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INFORMATION

Cruise 89 (First Leg) of the R/V *Akademik Mstislav Keldysh*: Climate Experiment in Interaction with the *Tu-134 Optik* Flying Laboratory

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Abstract—A unique climate experiment was carried out to study the composition of air and characteristics of the underlying surface in the Russian sector of the Arctic and Siberia. Synchronized research on board the R/V *Akademik Mstislav Keldysh* and the unique scientific facility (USF) the *Tu-134 Optik* flying laboratory were carried out in the South Kara Sea. The airborne and spaceborne optical satellite algorithms were validated to retrieve the sea surface characteristics during the cruise. For the first time on the Arctic shelf, data on methane concentration in the natural troposphere–near-surface atmosphere over sea–water column–bottom sediments system was obtained. Greenhouse gases fluxes were estimated simultaneously from the shelf area and adjacent land. Related research on recent and ancient sedimentation conditions and processes was carried out in the South Kara sedimentary basin, where huge oil and natural gas reserves are located.

Keywords: methane, aerosols, particulate matter, sinking particles, fluxes, biogeochemistry, climate, Arctic shelf, flying laboratory, climate experiment

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The processes of sedimentation and transformation of organic matter (OM) in the Arctic are closely related to global climate change and formation of fossils [4]. An important feature of the Kara Sea is the accumulation of large-scale petroleum reservoirs in its southern part [2] and a huge volume of river runoff containing methane as part of dissolved gases [3]. Offshore oil and gas provinces are being actively degassed: gas chimneys reach several kilometers in vertical height [6]. On land, such phenomena have not yet been reported. Fossil thermogenic fluids migrate to the seafloor surface over long periods of geologic time, but these natural bottom-up emission remain underestimated in atmospheric greenhouse gas budget [10]. Among greenhouse gases, carbon dioxide and methane make the largest contribution to Earth's heat balance. Cause-and-effect relationships of climate change and increased anthropogenic pressure on marine areas of Russia's Far North must be identified in interdisciplinary studies not only on the shelf, but also on adjacent land. In September 2020 [8], an experiment on measuring the composition of the troposphere was carried out in the Russian sector of the Arctic using a flying laboratory, but without accompanying marine research.

Cruise 89 (leg 1) of the R/V *Akademik Mstislav Keldysh*, in cooperation with the *Tu-134 Optik* flying laboratory, was carried out within the South Kara sedimentary basin from September 5 to 18, 2022, with additional work in the southeastern Barents Sea along the vessel's route to the port of Murmansk (Fig. 1). A combined study of modern and ancient sedimentation conditions and processes was carried out in the South Kara Sea; fluxes of particulate matter, greenhouse gases, and pollutants were also estimated. The scientific team, united by a common task onboard, included 60 researchers from nine institutes of the Russian Academy of Sciences and the following universities: the Shirshov Institute of Oceanology, Russian Academy of Sciences (RAS); the Zuev Institute of Atmospheric Optics, RAS, Siberian Branch; the Vernadsky Institute of Geochemistry and Analytical Chemistry of RAS; Federal Research Center of Biotechnology RAS; Moscow Institute of Physics and Technology; Lomonosov Moscow State University; Federal Research Center "Marine Hydrophysical Institute of the RAS"; Federal Research Center "Kovalevskii Institute of Marine Biological Research, RAS"; and St Petersburg University.

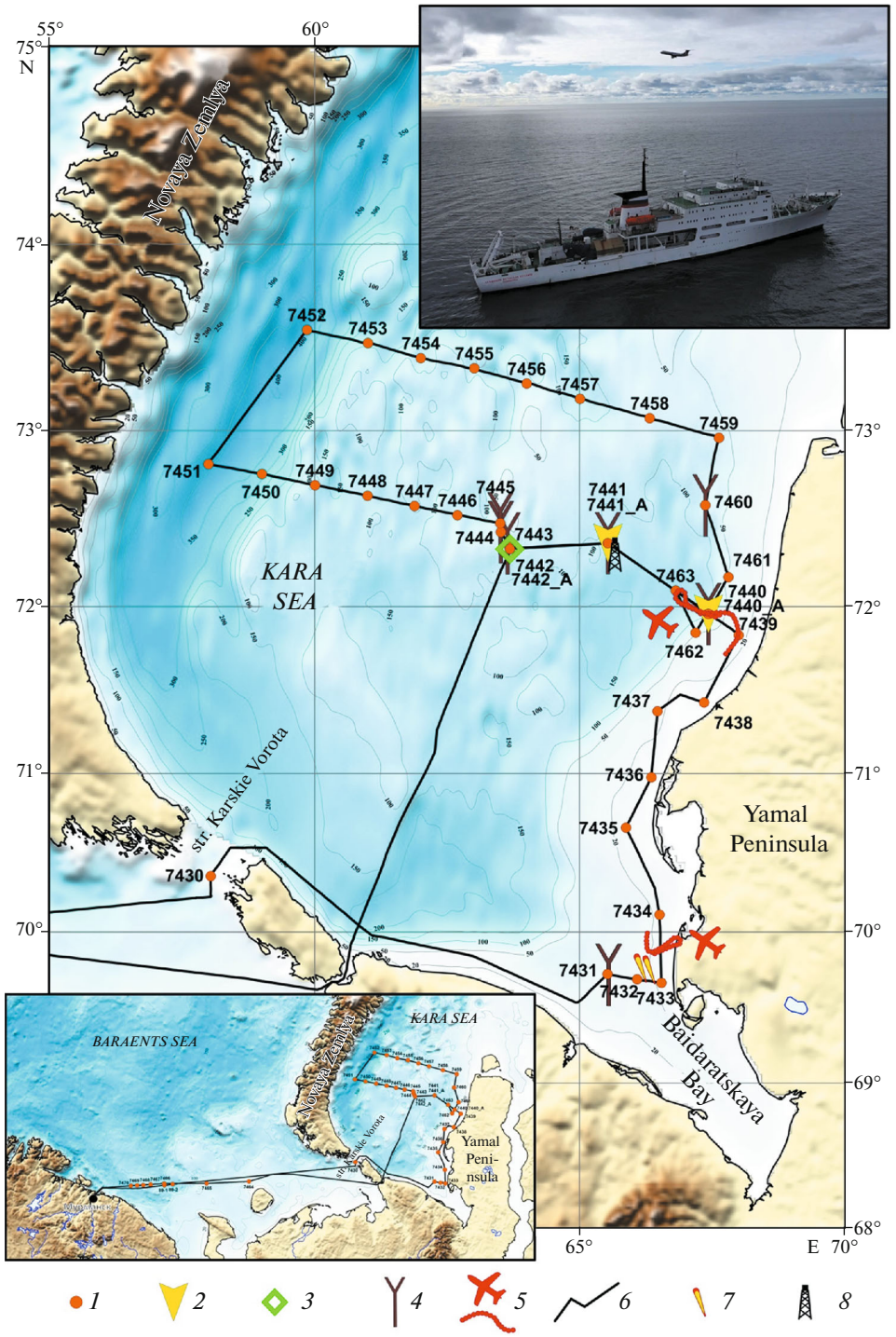

Fig. 1. Map of marine expeditionary research in South Kara Sea, September 08–15, 2022: (*1*) integrated stations (set of optical, hydro-optical, hydrological, hydrochemical, hydrobiological, microbiological, and sedimentological measurements and lithological and geochemical works for sampling upper undisturbed sediment layer using a multicorer); (*2*) integrated mooring stations with deployment and raising of automatic deep-sea sedimentation observatories; (*3*) mooring station with inclinometers; (*4*) integrated stations with samplings of long sediment cores using large-diameter gravity corer; (*5*) research polygons for direct overflight measurements with flight path of *Tu-134 Optik*; (*6*) vessel's route with continuous en route measurements (gas-chemical, optical, and hydro-optical); (*7*) gas flares according to echo-sounding profiling data; (*8*) Leningradskoe gas condensate field. Bathymetry is based on data from [5]. Insets: (bottom) entire route of vessel; (top) photo of synchronous works aboard R/V *Akademik Mstislav Keldysh* and *Tu-134 Optik* flying laboratory.

The climate experiment consisted of a set of measurements in situ in the water column and the near-surface atmospheric layer continuously along the vessel's entire route of (2275.4 nautical miles) and works at 44 oceanographic stations with the participation of the flying laboratory and satellite remote sensing of sea surface characteristics. The aircraft made direct passes over the ship at an altitude of ~90–200 m above the sea surface on September 9 and 10, 2022, to validate airborne algorithms for retrieving the characteristics of the underlying surface (suspended particulate matter (SPM), chlorophyll, dissolved OM, etc.) and measuring the composition of air and aerosols in the atmosphere and troposphere over the sea.

A set of hydro-optical measurements and continuous lidar profiles of the upper water layer were carried out. For the first time, data were obtained on methane concentrations in the troposphere–atmospheric near-surface layer–water column–bottom sediments system with simultaneous estimation of methane fluxes from the Vasyugan swamps, thermokarst lakes, and different types of landscapes of Western Siberia. The rates of microbial processes of the carbon and sulfur cycles in water and sediments were studied, as well as molecular phylogenetic diversity of the microbial communities associated with sediments. Isotopic geochemistry of hydrocarbon gases in sediments were carried out to reconstruct the nature of gas fluids. The role of natural sources in methane emission on the shelf has been studied: microseepage (diffuse degassing over petroleum basins), bubble methane release from the seafloor (cold methane seeps), and degradation of subsea permafrost, which began in this region ~18 ka ago [7].

On the Priyamal shelf at a depth of 13–32 m, signs of weak but stable methane diffusion from sediments were found everywhere. Relict permafrost, preserved in coastal areas of the shelf, is unstable, degrade, and do not act as a gas-impermeable layer [1, 9]. Elevated methane concentrations (up to 2.09 ppm) in the near-surface atmosphere were recorded locally: over a shelf zone of ~2-km long, where hydroacoustic anomalies, gas flares, have been recorded in the water column. In the troposphere over the West Yamal shelf, methane concentrations did not exceed the background values (≤1.98 ppm).

The sedimentation system of the South Kara Sea was studied: atmospheric aerosols–SPM–fluffy layer–bottom sediments, including a study of the hydrochemical and hydrological conditions. The particle fluxes were studied with two automatic deep-sea sedimentary observatories on the Priyamal shelf. Hydrocarbons in sediments, SPM, and the microlayer at the seawater–atmosphere interface were studied. A sedimentary stratum was sampled on the West Kara Step, which hosts unconsolidated gas-saturated sediments at the base of the exposed 6-m column. Gas-saturated muds and silts were sampled in the Baydaratskaya Bay and on the Priyamal shelf. The study of microfossils in sediments, in addition to lithological and isotope-geochemical proxies of the paleoenvironment, makes it possible to reconstruct the paleoclimate for modeling climate change in the present and future.

Thus, for the first time in the framework of the project of the Ministry of Science and Higher Education of the Russian Federation to conduct large-scale high-level research projects using USFs, a climate experiment was successfully carried out to study changes in air composition and characteristics of the underlying surface in the Russian sector of the Arctic and Siberia with synchronous research onboard a research vessel and flying laboratory.

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