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MARINE PHYSICS

Hydrological Characterization of the Ob' Inlet in the Summer and Autumn Seasons

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Abstract—The assessment of the hydrological regime under the high- and low-water conditions in the Ob' Inlet was based on the results of two comprehensive surveys performed by the VNIRO and IO RAS in the summer and autumn of 2010. The summer hydrological regime, which is associated with the peak of the biological activity, was compared with the late autumn one, which was closely followed by the freeze up. Special attention was paid to the assessment of the interseasonal variability of the hydrological state and the processes that continued in the area of the mixing of the riverine waters (the outflux from the Ob' Inlet) and the water of the Kara Sea. We followed the transition of the hydrologic front from the summer stratification (high waters) into the autumn distortion driven by the intensive mixing of the waters under a sharp decrease in the river discharge.

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INTRODUCTION

The Ob' Inlet is a basin unique in all senses. According to the terminology, it is an estuary of the Ob' River or a bay of the Kara Sea. However, in fact, it is a large unique natural object discernible on maps of any scale and combining features characteristic of both a river and a sea. The Ob' Inlet, being a collector and transformer of more than 500 km^3 of fresh runoff, represents a complex set of interrelated hydrological, hydrochemical, and biological processes. Of particular interest is the mixing zone of waters with different properties, namely, those of the of rivers Ob' and Taz, the freshened water of the Inlet itself, and the saline Kara Sea waters [1, 3, 15]. In particular, the processes in the zone of a hydrologic front (or, as it is often called, a marginal filter [8]) determine both the functioning of living organisms at the boundary, where the fresh-water biota is replaced by the marine one, and the regime of the Kara Sea entered by the Ob' River waters [13].

Surprisingly, the explorations of the Ob' Inlet have been sketchy and often associated with current needs in using the most rich opportunities of the region. In the historical perspective, the operative motives changed from interests of the fur trade and water ways development to the present day needs in the quite promising production of valuable hydrocarbons beneath the waters of the Inlet and in the aquatic area of the Arctic shelf.

The harsh climatic conditions and the lack of convenient infrastructure (settlements, roads, an efficient weather service, etc.) add difficulties. All this brings us to the statement of the fact of the absence of systematic and detailed complex research in the Ob' Inlet.

Such opportunities opened up for specialists of the Russian Federal Research Institute of Fisheries and Oceanography (VNIRO) and the Shirshov Institute of Oceanology (SIO RAS), who took part in two complex field missions in the Ob' Inlet in 2010 dedicated to studies of the hydrological, hydrochemical, and hydrobiological conditions [7]. The present paper is devoted to the evaluation of the hydrological processes in the Ob' Inlet during the summer–fall seasons of 2010.

THE STUDIED AREA AND RESEARCH TECHNIQUES

First, it is necessary to describe the specific features of the studied area. The Ob' Inlet extends by 800 km from the Ob' delta in the south to its marine boundary in the north. Its width varies from 30 to 90 km and the depth changes from 3 m (lengthwise the Yamsal'skiy (66°54′N, 71°45′E) and Nadymskiy (66°30′N, 72°20′E) bars) to 25 m (north of the merging with waters of the Taz Inlet). All of the above depths are reduced to the theoretically lowest levels according to the current navigational charts [2, 9]. According to the calculations of V.V. Ivanov [4–6], in total, the freshwater long-term mean runoff of 530 km^3 enters the Kara Sea through the Ob' Inlet. The Ob' River as a main artery determines the runoff regime. A specific feature of this river concerns the huge area of its basin (about 3 million km^2) distinguished by high degree of natural overregulation. All this leads to the fact that the

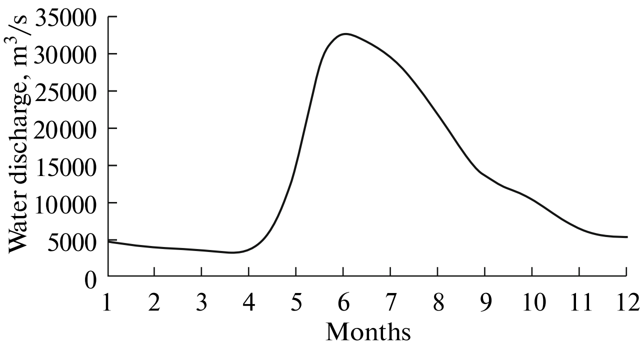

Fig. 1. Seasonal distribution of the Ob' River discharge from the long-term data [10].

flood wave is rather gentle and extends over the whole period of the ice-free water (Fig. 1).

It is worth noting the extremely strong intraseasonal variability of the hydrological regime of the Ob' Inlet. This is due to the large number of active factors: the river runoff, the tidal phenomena, and the atmospheric component as the onshore–offshore events whose amplitude is 2–3 times as high as the amplitude of the tidal oscillations [9, 11, 12, 14].

The observations were performed at 120 stations occupied in the Ob' Inlet from Cape Parusny (68°21′N) to the marine boundary of the inlet (72°40′N) from aboard the vessel OTA-777 hired from the Yuzhnaya Sudokhodnaya Kompaniya Ltd. The first survey took place as soon as the water became free of ice (from July 29 to August 17, 2010; during the high water conditions). The second survey was conducted just before the freeze (from September 18 to October 7, 2010; during the low water conditions).

The temperature and salinity were measured with CTD probes. The FSI:NXIC probe type served as the main instrument. Its data were fed into a computer and processed after each casting. We used an off-duty probe (Micro CTD (FSI), model MCTD3 (2000 m)) for the periodic field calibration during the first survey.

RESULTS

During the high water (summer survey), the katabatic currents prevailed, although the winds of the northern quarter dominating in the summer are able to strongly impact the regime. In total, the inlet can be divided into two parts. The "riverine" one extends up to 71°20′N, while the "marine" part occurs to the north of this conventional boundary.

The "riverine" part of the inlet bears all the features of a large river during the high water period. First of all, note the well-defined jet structure of the flow when the lateral water exchange is strongly limited in the background of the total vertical mixing. The temperature maps in Figs. 3b and 3c exhibit virtually full similarity of its estimates in the surface and near-bottom layers excluding the zone of merging of the Ob' and Taz waters north of Cape Kamennyi. The Taz waters, being cooler and denser, cut into the relatively warm Ob' water flow lengthwise the right shore and create a disturbance better expressed in the bottom layers. The zone of merging presses out the Ob' waters westwards (usually they gravitate to the right (eastern) shore) and stretches 80 km northwards, although the impact of the Taz waters, as judged from the pH estimates, can be traced in the jet lengthwise the eastern shore much further up to 71°N. In total, the Ob' waters with the temperature of 14–15°C at the inlet's entrance cool down to 11°C near Cape Kamennyi. The further rapid cooling to 3–4°C occurs after merging with the Taz waters and closer to the boundary of the "riverine" part. It is important to notice that the water temperature lengthwise the western shallower shore is substantially higher in reference to the eastern one where it passes the main body of the Ob' runoff.

A "cold anomaly" near the eastern shore at 70°50′N deserves to be mentioned. Here, the observed temperatures dropped to 1.3°C, which is the minimal value in the "riverine" part of the inlet. Probably, this took place because a large mass of ice caught on the shore in this region. Supposedly, this ice was driven by a hurricane wind of northern rhumbs, which preceded our studies in the region, or survived after the winter, which is more probable.

The subtleties of the contacts of the salty and freshened waters entirely determine the thermal pattern of the "marine" part of the inlet. Integrally, the salty waters as a strongly stratified cline occupy the whole near-bottom part of the aquatic area north of 72°N. This results in lower temperatures up down to negative values at the sites where the salinity exceeds 30‰ (Fig. 3). The river runoff is of primary importance in the surface layers thanks to the high water content. As a result, the maximal surface salinity does not exceed 1.5‰ under the conditions of weak mixing with the salinity cline (Fig. 3b). The exceptions are narrow belts lengthwise both shores in the northernmost part of the inlet, because the salty waters flow southwards faster at the sites of the minimal forcing of the powerful runoff of the Ob' River. Integrally, the flowing of salty waters into the river occurs more actively lengthwise the eastern shore throughout the zone of contact of the salty and freshened waters. The occurrence of a narrow band of salty waters mixed from the surface to the bottom and found in the neighborhood of Cape Drovianoy is apparently due to the local anomaly of the syzygial tides. The latter happen to be as high as 1.6 m, which substantially exceeds the level of this parameter in the surrounding aquatic area.

Integrally, transects 15 (Fig. 4) and 16 (Fig. 5) visualize the state of the frontal zone. In the first transect, which can be regarded as a quasi-longitudinal cross section, it is easy to see the frontal zone sharply stratified in temperature and salinity, which gently ascends to the surface when moving northwards. The fresh-

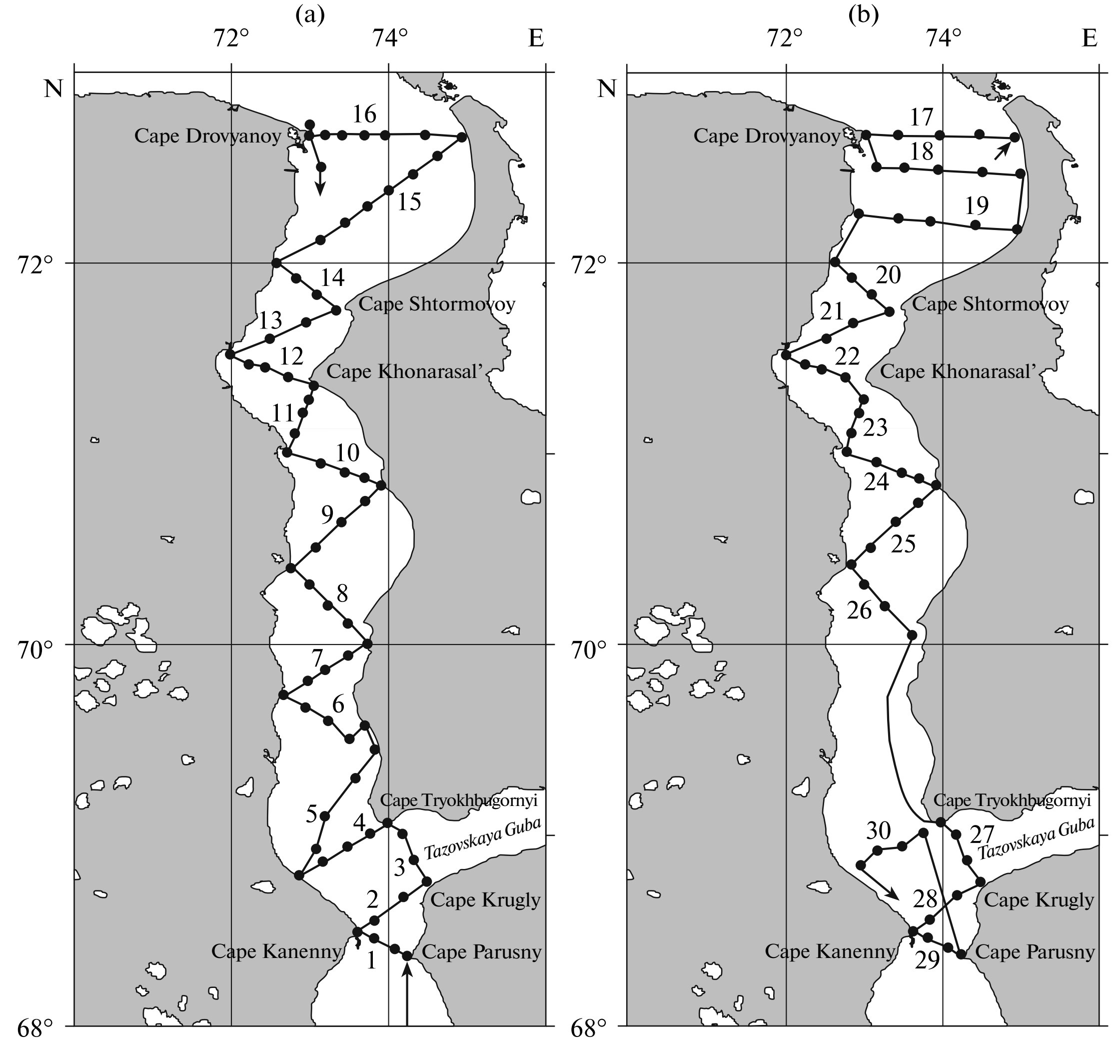

Fig. 2. Stations of the 1st (a) and 2nd (b) surveys in the Ob' inlet. The digits stand for the ordinal numbers of the transects.

ened or brackish Ob' water runoff occupies the upper layer of the zone, while the near-bottom domain belongs to the cold salty cline. The northernmost transect of the summer survey is representative too. Here, the marine and riverine waters are clearly distinguishable from each other with the latter being already considerably pressed to the surface (Fig. 5).

Quite different patterns took place during the second (fall) survey **in the period of low waters**, although only one month separates it from the first survey. The atmospheric factors gain primary importance in the environment of the inlet as the river runoff reduces by twofold. As a result, the "riverine" part of its area exhibits an extremely high degree of mixing of the whole water thickness. This follows from the distribution of the temperature, whose estimates fluctuate by about 3.5°C both in the surface and the bottom layers (Figs. 6a and 6c).

The jet nature of the river flow characteristic of the summer period vanishes. The patches of relatively high temperatures merely mark the direction of the Ob' flow, which lost half of its water content during this period. The aquatic area of the inlet divides into small density and temperature cells, which is a consequence of the high dynamics of the current processes due to the severe storms and storm-induced offset–onset events. All this leads to permanent changes of the vector of the acting flows. This demonstrates the zone of mixing of the Ob' and Taz waters, which turned out to be less clearly outlined as compared with the summer conditions. The powerful onset during our observations locked the Taz runoff and displaced it towards the left shore of the Taz Inlet after mixing with the Ob' waters.

However, the most evident seasonal changes occur in the neighborhood of the hydrologic front. This is easy to see on maps of the temperature and salinity in the north of the area (Fig. 6).

First, in the background of the diminishing water content, the river runoff north of 71°50′N increasingly

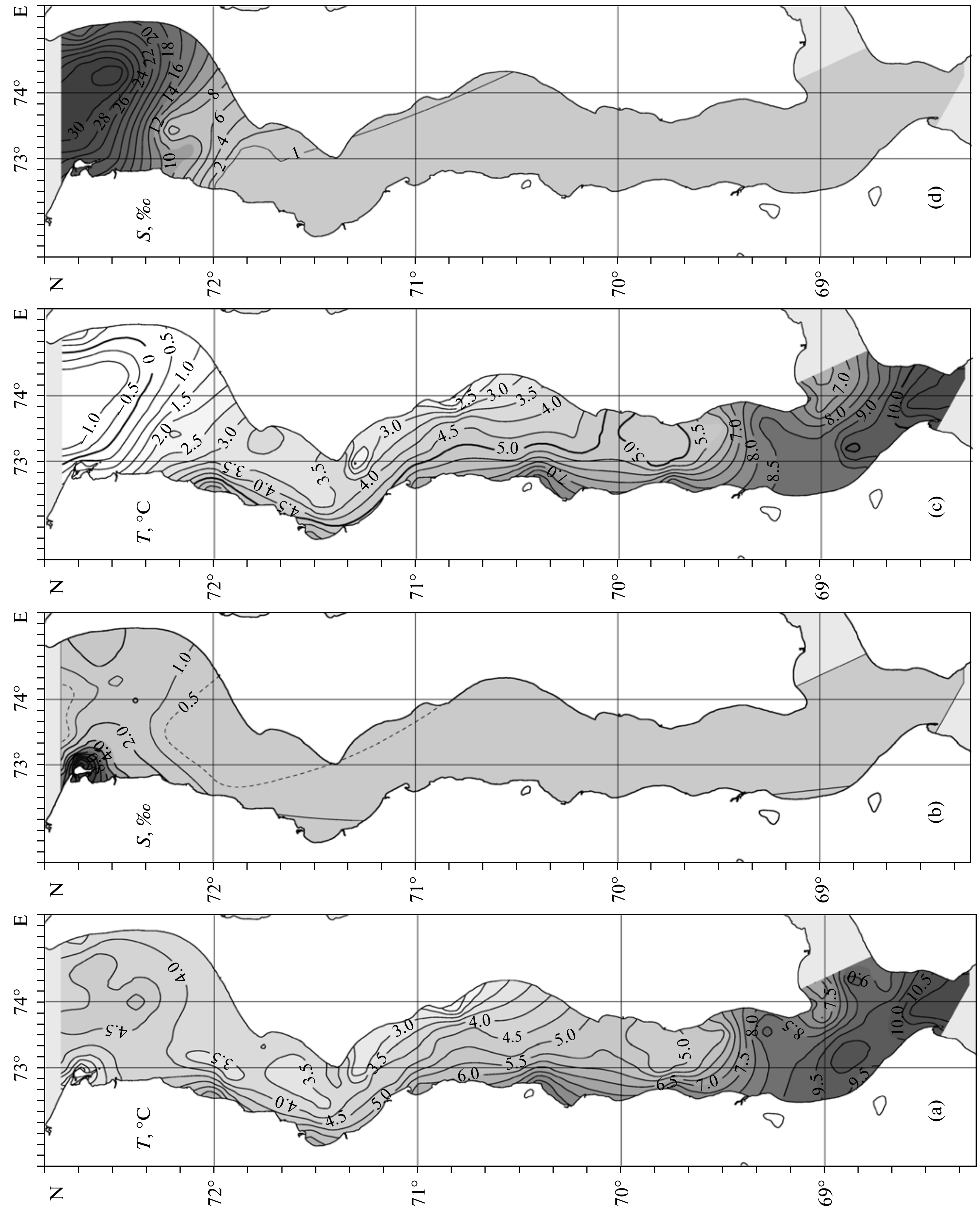

Fig. 3. Distributions of the temperature *T*, °C and the salinity *S* (‰) over the Ob' inlet in the summer in the surface (a and b) and near the bottom (c and d) layers.

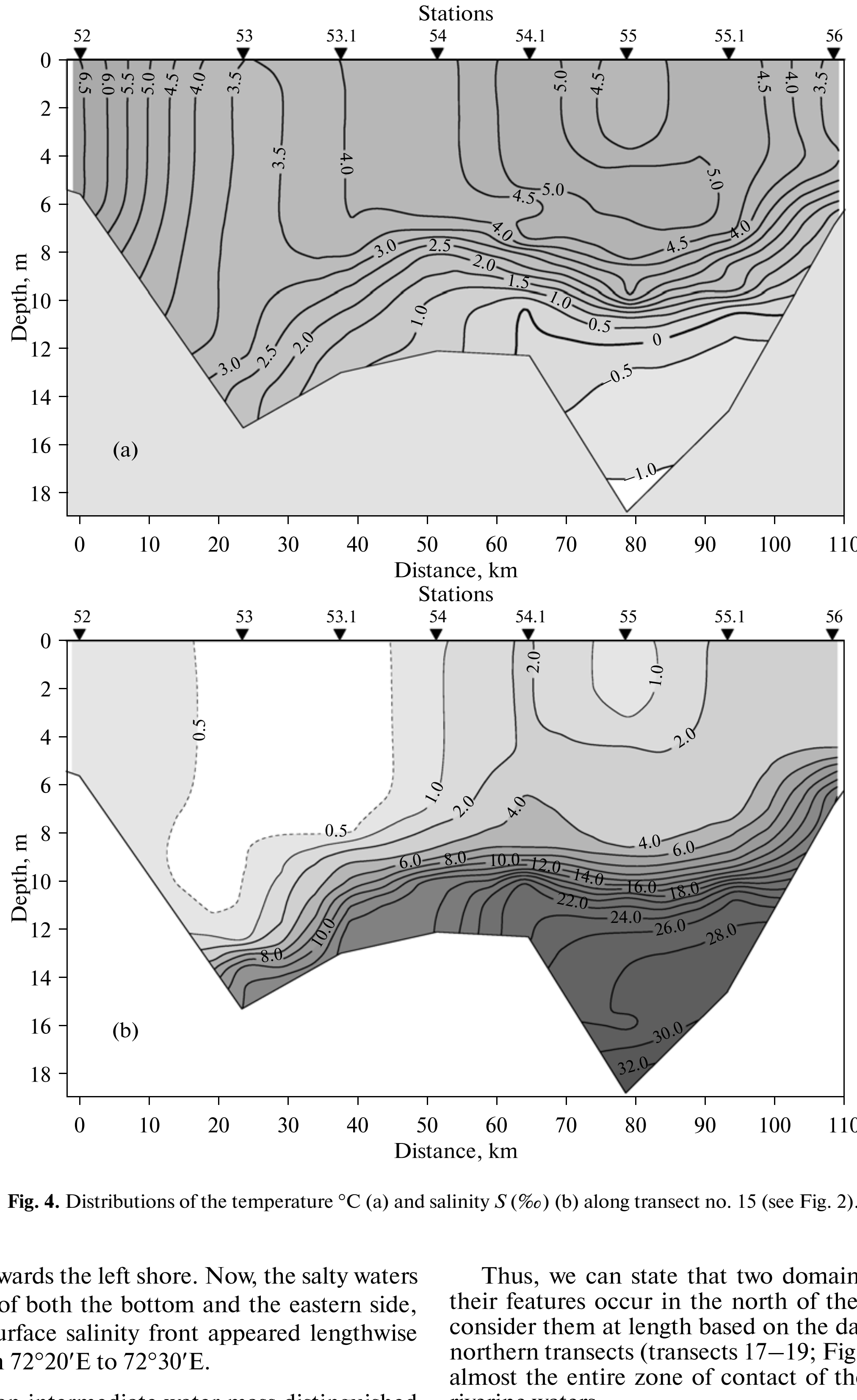

Fig. 4. Distributions of the temperature °C (a) and salinity *S* (‰) (b) along transect no. 15 (see Fig. 2).

gravitates towards the left shore. Now, the salty waters force it out of both the bottom and the eastern side, where the surface salinity front appeared lengthwise the axis from 72°20′E to 72°30′E.

Second, an intermediate water mass distinguished by a well-mixed homogeneous upper layer has emerged by this instant to the east of the front outside the zone of the river runoff's influence.

Thus, we can state that two domains differing in their features occur in the north of the inlet. Let us consider them at length based on the data from three northern transects (transects 17–19; Fig. 7) that cover almost the entire zone of contact of the marine and riverine waters.

In the western part of the inlet directly influenced by the river runoff, the salinity in the channel line of the latter makes up 3‰, while the flow itself (we

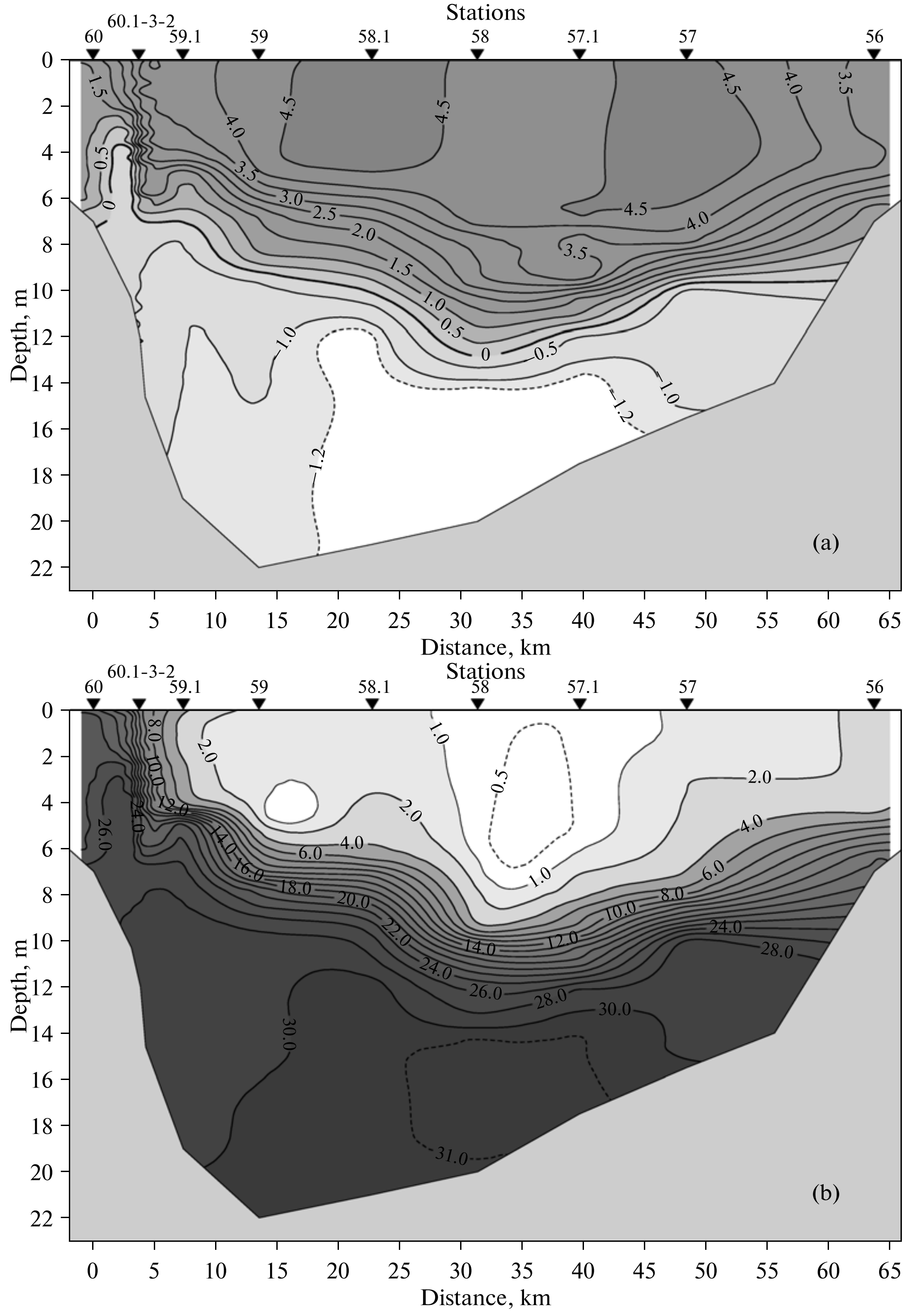

Fig. 5. Distributions of the temperature °C (a) and salinity *S* (‰) (b) along transect no. 16 (see Fig. 2).

delimit it conventionally by the isohaline of 6‰) gradually diminishes in the cross section and ascends as it mixes with the peripheral waters of higher salinity. The modified river waters occupy about 30 km at the western shore lengthwise transect 19 (Fig. 7c) at about 72°15′N and fill the whole cross section. In contrast, after the detachment off the bottom over the sill barrier (transects 18 (Fig. 7b) and 17 (Fig. 7a)), these waters are distinguishable only at the depth shallower than 5–8 m and give way to the dense salty waters in the underlying layers. The width of this conventional flow perceptibly diminishes too.

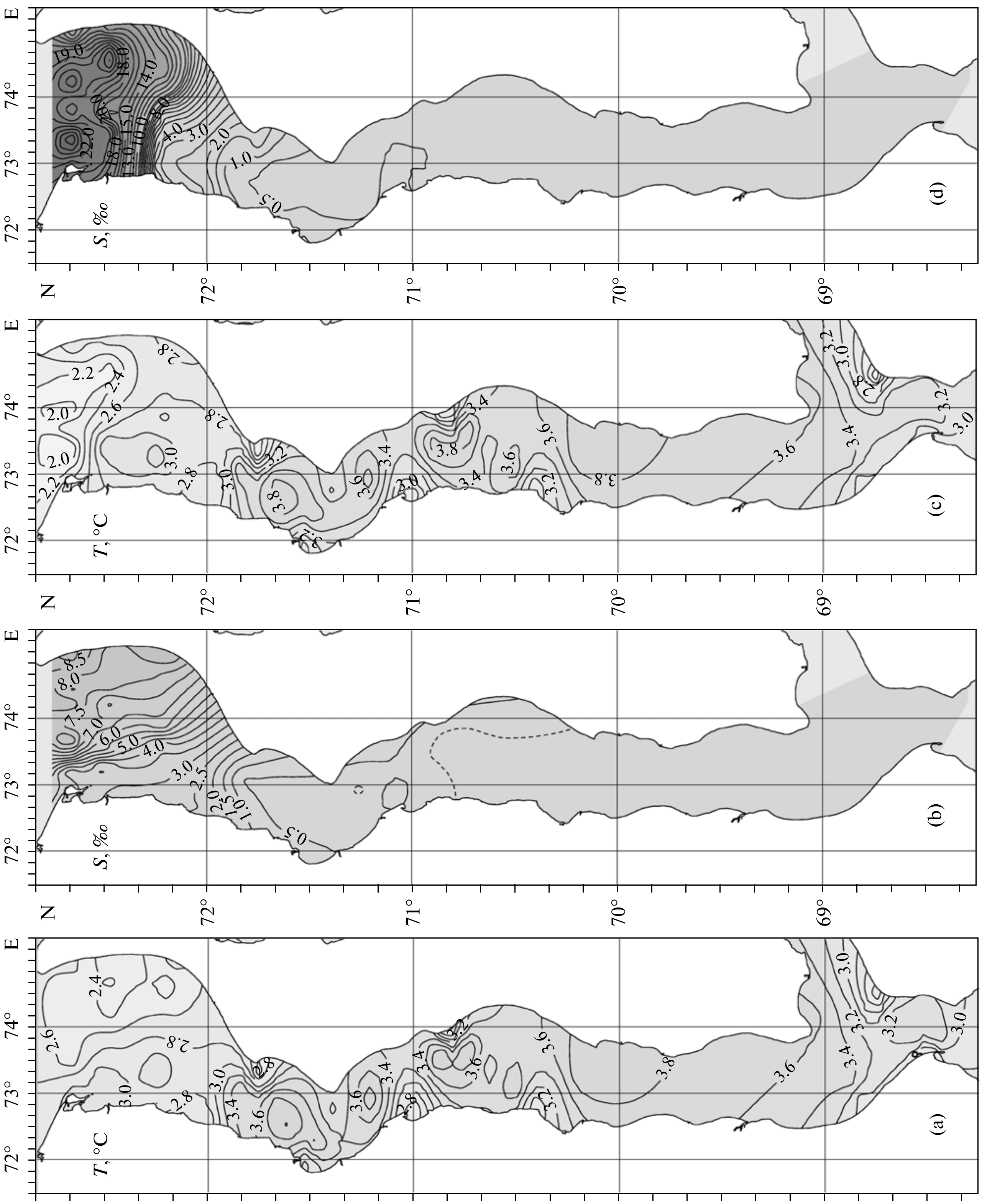

Fig. 6. Distributions of the temperature *T*, °C and salinity *S* (‰) over the Ob' inlet in fall in the surface (a and b) and near-bottom (c and d) layers.

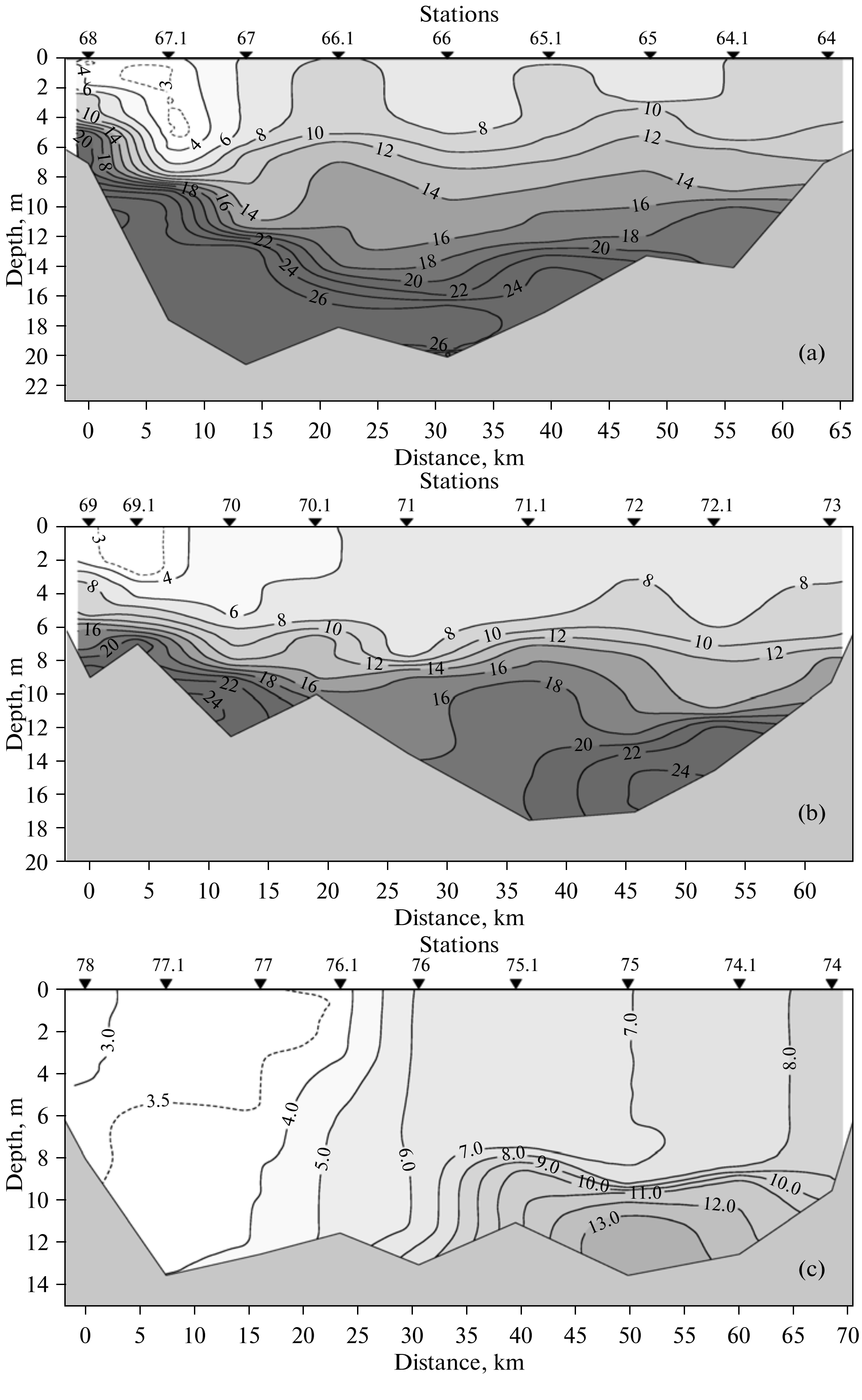

Fig. 7. Distributions of the salinity *S* (‰) along transects no. 17 (a), 18 (b), and 19 (c) (see Fig. 2).

In the east of the inlet, very strong mixing of the layers is recorded, which results in reduced salinity gradients from the surface to the bottom. For instance, the near-surface salinity in the northernmost transect (transect 17; 72°40′N) becomes as high as 8–9‰ in the zones outside the active surface runoff in the background of the respective decrease in the bottom values relative to the summer estimates down to 20–25‰ (Fig. 7a). Ten minutes south of and lengthwise transect 18, the degree of mixing markedly increases and the 8‰ isohaline underlies the virtually homogeneous upper layer 5 m thick (Fig 7b). Next, 20 minutes to the south lengthwise transect 19, the mixing gradually covers the water thickness down to the eight meter depth (Fig. 7c).

Integrally, the water stratification disappears south of 72°10′N, and the salinity estimates of the fully mixed waters gradually decrease southwards from 3–4‰ to 0‰ closer to the "narrowing" of the lateral profile of the inlet near 71°50′N (abeam of Cape Shtormovoy).

It is worth noting the influence of the orographic specificity of the northern part of the Ob' inlet upon the depth dependence and deformation of the hydrologic front. First of all, this is the so-called Ob' Sill (or bar) from 72°15′N to 72°25′N with the depths on the order of 10 m (reduced to the minimal ones) along with the trenches contoured by 15 m isobaths and oriented from the northwest to southeast. These circumstances, being superimposed on the westward deflection of the river flow, enhance the advection of salty waters lengthwise the eastern shores.

It is important to emphasize that the zone of contact of salty and fresh waters in the north of the inlet overcame the 72°N latitude and was displaced southwards by 30–40 km in reference to the summer localization.

CONCLUSIONS

Our studies allow us to evaluate the dynamics of the hydrological processes in the Ob' inlet during the free water period when works aboard a ship are feasible. It was possible to trace the main trends in the seasonal changes of the inlet's regime in the background of the variations of the significant factors that determine the regime. It was established that the whole aquatic area can be conventionally divided into two parts. The first one behaves as the riverine one. During the high water period, it resembles a drowned river but looks like a lake during the fall season. Another part is marine in nature. Here, everything is determined by the complex processes of the interaction of the fresh runoff and salty sea waters.

The hydrological situation in the north of the inlet was analytically treated at length at the stages of the high and low water content. It was established that a strongly stratified water structure with a clearly defined "classic" halocline in the bottom layer forms in the vicinity of the hydrologic front at the dominating high river runoff in the summer. The mixing processes are of primary importance during the fall season when the river runoff is relatively weak. As a result, the water stratification sharply weakens, the salinity gradients between the surface and the bottom diminish too, and the upper salty and well-mixed layer grows in thickness. The near-bottom tongue of the salty waters is not observed in the south of the contact zone, while fully mixed brackish water gently diminishes southwards up to zero in absolute units of salinity.

It is important to emphasize the strong variability of the processes in the Ob' inlet, where everything is determined by the intricate interaction of the runoff, the offset–onset events, the tides, and the winds. Therefore, here, we encounter not only the intraseasonal variability but also substantial daily and even hourly variability as well.

All the above indicates the extreme importance of the future organization of long-term stationary research at dedicated stations and transects in order to monitor the dynamics of the relevant factors during a day, week, or month. This could substantially advance our understanding of the processes in the Ob' inlet.

To conclude, it is important to again emphasize that the hydrological studies were conducted in conjunction with hydrochemical, biochemical, hydrobiological, and toxicological research. The value of these works is in the comparison of the results from different but closely interrelated areas of knowledge.

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