
Environmental Problems

Spreading and Transformation of River Discharge in the Arctic Ocean

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Received May 23, 2021; revised June 26, 2021; accepted July 10, 2021

Abstract—This paper is focused on research of freshwater discharge of the Great Siberian rivers (Ob, Yenisei, and Lena) in the Russian region of the Arctic Ocean. Discharges of these rivers form freshened surface layers with total area of hundreds of thousands of square kilometers, which strongly affect many climatic, physical, biological, and geochemical processes at the Russian Arctic seas. Based on the recent studies, it is shown that the freshened surface layer in the Eastern Arctic has inhomogeneous structure, spreading dynamics, seasonal and inter-annual variability caused by its formation by large estuarine rivers in the Kara Sea and large deltaic river in the Laptev and East-Siberian seas. The large-scale inter-basin transport of the freshened surface layer at the Arctic shelf is discussed, which is an important component of the freshwater cycle in the Arctic Ocean.

Keywords: river discharge, river plume, freshened surface layer, surface circulation, climatic processes, Ob, Yenisei, Lena, Arctic Ocean.

DOI: 10.1134/S1019331621060101

River plumes are freshened water masses that are formed as a result of mixing of river runoff and saline seawater. River plumes are formed in coastal marine areas in many regions of the world and are often large but thin sea surface layers. River plumes play an important role in global and regional ocean–land interactions. Significant flows of buoyancy, heat, terrigenous suspension, biogenic substances, and anthropogenic pollution enter the World Ocean with river discharge [1–6]. River plumes, being a transitional water mass between river runoff and seawaters, govern transformation and redistribution of these flows and thus play the role of a connecting link between continental and oceanic systems. Therefore, river plumes significantly affect many physical, biological, and geochemical processes in the coastal and shelf areas of the sea, including the formation of seawater stratification, coastal currents, the cycle of carbon and nutrients, the formation of primary production, changes in the morphology of the seabed, etc. [7–9]. The structure, dynamics, and variability of river plumes are key factors for understanding the mechanisms of the advection, convection, transformation, accumulation, and dissipation of continental runoff, as well as suspended and dissolved substances of riverine origin [10–13].

For a long time, there was no single term for river plumes as separate water masses in the Russian-lan-

guage scientific literature. Different terms were used to designate them, such as *outflows*, *drains*, *torches*, *plumes*, *plumages*, *lenses*, *desalination zones*, etc. *Plume* is a hydrodynamic term for the flow of a liquid or gas that propagates in a liquid or gas medium with a different density. This term has been widely used for many years in the Russian-language scientific literature to describe similar processes in various fields of earth sciences; first of all, there is the *mantle plume* [14, 15], as well as *hydrothermal plume* [16, 17], *convective plume* [18], and *meteoroid plume* [19]. The first scientific articles in Russian journals that used the term *river plume* appeared in 2010–2011 [20–22]. To date, dozens of scientific articles have been published in which the term *river plume* is actively used, and it has become generally accepted in the Russian-language scientific literature.

The Arctic Ocean is the only part of the World Ocean where the interaction of continental runoff and seawaters affects processes on a global scale. The Arctic Ocean, which occupies only 3% of the surface area and 1% of the volume of the World Ocean, receives significant continental runoff, accounting for about 11% of the total world runoff into the ocean [23], as a result of which large river plumes are formed. The distribution and mixing of river plumes determine the sea stratification in the area of seasonal sea ice formation, thereby affecting ice formation in the Arctic Ocean, seasonal fluctuations in the Earth's albedo, and the planetary climate [24, 25]. Freshwater runoff has a significant impact on many regional processes in the

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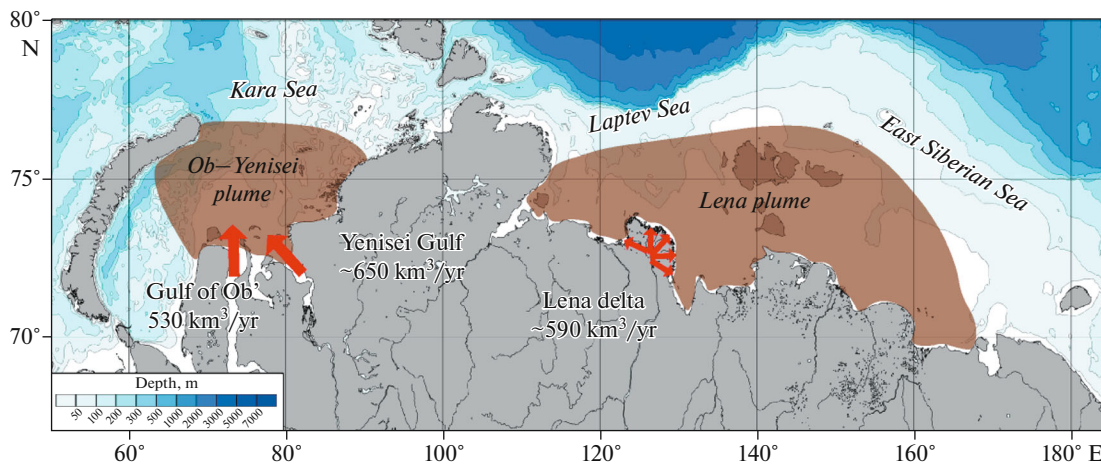


Fig. 1. Location and average annual runoff from the Gulf of Ob, the Yenisei Gulf, and the Lena delta; the distribution areas of the Ob–Yenisei plume in the Kara Sea and the Lena plume in the Laptev and East-Siberian seas.

Arctic, especially in coastal and shelf areas [24, 26–29]. Significant volumes of suspended and dissolved substances entering the sea with river runoff are retained in estuarine zones and affect the hydrochemical and hydrobiological structure of waters on the Arctic shelf [30]. Stratification formed by freshwater runoff restricts the supply of nutrients to the surface layer of the sea and negatively affects biological productivity in vast areas in the Kara, Laptev, and East-Siberian seas [31]. At the same time, stratification leads to a lower oxygen content and an increase in water acidity [32].

In recent decades, intensive research has been carried out on estuarine and shelf zones in the Arctic. As a result, a common understanding of the spatial and thermohaline characteristics of the river plumes formed by the Arctic rivers has been developed. The three largest rivers of the Russian sector of the Arctic—the Yenisei, Lena, and Ob—provide more than half of the continental runoff into the Arctic Ocean [33–35]. The Ob and Yenisei rivers flow into large estuaries (the Gulf of Ob and the Yenisei Gulf), located close to one another in the central part of the Kara Sea (Fig. 1). Because of this, the Ob and Yenisei plumes are formed in the estuarine waters and then merge into a single Ob–Yenisei plume, localized in the Kara Sea [36, 37]. The Lena River flows into the southeastern part of the Laptev Sea through a vast delta, one of the largest river deltas in the world [38]. The Lena plume is formed in the near-delta area and spreads further into the eastern part of the Laptev Sea and the western part of the East-Siberian Sea [39] (see Fig. 1).

The process of transformation of freshwater runoff in these plumes includes two successive stages: horizontal advection in summer and vertical mixing in fall and winter [40, 41]. The overwhelming part of the annual runoff of the Arctic rivers of Russia enters the Arctic Ocean over several months of the summer

freshet and during this period the Ob–Yenisei and Lena plumes are formed. These plumes spread as thin (less than 15 m) and slightly saline (less than 15 PSU) water masses over a large area on the shelf of the Eastern Arctic. After the end of freshet, the salinity and thickness of the plumes gradually increase as a result of their mixing with the underlying seawaters under the conditions of low continental runoff. The almost complete absence of runoff of Siberian rivers during the long fall–spring low-water season leads to the final dissipation of the freshened surface layer. By spring, the surface salinity in the Kara, Laptev, and East-Siberian seas rises to the background values.

An interesting paradox arose in the study of the Ob–Yenisei and Lena plumes. The total freshwater runoff that forms the Ob–Yenisei plume in the Kara Sea is 1.5 times larger in volume than the runoff that forms the Lena plume in the Laptev and East-Siberian seas. Despite this, the area of the freshened region in the Laptev and East-Siberian seas (300 000–500 000 km²) is 1.5–2 times larger than in the Kara Sea (200 000–250 000 km²) (Fig. 2). The interannual variability of the area of the distribution of these plumes also differs greatly. The Ob–Yenisei plume each year occupies approximately the same area in the central part of the Kara Sea; the interannual variability of its outer boundary is low [40] (see Fig. 2a). The position and area of the Lena plume, on the contrary, have significant interannual variability determined by wind conditions during the ice-free period of the year (July–October) [41] (see Fig. 2b). The prevailing westerly winds make the plume move towards the coast of Siberia, as a result of which it is localized in the southern parts of the Laptev and East-Siberian seas. In this case, its meridional length (<250 km) and area (~300 000 km²) are relatively small. With strong easterly winds, on the contrary, the Lena plume spreads over a large area (up to 500 000 km²) in the central parts of these seas, its

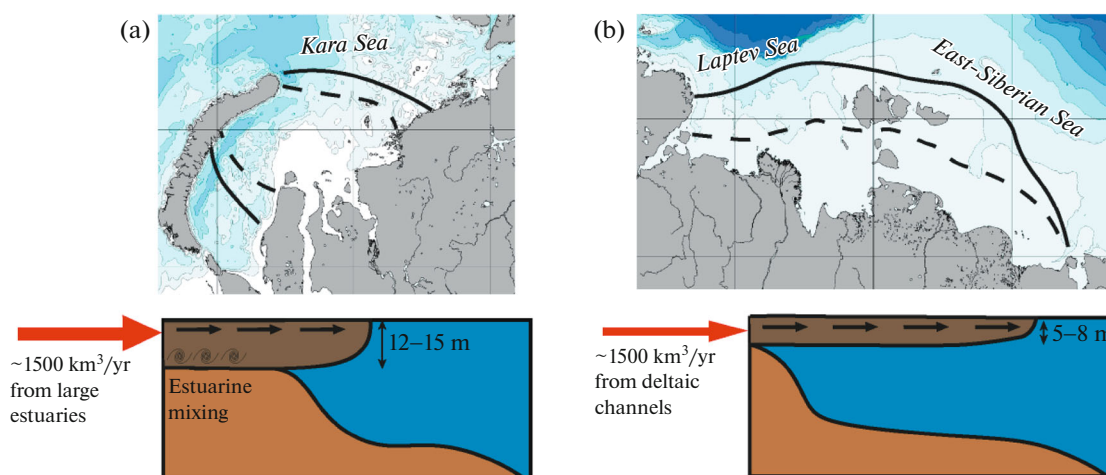


Fig. 2. Interannual variability of the location of the outer boundary of (a) the Ob–Yenisei plume and (b) the Lena plume at the end of the ice-free period (the solid line designates the mean long-term maximum, and the dotted line, the mean long-term minimum). Scheme of the formation (a) of the Ob–Yenisei plume by the runoff from large estuaries and (b) of the Lena plume by the runoff from deltaic channels.

meridional length increasing to 500–700 km. Recent studies have revealed the cause.

Based on the analysis of field data collected during several dozen marine expeditions over the past 20 years, it has been shown that the thickness of the Lena plume during its formation in the near-delta water area (5–8 m) is approximately two times less than that of the Ob–Yenisei plume (12–15 m) [40, 41]. This difference is due to the morphology of the estuarine and deltaic freshwater sources. The Lena River flows into the Laptev Sea through numerous narrow (up to several kilometers) and shallow (up to 5–10 m) delta channels along a 250-km stretch of the seacoast, while the Ob and Yenisei rivers flow into the Kara Sea through wide (30–60 km) and deep (15–20 m) estuaries. Because of this, salty seawaters practically do not penetrate into the shallow deltaic channels of the Lena River, in contrast to the deep estuaries of the Ob and Yenisei. Thus, the Lena freshwater runoff enters the sea from numerous channels and forms a relatively shallow plume (see Fig. 2b). The Ob and Yenisei runoffs, on the contrary, intensively mix with salty seawater in the estuaries and form a relatively deep plume (see Fig. 2a).

Thus, during its primary formation, the Lena plume has a smaller vertical scale but spreads over a larger area of the sea than the Ob–Yenisei plume. This factor explains the larger area of the Lena plume compared to the Ob–Yenisei plume with a smaller volume of the river runoff forming it. This factor is also responsible for the significant interannual variability of the Lena plume, caused by the variability of the wind effect. The wind impulse is practically not transmitted below the boundary between the river plume and the underlying sea because of a sharp leap in density in these layers. As a result, the wind energy is concentrated in a relatively thin near-surface layer, and

the intensity of the wind transport of the river plume is the greater, the smaller its thickness. Therefore, the Lena plume is much more susceptible to the impact of wind than the Ob–Yenisei plume.

An important but still understudied question is the fate of river plumes in the cold season. As shown above, two large areas of surface freshening are formed in the Eastern Arctic in summer and fall. In winter, these waters are completely covered with ice, which is why there are practically no field measurements, and the structure of the plumes during this period is unknown. Rare measurements show that freshening is no longer observed in spring before the onset of the flood. The question arises: How and where does it go? There are several possible scenarios for this process. First, after the decrease of the river runoff and the formation of the winter ice cover, the river plumes can be completely removed from the regions of their formation. Owing to the influence of the Coriolis force, this can occur in two possible directions: northward to the deep central part of the Arctic Ocean and eastward along the coast of Siberia [25, 42, 43]. Second, the river plumes can mix within the shelf, that is, directly in the places of their formation in the warm season. The measurements carried out over the past 20 years have shown that during the ice-free period of the year, the Ob–Yenisei and Lena plumes are often transported eastward along the continental coast, while the northward transport beyond the shelf boundary is not observed [44]. The eastern transport is neither stationary nor continuous and depends both on the regional impact of the wind and on the amount of freshwater accumulated in the river plume [44, 45].

At the end of October 2020, during an expedition on the R/V *Akademik Mstislav Keldysh*, measurements were carried out in Vilkitskii Strait, which separates

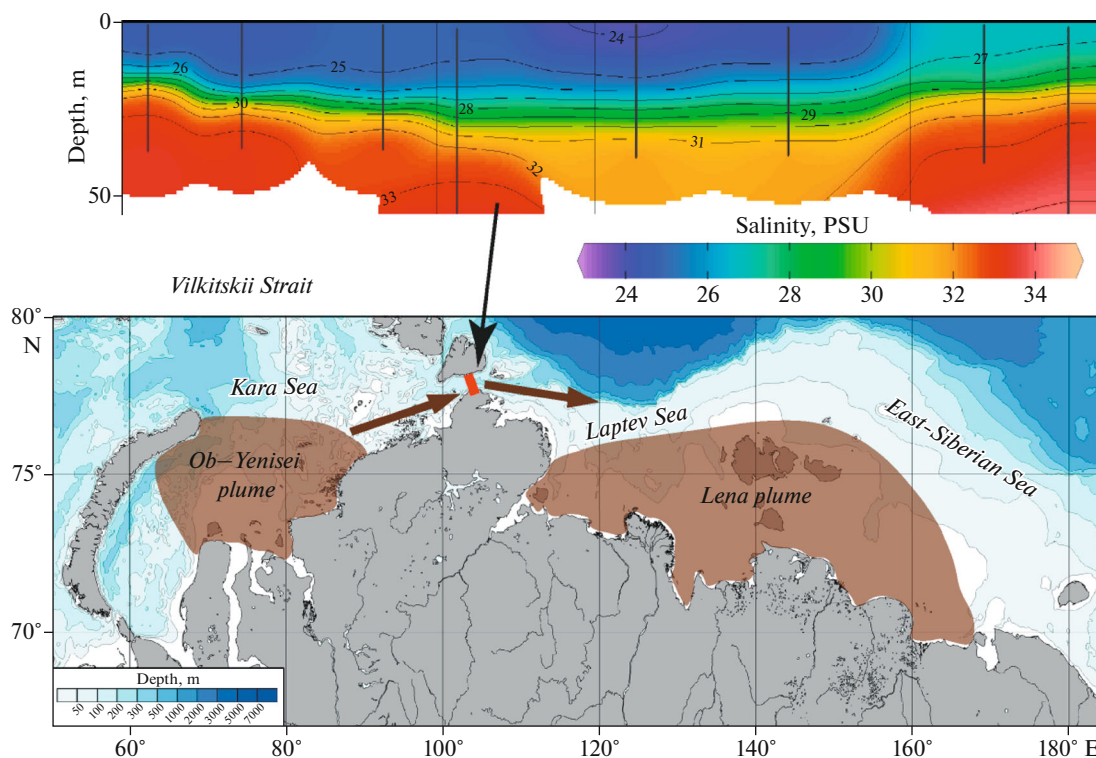


Fig. 3. Distribution of salinity across Vilkitskii Strait (red line on the map) at the end of October 2020 (top), illustrating the intense freshwater transport from the Kara Sea to the Laptev Sea (brown arrows on the map) (bottom).

the Kara Sea and the Laptev Sea. The importance of this work is explained by the fact that measurements on the trajectory of the eastern transport of the Ob–Yenisei plume were first carried out in late fall immediately before the onset of ice formation, that is, during the period of the maximum accumulation of freshwater runoff in the Ob–Yenisei plume. These measurements were the first to record intense zonal freshwater transport from the Kara Sea to the Laptev Sea (Fig. 3). The salinity of the surface layer along the entire width of Vilkitskii Strait was lower than that of the freshwater source, near the Gulf of Ob. Thus, the measurements showed the beginning of an intense eastern transport of the Ob–Yenisei plume from the Kara Sea to the Laptev Sea, which apparently continues after the formation of the ice cover. This result is evidence in favor of the dominance of the eastern transport of the river plumes that form in the seas of the Russian Arctic in winter. Nevertheless, to confirm this conclusion, additional measurements are required, primarily long-term measurements of salinity at anchored stations on the northern and eastern margins of the seas under study in winter.

The Arctic Ocean is the only area of the World Ocean where the interaction of continental runoff and seawaters affects processes on a global scale. Large riv-

ers flowing into the Arctic Ocean, primarily the Lena, Yenisei, and Ob rivers, form areas of surface freshening in the Russian sector of the Arctic with an area of hundreds of thousands of square kilometers. The spread and mixing of river flow in the Arctic determine the stratification of the sea in the area of seasonal ice formation, thereby affecting ice formation in the Arctic Ocean, seasonal fluctuations in the Earth's albedo, and the planetary climate.

In the context of the ongoing climatic changes (an increase in river runoff and a decrease in sea ice in the Arctic Ocean), specialized studies of the current state of the freshwater cycle in the Arctic are of great importance. The study of the processes of the distribution and mixing of the runoff of the great Siberian rivers in the seas of the Russian Arctic, carried out over the past 20 years, has made it possible to trace in detail the structure, dynamics, and variability of the Ob–Yenisei and Lena plumes. It has been established that the primary formation of these river plumes in the estuarine and deltaic waters of large rivers determines the hydrological structure of the freshened surface layer of the sea on the scale of the entire shelf of the Eastern Arctic. Thanks to the data obtained, fundamentally new ideas are being formed about the internal structure, the dynamics of distribution, and the seasonal and interannual variability of the large-scale freshened surface layer on the shelf of the seas of the Russian Arctic.

The results obtained form the basis for the study of many physical (water circulation, stratification), biological (ecosystem productivity), and geochemical (carbon and nutrient cycle, acidification) processes on the continental shelf and the slope of the Russian Arctic. In addition, the study of the transport and transformation of freshwater runoff in the seas of the Russian Arctic is of key importance for understanding the seasonal processes of ice formation and ice melting on the scale of the entire Arctic Ocean. On this basis, it is possible to build forecasts and assessments of the consequences of global climatic changes occurring in the Arctic zone of the Russian Federation under the influence of natural and anthropogenic factors. This is also important from the point of view of the development of the Northern Sea Route.

FUNDING

This study was supported by the Ministry of Science and Higher Education of Russia (topic 0128-2021-0001) and a presidential grant for the state support of young Russian scientists (candidates of sciences) within project no. MK-98.2020.5.

CONFLICT OF INTEREST

The author declares that he has no conflict of interest.

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Translated by B. Alekseev