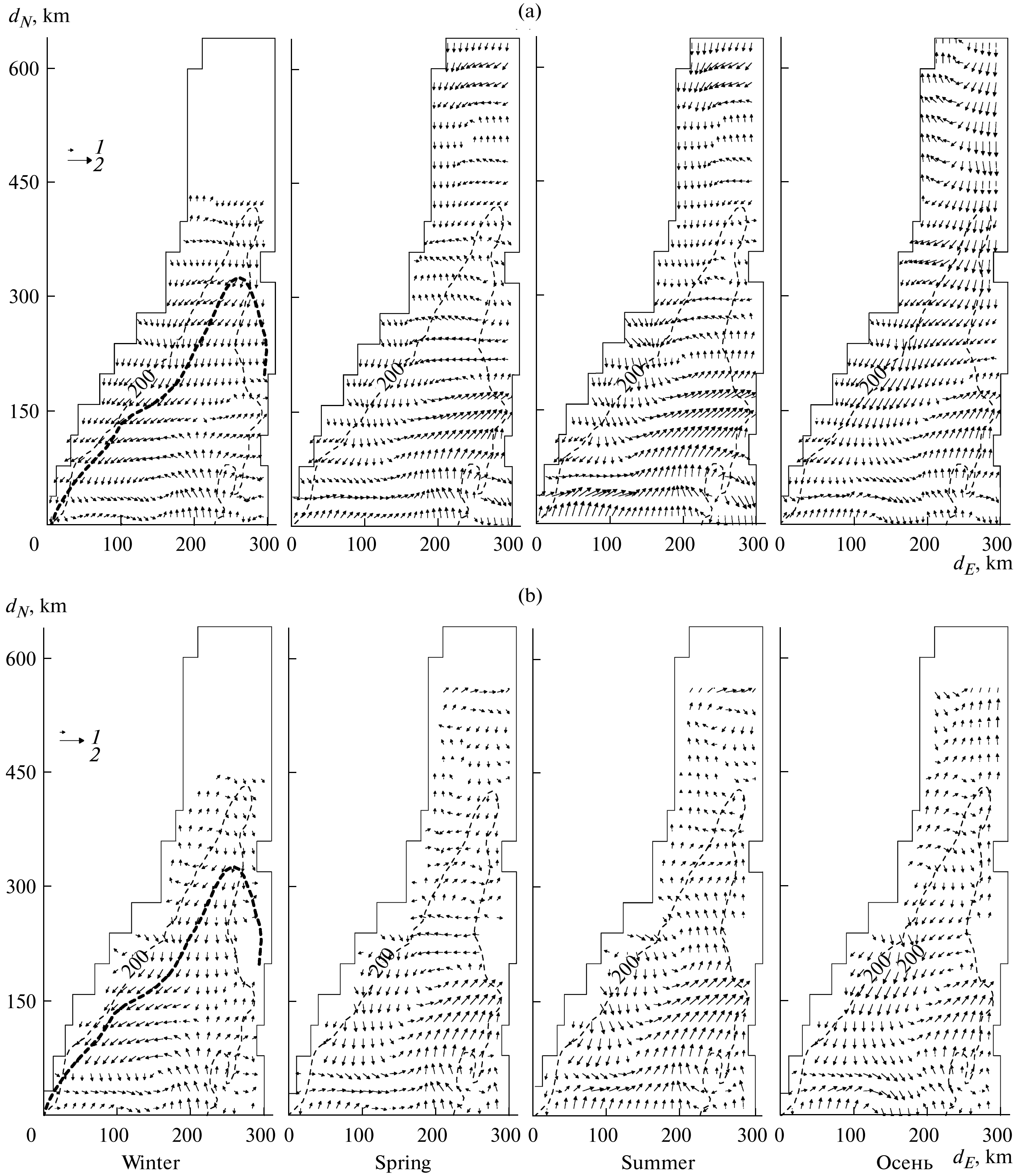

Fig. 3. Calculated water circulation (a) on the surface and (b) at 50-m horizon in Tatar Strait for seasons (thick dashed line is for mean annual position of ice edge [23]; (*1, 2*) are flow velocities 0.05 and 10 cm/s, respectively.

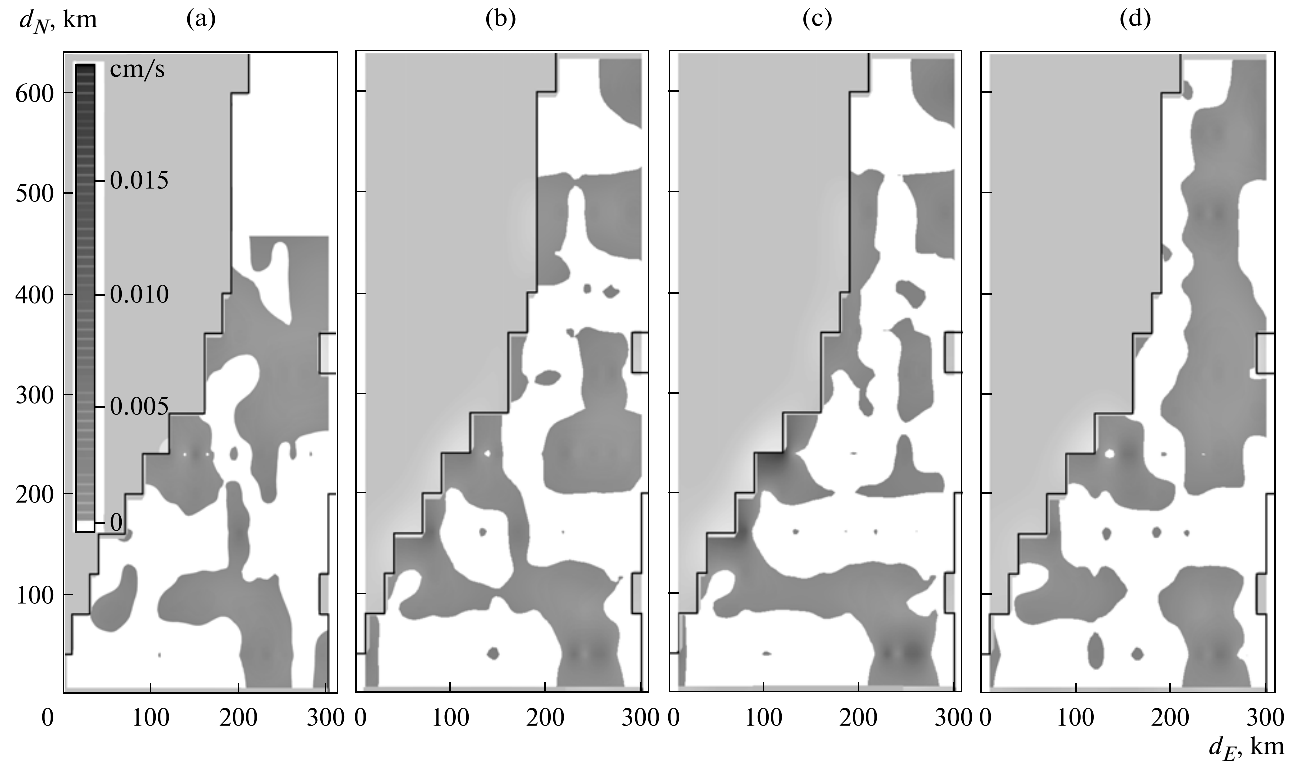

Fig. 4. Vertical motion of waters in Tatar Strait at 20-m horizon over seasons (water sinking areas are shaded). (a) winter, (b) spring, (c) summer, (d) autumn.

40 miles in length, which can be distinctly seen south of Lamanon and Slepikovskogo capes.

The Primorskoe Current can be clearly seen throughout the year in the active layer in the southwestern Tatar Strait; its major jet runs parallel to the coastline at a distance of 50–100 km. Maximal flow velocities are attained in subsurface horizons (50–150 m) in the warm seasons of the year and in surface horizons (0–100 m) in winter. Flow velocities vary synchronously with the intensity of the Tsushima Current: the maximum of meridional flow velocity component (up to 3.0 cm/s) is attained at 75 m in August and minimum (2.2 cm/s) at the surface in February. This fact is a manifestation of the genetic interaction between flows.

The presence of the main jet of the Primorskoe Current in subsurface horizon is the consequence of sinking of the major jet of Tsushima water near Slepikovskogo Cape, which can be clearly seen in the maps of the spatial distribution of vertical flow velocities (Figs. 4a–4d). The maximal velocities of water sinking in the warm season of the year ($>15 \times 10^{-3}$ cm/s) are attained in the 10–15-mile zone near the cape. In winter, the zone of water sinking is located 15–20 mile further to the south and the vertical velocities in it are 2–3 times less.

In lower layers (from the depth of 100–200 m down to the bed), stable northward transfer of water takes place along the continental coast and southward transfer, along Sakhalin coast. Both flows move near continental slope with about the same velocities (the meridional velocity component is 1–2 cm/s), which only slightly vary from season to season (Fig. 3a, b). The maximal velocity of the northern water flow is observed at 500–800 m, and that of the southern flow, at 300–600 m.

Analysis of the calculated schemes of horizontal water circulation on the surface shows that weak anticyclonic water circulation persists in winter in the shallow part of the strait north of 49°30′N. As shown above, this circulation starts forming in October and reaches the maximal development in November (Fig. 3a). The meridional velocity component decrease 20–50 times by winter, though as soon as late March, as can be judged from lower water salinity (by 1‰ on the average), the jet of the Schrenk Current with a characteristics width of the flow of 20–30 km starts forming along the continental coast [13]. Some indirect evidence (including the position of Amur water spreading boundary, which was clearly determined by ice reconnaissance flights) suggests that the Schrenk Current also exists under ice cover in January–February. In the summer, water freshening in the area near the Schrenk Current is maintained due to the contact of seawater on the northern periphery of the cyclonic vortex with river water directly entering Tatar Strait through Nevel'skogo Strait.

Southward water motion dominates in the surface layer all over the northern part of the strait in April. In May, along with the development of summer monsoon, water circulation with cyclonic direction starts forming north of Syurkum Cape. This circulation causes water rise and persists in the area until the beginning of autumn rearrangement of water circulation (until September, inclusive).

A series of mesoscale vortices that form near the southern boundary of the northern area should also be mentioned for the spring period. These are conjugate vortices with opposite rotation directions northwest from Lamanon Cape and northeast from Krasnyi Partizan Cape. The governing role in the formation of the anticyclonic vortex belongs to the coastline configuration (the protruding Lamanon Cape), while that for the cyclonic vortices on the opposite side of the strait is due to their permanent feeding by deep-sea waters entering through the deep trough. This type of circulation persists here throughout the warm season (it is only their scale and intensity that vary).

The formation of the coastal water upwelling in May–September in the coastal areas between Syurkum and Krasnyi Partizan capes has been mentioned before [3, 20, 24]. This upwelling is also reliably identified on satellite maps of surface water temperature. The cause of its formation is the summer monsoon, creating steady alongshore wind. In the northern hemisphere, it causes offshore Ekman water transfer in the surface layer and hence, one-way water divergence in a narrow coastal zone. Mass flux continuity ensures the formation of ascending water motion near the shore and a compensating current in intermediate layers. In the presence of pronounced thermal stratification, the coastal upwelling forms anomalously low water temperature on the sea surface owing to the ascending of deep-sea water [1].

Overall, mean water motion velocity on the surface of area 1 in the spring vary from 2 to 7 cm/s; the maximal velocities, as was shown by the results of earlier model calculations [3, 20], are attained in its extreme northern part. During the ice-free period, water motion at 50-m horizon (Fig. 3b) has an opposite direction relatively to the active layer and the flow velocities decrease by half (1–4 cm/s).

In all seasons, the major factor that forms water circulation in the active layer in the southern, deep-sea part of the strait is the Tsushima water that inflows west of Moneron Island and spreads mostly northeastward. The eastern branch of this flow permanently generates an anticyclonic vortex around Moneron Island with a characteristic diameter of 40–50 miles. The major portion of this flow turns westward at Sakhalin coast (near 47–48°N) and, reaching the western coast, moves southwestward as the Primorskoe Current. The result is the formation of a general vortex with predominantly cyclonic direction in the upper layer of the southern part of the strait; the center of this vortex changes its place from season to season, depending on the intensity of the northern branch of the Tsushima Current entering the strait and the dominating direction of monsoon winds.

In winter, the width of the Tsushima water flow in the surface layer at the southern boundary of Tatar Strait does not exceed 50 km. At the latitude of Lopatin Cape, the flow separates into three branches (western, central, and eastern), resulting in a more than twofold increase in the flow width. The western flow forms a cyclonic vortex 50–60 miles in diameter in the middle of the strait; the center of the vortex lies almost at the same latitude. The major jet of the central flow passes ~30 miles from Slepikovskogo Cape almost strictly northward and, after flowing along the southwestern part of the shallow adjacent to Delanglya Bay, turns southwest at 47°30′N. The weakest, eastern flow reaches the shore of Sakhalin Island and turns southward, preventing the development of ice at the coast between Slepikovskogo Cape and Lopatina Cape, allowing the water areas of the seaports of Kholmsk and Nevel'sk to be classified as ice-free ports (Fig. 3a).

As mentioned above, the decline in the general velocity of Tsushima water flow causes the main zone of water sinking near the southwestern Sakhalin coast to shift 10–15 miles south of Slepikovskogo Cape. In winter, the water sinking velocity here attains an annual minimum (down to 5×10^{-3} cm/s) (Fig. 4a). At the same time, a flow of water from the Sea of Okhotsk clearly manifests itself in the spatial distributions of all characteristics under consideration from the surface to the bed. This flow is strongest in February, when it occupies >2/3 of the strait area between Sakhalin and Moneron islands and has characteristic velocities of 0.5–1.5 cm/s.

The position and configuration of 0°C isotherm in the surface layer follows, as the first approximation, the mean annual position of the ice edge [23]. It is worth mentioning that, by virtue of specific features of ice regime in the southeastern part of Tatar Strait, active ice melting because of the permanent contact with the warm waters of the Tsushima Current takes place throughout the winter on the edge of the ice massif, which is steadily drifting southward under the effect of monsoon. Therefore, the position of ice edge, which can be adequately and promptly determined from satellite images, allows one to judge, as the first approximation, about the propagation boundaries of Tsushima water and to assess the intensity of its flow for prognostic purposes.

In spring and summer, in the period of maximal activity of summer monsoon, water inflows into the strait in the surface layer practically throughout its southern boundary. The only exceptions are narrow coastal zones, where water flows out of the strait. The center of the general cyclonic water vortex shifts 30 miles to the north in the spring and 30–40 miles more to the northeast in the summer and stays in the center of the strait at 47°30′N. In the autumn, as the flow from the northern part of the strait becomes more intense and the activity of Tsushima water flow decreases, the center of cyclonic water vortex gradually shifts in the opposite direction.

The values of calculated flow velocities on the surface are maximal in August (up to 9–10 cm/s). The velocities are largest near Slepikovskogo Cape in the spring (~7 cm/s) and in the northeastern part of the strait in the autumn (~9 cm/s). The inflow of water from the Sea of Okhotsk along the southwestern Sakhalin coast in the warm half of the year is much weaker than in the winter, though in the surface horizons, this can be seen both in the spatial distribution of water temperature and in its salinity [13].

The spatial distribution of flows in all seasons at 50 m generally confirms all these characteristic features of water circulation: water motion in the southern part is the same as in surface horizons, while in the northern part, the direction of water motion in bottom layers changes in the cold period (Fig. 3b). The calculated flow velocities vary from 3–4 in February to 5–6 cm/s in August.

The reliability of the estimates of water circulation in the eastern part of Tatar Strait obtained with the use of BOM can be assessed based on indirect data. Thus, the larvae of Kamchatka crab at the planktonic stage of development are commonly recorded near western Sakhalin coast in late March–early April. At this stage, the larvae can be used as a passive tracer, whose position can be identified by the density of accumulation and development stages during ~80 days. The distribution character of Kamchatka crab larvae in the period of hydrobiological surveys in 1991–1999 showed them to be mostly transported from the major reproduction zone (46°40′–47°30′N) in two directions: the northward direction, resulting in larvae accumulations near Lamanon Cape, and in the southern direction, causing the permanent presence of a small accumulation of larvae south of Lopatina Cape. The presence of two isolated accumulations of larvae can be explained by the fact that the mass change of crab larvae at the planktonic development stage begins in the southern part of the reproduction zone and only 1–2 weeks later reaches its northern boundary. The mean larva transfer velocity in the 0–80-m layer was estimated at 2–4 cm/s, which is completely confirmed by the calculation results given above [8].

The largest larva concentrations were recorded in the coastal zones; though the larvae at this stage spread over vast areas. The majority of larvae settle on shallows in Delanglya Bay, where the conditions are favorable for their further growth and the development of young fish. Less dense accumulations of young fish occur in areas north of Lamanon Cape, at Slepikovskogo Cape and south of Lopatina Cape. Individual cases of young Kamchatka crab catches were recorded along Sakhalin coast north of 51°N [8]. The calculation schemes of water circulation given in this paper convincingly demonstrate the possibility of such transfer of larvae, depending on the location of reproduction zones.

In the southeastern part of the strait, the largest accumulations of Kamchatka crab young were recorded in areas with higher benthic biomass, among which Delanglya Bay features the maximal characteristics [8]. Favorable conditions for the development of aquatic animals form here as the result of Tsushima water rising and spreading in bottom horizons of the bay down to depths of 20–30 m. Calculations carried out in this study show that Tsushima water is present in this area throughout the year. The northward water motion along the continental slope inevitably causes rising of deep waters. The higher concentration of biogenic substances in the bottom horizons in Delanglya Bay was recorded for the first time in [15], though this fact was not correctly explained in that time. In years with slower circulation and in winter months, this effect is most distinct in bottom horizons not only in terms of higher concentrations of biogenic substances, but in terms of higher water salinity as well. When circulation processes are normally developing, the manifestation of this effect in terms of hydrological–hydrochemical characteristics is somewhat shaded.

Biologist believe that the penetration of crab larvae with the water of the Sea of Okhotsk from Aniva Bay and their settling in the zone favorable for their development south of Lopatina Cape is impossible. Our calculations show this to be possible both theoretically and practically. However, the state of crab larvae at planktonic development stage forms, on the average, a month later; therefore, to detect and identify them, trawl surveys should be carried out in later time.

Comparing the current velocities obtained from BOM with the results of other model calculations shows them to be ~2 times less than the velocity values obtained in [3, 18, 20] and to be in good agreement with the data given in [14, 25]. This difference in calculated values appears to be due to the effect of wind taken into account in some manner in the cited papers. In this paper and in [14], where semicentennial regular observation series of hydrological parameters and smaller step in the model grid were used, it was assumed that the effect of wind is already accounted for in the space and time distribution of water density fields.

According to data of many-day instrumental observations carried out mostly in the shelf zone, the general background of total current velocities in the surface layer varies between 10 and 30 cm/s. The measured values of maximal velocities of total currents in the Sea of Japan were 50–60 cm/s, while in individual areas (straits and water areas subject to the effect of boundary currents), the maximal velocity reaches 100–147 cm/s [20].

CONCLUSIONS

Two layers with opposite directions of water circulation can be clearly identified in the vertical direction in Tatar Strait. The interface between the layers lies at 30–50 m in the northern part of the strait and at 150–300 m in its southern part. The direction of water motion in the northern part of the strait synchronously changes to the opposite from winter to summer, while in the southern part of the strait it is stable all over the year: the direction of water rotation is mostly cyclonic in the upper part and mostly anticyclonic, in the lower part. Therefore, the results of analysis of integral water circulation may lead to incorrect conclusions.

The West-Sakhalin Current, which is identified by some researchers along the western coast of Sakhalin (from Lamanon Cape to Kril'on Cape) does not exist as a single current. It manifests itself in individual parts in different months either through the formation of sufficiently stable mesoscale vortices (like in the spring in Delanglya Bay), or as the formation of compensation currents with a characteristic length of 30–40 miles, which can be clearly detected south of Lamanon and Slepikovskogo capes.

The northern branch of the Tsushima Current, which enters Tatar Strait, is genetically related with the Primorskoe Current. The presence of the main jet of the Primorskoe Currrent in the warm period in subsurface horizons is the consequence of the sinking of the main jet of Tsushima water near Slepikovskogo Cape. In the cold season, current velocity in the zone of water sinking decrease 2–3 times; therefore, the main jet of the Primorskoe Current can be clearly detected in surface horizons.

The calculated current velocities are in good agreement with the results of some model calculations and with indirect data (in particular, with the drift velocity of Kamchatka crab larvae), though they look underestimated relative to some modeling results. This difference appears to be attributable to the fact that some researchers, who used averaged thermohaline data for their diagnostic calculations, also introduced data on wind regime in their calculations; however, its effect, in the authors' opinion, is indirectly accounted for in the averaged thermohaline fields.

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