

Results of Monitoring the Surface Fields Dynamics in the Black Sea Waters Using a Ferry Box System

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Purpose. The purpose of the paper is to discuss practical results of pilot running of a domestic ship ferry box system.

Methods and Results. The results were obtained in course of *in situ* studies of structure and spatial-temporal variability of optical, hydrological and hydrochemical fields of surface water during the complex cruises in which the scientists from Marine Hydrophysical Institute, Russian Academy of Sciences, participated in 2015–2017. The considered polygons were of different scales and located nearby the Southern Coast of Crimea. The ferry box measurements were carried out continuously in real time with high spatial resolution and showed good reliability.

Based on the contact ferry box surveys carried out at the test sub-satellite polygons near the Herakleian Peninsular, the background structure of the surface water hydrophysical fields was mapped. In the polygon surface layer, small-scale water lenses were authentically identified. They accompany the intensive hydrological torch-type formations that arise in an outbreak of industrial and sewage waters discharge near the bottom and then reach the surface.

Conclusions. The information of the ferry box system surveys carried out at the large-scale polygons during the cruises of R/V *Professor Vodyanitsky* (the 89th – October, 2016 and the 98th – November, 2017) nearby the Southern Coast of Crimea provided new *in situ* data that were impossible to obtain by contact methods. The represented results demonstrate high information content of the ferry box measurements, its efficiency and possibility of its further application for studying hydrophysical processes and phenomena in a wide range of their variability and in various weather conditions. The principle possibilities and further prospects of the ferry box system in obtaining new notions on submeso- and small-scale hydrodynamic processes are confirmed. Besides, the system implies development both of the approaches for rational use of marine resources near the Crimean and Sevastopol coasts and the elements of the advanced technology for the instrumental shelf monitoring in critical situations.

Keywords: the Black Sea, vortex-wave hydrodynamics, coastal shelf zone, instrumental monitoring, measuring complex.

Acknowledgments: the study was carried within the framework of the state order on theme No. 0827-2018-0004 “Complex Interdisciplinary Research of the Oceanological Processes Conditioning Functioning and Evolution of the Black and Azov Sea Coastal Zones”.

For citation: Kuznetsov, A.S., Shapovalov, Yu.I. and Shapovalov, R.O., 2019. Results of Monitoring the Surface Field Dynamics in the Black Sea Waters Using a Ferry Box System. *Physical Oceanography*, [e-journal] 26(4), pp. 341-349. doi:10.22449/1573-160X-2019-4-341-349

DOI: 10.22449/1573-160X-2019-4-341-349

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Introduction

Development of the observational system in the Azov-Black Sea basin coastal zone, working-out and improvement of approaches, technologies and algorithms for marine environment monitoring with complex interdisciplinary studies of the hydrodynamics of various-scale processes on the shelf comes at an opportune time. Water dynamics of the Russian Black Sea shelf are determined by the Black Sea Rim Current (RC) and a combination of intensive, multi-scale vortex-wave, vergent and other water movements [1–4]. Marine Hydrophysical Institute

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(MHI) introduced a modern concept for the instrumental monitoring development [5]. On its basis, a cluster of instrumental measuring complexes was created. The development is an element of the experimental system for controlling natural and anthropogenic impacts on the shelf zones of the Black Sea coast of the Russian Federation based on satellite and contact data [6, 7]. The monitoring system of the state and dynamics of the coastal shelf waters is implemented on the basis of exclusive information technology and instrumental MHI developments at the stationary Black Sea Hydrophysical Polygon [4, 6], as well as during multi-scale polygon surveys near the Southern Coast of Crimea water area using research vessels [7, 8]. According to the long-term monitoring of the water dynamics of water at the stationary Black Sea Hydrophysical Polygon, background characteristics of the regime and large-scale variability of coastal currents in the South Coast of Crimea were identified. Series of consecutive operational vessel surveys of the water area are carried out in order to obtain new scientific knowledge about the spatial and temporal variability of oceanological fields and the characteristics of intensive hydrodynamic formations in the Russia economic zone off the Crimea coast. Carrying out comprehensive field studies permits to regulate and systematize the contribution of multi-scale natural processes to the shelf water dynamics at high resolution and measurement accuracy. Practice of a full-scale experiment carrying out clearly demonstrates that for reconnaissance and detailed surveys of the water area, measurements of the near-surface sea layer characteristics in real time when pumping outboard water on the move through the ferry box system are necessary and quite effective. Such measurements can significantly save the time of expeditionary research, supplement and detail the hydrophysical data obtained in expeditions by traditional methods (hydrological and hydro-optical sensing, ADCP measurements and analysis of water samples). When studying small-scale and sub-mesoscale processes and phenomena with a spatial scale from several tens to hundreds of meters to kilometers, the ferry box system of hydrophysical associated measurements provides fundamentally new opportunities for detailing the fields of hydrophysical characteristics that are inaccessible when surveying polygons based on fixed grids of stations. These capabilities are especially important for the fixation and contact research of anthropogenic phenomena such as accidental discharges of pollution into the sea from coastal and marine sources.

Technological features of measurement

Numerous aerospace surveys of the sea surface everywhere and systematically demonstrate contrasting differences in the structure of the fields of contacting volumes of surface waters. These inhomogeneities in the structure of surface fields arise from the dynamics of waters with different hydrological and optical characteristics. Since the 70s of the last century, for studying the dynamics of surface waters, domestic institutes have been regularly using hydrophysical probes installed on board a ship on expeditions with forced pumping of outboard water through them. Institute of Oceanology of the Russian Academy of Sciences used such flow systems for research in the Atlantic and in the Arctic seas [9, 10]. Using such a system, Marine Hydrophysical Institute carried out unique contact studies of the structure and dynamics of surface hydrographic fronts in the Aegean Sea near

the Dardanelles Strait [11]. Since 2000, foreign oceanologists have been actively using in practice similar flow systems [12, 13] called the Ferry Box. Taking into account the unique experience of our own constructive development of such systems and modern instrumental capabilities, MHI has created a domestic ferry box system with high performance characteristics. Basic information about the basic structure and technical characteristics of the complex is presented in [14].

Operating experience of the new complex in natural conditions during 2015–2017 demonstrated its high performance, reliability and allowed to optimize the structure and technology of research. On board a vessel in a flow container is a set of meters: temperature (T) with an accuracy of 0.015 °C, electrical conductivity with an accuracy of 0.02 mS/cm and salinity (S) with an accuracy of 0.03‰ PSU, an indicator of hydrogen ion activity (pH) with an accuracy of 0.03 units and the concentration of oxygen dissolved in water with an accuracy of 0.2 ml/l. The complex includes a turbidimeter module for measuring the water turbidity (M) with an accuracy of 0.5 NTU (Nephelometric Turbidity Unit) and determining the concentration of total suspended matter in water, a modem for binding current measurements to geographic coordinates and exact time and a temperature meter sea water with an accuracy of 0.2 °C and sensitivity of 0.01 °C, towed in situ in the surface sea layer. The complex continuously records the characteristics of oceanographic fields along the route of the vessel in a geographic coordinate system. At oceanographic stations in the grid points of the polygon onboard the ship, vertical profiling of water characteristics with a set of hydrological probes is carried out in a drift. Based on these experimental data, the stability of the metrological and operational characteristics of the complex are estimated.

A characteristic feature of the current state of the Black Sea shelf waters and, above all, of the South Coast of Crimea coastal zone is the presence of a high level contamination of the near-surface waters with oil products and surface-active substances in various migration forms. Continuous pumping of surface water leads to intense contamination of sensors and reduce the accuracy of measurements. Using synchronous measurements of the ferry box system and high-precision optical hydrological hydrochemical probes in the near-surface layer *in situ* [7, 8], as well as simultaneous sampling of near-surface waters and their online analysis *in vitro*, the temporal variability of the sensor characteristics of the complex was monitored. Under conditions of particularly intense pollution of the marine environment, a three-day interval between the procedures for routinely cleaning the sensors was experimentally selected for measuring the activity index of hydrogen ions, the concentration of oxygen dissolved in water and the turbidity of water. At the same time, passport errors of all the instruments are fully preserved [14], which reliably ensures continuous studies of the characteristics of small scale, medium scale and synoptic hydrodynamic formations with the specified accuracy.

Outboard seawater enters the primary measuring converters of the complex through a hydraulic flow system from a depth of 1–2 m. On small size research vessels, the complex's own full flow system is used, and on the R/Vs of *Professor Vodyanitsky* type, outboard seawater is taken through the feed system hydrant. When pumping seawater from the place of their intake to the sensors, the standard flow system introduces a temporary delay in the flow of water reaching 20 s. When using the R/V's pipeline, this delay reaches 3 minutes. When applying a standard

flow system and vessel speed up to 1 node, the change in coordinates of the location for determining ferry box system measurements in time does not exceed ± 5 m. In such a situation, the coordinates of the water intake and the location of the vessel do not practically differ. Under the standard flow system of the complex operation and the vessel speed increases, such spatial differences become significant. For example, when the vessel speed is 8 knots, these discrepancies reach 80–100 m, and when using the R/V's pipeline, they exceed 850 m. The actual coordinates of the hydrodynamic formations are calculated when processing the initial data of the complex, taking into account the delayed arrival of the outboard water to the primary measuring converter route.

Results and Prospects of the Research

The duration of the survey and the size of the hydrophysical polygons are determined by the goals and objectives of the field experiment. A priori information on the spatial and temporal scales of variability of the studied natural processes and hydrometeorological conditions is taken into account when planning works. The technology of integrated instrumental monitoring provides for obtaining a set of data of spatial sections of near-surface fields and corresponding vertical profiles of hydrological characteristics at drift stations along the sections. Mapping the characteristics of hydrophysical fields from contact polygon surveys and synchronous satellite images of the sea surface allows to study the patterns and characteristics of hydrodynamic inhomogeneities of various spatial and temporal scales, which are clearly demonstrated by the results of onboard expeditionary MHI studies.

The work [8] presents the results of a study of the seasonal and synoptic variability features of the water structure in the RC area based on materials of two consecutive vessel surveys by *Sea-Bird 911 plus* probing complex of a large-scale polygon in the Russia economic zone near the coast of Crimea, including those obtained in October 2016 in the 89th cruise of the R/V *Professor Vodyanitsky*. As indicated in [8, p. 33], “weather conditions did not allow measurements between the 34° and 35°E meridians in the 89th cruise”, i.e., probing in this area of 72×140 km were not carried out. At the same time, despite the stormy weather conditions, the ferry box system survey of this water area during the course of the vessel was carried out completely.

Fig. 1 shows the spatial distribution of the characteristics of near-surface waters according to the results of the continuous ferry box system survey for the entire large-scale polygon in the Russian sector at the South Coast of Crimea. Thus, the results of ferry box system measurements carried out during the cruise supplement the work [8] with data on the spatial variability of near-surface waters between 34° and 35°E. A comprehensive survey of the large-scale polygon near the SCC was performed for 12 days, October 7–19, 2016. An individual box ferry survey of this polygon in continuous mode can be carry out in just 4 days regardless of weather conditions with a cruising speed of the vessel of 8 knots.

During the survey of a large-scale polygon (Fig. 1), the grid step between the nodes of the hydrological stations is usually 5–15 miles, which is an order of magnitude more and more than the characteristic spatial dimensions of the submeso- and small-scale hydrodynamic formations existing in the Black Sea.

The presence of an intensive small-scale formation at the station introduces methodological errors and distortions in the values of the background characteristics. The undoubted advantage of ferry box system measurements is the high spatial resolution, which allows real-time detection of the location and size of localized hydrodynamic formations for further study of their dynamics. In such studies, the contribution of methodological errors to large-scale water dynamics can be taken into account and leveled.

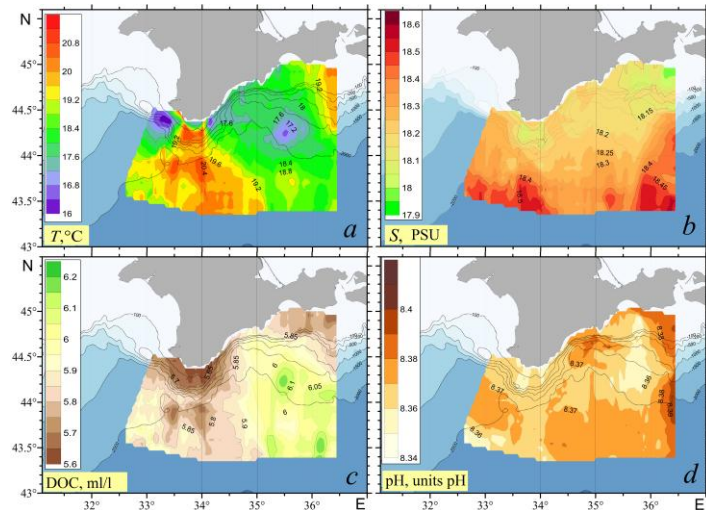


Fig. 1. Spatial distributions of temperature (a), salinity (b), dissolved oxygen concentration (c) and the hydrogen ion activity index (d) in the surface layer (1–2 m) on the large-scale polygon nearby the Southern Coast of Crimea based on the ferry box system measurements in the 89th cruise of R/V *Professor Vodyanitsky*

Fig. 2 shows spatial distribution of the characteristics of near-surface waters as a result of continuous ferry box system survey in the 98th cruise of the R/V *Professor Vodyanitsky* on November 15–19, 2017. In the coastal zone of the eastern part of the Feodosia Gulf near the Chauda River against the background of large-scale variability of the shelf waters in temperature, salinity and dissolved oxygen concentration fields in the near-surface layer, a lens of foreign water (section A in Fig. 2) with horizontal dimensions less than 7 km is reliably distinguished. It has significantly lower values of T (up to 12 °C), S (up to 17.65 PSU) and increased dissolved oxygen concentration contain (up to 6.8 ml/l). An increase in water turbidity is observed to the southeast of Chauda Cape (Fig. 2, d). Dots in Fig. 2 indicate the location of stations performed in 9-mile (17.7 km) steps in the indicated section of the water area. Identified according to the ferry box system measurement data, section A is localized between the stations of the polygon and is not separately distinguished according to the hydrological probing data. The program of oceanographic studies of the Black Sea in the 98th cruise of the R/V *Professor Vodyanitsky* did not set the task of a detailed study of the nature of the origin and dynamics of such a local formation.

According to the data of long-term expeditionary research, such submeso- and small-scale formations of various nature appear and exist permanently at the South

Coast of Crimea. Aerospace monitoring tools explicitly and regularly register on the sea surface along the Black Sea coast a system of small-scale hydrodynamic formations. Among them, a special place occupy quasistationary formations that are generated at the bottom exit of sewage collectors when discharging large volumes of industrial wastewater from land. A comprehensive study of the processes of genesis, dynamics, the role of such a new type of intensive small-scale formations and their manifestations on the sea surface in the form of near-surface plumes (lenses of foreign water) is an urgent task due to the intensive growth of anthropogenic loads with limited assimilation capacity of marine coastal ecosystems. Priority in situ studies of the such waters dynamics when monitoring anthropogenic effects on coastal waters were previously carried out by domestic scientists, the results of the studies were published in [15] and in subsequent original works. In 2015–2016 under an agreement with the Research Institute of Aerospace Monitoring AEROCOSMOS (Moscow), MHI carried out a cycle of vessel contact surveys to study small-scale water dynamics at the test subsatellite polygon at the Heraklean Peninsula (Cape of Chersones) [7]

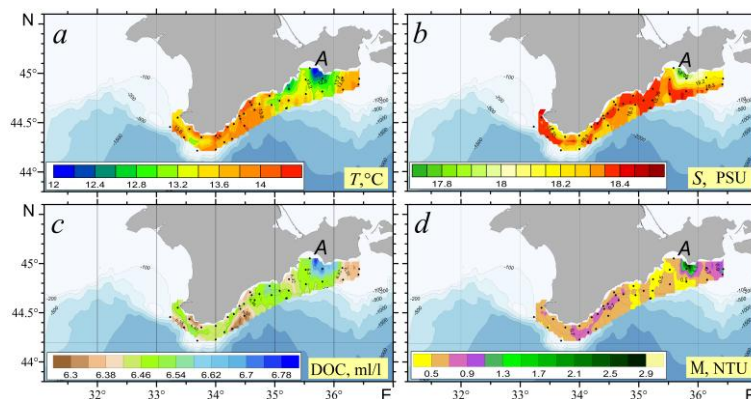


Fig. 2. Spatial distributions of temperature (a), salinity (b), dissolved oxygen concentration (c) and water turbidity (d) in the surface layer (1–2 m) on the shelf of the South coast of Crimea according to the ferry box measurements in 98th cruise of R/V *Professor Vodyanitsky*. Letter A indicates the position of small-scale water lenses

Measurements were carried out in the far zone, near the regular bottom sewage discharge of the wastewater treatment plant in the southern part of Sevastopol (sections 2-7), as well as in the near coastal zone, near the emergency breakthrough section of the wasteline (sections 8-22) (Fig. 3). According to the soundings at drift stations of a small-scale polygon, performed with the step of 0.5 km, the background hydrophysical characteristics of the considered water area were determined. Continuous reconnaissance ferry box system surveys provided an effective search, detection and detailed study of the spatial size and dynamics of the waters inside the intensive small-scale flare type formations against the background of large-scale variability. To improve the accuracy of determining the coordinates of the considered formations, ferry box system surveys were carried out in drift, taking into account the cumulative effect of surface currents and driving wind on the vessel movement. In the distant zone of the polygon, the depth of the site of the near-bottom sewage discharge (Section 7 in Fig. 3, a) was 88 m at

a distance of about 3.5 km from the coast. Manifestations of the near-surface plume of waste water in this zone were recorded on May 21, 2016 in the fields of temperature (Fig. 3, *b*) and salinity, in pH distributions, dissolved oxygen concentration and turbidity of water. This plume with spatial dimensions within 0.45–1.1 km was revealed at a distance of about 600 m in the northwestern direction along the stream from the place of the regular bottom discharge of industrial wastewater. In the near zone of the polygon, due to a defect in the sewage collector, with a burial depth of 30 m and a distance of about 0.7 km from the coast, there were intermittent intense flares of wastewater from the bottom to the surface. Manifestations of the near-surface plume with a spatial size of about 0.55 km in the near zone were recorded on May 20, 2016 in turbidity fields (Fig. 3, *c*), as well as in temperature, salinity and dissolved oxygen concentration fields. According to the ferry box system survey from September 12 and 13, 2016, in the same place immediately at the moment of the next

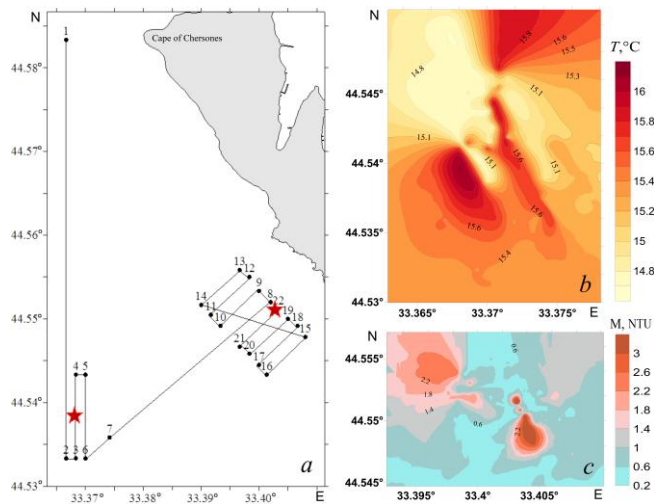


Fig. 3. Scheme of the research vessel movements during the ferry box surveying the sub-satellite test polygon nearby the Herakleian Peninsula (*a*) in its remote (points 2–7) and near (points 8–22) zones. Asterisks denote locations of the surface plumes resulted from the bottom torches of the industrial and sewage water discharges – *a*. Spatial distribution of: temperature in the surface layer (1–2 m) in the polygon remote zone based on the ferry box survey on 21.05.2016 – *b* and water turbidity in the polygon near zone – on 20.05.2016 – *c*

sewer discharge, the most intense near-surface plume with a length of 2.7–3.3 km was detected in the spatial distribution of water characteristics. Plume visually manifested on the sea surface, spreading in the direction of the coastal current [16]. The emergency breakthrough of the buried drains in the near zone leads to pollution and eutrophication of the waters of the coastal sea ecotone at the Herakleian Peninsula, disruption of the balance of the shelf SSC ecosystems and the significant losses of the recreational potential of marine natural resources in the region of Sevastopol. The results of the study of small-scale dynamics of coastal waters are of fundamental importance for the design and repair of wastewater treatment plants in the southern part of Sevastopol, including a sewage collector

with in-depth production of industrial wastewater in the coastal ecotone of the sea near the Heraklean Peninsula.

Conclusion

Practical results obtained in 2015–2017 in field studies of optical-hydrological-hydrochemical fields of near-surface water by a ferry box measurement system, demonstrate highly informative measurements and efficiency, including its application in adverse weather conditions. The complex is a unique and reliable tool for the rapid acquisition of scientific knowledge about multi-scale hydrodynamic processes in the coastal zone. Such knowledge is necessary for the development of approaches to the rational use of the resource potential of marine areas near the coast of Crimea and Sevastopol.

In recent years, dozens of foci of occurrence of an extremely high level of local pollution of the coastal waters of the Black Sea have been identified and eliminated near the Crimea coast. They were caused by accidents, catastrophes and natural disasters. At the same time, the applied task of minimizing the most probable risks for the waters of the active development of marine resources and the discharge of industrial wastewater is formed to prevent possible natural and man-made disasters with the onset of zones of crisis ecological situations.

The development and use of elements of promising technology of instrumental crisis monitoring in the coastal landscapes of the shelf, implemented at Marine Hydrophysical Institute of the Russian Academy of Sciences [17], contributes to solving this problem. The creation of specialized measuring hydrophysical complexes allows a rapid detection of intensive natural and anthropogenic formations and detalization of their characteristics using contact methods. Such unique domestic developments include the ferry box measurement system for monitoring the dynamics of the fields of the near-surface waters of the Black Sea.

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Contribution of the co-authors:

Alexander S. Kuznetsov – scientific analysis and summarizing of the data obtained from the situ experiments, estimation of the perspectives of applying the complex in the fields' monitoring

Yuriy I. Shapovalov – development and construction of the FBMC complex, data obtaining and processing

Rostislav O. Shapovalov – obtaining and processing of the data obtained from the situ experiments using FBMC and probing complexes

All the authors have read and approved the final manuscript.

The authors declare that they have no conflict of interest.