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MARINE PHYSICS

Propagation and Transformation of Waters of the Surface Desalinated Layer in the Kara Sea

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Abstract—A new method for the calculating propagation of brackish waters from the Ob-Yenisei estuary in the Kara Sea is proposed. This method is based on satellite altimetry measurements and meteorological data. Surface currents in the upper layer are estimated as the sum of geostrophic and parameterized wind-driven transport. Geostrophic velocities are calculated using altimetry-derived sea-level anomalies and mean dynamic topography. The method has been used previously to calculate surface currents in the Black Sea [7, 12]. In this paper it has been successfully verified on the basis of comparisons with field observations of surface salinity and satellite images of sea-surface chlorophyll in the Kara Sea.

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INTRODUCTION

The upper desalinated layer (UDL)is one of the main hydrological structures that are well pronounced in the Kara Sea during the summer period [5]. The formation of this layer is associated with floods of the rivers Ob and Yenisey. About 30% of the total yearly runoff of these rivers is discharged into the sea in June [17]. The mixing of riverine and salty waters results in the formation of the UDL, which covers the vast Ob–Yenisey near-shore zone and measures 10–25 PSU in salinity and 5–15 m in thickness.

Further propagation of the UDL over the area of the Kara Sea develops under the influence of wind drift and geostrophic currents [6]. The "western," "central," and "eastern" types of propagation are usually distinguished [8, 9]. The travelling of a considerable fraction of UDL waters west- and southwestwards is characteristic of the western type. In this case, the UDL waters reach the eastern shores of Novaya Zemlya in August to September. This type of propagation took place in 1993, 2007, and 2011, when SIO RAS performed expeditionary research onboard the RV *Dmitri Mendeleev* (cruise 49, 1993) [1] and RV *Akademik Mstislav Keldysh* (cruise 54, 2007 and cruise 59, 2011) [2, 4, 5]. The UDL travels mainly northwards under propagation conditions of a central type and eastwards along the Siberian shores towards the Laptev Sea when an eastern type of propagation prevails.

A number of authors have hypothesized that the occurrence of one or another type of UDL propagation depends on interannual differences of wind forcing (see, for instance, [16]). However, the first attempt of the quantitative study of the UDL travel due to wind drift was undertaken in [4]. On the assumption that the entire Ekman transport is concentrated in the UDL and develops orthogonally to the right of the wind direction, it is demonstrated in this study that the northerly wind, prevailing in July to August 2007, was able to cause the westward transport of UDL waters, which agrees with observations. However, this simplified approach to the evaluation of the motions of the UDL waters ignores that UDL drift is not quite Ekman transport [3] and that geostrophic currents have a pronounced effect. This prevents the description of an actual configuration of UDL domain and its variability in time and space.

At the same time, it was assumed [5] that the self-organizing dynamics of UDL waters, caused by the increase of the sea level over the area of desalination, plays an important role in the transport of desalinated waters. As a result, an anticyclonic circulation must occur in the frontal zone of the UDL as a consequence of geostrophic adjustment and the area of desalinated water should take a form of a large surface anticyclonic lens similar to that modeled in laboratory experiments [11].

Possibly, the main currents (the Yamal current, the eastern Novaya Zemlya current, the current of the St. Anna Trough) contribute slightly to the transport of the UDL, which is mainly northeastwards. The northward propagation of the UDL waters seems to be limited by a dynamical frontal zone, which belongs to the area of Novaya Zemlya and is related to the eastern Novaya Zemlya current and the current of the St. Anna Trough [5, 6].

A new approach to the calculation of currents in the upper mixed layer, based on using the mean dynamic topography of the sea surface (MDT), regular data of satellite altimetry on sea-level anomalies (SLA), and the parameterization of wind drift, can serve as a framework for implementing the joint consideration of the impact of wind drift and geostrophic

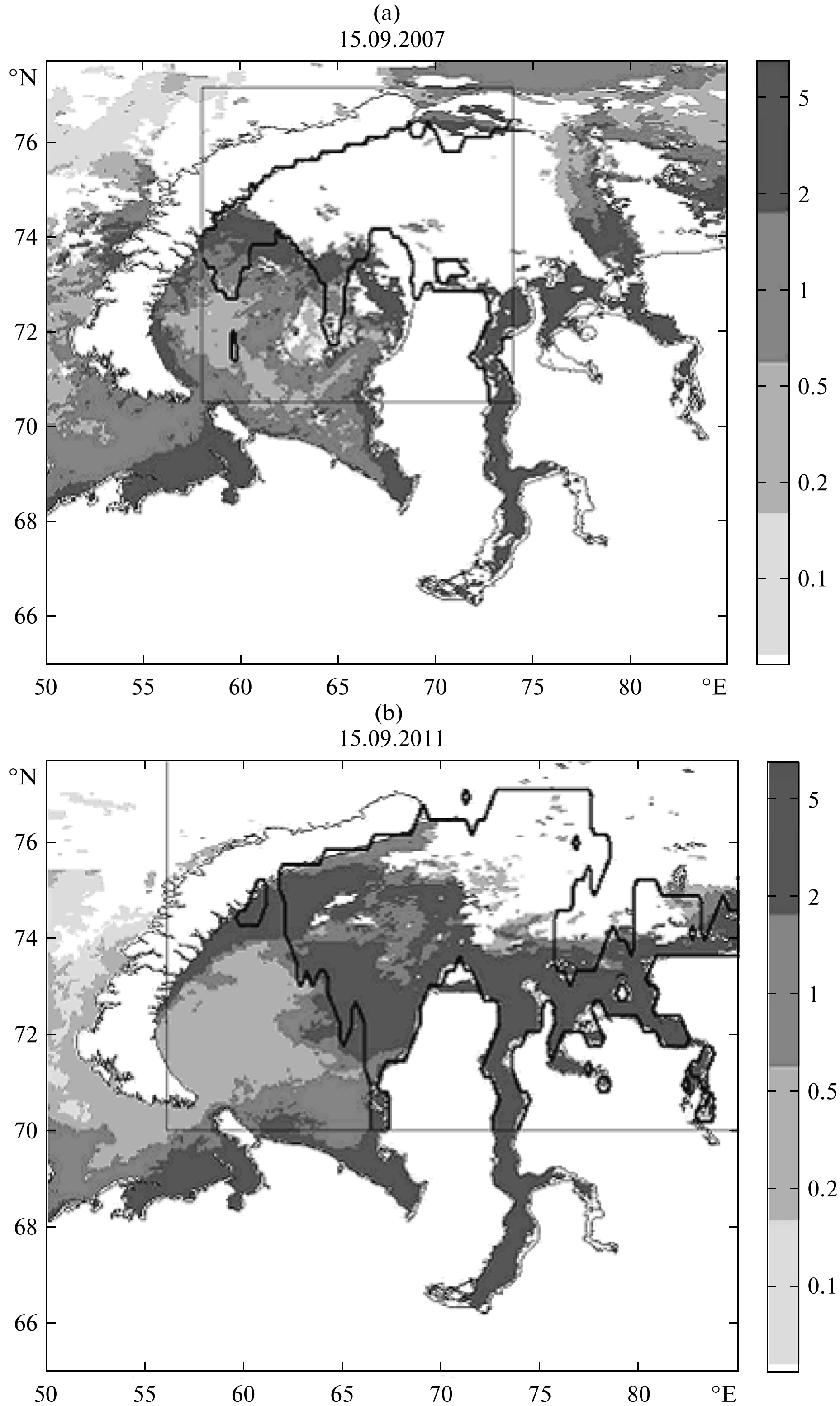

Fig. 1. Distributions of satellite chlorophyll in the Kara Sea in September, 2007 (a), and September 2011 (b), along with the superimposed outlines of the UDL frontal zone in the salinity field based on the data of expeditions in September, 2007, and September, 2011, respectively. The scale of chlorophyll concentration in mg/m^{-3} is on the right.

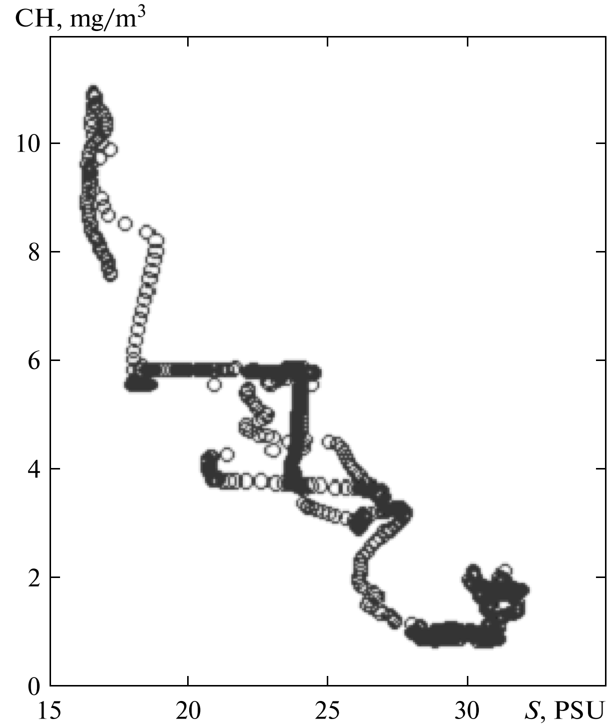

Fig. 2. The concentration of satellite chlorophyll, mg m^{-3} (CH, ordinate axis) as a function of the surface salinity, PSU (*S*, abscissa axis), recorded with a flow-through system when crossing the UDL fronts along the itinerary of travel of the RV *Akademik Mstislav Keldysh*, cruise 59, in the Kara sea in September 2011.

currents (both background flows and self-organizing currents in the UDL area) upon the propagation of desalinated waters from the Ob–Yenisey near-shore zone over the aquatic area of the Kara Sea. This approach has already been used for describing the surface currents in the Black Sea [7, 12]. The present paper is dedicated to the application of this approach to the description of UDL dynamics in the Kara Sea, to its verification based on comparison of the data of field observations, and to the analytical treatment of the results of calculations.

Surface chlorophyll as a tracer of UDL waters. Verification of the technique for calculating the propagation of UDL waters on the basis of comparison with field data suffers from a substantial temporal limitation because the Kara Sea expeditions of 2007 and 2011 were performed in September. For these reasons, it is important to find a fairly reliable remotely detectable tracer allowing us to monitor the propagation of UDL area using satellite data. Surface chlorophyll a (chl a), whose concentration is retrievable from satellite data ("satellite chlorophyll" in what follows), is such a tracer. It should be noted that we are not interested in the quantitative correspondence of the concentration of satellite chlorophyll to the content of chlorophyll found from in situ determinations.

The similar behavior of satellite chlorophyll and surface salinity in the UDL area was discovered while analyzing data from 2007 [5] but was not yet studied and described. Here we make up for this deficiency. The idea of the correspondence of satellite chlorophyll with surface salinity in the UDL area is based on the fact that riverine waters transport large amounts of nutrients that support phytoplankton production in this layer during the whole period of its lifetime. Therefore, the aquatic area occupied by the UDL, must exhibit a higher content of chlorophyll a and a yellow substance than the surrounding areas, excluding the areas of upwellings and fronts, as is corroborated by observations.

Figure 1 shows maps of satellite chlorophyll, averaged over September 2007 and September 2011, and the superimposed contours of the frontal zone of UDL in the field of the surface salinity (isohaline 24 PSU). These maps were composed from the data of expeditions of September 2007 and September 2011, respectively. Unfortunately, the September maps of satellite chlorophyll are not quite informative because of data gaps owing to cloudiness. Nevertheless, it is evident that the western boundary of the domain of higher chlorophyll concentration approximately coincides with that of the isohaline 24 PSU (isohaline 25 PSU is used to mark the boundary of the UDL area in [17] and other sources).

Based on this coincidence and the ship-borne measurements of chlorophyll fluorescence and surface salinity, which indicate higher content of chlorophyll a in the UDL area in reference to the background level [4], we consider satellite chlorophyll to be a tracer of UDL waters. This is corroborated by the analysis of maps of satellite chlorophyll (MODIS AQUA, MERIS-Envisat) for the period from June to September 2011, which allowed us to follow the propagation of the area of higher chlorophyll concentration from the Ob-Yenisey estuary to the eastern shore of Novaya Zemlya. A strong correlation of the concentration of satellite chlorophyll and salinity near the UDL fronts is demonstrated by Fig. 2 as well. This shows a correlational dependence of satellite chlorophyll, measured along the ship tack, across the UDL fronts, and the surface salinity recorded in the same ship tack in September, 2011 (cruise 59 of RV *Akademik Mstislav Keldysh*). When plotting these dependences, we used satellite data of 4 km spatial resolution averaged over a period of three days and interpolated to sites of ship-borne measurements (about 300 m pitch).

From here on we shall use maps of satellite chlorophyll to compare the results of the calculation of the outlines of the UDL area in different months of its occurrence.

CALCULATION OF GEOSTROPHIC CURRENTS USING THE METHODS OF DYNAMIC TOPOGRAPHY AND SEA LEVEL ANOMALIES

In order to calculate the velocities of geostrophic surface currents in the Kara Sea, use has been made of maps of full-scale dynamic topography obtained from

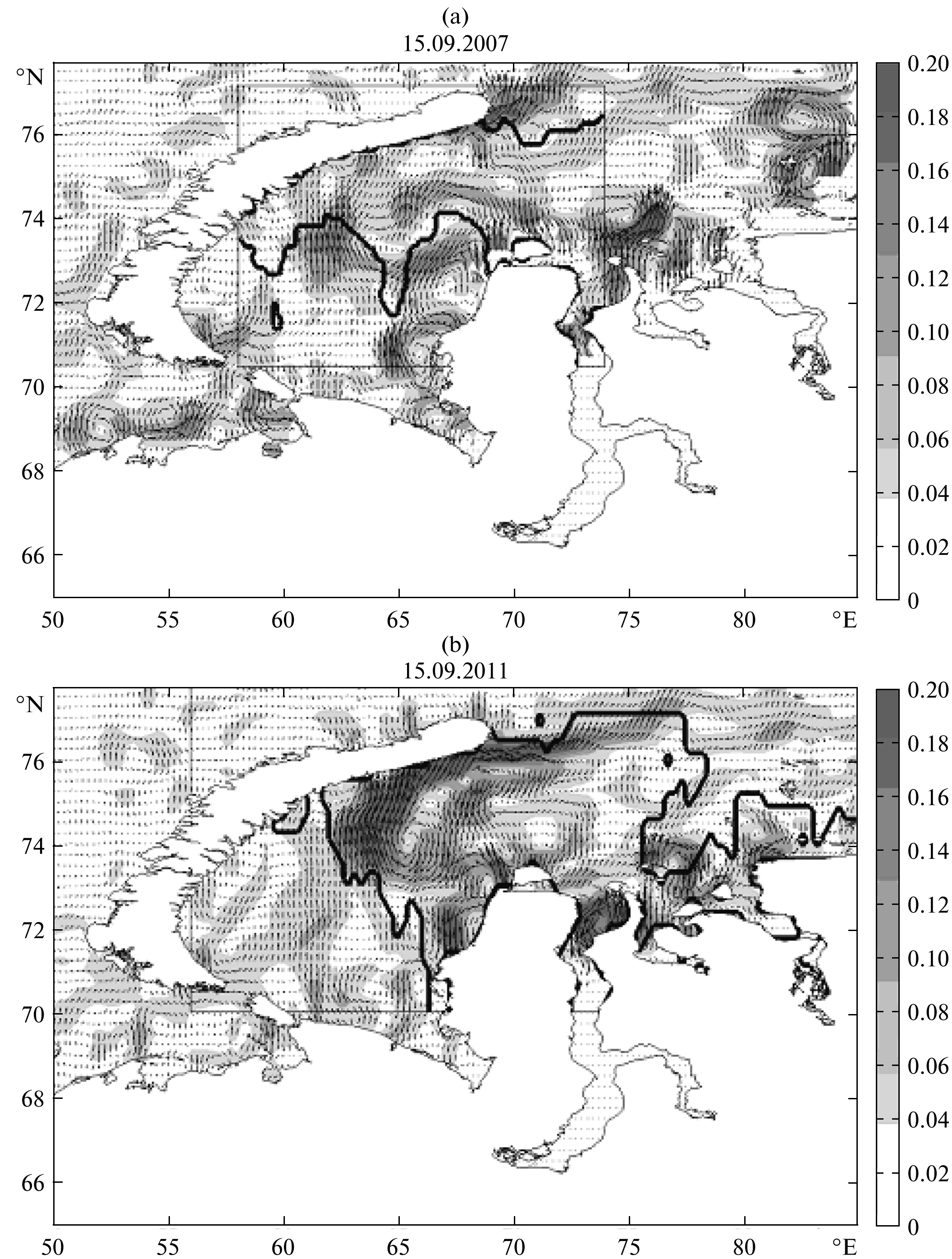

Fig. 3. Maps of geostrophic currents of September 2007 (a) and 2011 (b). Scale of velocity, cm s^{-1}, is on the right. The black contour designates the UDL front from the ship-born measurements (isohaline 24 PSU).

the AVISO archive (http://www.aviso.oceanobs.com). Dynamic topography has been determined as a sum of mapped sea-level anomalies, calculated from the mean dynamic topography from [14, 19] and combined along-track measurements of present-day satellite altimeters with the help of the algorithms, developed in [13–16]. The time and space resolution of mapped data measured 7 days and 0.25°, respectively.

Surface geostrophic velocities of currents were found from the equation of geostrophic equilibrium:

$$u_g = -\frac{g}{f}\frac{\partial h}{\partial y}, \quad v_g = \frac{g}{f}\frac{\partial h}{\partial x}. \tag{1}$$

Here u_g, v_g are geostrophic velocities, h is dynamic height, g is freefall acceleration, f is the Coriolis parameter.

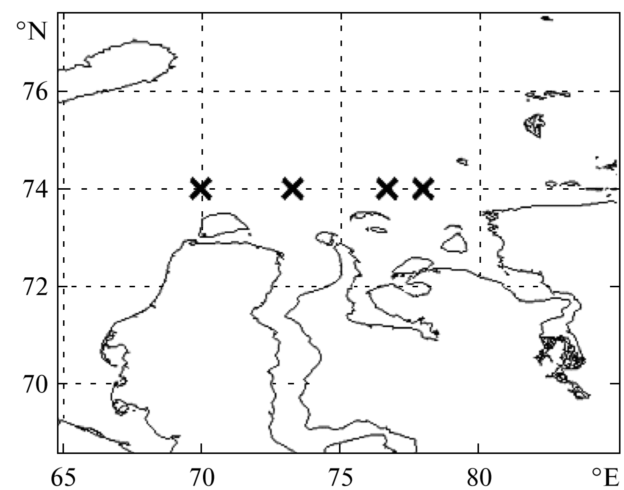

Fig. 4. Locations of sites of release (crosses) of the Lagrangian particles in the Ob-Yenisey estuary.

The monthly mean geostrophic maps for 2007 and 2011 are given in Fig. 3 along with the outlines of the UDL area (isoline 24 PSU) composed on the basis of expeditionary data of September 2007 and 2011. From this figure we notice that the anticyclonic circulation arises in the center of the Kara Sea during summers of these years and that western boundary of the gyre approximately coincides with the western UDL boundary. Calculations show that anticyclonic circulation enhanced from July to August as it moved northwards in 2007 or eastwards in 2011. The anticyclonic cell continues to intensify (the winds of northerly rhumbs continue "to operate" during the first half of the month). In September 2007 it slightly weakens as compared with August because the direction of prevailing wind changes from northerlies to southerlies. In October 2007 and 2011, the anticyclonic cell weakens but the northeastern current intensifies. Its velocity becomes as great as 0.2–0.3 m/s. This corresponds to the autumnal changing of the direction of prevailing winds, when the northerlies give way to the southerlies.

PARAMETERIZATION OF WIND DRIFT OF UDL WATERS

As already noted, the correct reproduction of the summer–autumn propagation of UDL waters in the Kara Sea is possible only on the basis of the known surface geostrophic currents and adequate parameterization of wind drift, which is the main factor of the interannual diversity of patterns of UDL propagation [8, 9].

In order to examine the variability of the wind, use has been made of the data of the NCEP (National Centers for Environmental Prediction) on a one-degree regular grid at a six-hour interval, available at http://oceandata.sci.gsfc.nasa.gov/. The data from NCEP reanalysis provide information on the parameters of the state of the atmosphere based on the assimilation of meteorological observations with the help of an ensemble of dynamical models of the state of the atmosphere.

According to the foregoing, the propagation of UDL is conditioned mainly by two processes: geostrophic circulation and integral wind-driven transport.

Geostrophic currents were calculated with formulas (1) using data of satellite altimetry. The rate of integral wind-driven transport of UDL waters *Ue* was determined with the formula [18]:

$$Ue = \tau/\rho_w f H_0, \text{ where } \tau = c_d \rho_a |v| v. \qquad (2)$$

Here τ is the wind stress, $\rho_w = 1000$ kg/m^3, and $\rho_a = 1.3$ kg/m^3 are the densities of water and atmosphere, respectively; v is wind velocity, $f = 1.4 \times 10^{-4}$ s^{-1} is the Coriolis parameter, and H_0 is the characteristic thickness of the UDL [5]. The value of wind-drag coefficient Cd varies from one calculation to another, from 0.8×10^{-3} to 1.8×10^{-3} (see below).

According to classical theory [10], the integral Ekman transport due in the North Hemisphere in homogeneous deep basin should be directed at an angle $\alpha = 90°$ to the right of the wind direction. Under real conditions, this angle α can be smaller due to the fact that the UDL, which accumulates the wind effects, has limited thickness [3]. In addition due to the nonstationary nature of the wind, drift current has no time to accomplish a full turn during the period characteristic of the wind variability. In our study, we calculated the integral wind-driven transport of the UDL for different values of the angle α to the right of the wind direction with the aim to determine the angle that allows the optimal coincidence of calculation results and expeditionary survey of the field of surface salinity and satellite chlorophyll *a* data. The trajectories were calculated with the Lagrangian particle-tracking model (see below).

The total current velocity in the surface layer was defined as $\vec{V} = \vec{V}_g + \vec{U}_e$, where $\vec{V}_g$ is the geostrophic velocity. In order to find the trajectories of the Lagrangian particles, the full velocities were linearly interpolated to the time and coordinates of a particle. Next, we calculated the particle's displacement according to the Euler method $\vec{r}_{i+1} = \vec{r}_i + \vec{V}dt$. In our calculations, the time interval *dt* was 6 h, which corresponds to the discreteness of wind velocity data.

CALCULATION OF TRAJECTORIES AND VELOCITIES OF PROPAGATION OF UDL WATERS FROM THE OB-YENISEY ESTUARY

Stationary sources of particles were placed at four sites of the Ob-Yenisey estuary (crosses in Fig. 4) in order find the trajectories of the propagation of the UDL waters. The first particle was released on July 1 of each year, which is close to the end of the period of the most intensive total discharge of the Ob and Yenisey rivers. The calculation lasted three months until

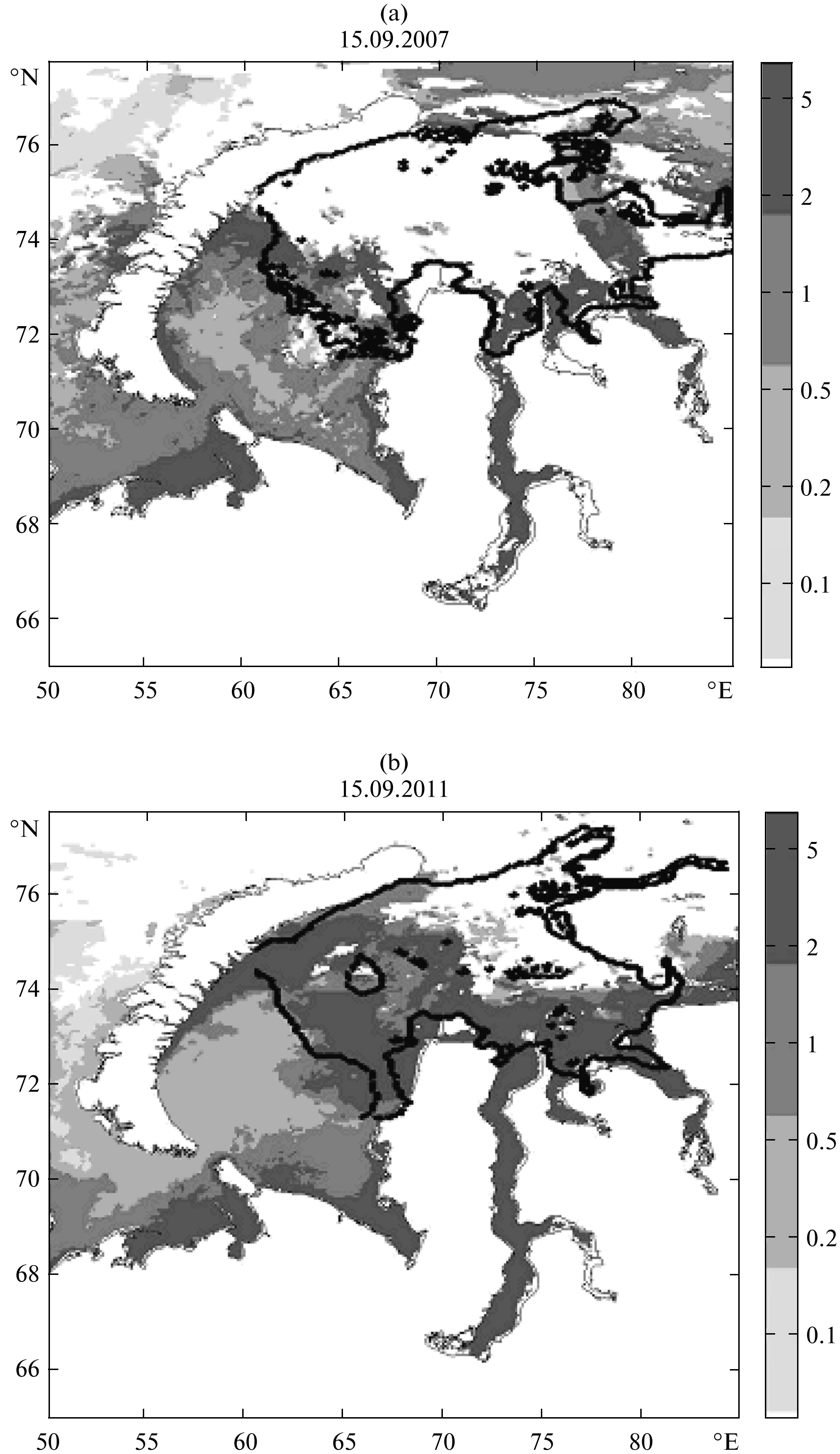

Fig. 5. The outlines of the area of virtual tracers obtained at $c_d = 1.4 \times 10^{-3}$ and $\alpha = 45°$ and superimposed on the map of satellite chlorophyll for September 2007 (a) and 2011 (b).

October 1. By the end of calculations, about 350 particles had been released from every site and the trajectories of their propagation were found. Sites for releasing the particles were chosen to be distributed along 74° N opposite the Ob-Yenisey estuary. This choice is based on two facts: first, satellite measurements show

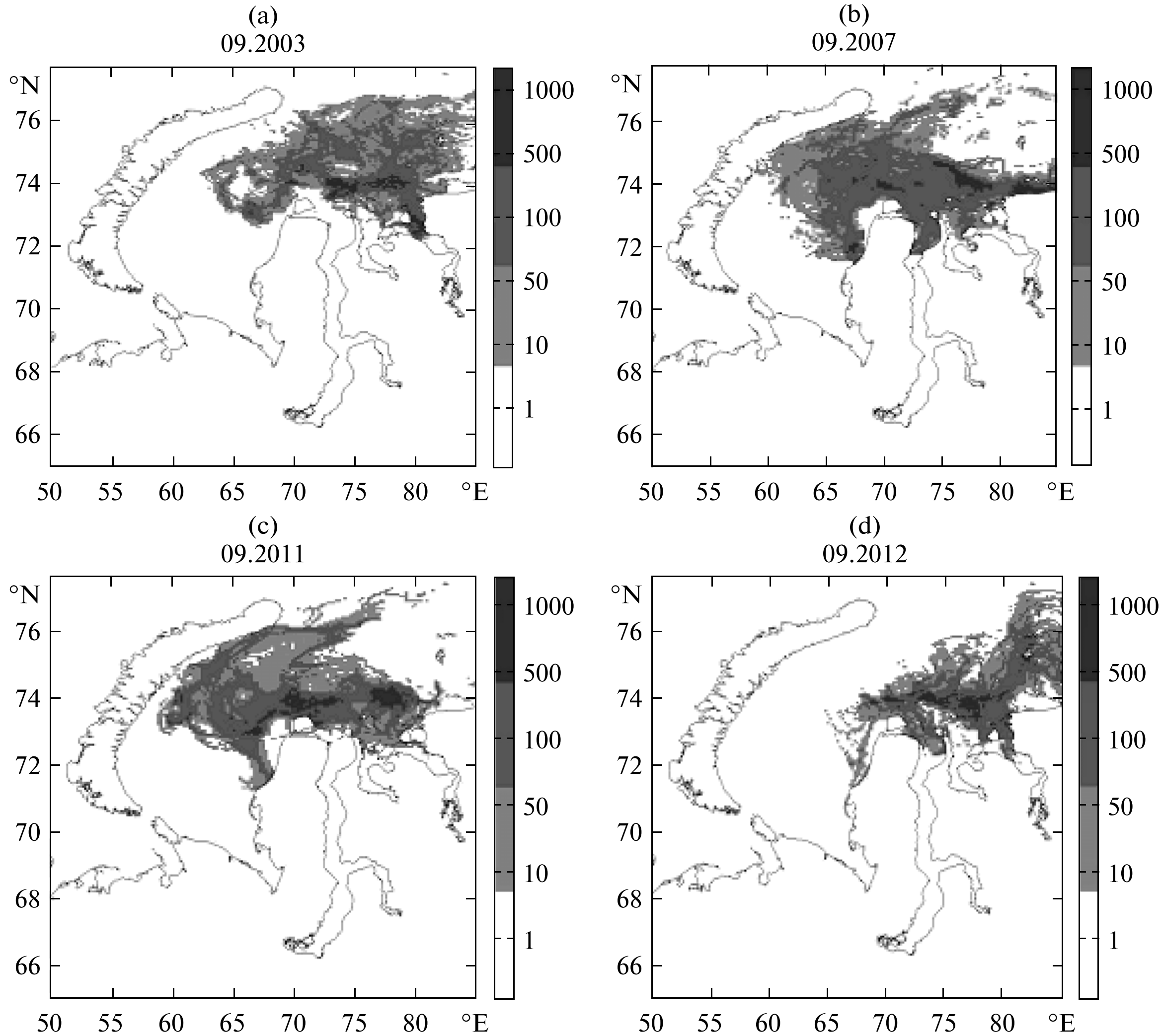

Fig. 6. Propagation of waters, desalinated with the discharge of the Ob and Yenisey rivers, from July 1 to September 15 in 2003 (a), 2007 (b), 2011(c), and 2012 (d).

that UDL waters reached this area at the end of June; second, the chosen places are rather far from river mouths, where ageostrophic dynamics can be significant.

Calculations were carried out for four years: 2007 and 2011, as years of expeditionary studies, useful for calibrating calculations, and 2003 and 2012 as years of wind conditions substantially different than those in 2007 and 2011.

A series of calculations were undertaken to estimate the optimal values of coefficient c_d and angle α. The magnitude of c_d varied from 0.8×10^{-3} to 1.8×10^{-3} with an interval of 0.2×10^{-3}, while the angle α was changed from 40° to 75° with an interval of 5°. We selected the optimal parameters by comparing the maps of the concentration of virtual tracers and the fields of the concentration of satellite chlorophyll. To calculate the concentration of tracers at a point, we summed up the number of all particles that passed the respective box. The size of box is chosen to be $0.2 \times 0.2°$.

A comparison of calculations of 2007 and 2011 and maps of the satellite chlorophyll revealed that that the former are the most sensitive to the choice of the wind-drag coefficient: at $c_d \geq 1.6 \times 10^{-3}$ the tracers move to the west and to the north compared to the UDL boundaries but at $c_d \leq 1.2 \times 10^{-3}$ the tracers did not reach this boundary. Besides, at $c_d \geq 1.6 \times 10^{-3}$ the virtual tracers arrive at shores of the Novaya Zemlya in July, which never happens in real situations. It was acknowledged that calculations at $c_d = 1.4 \times 10^{-3}$ and $\alpha = 45°$ secure the best coincidence of maps of satellite chlorophyll and the surface salinity (see Fig. 5). Note that local minimum of concentration of satellite chlorophyll took place in the center of the southwestern Kara Sea, which is successfully reproducible with the help of calculations (Fig. 5).

It should be noticed that neither c_d nor α are constants, since they depend upon diverse parameters: c_d grows with wind velocity and changes with the stability of the near-water layer of the atmosphere, while α is dependable on duration of wind forcing, thickness of the UDL, and its vertical stability. For these reasons, the use of approximations involving constant coefficients c_d and α results in errors which exhibit, among other things, a narrowing of the area covered with the tracers, as compared to the actual UDL area. Ignorance of the thickness H of desalinated layer and its spatial–temporal variability is a source of errors too. We used $H = 10$ m in calculations, to which observations correspond, on average [5].

Nevertheless, with all above reservations, the use of the above model for the calculation of the propagation of the Lagrangian particles provides an opportunity to approximately retrieve and examine the history of the propagation of riverine waters in the Kara Sea for all years since 1992, when high-precision satellite altimetry appeared, to the present. Based on the calculations, Fig. 6 demonstrates the propagation of riverine waters in 2003, 2007, 2011, and 2012.

The trajectory of the desalinated waters in the Kara is visualized in Fig. 7 as pathways of particles for three moths of calculations. The particles were released one after another on July 1 and 10, 2011. It is easy to see that the particles, being released at a ten-day interval at the periphery of the Ob-Yenisey estuary, were entrained with the anticyclonic gyre and moved initially westwards to Severnaya Zemlya, after which their pathways part: the first ones reach the east shores of the Novaya Zemlya and then travel northeastwards, while the particles of July 10 release travel southeastwards with the anticyclonic circulation. The diversity of pathways of the Lagrangian particles, released from several sites and at different times, makes possible to achieve an appropriate density of "coverage" of certain fraction of the sea area by pathways. We consider this area a domain of UDL propagation. The question of the optimal choice of the number of sites for Lagrangian-particle release and their positioning for the most representative reproduction of the UDL area is still an open question

A control experiment was fulfilled to assess the impact of the parameterized integral transport of the UDL waters. Calculation was performed from July to October 2007 using only wind-driven currents, and geostrophic currents were believed to be absent (Fig. 8). The results in this figure are rather interesting: Lagrangian tracers traveled within a narrow stripe virtually along parallel lines inclined by 45° to the left of the northward direction. Such pathways result from the fact that either northerlies or southerlies prevailed during the summer–autumn period in 2007 in the southwestern Kara Sea. Only combined accounting for the integral wind-drift transport and geostrophic currents gives results of calculations close to observations (Fig. 6b).

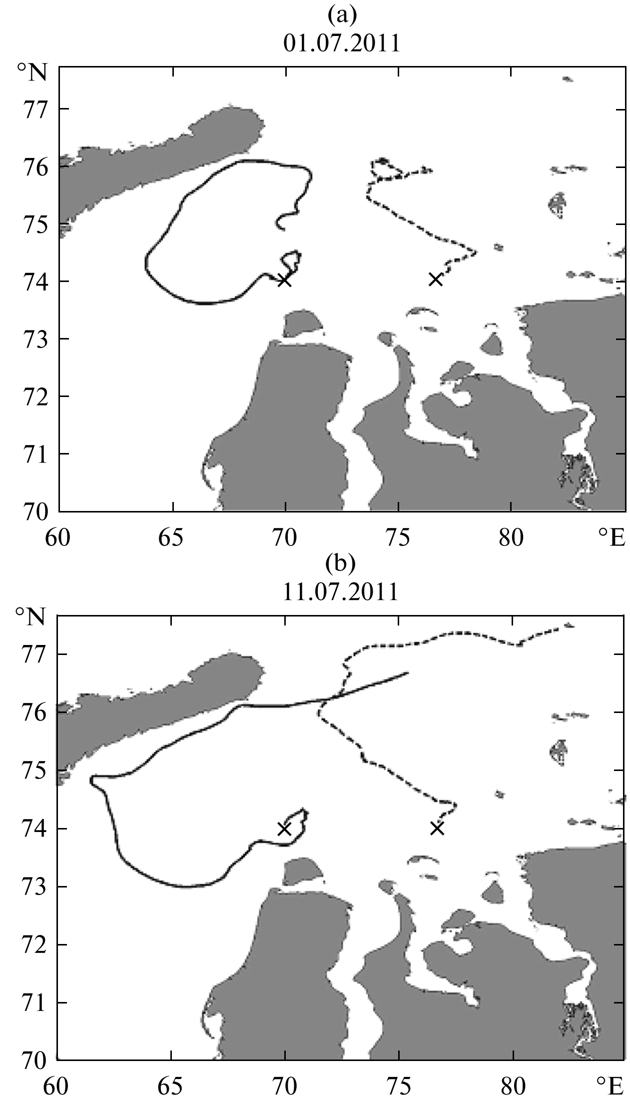

Fig. 7. Examples of pathways of virtual tracers released on July 1, 2011 (a), and July 11, 2011 (b). Crosses mark the starting points of pathways.

DISCUSSION AND MAIN CONCLUSIONS

Figure 9 shows the results of calculations of wind velocity averaged over the Augusts of the years 2003, 2007, 2011, and 2012. It is evident that the wind field was not the same in all four cases during this month that is a key period for propagation of the UDL in the Kara Sea. The mean southern and southeastern winds were characteristic of August 2003; the northern and northeastern winds were typical of August of 2007 and 2011 (wind was stronger in 2011); the northwestern wind prevailed in 2012. It follows from calculations at $c_d = 1.4 \times 10^{-3}$ and $\alpha = 45°$ that the distinctions in wind effects lead to different areas of the UDL area

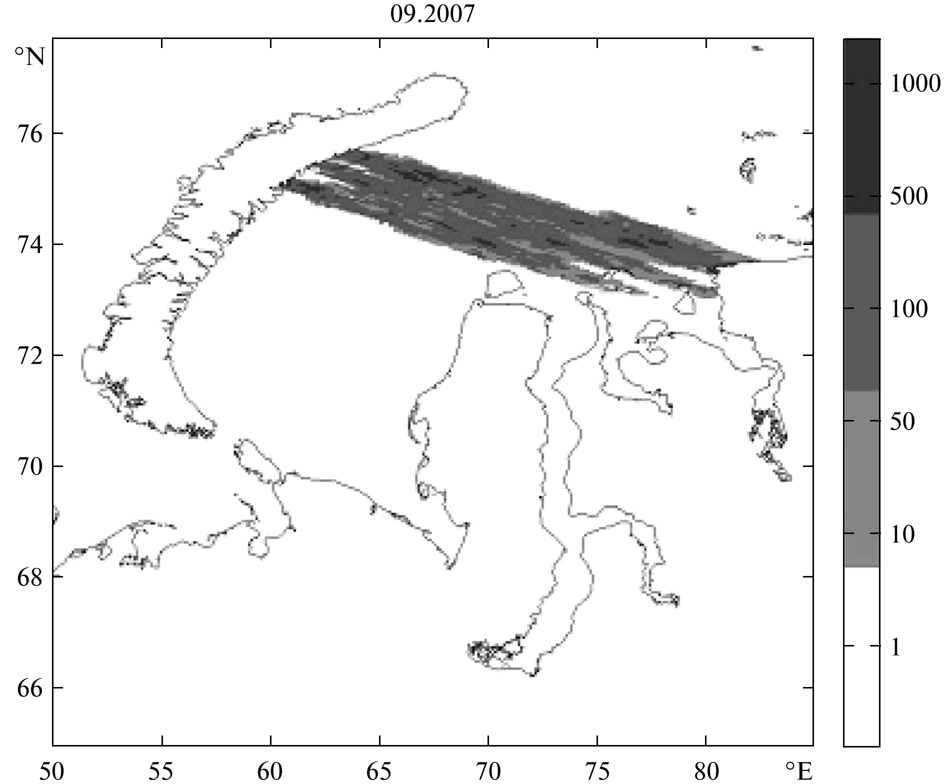

Fig. 8. Calculations of virtual tracers travel without regard to geostrophic velocity.

(see Fig. 6). The "central" type of UDL propagation prevailed in 2003 (Fig. 9a), the western type occurred in 2007 and 2011 (Figs. 9b and 9c), and the eastern type took place in 2012 (Fig. 9d).

The most pronounced difference in the patterns of propagation of the UDL waters was observed in 2011 and 2012. In both cases, winds of northerly rhumbs prevailed. However, northeasterlies prevailed in 2011 and northwesterlies dominated in 2012. Under northeasterly conditions, integral Ekman transport declines by 45° to the right of the wind direction, which actually leads to the westward direction of UDL propagation. Under the northwesterly regime, the same declination drives the UDL to the south, but the land is located south of the Ob-Yenisey estuary. Here the UDL hits the land and forms a belt of desalinated waters. In this belt, water flows eastwards due to geostrophic adjustment, which occurred in 2012, according to calculations. Thus, a relatively small change in wind direction from the northeast direction in 2011 to the northwest in 2012 resulted in a radical change in UDL propagation.

In the future, we plan to check the results of calculations by comparing them to satellite data on surface salinity obtainable with the satellite sensor SMOS (Soil Moisture and Ocean Salinity) equipped with a microwave radiometer for measurements of the soil moisture and surface salinity of the World Ocean.

To sum it up, we highlight the following inference of our study. The horizontal propagation of UDL waters develops due to two main forces: wind drift and quasi-geostrophic circulation, which is self-organizing in the domain of frontal boundaries of the UDL area (Fig. 1). Calculations without accounting for this circulation and based exclusively on wind drift are unable to reproduce true pathways of propagation of the UDL waters (see Fig. 8).

How do drift and quasi-geostrophic currents in the UDL domain coexist? This is a sophisticated issue requiring further investigation. As a first approximation, it may be stated that quasi-geostrophic circulation exists in the UDL domain due to low friction at the lower interface of the UDL and is supported by the difference of the sea level inside and beyond this domain. It prevails at mild winds but stronger winds lead to wind-drift domination.

The wind drift of the UDL waters in the Kara Sea is not classical. The integral transport of the UDL water is directed only 40°–50° to the right of wind direction instead of 90° which is attributable to the limited thickness of the UDL and the nonstationarity of the wind forces.

Our method of the calculation of horizontal propagation of UDL waters from the Ob-Yenisey estuary over the Kara Sea may be useful for both diagnostic analysis and operational goals, for instance, for

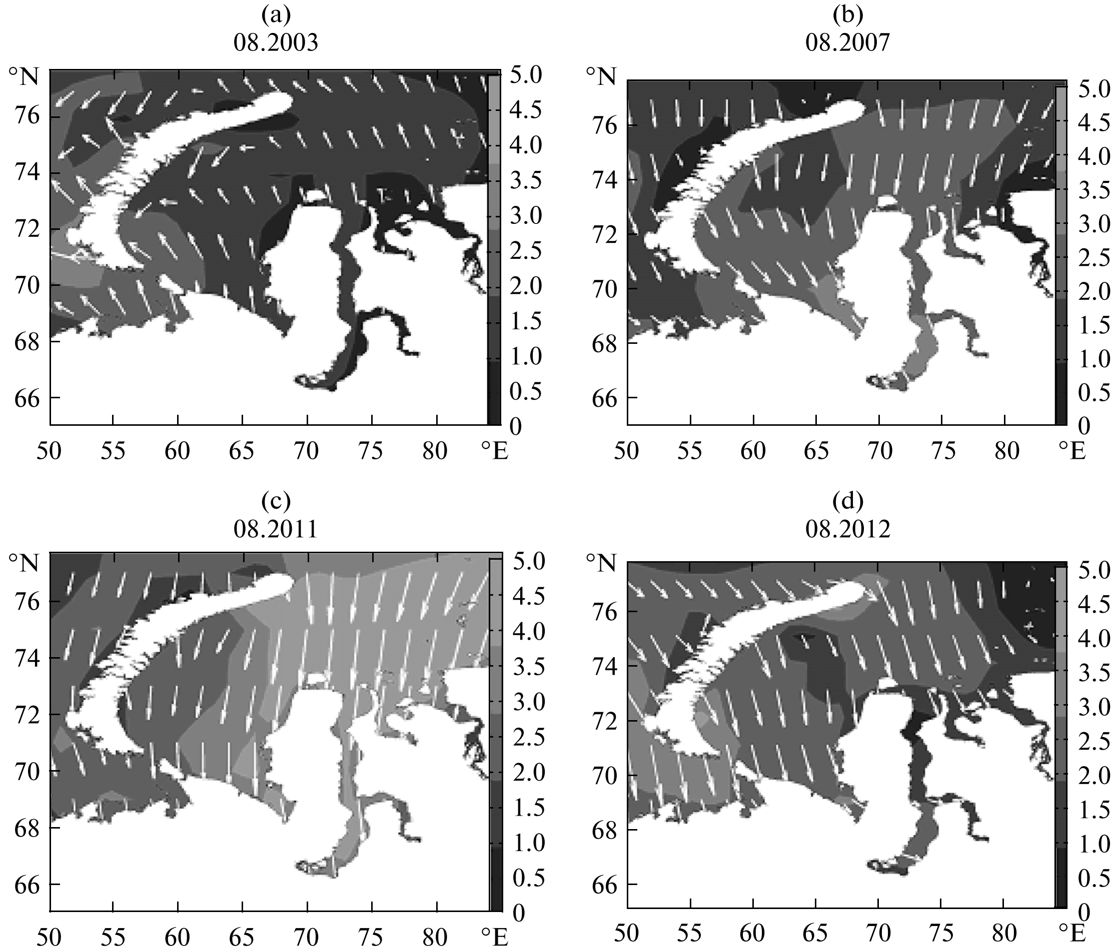

Fig. 9. The August mean vectors of wind velocity (arrows) over the southwest Kara Sea in 2003 (a), 2007 (b), 2011 (c), and 2012 (d). Shades of grey indicate velocity magnitudes whose scale is on the right in m/s^{-1}.

obtaining a priori information on outlines of the UDL domain when preparing an expeditionary research. This will be helpful for the optimal planning of a field mission and to spare extremely expensive ship time. It should be noticed that calculation technology will be improved and completed in the near future.

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