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Manifestation Specifics of Hydrodynamic Processes in Satellite Images of Intense Phytoplankton Bloom Areas

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Abstract—The paper summarizes the results of the long-term complex satellite monitoring of the Black and Baltic seas. Data from synthetic aperture radars (SARs) constitute the experimental basis for the investigation of satellite. In addition to radar data, the data of the visible and infrared bands from MODIS Terra/Aqua, MERIS Envisat, Landsat series sensors are used. The features of the manifestation of hydrodynamic processes, submesoscale eddies in particular, in satellite radar and optical images in a period of intense phytoplankton bloom are discussed. A relationship is established between the intensity and duration of the phytoplankton bloom in the regions of observation and the frequency of the appearance of long-lasting wakes behind moving ships in SAR images. These wakes appear as long narrow bright bands of enhanced backscattered signal extending for tens and sometimes hundreds of kilometers. It is proposed to consider the wakes of this type as indicators of the areas and duration of intense phytoplankton bloom. Satellite observations over the Black and Baltic Seas conducted for more than ten years have shown that long-lasting ship wakes are influenced by powerful jet streams, such as those associated with the passage of eddies that leads to shifts and deformations. By comparing the true route of a ship with its wake in the satellite image, it is possible to obtain detailed information about the parameters of currents.

Keywords: satellite monitoring, satellite radar imagery, sea surface, eddy structures, ship wakes, algal blooms, phytoplankton, biogenic slicks, Baltic Sea, Black Sea

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INTRODUCTION

For over three years, starting from January 2009 to April 2012 (when the Envisat satellite orbital mission was completed), we have conducted daily operational satellite monitoring of the Baltic, Black, Azov, and Caspian seas. The monitoring was based primarily on the data from satellite radars ASAR Envisat and SAR ERS-2 that were obtained in a near-real-time mode from three European stations of acquired and primary processing of data MATERA, KIRUNA, and ESRIN. In addition to the radar data, we analyzed the data obtained in the visible and infrared bands: MODIS Terra/Aqua, MERIS Envisat, TM Landsat-5, and ETM+ Landsat-7. In the period from 2012 to 2014, satellite observation of the four seas was continued using radar data from Radarsat-2, TerraSAR-X, and TanDem-X; multispectral data from OLI Landsat-8; and hyperspectral data from Hyperion and HICO (Lavrova et al., 2011, 2012, 2014; Lavrova and Mityagina, 2012; Mityagina and Lavrova, 2012; Mityagina and Lavrova, 2012; Bondur and Grebenyuk, 2001; Bondur, 2004; Bondur et al, 2012). Since October 2014, it has been possible to use the Sentinel-1 radar data. The monitoring of the Baltic, Black, Azov, and Caspian seas was focused on the identification and investigation of hydrodynamic processes characteristic of these water areas and their manifestation in satellite images taken in different bands of the electromagnetic spectrum and under different environmental states. Another important aspect of satellite monitoring was the estimation of the ecological state of the seas and the identification of the areas most prone to natural and anthropogenic pollution of the sea surface.

In recent years, there has been a significant decline in the proportion of anthropogenic pollution caused by the discharge of water containing oil from ships. In particular, this applies to the Baltic Sea, where the international organizations conduct targeted satellite monitoring of oil pollution within the CleanSeaNet program (http://www.emsa.europa.eu/operations/cleanseanet.html). Simultaneously, the eutrophication of water bodies, the saturation of water bodies with biogenic elements accompanied by the increase of the biological productivity of water basins has become a serious environmental problem. As a result of water eutrophication and regional climate change, processes leading to the abnormal blooming of waters began to occur in areas where it was not previously observed. The eutrophication of the surface waters of the marginal and internal seas is an important problem that is becoming more relevant with each passing year. Harmful algal blooms can have an inhibitory effect on the aquatic biota because of oxygen starvation and the release of toxic metabolites. This problem is most relevant for the Baltic Sea, Azov Sea, the north western part of the Black Sea, and the northern part of the Caspian Sea. According to the satellite monitoring data, abnormal phytoplankton blooms also periodically occur in the southern part of the Caspian Sea. In recent years, the situation in the Baltic Sea has been particularly difficult. As is known, the Baltic Sea is subject to intense blooms of cyanobacteria (blue-green algae) in almost all its waters. The scientists of the Baltic countries, in particular from Sweden and Finland (Hansson and Hakansson, 2007) daily monitor the algal blooms, create online bloom maps, and make forecasts for the near future (http://www.smhi.se). Their monitoring is based on the data from MODIS Terra/Aqua and on the results of in situ measurements from standard stations. In recent years, the information collected from the ferries sailing between ports, such as Tallinn–Helsinki or Stockholm–Helsinki, have been also used. Given that the Baltic Sea area is characterized by cloudy weather, the use of only optical satellite data greatly reduces their monitoring capabilities, and the results of field measurements are only available for a limited number of areas. Space radar imaging, which is independent of cloud cover and illumination, could expand the satellite monitoring possibilities. Modern radars have made it possible to obtain information with high spatial resolution (from several meters) and for large areas. However, the problem of the steady and reliable detection of blooming areas or types of algae based on satellite radar data has not been solved so far. It is well known that during the intense algal blooms the biogenic slicks or entire mats that quench the gravity–capillary waves are formed on the water surface. On radar images (RIs), these slicks or mats are manifested in the form of slicks, dark areas with low radar signal strength. These biogenic slicks are good tracers for the visualization of many hydrodynamic processes, submesoscale eddy structures in particular.

However, such low scattering regions can have a different origin. For example, they can correspond to regions with little wind or wind shadow (near the coast), or they can be oil slicks. The wind has a great impact on the biogenic slick and, thus, on the radar signal generation. In the case of a wind speed greater than 8–10 m/s, the slick breaks up. Accumulations of algae on the surface are not observed, and the radar signal scattering is enhanced.

This paper discusses the features of the manifestation of hydrodynamic processes, submesoscale eddy structures in particular, during intense phytoplankton bloom and proposes a method for the identification of blooming areas by the radar images of long-lasting wakes of moving ships.

MANIFESTATION OF SUBMESOSCALE EDDY STRUCTURES

The main sources of satellite data for the investigation of submesoscale eddy structures in the monitoring regions and radar images were visible band data. On the radar images, eddies and eddy dipoles are visualized either by passive tracers or by changes in contrast in the convergent-divergent zones. During intense phytoplankton bloom, the number of passive tracers, which are primarily biogenic slicks dramatically, increases. They suppress the small-scale component of the sea waves and, thus, smooth the sea surface. The slicks engage in orbital motion and draw eddies and eddy dipoles in sufficient detail. It makes it possible to assess their spatial characteristics and determine their vorticity sign (Lavrova et al., 2011). Usually these eddy structures are either eddy dipoles or dipole packages. Single eddies, in most cases with cyclonic vorticity, are observed much less frequently. The characteristic sizes of such eddy structures range from several hundred meters to tens of kilometers (Fig. 1). In our opinion, the main mechanism of their generation is the wind field vorticity. This assumption is confirmed by the fact that quite often vast areas occupied by the accumulation of submesoscale eddies are located near the boundaries of atmospheric fronts, which are characterized by strong wind inhomogeneities (Lavrova et al., 2012).

It should be noted that in addition to the necessary condition, the presence of a large number of biogenic slicks or accumulations of algae, the wind conditions of the radar survey are significant for the manifestation of eddies in radar images. The wind speed of 3–7 m/s is optimal, since in this case short gravity–capillary waves that cause the Bragg scattering of the radar signal already exist, but the wind has not yet had a devastating effect on the slick surface (Dokken and Wahl, 1996). At higher wind speeds, the slick is destroyed, and at lower speeds the backscattered signal strength decreases, and in the still wind area no hydrodynamic processes manifest themselves. This explains the fact that in two successive radar images obtained during intense phytoplankton bloom but under different wind conditions, the eddy activity pattern can be quite different.

For different water areas of the same sea, and even more so for different seas, the phytoplankton bloom period differs. For the Black and Baltic Seas, there are spring–summer and autumn blooming peaks. The autumn peak is usually less pronounced. However, even not as significant as in the spring–summer period, an increase in the concentration of biogenic slicks makes it possible to clearly identify submesoscale eddy structures in the radar images (Fig. 2).

The high spatial resolution visible band satellite data obtained during the water bloom also provide a unique opportunity to investigate submesoscale eddies. The signal detected by the sensors in the visible band is determined by scattering on the hydrosol (phytoplankton and suspended mineral particles), as well

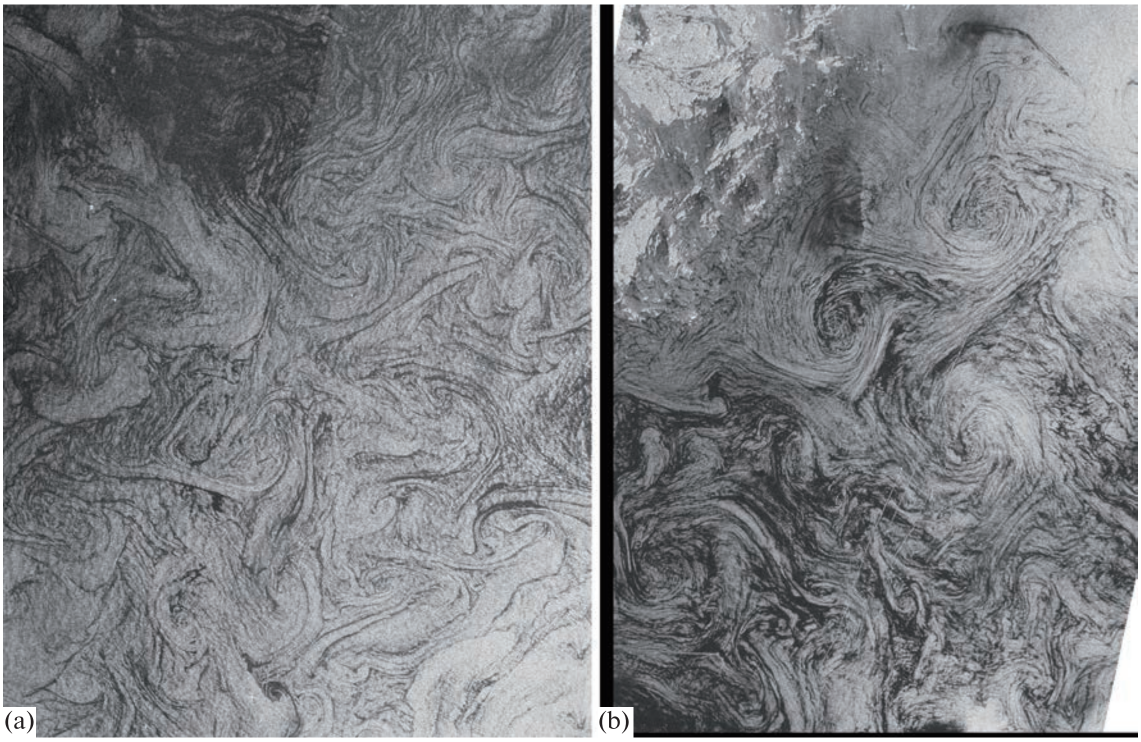

Fig. 1. Manifestation of submesoscale eddies in radar images: (a) in the Black Sea, in the area of the Danube river mouth. The fragment (86 × 106 km) of the ASAR Envisat image obtained on Aug. 21, 2009, at 0814 GMT and (b) in the western part of the Baltic Sea. The fragment (76 × 106 km) of the SAR ERS-2 image obtained on June 21, 2009, at 0947 GMT.

as by the reflection of solar radiation from the sea surface that manifests itself the most in the solar flare region. Hydrosols can be considered as passive tracers of surface currents, and the frontal zones formed by them, as a rule, correspond to the current lines. Color synthesized visible band images can best be used to identify areas of cyanobacterial blooms characteristic of the Baltic Sea. In periods with long, warm, sunny, and windless weather, cyanobacteria combine in aggregates that float to the surface and form surface or subsurface accumulations. In visible band satellite images, cyanobacteria appear as bright narrow bands (filaments) or entire accumulations. The color of these spots depends on the stage of algae development, from bright green to reddish-brown. The use of sequential images for the same water area makes it possible to obtain unique information about the field of the surface currents, and identify major hydrodynamic structures that define meso and submesoscale variability of the current field in the investigated region with a precision unattainable for modern hydrodynamic models. In particular, during intense cyanobacteria blooms, eddies and eddy dipoles manifest themselves particularly well in the visible band satellite images of the south eastern Baltic area (Lavrova et al., 2008).

Under certain circumstances, the eddies and eddy dipoles can be directly detected in the visible band images in the solar flare region. In this case, the signal is generated by sea surface irregularities, such as biogenic slicks that act as tracers, just as it occurs in the radar image.

It should be noted that the detailed picture of the submesoscale eddy activity in the waters of the entire sea and not only in the coastline zone is observed during intense blooming. The rest of the time, because of the lack of passive tracers, eddy structures are identified either along the coast, where there are always slicks of surface-active substances not necessarily related to phytoplankton blooms either in the fields of the surface temperature or upward radiation, albeit, in less detail.

FEATURES OF THE MANIFESTATION OF SHIP WAKES IN SATELLITE IMAGES IN INTENSE PHYTOPLANKTON BLOOM AREAS

Based on the analysis of satellite radar data obtained during long-term monitoring of water areas of different seas, we identified numerous cases of ship wakes that manifest themselves in satellite radar images in the form of extended bright bands of an enhanced radar signal (Lavrova et al, 2014; Mityagina and Lavrova, 2014). The joint analysis of satellite radar and optical data suggests that most frequently long-lasting ship wakes that manifest themselves as enhanced radar scattering bands are observed in the

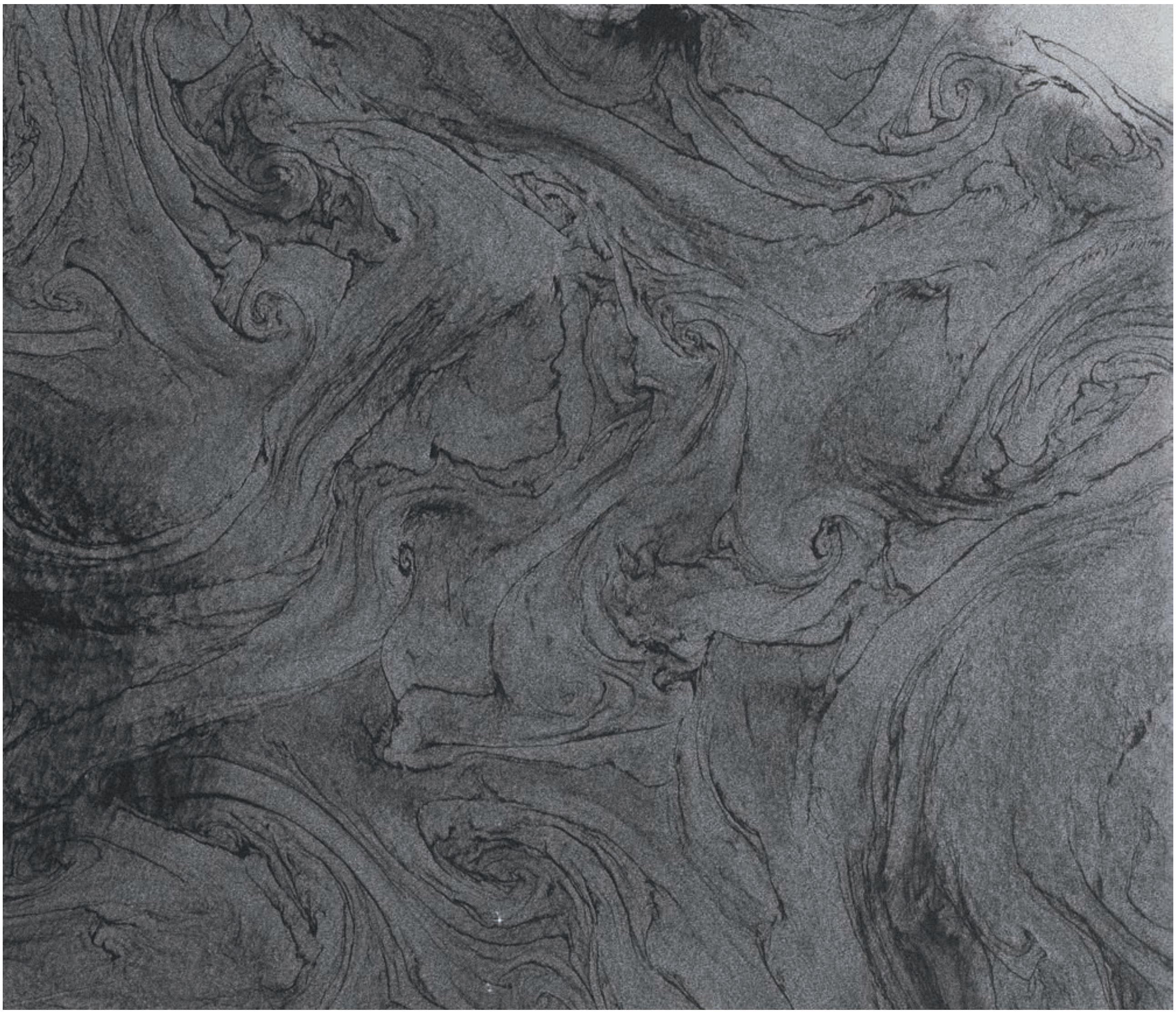

Fig. 2. Manifestation of submesoscale eddies in the radar image during autumn phytoplankton bloom. The fragment (220 × 190 km) of the Sentinel-1 image obtained on October 26, 2014, in the eastern part of the Black Sea.

areas with intense phytoplankton bloom at the time of observation. It was determined that these ship wakes are relatively long-lasting structures and their lengths can reach hundreds of kilometers. It should also be noted that not the whole wake but only a part of it can be shown in the radar image because of the survey geometry. On the other hand, in heavy traffic areas, the ships can directly follow each other or move toward each other, and there is a risk of counting two wakes as one. Based on the length of the wakes detected by the radar data and by setting the average ship speed to 15 knots (28 km/h), which can be considered the average value for large ships that leave long-lasting wakes, we obtain a rough estimate of the life expectancy for such wakes of up to six hours. For comparison, it is rarely possible to observe a usual wake with a length of more than 10–12 km in the radar image.

Examples of high-brightness long-lasting wakes that manifest themselves in the radar data are shown in Fig. 3. Figure 3a shows a fragment of the radar image obtained over the western part of the Black Sea near the Danube river mouth, and Fig. 3b shows a fragment of radar images obtained over the south eastern part of the Baltic Sea. The insets show the radar signal variation along section lines across the wakes. The backscattering enhancement in the wakes of the ship at 5–6 dB relative to the average level can be clearly seen. The width of the wakes is about 300–350 m. The visible lengths of the wakes are up to 60 km (Fig. 3a) and 88 km (Fig. 3b).

A possible explanation for the long “life” of ship wakes during intense blooming can be as follows: by moving through an accumulation of algae, a ship leaves a trail of clear water on which ripples are formed

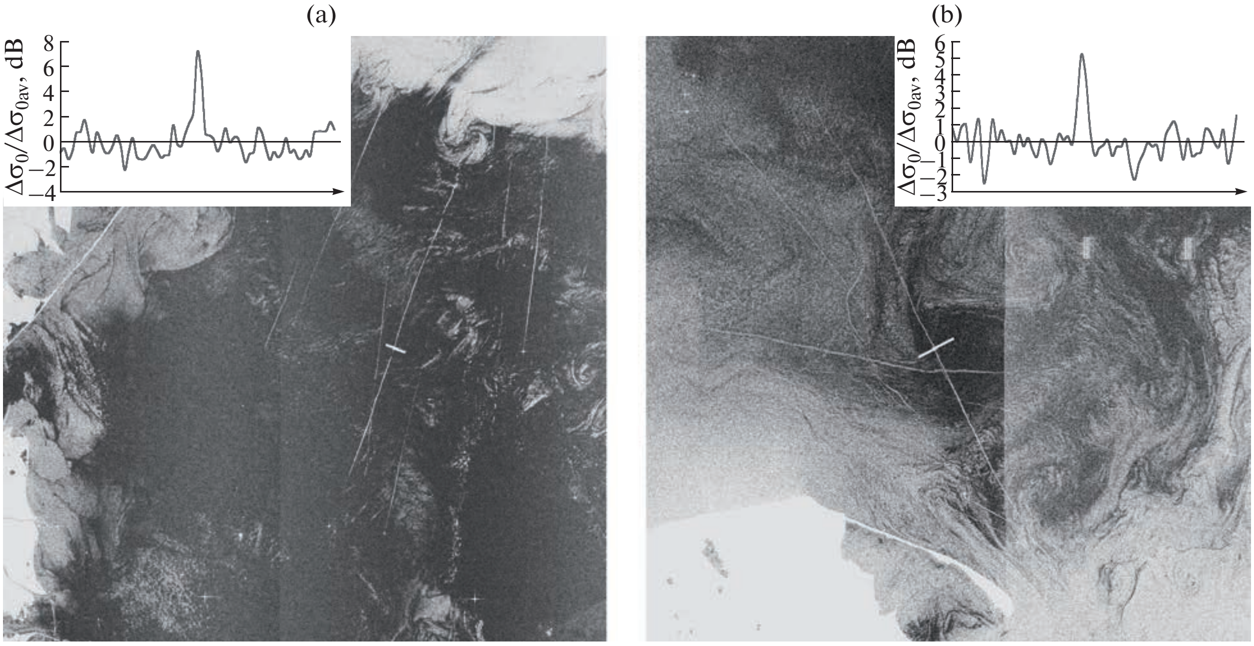

Fig. 3. Fragments (105 × 105 km) of ASAR Envisat images obtained (a) on June 21, 2010, at 0811 GMT over the western part of the Black Sea in the area of the Danube river mouth and (b) on Sept. 6, 2009, at 0855 GMT over the south-eastern part of the Baltic Sea. Insets show radar signal variations caused by near-surface manifestations of the long-lasting ship wake along the section line.

under the action of the wind which, in turn, are responsible for an increased scattering of the radar signal (Fig. 4). Our observations show that in the case of relatively light winds such a trail can remain open for quite a long time without significant expansion.

Long-lasting ship wakes manifest themselves on both the radar and optical images of high spatial resolution. Figure 5a shows fragments of satellite radar images obtained over the central part of the Baltic Sea and the western part of the Black Sea. These images contain manifestations of long-lasting ship wakes along the main shipping routes. Figures 5b and 5d show the corresponding color synthesized fragments of images obtained using the Landsat-5 TM sensor over the same areas at times close to the time of the radar surveys. Based on the analysis of the color synthesized images, it can be argued that there was an intense accumulation of algae in these areas, which in the summer serves as a well detected tracer that shows the position of convergent-divergent zones and accordingly the structure of the currents. Eddies, filaments, mushroom-shaped currents, and narrow elongated bright bands corresponding to the wakes of ships can be clearly seen.

Fig. 4. Blooming of cyanobacteria in the Baltic Sea near Landsort on July 27, 2008. © SMHI.

SEASONAL AND INTERANNUAL VARIABILITIES OF MANIFISTATIONS OF LONG-LASTING WAKES IN SEA SURFACE RADAR IMAGES

In order to confirm the hypothesis that long-lasting wakes are actually observed in areas of intense phytoplankton bloom, radar data from ASAR Envisat and SAR ERS-2 obtained over the waters of the Baltic and Black seas in the period from February 2009 to December 2011 were statistically analyzed.

The schematic maps of the spatial distribution of long-lasting ship wakes in the Baltic Sea identified based on the satellite radar data for 2009–2011 are shown in Fig. 6. The schematic maps present data for the period from April to September, because in the remaining months almost no manifestations of long-lasting wakes were detected in the radar images.

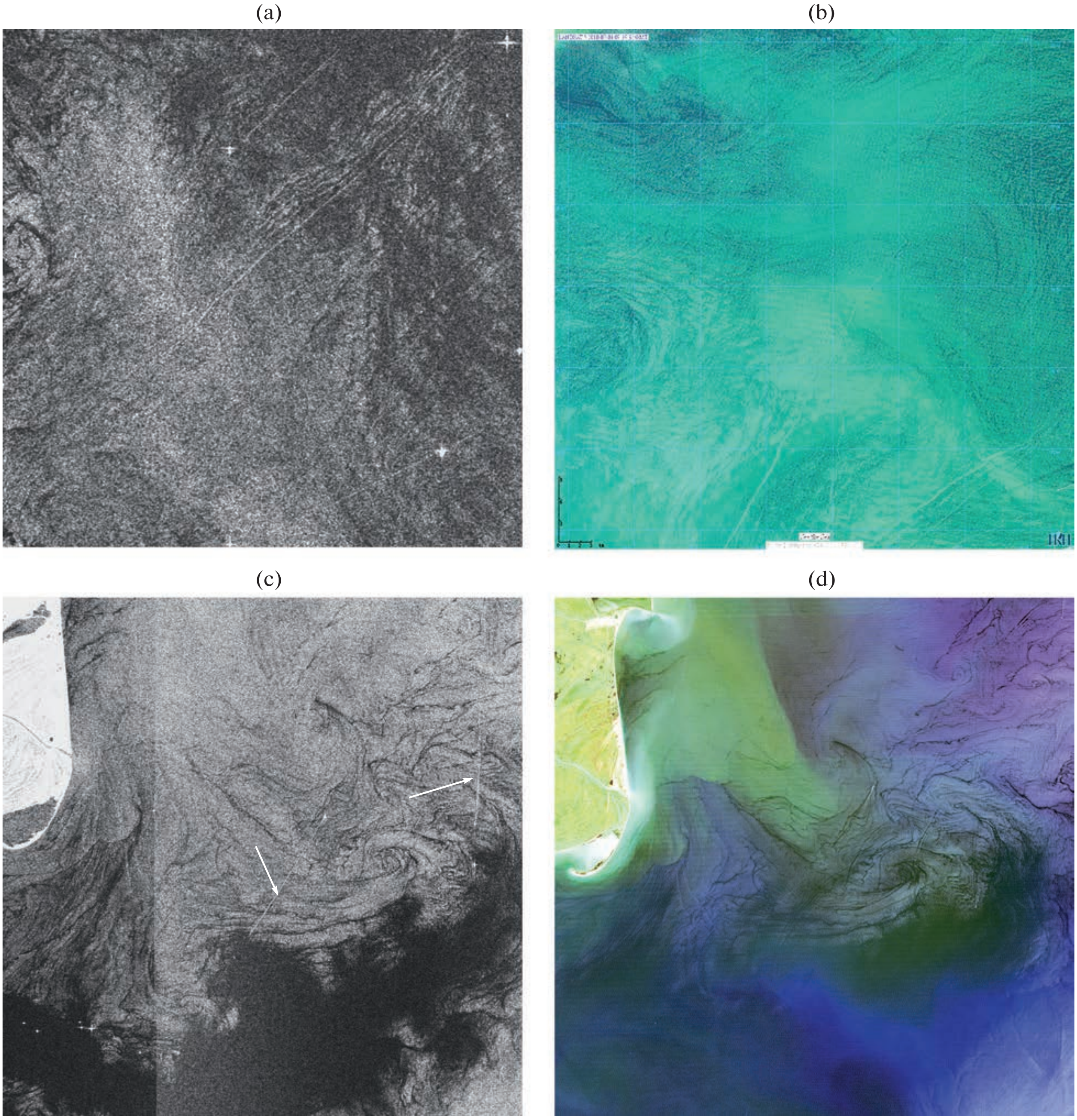

Fig. 5. (a) Manifestations of long-lasting ship wakes on the Envisat ASAR image of the Baltic Sea surface area on July 2, 2010, 2027 UTC. (b) Color synthesized image of the sea surface area of the Baltic Sea obtained by the Landsat-5 TM sensor (channels 3, 2, 1) on July 3, 2010. (c) Manifestations of long-lasting ship wakes on Envisat ASAR image of the part of the Black Sea surface area on June 23, 2011, at 0814UTC. (d) Color synthesized image of the Black Sea surface area obtained by the Landsat-5 TM sensor (channels 3, 2, 1) on June 23, 2011.

The diagram that shows the distribution of the lengths of the radar images of the long-lasting ship wakes identified in the Baltic Sea for 2009, 2010, and 2011 is given in Fig. 7.

The diagram shows that the characteristic lengths of the wakes of this type constitute 10–50 km, but in some cases they can be longer than 150 km. There is a significant interannual variability of the distribution of the lengths of the radar images of long-lasting ship wakes. For each month, the percentage of images with long bright wakes to the total number of radar images obtained for this month was determined. The results of the statistical analysis are presented in Fig. 8.

The results from Fig. 8 were obtained for the whole of the Baltic Sea, including the Gulf of Bothnia and the Gulf of Finland, which is fundamentally incorrect,

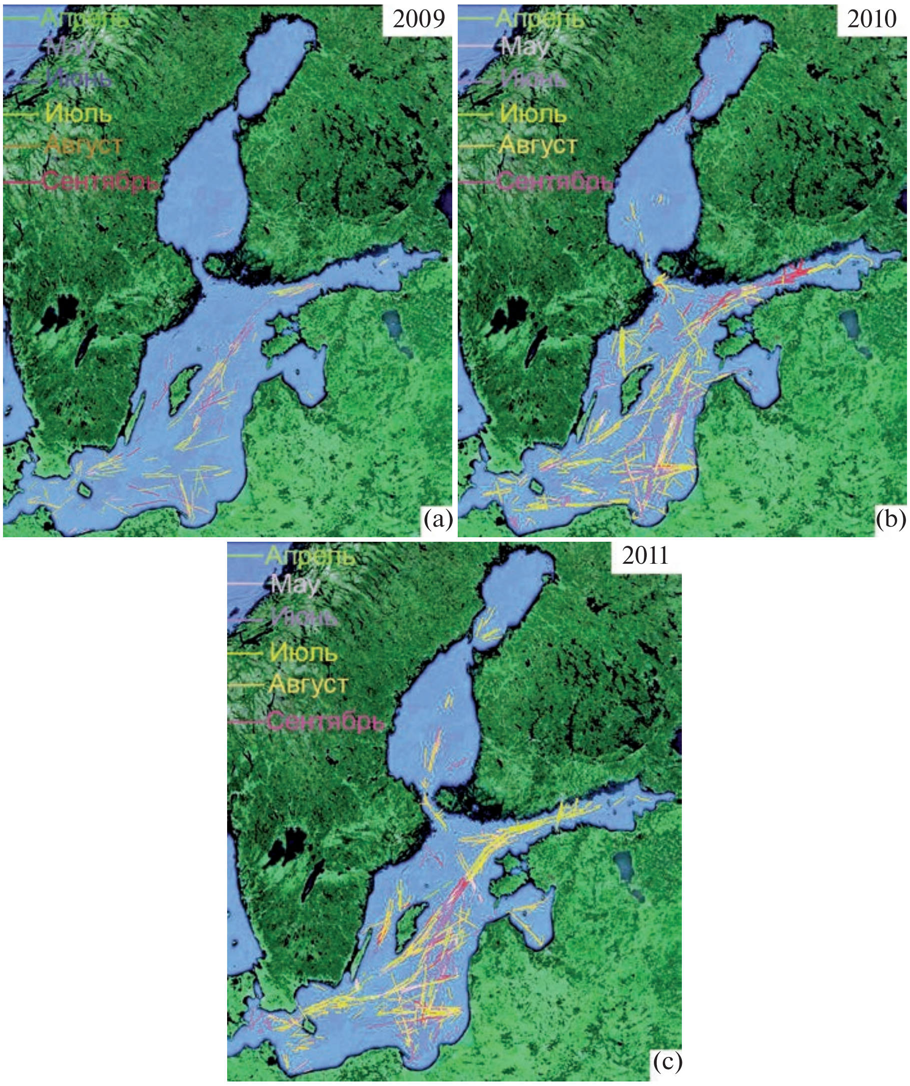

Fig. 6. Generalized schematic maps of the distribution of long-lasting ship wakes detected in radar images of the Baltic Sea for 2009 (a), 2010 (b), and 2011 (c).

because the blooming occurs in different areas in different periods. However, these characteristics are quite informative for the understanding of the interannual variability of the intensity and duration of phytoplankton blooms and are confirmed by the published data on the quantitative content and variability of the phytoplankton species in different parts of the Baltic Sea, obtained in situ by experts of the Swedish Meteorological and Hydrological Institute during annual monthly cruises onboard the research ship Argos (Johansen and Skjevik, 2009; Johansen, 2010; Skjevik, 2011), as well as by the data on the occurrence and duration of cyanobacteria blooms accompanied by the formation of surface agglomerations given in the HELCOM reports (Hansson and Öberg, 2009, 2010, 2011).

In particular, a high percentage of the manifestation of long-lasting ship wakes detected in radar images in April 2009 (see Figs. 6a and 8) can be explained by the early onset of phytoplankton blooms in the southern and eastern parts of the Baltic Sea. The graphs of the integrated chlorophyll content measured in situ at the stations in the Hanö Bight, the southern Baltic, to the east of Gotland (Gotland Deep), and the eastern Baltic, the peaks corresponding to the measurements held in April, when the bloom of diatoms and dinoflagellates was detected, can be clearly distinguished (Fig. 9).

The summer blooms of cyanobacteria were not highly intense and were observed throughout the summer in different parts of the Baltic Sea area (Fig. 10a). Accordingly, the diagram of the manifestation of increased intensity wakes for 2009 (Fig. 8) has a sloping shape without sharp peaks.

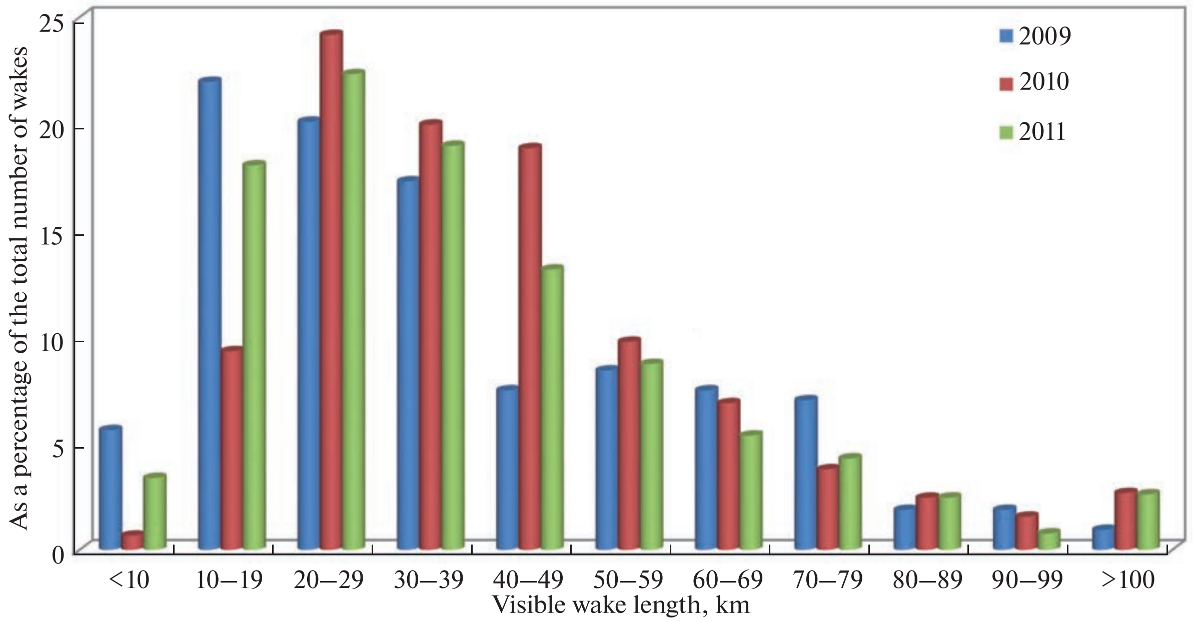

Fig. 7. The distribution of lengths of radar images of long-lasting ship wakes found in the Baltic Sea in 2009–2011.

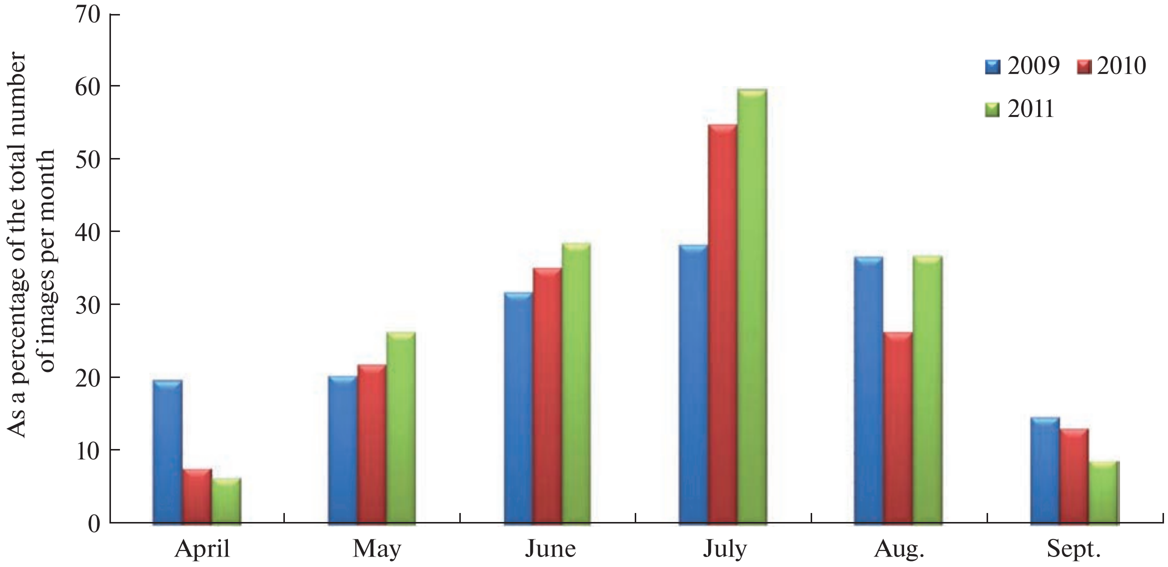

Fig. 8. The percentage of radar images containing manifestations of long-lasting ship wakes in different months of 2009–2011, to the total number of images per month.

In 2010, in the spring, the averagely intense bloom of diatoms and dinoflagellates was recorded at almost all measuring stations (Fig. 9). The cyanobacteria blooms peaked in July followed by a sharp decline in August (Fig. 10b). In April 2010, many manifestations of long-lasting ship wakes were found in the radar images (Figs. 6b, 8), and the peak of the diagram shown in Fig. 8 was in July, while its sharp decline was observed in August.

In 2011, intense spring bloom was still observed in the southern Baltic Sea, but there was almost none in its eastern part (Fig. 9). However, the summer bloom of cyanobacteria was long-lasting and extended to a large part of the sea waters including the Gulf of Bothnia (Fig. 10b). Accordingly, in April 2011, the number of manifestations of long-lasting ship wakes (Figs. 6b, 8) in the radar images was found to be the lowest for three

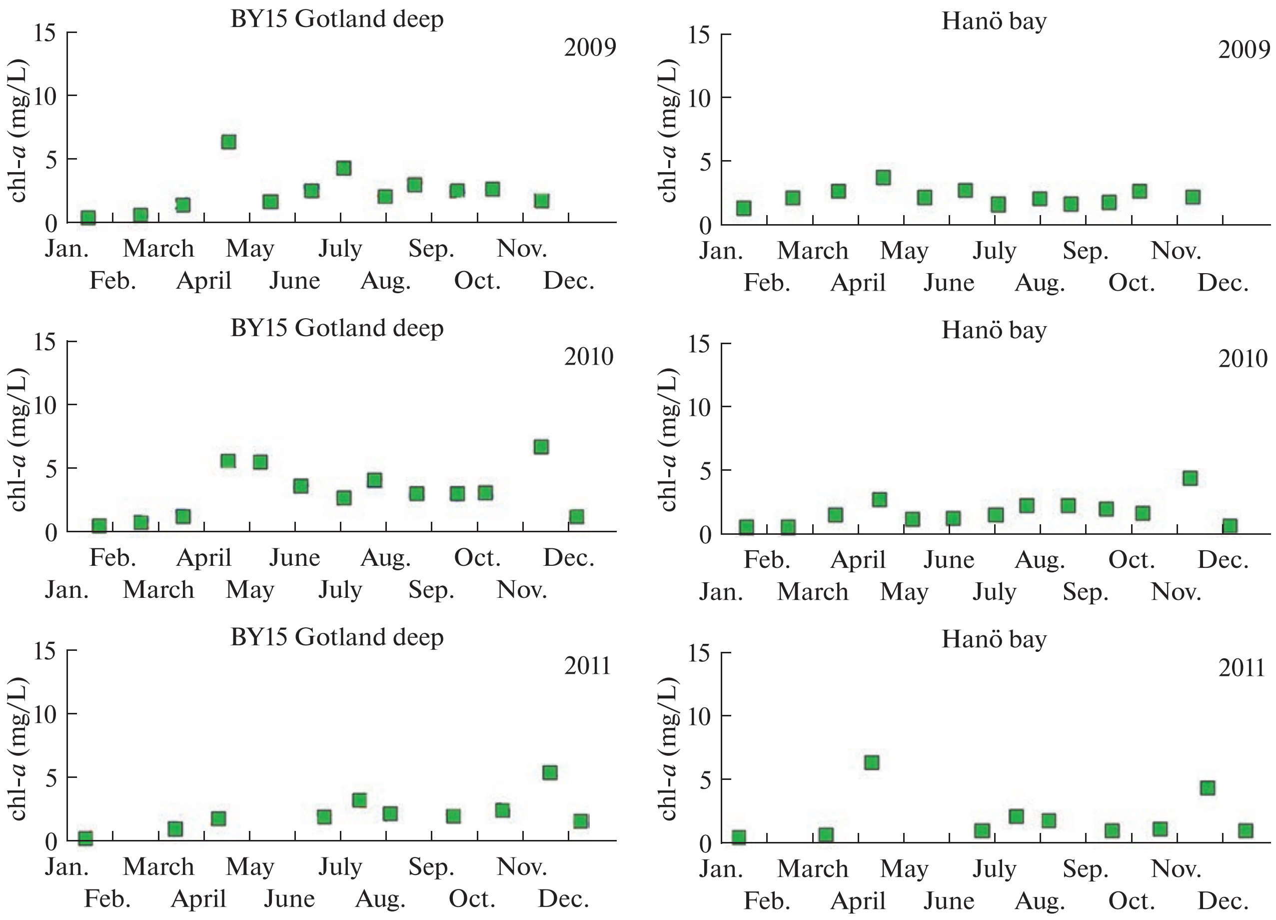

Fig. 9. The average content of chlorophyll *a* from the surface layer to a depth of 20 m measured in situ (in accordance with (Johansen and Skjevik, 2009, 2010, 2011)).

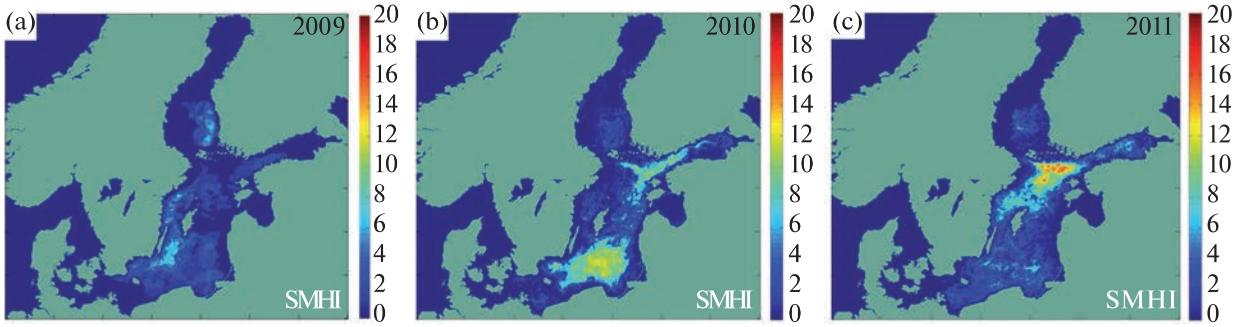

Fig. 10. The number of days when the bloom of cyanobacteria was observed accompanied by the formation of surface agglomerations: (a) 2009; (b) 2010; (c) 2011 (Hansson and Öberg, 2009, 2010, 2011).

years. The diagram shown in Fig. 8 is characterized by the broad and gradually decreasing maximum.

The above data on the spatial and temporal variability of the areas of active phytoplankton blooms in the Baltic Sea are in line with the schematic maps of the long-lasting wakes presented in Fig. 6 that were identified by us using satellite radar imagery and explain the interannual variability of the monthly distributions of the manifestation of increased intensity wakes in the satellite data presented in Fig. 8.

The statistical analysis of the satellite data obtained over the Black Sea showed that the main areas of the

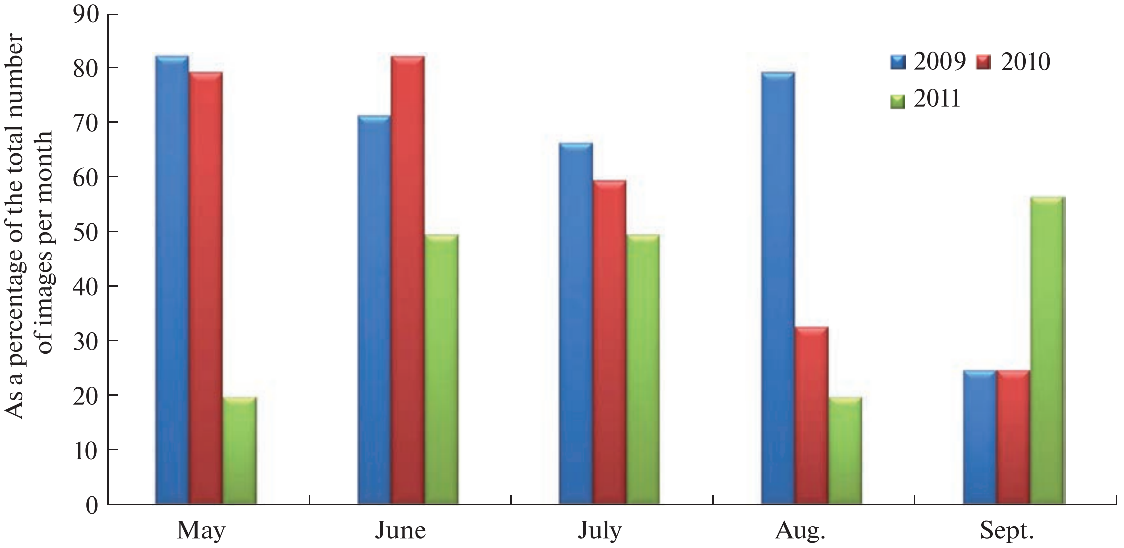

Fig. 11. The percentage of radar images containing manifestations of long-lasting ship wakes in the western part of the Black Sea in different months of 2009–2011 to the total number of images per month.

manifestation of long-lasting ship wakes with enhanced brightness were the north western, western, and south western parts of the sea. This is consistent with data on chlorophyll *a* concentrations. In the north eastern part of the sea along the main shipping routes only isolated incidents of the manifestation of this type of ship wakes were identified (Fig. 12).

The interannual and seasonal variability was estimated for the western part of the Black Sea (Fig. 11). As can be seen from the diagram, highly bright ship wakes are observed mainly from May to July, which corresponds to the duration of the spring–summer blooming in this area. In 2011, the autumn blooming peak was clearly manifested. In the Black Sea, such a comprehensive monitoring of blooming as in the Baltic Sea was not carried out with regular in situ measurements, the results of which are promptly put online and are freely accessible. Therefore, the obtained results of the observations for long-lasting ship wakes were compared only with chlorophyll *a* concentration maps, created according to the MODIS-Aqua data.

We note that the long-lasting ship wakes are of interest not only as a poorly investigated object. The use of the results of satellite observations of wakes of this type can bring significant benefits in solving the problem of the identification of areas and durations of the intense phytoplankton bloom. Simultaneously, the visible wake length can serve as an indirect parameter that influences the water area occupied by blooming.

SHIFT OF THE SHIP WAKE AS AN INDICATOR OF THE MANIFISTATION OF THE FINE STRUCTURE OF THE CURRENTS

Since highly bright wakes remain on the surface of the sea for quite a long time without any significant changes, it makes it possible to use the information on the shift of the ship wake from the ship route that left the path for the investigation of marine currents.

An example of the influence of a strong jet stream associated with the eddy dipole on the destruction of the ship wake is shown in Fig. 12. In this fragment of the color synthesized image from the Landsat-5 TM obtained in the north eastern part of the Black Sea on June 7, 2011, in the solar flare region, against the background of a large number of slicks formed by surfactants under intense phytoplankton bloom, the eddy dipole and the ship wake are clearly seen. Note that the ship crosses not the eddy parts of the dipole but its leg, where the currents are usually the most intense. For example, the 2700-meter part of the wake is separated from the almost linear wake under the influence of the jet stream zigzag outlined by the zigzag slick. Another two less significant distortions are observed in the western part of the wake. All wake breaks are connected to the slick bands. According to our ground-truth observations, slicks are often located in convergent zones, where the direction of the currents changes (Lavrova et al., 2012). It is possible that in the considered case multidirectional currents “tear” the ship wake in different directions causing its distortion.

The image of the almost parallel wakes of two ships that passed by close to each other one after another (Fig. 13) makes it possible to quantitatively estimate the velocity variations at the wake breaks, since it can be used to estimate the distance from the wake breaks to the ship. Considering that the ship speed is known to be ~15 knots, it is possible to estimate the time during which the wake was shifted by the current and calculate current component normal to the wake by the wake shift. It is of interest that in this case after abrupt increases of the current (directed to the north

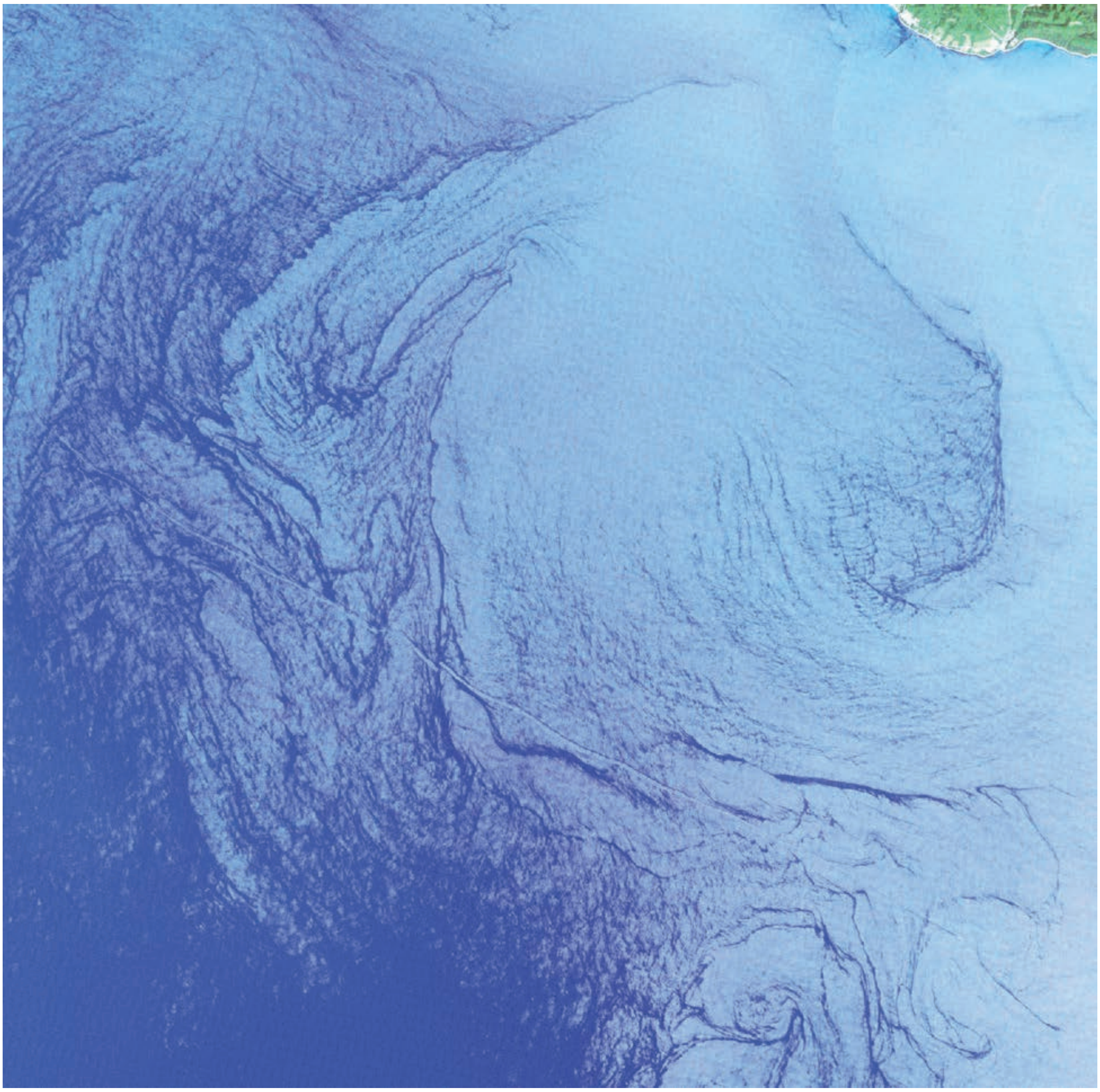

Fig. 12. Breaking of the long-lasting ship wake because of the influence of a strong jet stream. The fragment of the color synthesized image from the Landsat-5 TM sensor (channels 3, 2, 1) obtained from the north-eastern part of the Black Sea on June 7, 2011, in the solar flare region.

west), accompanied by breaks of the wakes, their direction did not change to the opposite one, as in previous cases, but gradually weakened, so that they were not shifted further until the next abrupt increase.

By comparing the true route of the ship with its wake, it is possible to obtain more complete information about the current component normal to the ship wake along the whole route; however, for this purpose, it is necessary to have access to the data on the ship's motion. It is possible to go to the full current vector pattern along the route in the case of a sufficiently clear pattern of slicks except for the places where the slicks are stretched along the ship's route.

A stepwise distortion of the long-lasting ship's wake clearly associated with the influence of the eddy currents appears even more impressive. The ERS-2 SAR image obtained on June 24, 2011, contains the surface manifestations of the ship wakes left by the ship that intersected the eddy dipole in the southern part of the Baltic Sea (Fig. 14). The breaks of at least two ship wakes are clearly manifested. These breaks are clearly associated with jet streams in the eddy dipole, which has a more pronounced cyclonic part. This eddy was caused by sustained western and south-western winds in the southern part of the atmospheric cyclone.

Let us consider the left wake (Fig. 14) left by the ship that sailed from the Gulf of Gdansk by the 333° route. The view of this wake in the radar image makes it possible to associate it with the processes inside the turbulized layer of water over the stern of the ship (Ermakov and Kapustin, 2010), when the effect of currents rather than the purely wind drift of oil tracks on the water surface can be regarded as the main reason for the wake distortions, as it was, for example, in the case described in (Sabinin and Lavrova, 2011). Unfortunately, we do not have data on the ship's route, but in order to somehow associate the wake deformation with its shift by the current, the simplest (and simultaneously the most plausible) assumptions of the route linearity and the constancy of the ship speed were made. Let us once again take 15 knots as the ship's speed that can be considered as a kind of average value for large ships that leave long-lasting wakes.

Let us represent the current speed at each point of the ship's route as a vector decomposed into two components: the current rate across the route and along the route. The current speed across the route at each point of the wake was calculated as the ratio of the drift across the route to the time elapsed since the ship passed that point to the time of the radar survey (it can be calculated if the distance from this point to the ship at the time of the survey and the average ship speed are known). The longitudinal velocity can be estimated by the inclination of the slick bands to the route, which stretch along the jet streams and reflect well the flow direction (see, e.g., (Munk et al., 2000)). Figure 14 shows many slicks (dark bands of the smoothed sea surface), outlining the spatial structure of the currents in the eddy.

The developed method described in (Lavrova and Sabinin, 2015) made it possible to identify the jet and 1 the eabrupt surges of currents in the mesoscale cyclonic eddy of, apparently, topographical origin that emerged in the southern part of the Baltic Sea after the long western and south western winds. In this eddy, asymmetric jet streams with speeds up to 0.2 m/s and a width of 3–5 km close to the internal Rossby radius were twisted counterclockwise around the eddy center, where at a distance of less than 100 m, the current abruptly changed its direction from south west in the north east with a surge in speed of about 0.2 m/s. Such abrupt but somewhat smaller in amplitude speed changes (up to 0.05 m/s) that manifested themselves in other areas at the boundaries of the jets in the form of breaks of the ship wake are hardly to be associated with measurement errors, because their main source is the lack of accurate information about the route of the ship that left the wake, primarily on the absolute values of the speeds rather than their change along the wake. It seems that the found speed changes are quite natural because of the three-dimensionality of the fine spatial structure inherent in sea currents. The fine-structure variability of sea currents in the horizontal direction, as opposed to the vertical one, as well as the small-scale jet nature of the currents, is usually not investigated by researchers because of the difficulty of adequate field measurements and computer simulation. We assume that the special experiments that would include the discovery of a suitable object (eddy, jets of streams, etc.) by remote sensing method and the measurement of currents from the ship crossing this object under conditions when the ship has a long-lasting wake could contribute to the development of satellite oceanology from the observational and experimental stages.

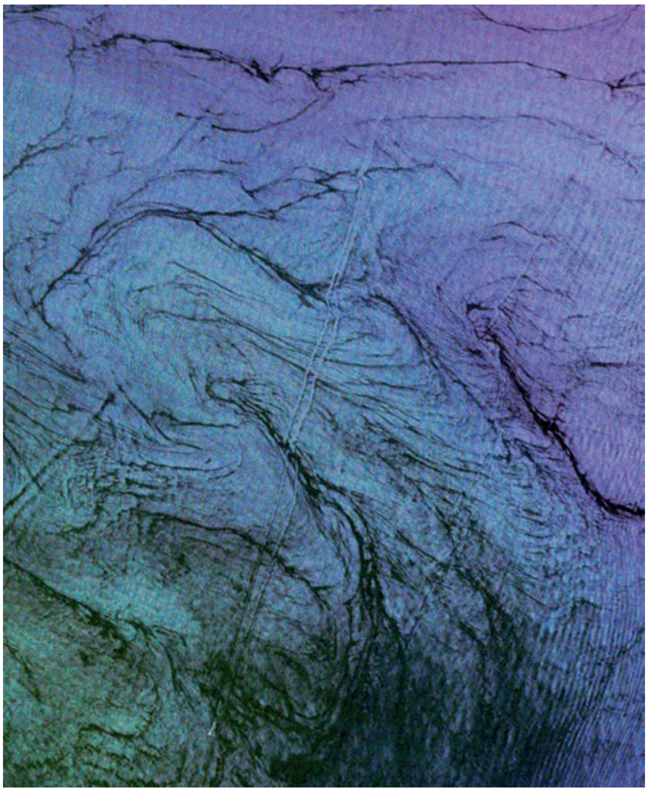

Fig. 13. The shift of the ship wakes because of strong currents. A fragment of the color synthesized image from the Landsat-5 TM (channels 3, 2, 1) obtained in the western part of the Black Sea on June 23, 2011, in the solar flare region.

CONCLUSIONS

The long-term satellite monitoring of the Black and Baltic Seas showed that during intense phytoplankton blooms, a large number of biogenic slicks are formed on the sea surface that serves as a good passive tracer for the exploration of submesoscale hydrodynamic processes based on satellite remote sensing data. In water bloom areas, the wakes behind moving ships manifest themselves in the form of high

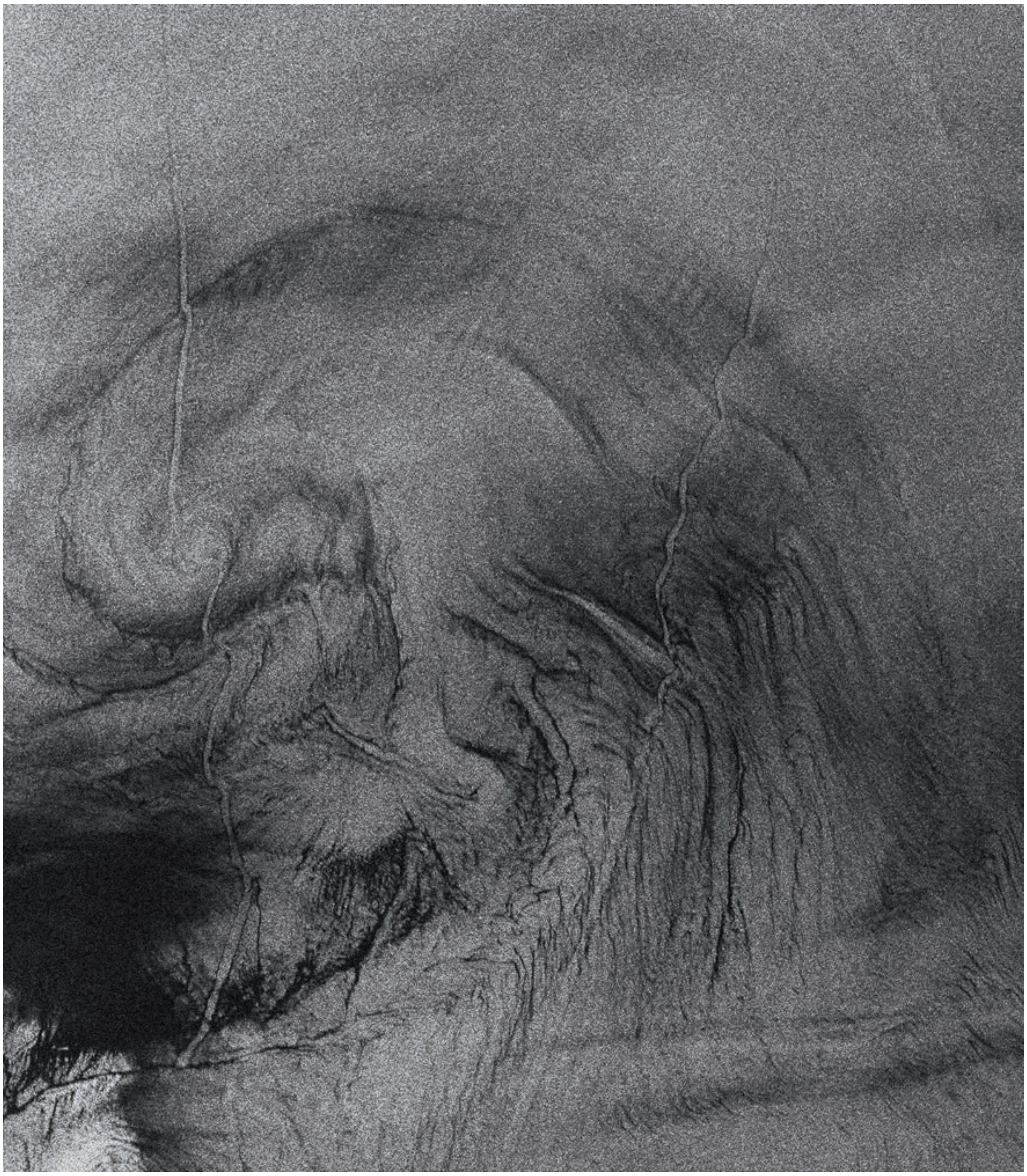

Fig. 14. The shift of the long-lasting ship wakes under the influence of currents in the eddy dipole. The fragment (30 × 34 km) of the SAR ERS-2 image obtained in the south-eastern part of the Baltic Sea on June 23, 2011.

brightness bands, their lengths reach 200 km, and for several hours they remain on the sea surface almost unchanged. The use of satellite observation results of these long-lasting wakes makes it possible to identify the areas and determine the duration of intense phytoplankton bloom.

The curvature of ship wakes of this type can be used to estimate fine-structure inhomogeneities of the near-surface currents in the range of small-scales (tens to hundreds of meters) that still cannot be investigated by other methods.

According to the satellite observations, the speed and direction of the currents can change abruptly for less than a hundred meters.

The banded structure of extended and/or spiral slicks is associated with narrow filaments in the current field and not with the inhomogeineites of the near-surface wind, as it was assumed in the fundamental work of Munk et al., (Munk et al., 2000).

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