A peculiar water regime of currents in the area of the eastern Sakhalin shelf

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Introduction

The shelf zone of East Sakhalin is characterized by complex spatial–temporal variability of water circulation and current fields, hydrological characteristics and their vertical distribution. It is conditioned by the combined effect of multiple factors: atmospheric influence, intensive water exchange with open sea areas, inhomogeneous velocity fields of tidal currents promoting eddy formation, and the Amur water influence (Leonov, 1960; Moroshkin, 1964; Moroshkin, 1966). Although the shelf is promising for the regional economy, it is poorly studied. This is true for mostly late autumn and winter; due to severe and long winters, observations were carried out mostly during the warm seasons.

The concept of water circulation in the area has been developed on the basis of the dynamic method (Leonov, 1960; Moroshkin, 1964; Moroshkin, 1966) and numerical modeling carried out for the Okhotsk Sea at large (Kozlov, 1972; Zyryanov, 1977; Luchin, 1987; Martynov and Kuzin, 1995; Kozlov and Makarov, 1996). Except for Martynov and Kuzin (1995) and Kozlov and Makarov (1996), the idea of cyclonic water circulation in warm and cold seasons is promoted. However, it is noteworthy that shallow depths and the considerable meridional extension of the East Sakhalin shelf makes circulation there to be sensitive to relatively strong local monsoons capable, under certain conditions, of transforming the global sea level gradient and, consequently, the structure of coastal currents. Such inter-year variations of current fields are not accounted for by the dynamic method. This work reveals a peculiar regime of the East Sakhalin shelf currents by synthesis of numerical modeling results with data describing seasonal density fields, typical wind situations, and long-term instrumental measurements.

Water circulation and current fields are calculated over the three-dimensional diagnostic model of the Ekman type (Sarkisyan, 1977; Peng and Hsueh, 1974). Its first version for the coastal sea around Sakhalin and experimental results are given by Budaeva et al. (1980). This model has been tested many times, thus its quality and adequacy characteristics are not considered here.

Model description

Ocean hydrodynamics equations written in the Cartesian coordinate system with hydrostatic approximations, the Boussinesq equations, and seawater incompressibility equations, ignoring horizontal turbulent exchange, are used. The system of initial equations is closed by a continuity equation. Basic equations of the model are as follows:

$$\begin{aligned} &A\,U_{zz} - i\,WU = gG + (g/r_0)\,F; \\ &u_x + v_y + w_z = 0; \\ &z = 0:\ AU_z = -T/r_0; \\ &z = H(x,y):\ U = 0, \end{aligned} \tag{1}$$

where

$$U = u + iv,\ G = h_x + i h_y,\ T = T^{(x)} + iT^{(y)},$$

$$F = f^{(x)} + f^{(y)} \equiv \int_0^z (r_x + i r_y)\,dz \tag{2}$$

The origin of the coordinates rests on an undisturbed oceanic surface $z = 0$, the x axis is directed eastward, y axis northward, z axis vertically down, u, v, w are components of current velocity directed along x, y, and z axes, respectively, $T^{(x)}$, $T^{(y)}$ are components of tangent wind stress on the sea surface, A is the coefficient of vertical turbulent exchange, W is the Coriolis parameter, r is sea water density (r_0 is the mean sea water density in the model area), g is free fall acceleration; H is sea depth, and h is elevation of the given level and subscript means differentiation.

The integral function of a current is determined by the introduction of full flows

$S = \int_0^H U dz = (S(x) + iS(y))$, with the help of the continuity equation:

$$-Y_y = S^{(x)}, Y_x = S^{(y)} \qquad (3)$$

The problem is not completely set up without corresponding boundary conditions for Y. Y. values, calculated on the basis of quasi-geostrophic relations from the formula of Sarkisyan (1977), which were set on vertical flank boundaries of the open contour of the model area:

$$Y_{boundary} = -\frac{g}{(r_0 l_1)} \int_0^H (zp\ dz) \qquad (4)$$

To make $Y_{boundary}$ values on the contour comply with the ones inside the area, $r¢$ anomaly, determined from equation (5), was used in formula (4) instead of r.

$$r¢\,(x, y, z) = r\,(x, y, z) - \overline{r}\,(z), \qquad (5)$$

where r is the seawater density near bottom and $r\ (z)$ is the arithmetic mean for all points on a horizon.

The values $\overline{r}$ and $Y_{boundary}$ were calculated for each individual season using seasonal climatic temperature and salinity. Then (DY) currents were corrected on the boundaries of the model area for balance.

An elliptic equation for Y is approximated with the help of a monotonic difference scheme of second order precision (Kozlov, 1977) having conditions on the convergence of the iterational Gauss–Zeidel method which solves the system of linear equations for Y values at the nodes of the grid area.

In numerical realization of the model, the key problem is calculating the F function in equation (1). The classical approach involves the use of the whole three-dimensional density field; it is not easy and requires accurate quantitative and qualitative deep-sea hydrology. Additionally, "*bottom straightening*" (replacement of variables of $z¢ = z/H(x, y)$ type) used in the numerical model helps to fulfill correct numerical differentiation over space, but brings about an additional problem, that is, the interpolation of initial density fields to the nodes of the grid. This is why, for density parameterization, the authors used the modified Yoshida model (Yoshida, 1965) which was chosen because it demonstrated good ability to reproduce adequate structure of current fields in the surface layer and distinct analytical solution of equation (1) for horizontal velocities. The model also gives way to simplifications for the case of a deep sea. At $d = s_t + (r_¥ - 1)/d^*$, where s_t is conventional density, d^* is the characteristic scale of density variability, and $r_¥$ are density values for great depths, the vertical structure of density is determined over the following relation:

$$d\,(x, y, z) = \overline{\delta}\,(x, y) \times [1 + z/c\,(x, y)] \times \exp(-z/c\,(x, y)), \qquad (6)$$

where $\overline{\delta}(x, y)$ coincides with real density distribution on a sea surface. The c parameter, indicating the depth of a density jump, is numerically determined for each station from the condition of the model and real "heat content" equality in a water column $f = \int_0^H d\ dz$.

Initial data

The structure of water circulation and three-dimensional current field of the sea around East Sakhalin between 43°50′–54°30′N shoreline and 146°00′E have been studied with the help of 1947–1995 deep sea oceanographic observations and wind situations typical for summer and autumn. Typical wind fields were calculated by setting field data at the fixed sites of the related area and their subsequent interpolation. Calculations were made within the grid that approximated the area under study into the cells 20 × 20 minutes in size. The grid had 282 nodes; maximal depth of the investigated area made up 3200 m. Water transport through the La Peruse and Kunashir Straits was set in accordance with Sekine (1990).

Below is a description of dynamic processes on the shelf of East Sakhalin influenced by the winds mostly typical for summer and autumn, that is, by the winds of the greatest reoccurrence (P).

Summer modification of the scheme of surface currents

South-directed winds (P = 40.8%)

These winds occur most often. The dynamic structure of currents typical for summer is shown in Figure 1. It is manifested in the generation of mesoscale anticyclonic eddies (A_1, A_2) and a north-directed coastal current. This northern current blocks the East Sakhalin Current and pushes its axis eastward, outside the outer edge of the shelf. A zero isoline moves seaward beyond 144°E. Anticyclonic eddies accumulate the transformed Amur River waters and condition the thermal regime of coastal waters in summer. Stable southern winds blowing along North-East Sakhalin intensify the northeastern branch of the Soya Current and anticyclonic system of currents in Aniva and Terpeniya Bays. The described situation contradicts the common view of currents in the area under study. However, it is noteworthy that weak southern winds do not change the general distribution of surface currents along North-East Sakhalin. The only factor they decrease is the velocity of currents directed northward. In time the generation of north-directed currents coincides with spring reconstruction of atmospheric circulation, that is, the period of considerable winter monsoon weakening and changing of northwestern winds for south and southeastern.

Southwestern winds (P = 15.6%)

In the shelf area of North-East Sakhalin this type of summer wind ranks second. Under stable southwestern winds a narrow alongshore current flowing northward at 5–15 cm/s is unchanged only in the area to the north of 50°N. In general, the transport of surface waters for the East Sakhalin coastal area is predominantly northeast- and east-directed. A surge of waters is registered in the eastern parts of Aniva and Terpeniya Bays. (Fig. 1b and e).

Southeastern and eastern winds (P = 14.6%)

These winds are the most water-surge dangerous. The field of currents reveals an intensive current flowing to the north at 10–20 cm/s and the formation of major cyclonic eddies at the southern and northern steep slopes. In La Perouse Strait the east-directed winds cause the Soya Current to sink.

Northern and northeastern winds (P = 7%)

Notable changes in the general summer scheme of surface currents are observed under stable northern and northeastern winds. In the northern part of the area under study deep-sea waters surging over the shelf edge cause the current to diverge: around 53°–54°N some waters turn to the northeast and block the south-directed transit of diluted Amur water along the Cape Elizabeth beam. The main current turns to the southwest (south) and, flowing along the northeastern coasts of Sakhalin, enters Terpeniya Bay. A notable activation of cyclonic eddies takes place at the southern steep slope. The southwestern mode also prevails on the shelf of South-East Sakhalin influenced by north and northeast winds predominating along the vectors of the surface alongshore currents. Dynamically active zones, where velocity of surface currents exceeds 50 cm/s, are shallow coastal regions of the shelf and areas around the capes.

Autumn modification of the scheme of surface currents

Western and northwestern winds (P = 46%)

The influence of stable west and northwest winds intensifies the East Sakhalin Current (> 50 cm/s) and coastal surface water drive (most intensive under northwest winds). Under this type of wind condition the formation of a vast cyclonic eddy Z_1 in the north of the area and an anticyclonic eddy A_1 at the southern steep slope is distinguished in the integral water circulation field (Fig. 2a and d). The structure of currents in the south of the area is complex and mostly two-layered. Compensating currents are north-directed.

Northern winds (P=18.6%)

In autumn this wind type ranks second. Under northern winds the surface currents of East Sakhalin are characterized by: polarization of southern vectors, intensification of the East Sakhalin Current and especially its western branch, water drive in Terpeniya and Aniva Bays and a surge of water near the northern coast of Hokkaido. A cyclonic eddy Z_1 exists at the northern steep slope. Another cyclonic eddy Z_2 is formed at the southern steep slope (Fig. 2b and e).

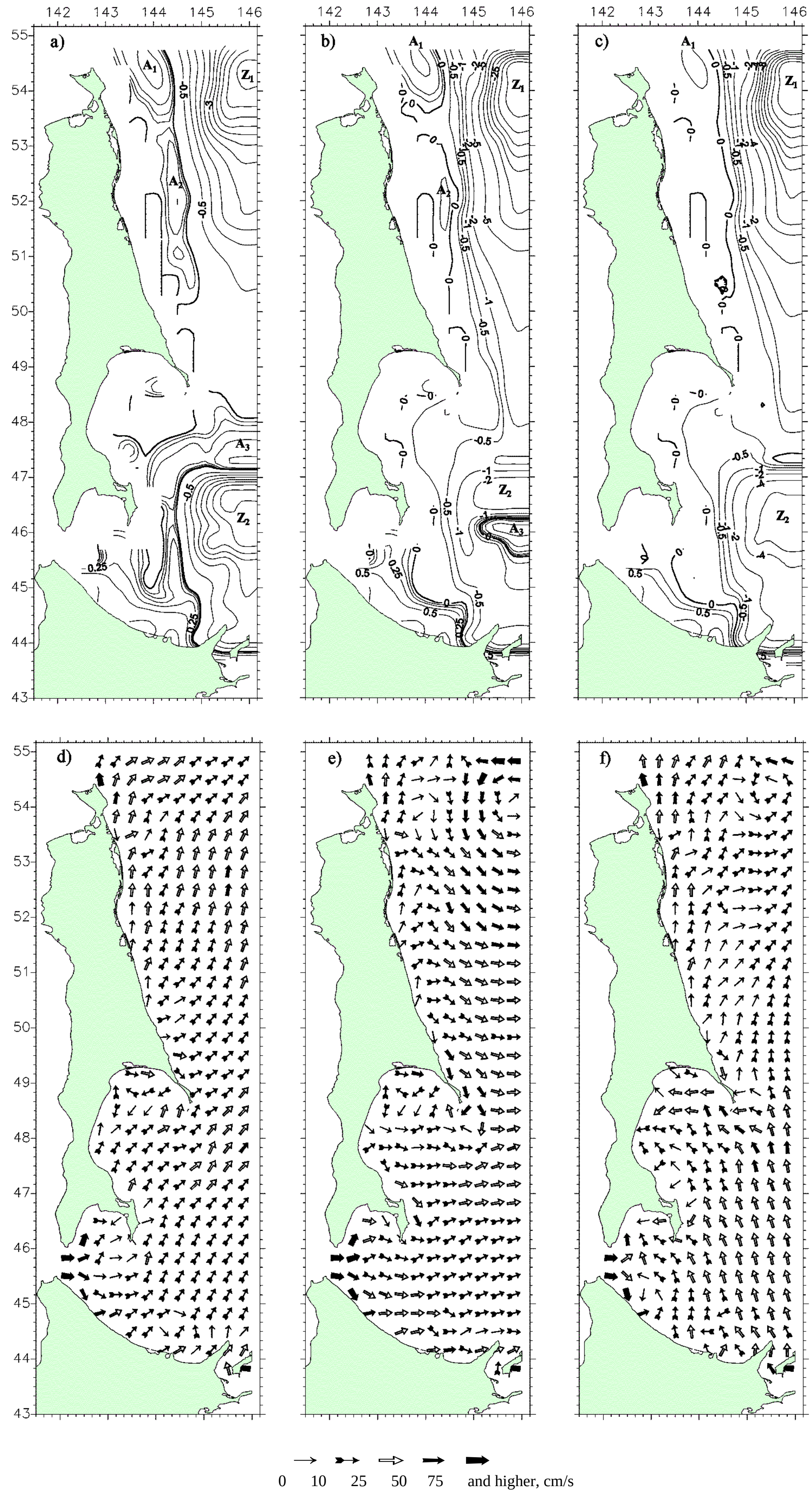

Fig. 1 Typical schemes of integral water circulation (a, b, c; in Sv) and surface currents (d, e, f) in summer: (a, d) southern winds ; (b, e) southwestern winds; (c, f) southeastern and eastern winds (> 4 m/s).

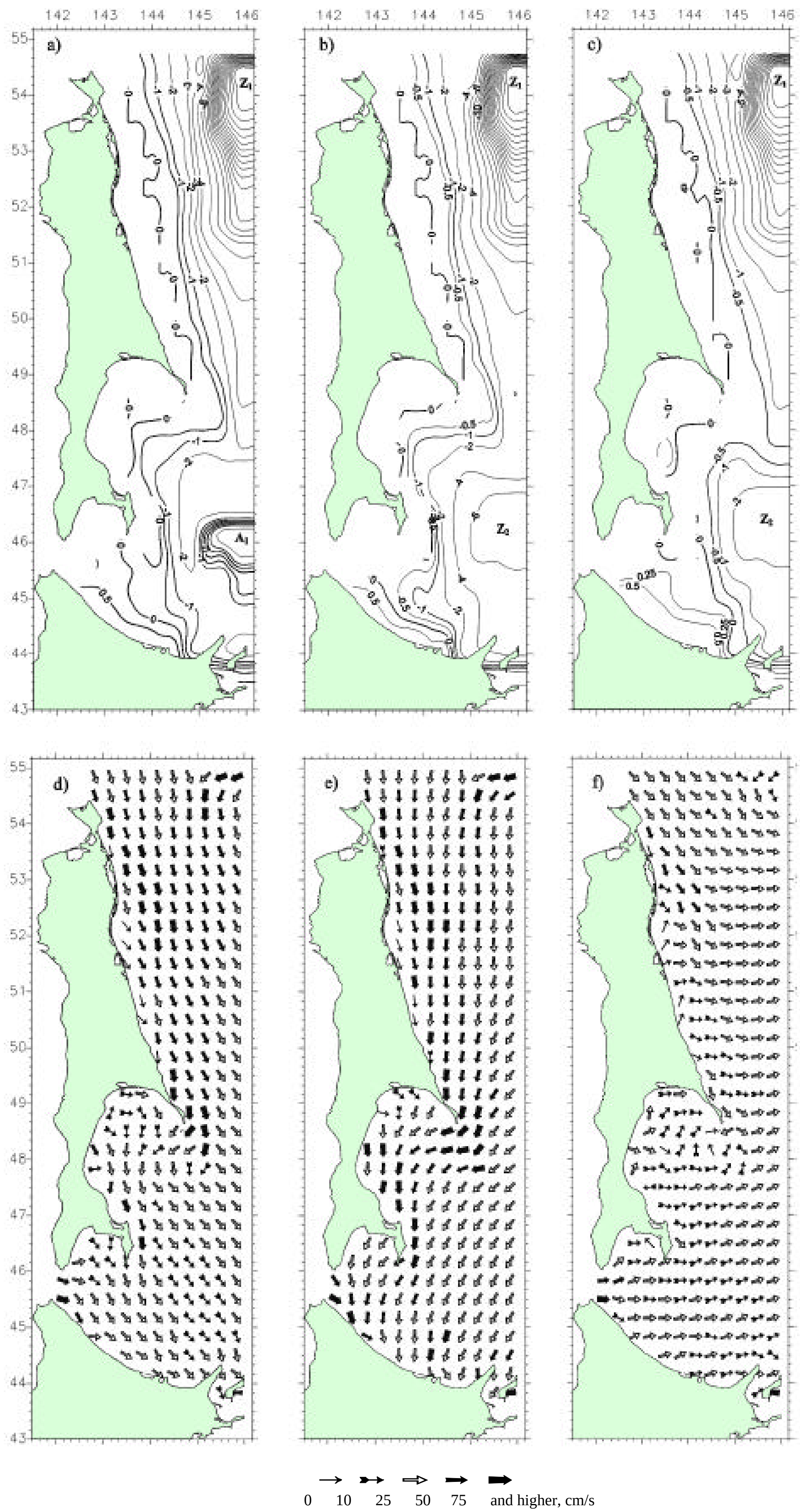

Fig. 2 Typical schemes of integral water circulation (a, b, c; in Sv) and surface currents (d, e, f) in autumn: (a, d) western winds, (b, e) northern winds, (c, f) southern and southwestern winds (> 4m/s).

Southern and southwestern winds (P = 18%)

Under stable southern and southwestern winds the general transport of surface water is northeast-directed, that is, away from the shoreline. The system of currents both on the sea surface and near bottom is predominantly anticyclonic. This situation may result in the shift of the East Sakhalin Current's axis to the shelf edge, the absence of its western branch on the Terpeniya Bay beam, and generation of the vast anticyclonic eddy to the east of Elizabeth Cape. The surge of waters in the eastern part of Terpeniya Bay prevents penetration of seaward waters into the bay. However, in autumn under weak southern winds and calm sea, the seaward waters, namely, the waters of the western branch of the East Sakhalin Current, meet no obstacles and easily enter the eastern part of Terpeniya Bay. Modal velocities of surface currents influenced by stable southern and southwestern winds reach 25–35 cm/s (Fig. 2c and f).

Eastern and northeastern winds (P = 7.8%)

Under these winds the general transport of surface waters is directed mostly to the northwest, that is, to the shoreline. Near the southwestern coasts of Sakhalin and in the western part of the La Perouse Strait the surge of waters takes place; it decreases the Okhotsk/Japan sea-level gradient. The durable influence of northeastern and eastern winds can even change the gradient sign in La Perouse Strait and bring about a west-directed surface current, that is, to block the Soya Current. Under such conditions the vertical structure of currents on the shelf of East Sakhalin has two well-distinguished layers. Maximal velocities of surface currents may reach 50 cm/s and even higher around Aniva and Terpeniya Capes.

Winter regime of currents

Real winter parameters of currents were obtained by the analysis of long-term instrumental measurements carried out by the experts of Sakhalin Energy Investment Co. Ltd. for the Piltun-Astokhskoye oil field in 1996–1997. Station sites were located in the area of the East Sakhalin Current as it is the principal element of water circulation in the area of East Sakhalin. The measurements were made each 60 minutes by integrating instruments (ADCP- (01) 0129 and whilsl-600072) installed on the moored autonomous buoys.

Total currents

In winter (December–April) the regional surface currents on the shelf of East Sakhalin are characterized by the monomodal regime. The modal sector includes 135°–170°, the general direction of the current is south-southeast, and probability is 25–68% (Fig. 3a). The bimodal regime is characteristic of near-bottom currents. It is manifested in reciprocating motion mostly observed along the NNE–SSW axis. (Fig. 3b). Modal current velocities reach 10–20 cm/s and 20–30 cm/s; maximal velocities are 2–3 times higher. However, probability of maximal velocities is very low.

Two periods (transit and quasi-stationary) with different variability parameters are distinguished in the regime of surface currents in winter (Fig. 3a and c). The transit period is characterized by high variability of current direction (November) and velocity (December–January, 5–140 cm/s). A quasi-stationary period (modal velocities 10–20 cm/s, general direction south-southeast) includes February–April, and in time coincides with relatively stable ice cover over the Okhotsk Sea part of the shelf and notable weakening of tidal currents. It is characterized by relatively low variability of current velocity and direction.

Tidal currents

Regional currents of the East Sakhalin shelf are strongly controlled by tides; their reaction to high-low tides is observed the whole year round. Briefly, tidal currents are characterized as follows: they are of reverse character with modal vectors oriented at a small angle to the general N-S axis; their yearly variability cycle includes well-distinguished periods with asymmetric probability diagrams ($\Delta P \cong 6–8\%$); in January–April (June) the better pronounced are the currents directed northward, in the warm season they are the ones directed southward.

It is noteworthy that for most of the year tidal currents in the surface layers are directed against the predominant monsoon winds. Thus, during the warm season the predominant winds are those directed from the south and southeast, and the vectors directed to the (modal sectors 169°–191° and

146°–169°) in the general tidal current. During the cold season the predominant winds are directed from the north, and modal vectors directed to the north on variability diagrams of tidal currents (349°–11°, 11°–34°, 326°–349°).

Intensification of tidal currents with depth is another peculiarity of winter hydrodynamics. This peculiarity is also manifested in the profile configuration of total current velocity. The increasing velocity modulus of tidal currents in the direction of the seafloor is best pronounced in November–April. The average vertical shift of velocity between surface and near-bottom layers reaches 6–7 cm/s. This phenomenon is not completely understood.

In variability of the tidal current velocity modulus in surface layers the predominant is a yearly harmonic with maximum in August and minimum in March, near bottom it is a half-a-year harmonic with maximum in December, May–June and minimum in March and September. On the shelf of North-East Sakhalin at large, the absolute minimum of tidal currents takes place in March, and in time coincides with the stable ice cover over the Sea of Okhotsk.

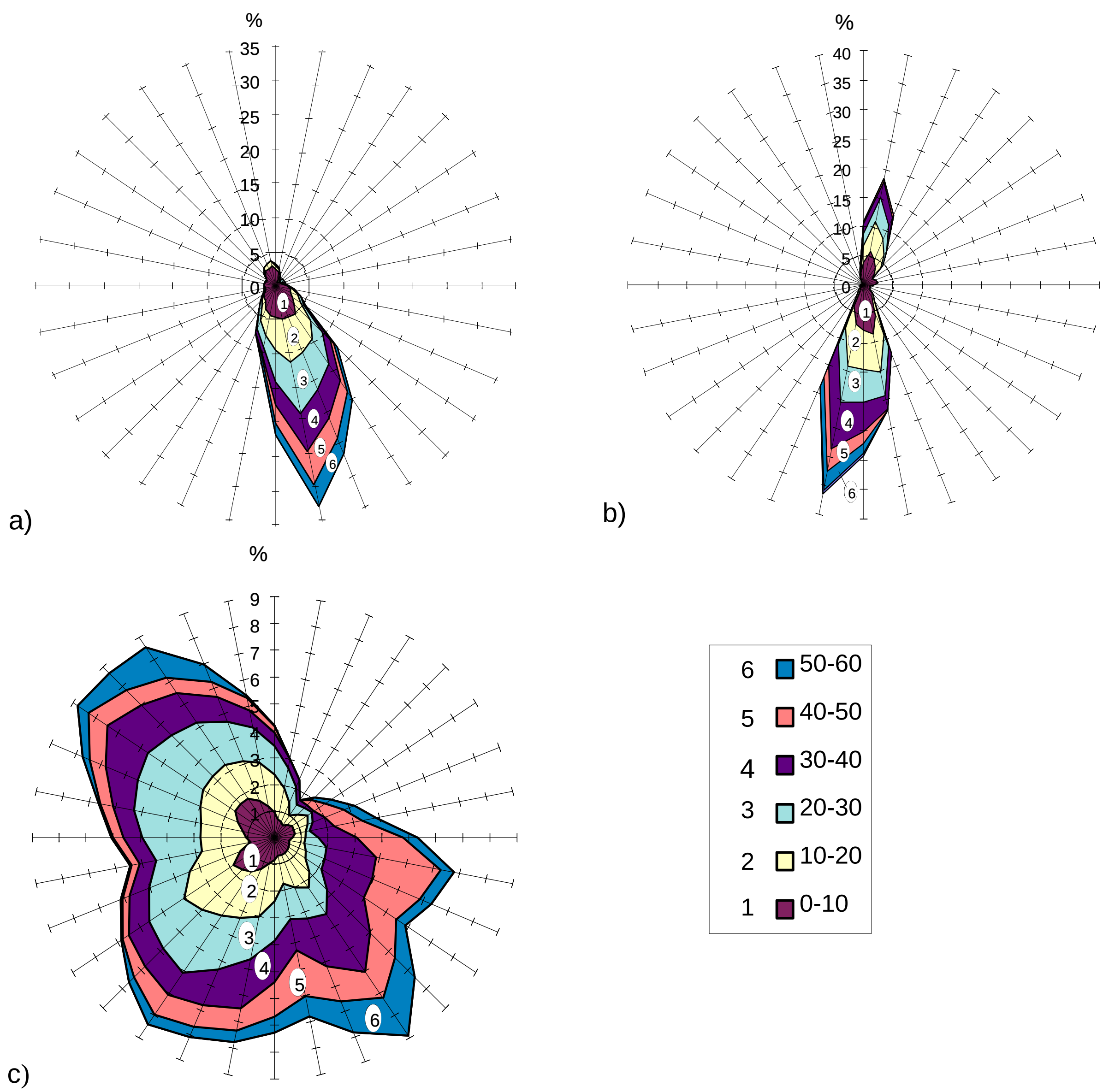

Fig. 3 Diagrams showing distribution of empiric probabilities of vector and velocity of the surface current (%). (a) March, (b) near-bottom horizon, March, and (c) November.

Conclusions

Model calculations made for the shelf of East Sakhalin proved its field to be dynamic and considerably dependent on the characteristics of a wind type situation. In the monsoon regime observed over the eastern Sakhalin shelf, two general types of sea water circulation are conventionally distinguished: summer and autumn (winter). The summer horizontal structure of currents is characterized by the shift of the East Sakhalin Current's axis to the shelf edge and the generation of northern currents with prevailing north–northeastern modes in the surface water. The autumn structure is characterized by southern flow intensification and prevalence of southern and southeastern modes in the vectors of surface currents. The integral transport of waters to the south in this period reaches about 1–2 Sv.

In the winter regime of surface currents two periods are distinguished: transient (November–January) and quasi-stationary (February–April). The vector of the averaged coastal current in surface layers is characterized by a mono-modal type of distribution (S-SE), and the vector of the near-bottom current by a bimodal one (SSE-NNW).

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