Radar manifestations of ship wakes in algae bloom zones

Marina I. Mityagina and Olga Yu. Lavrova
Space Research Institute, Russian Academy of Sciences,
117997, Moscow, Russia, Profsoyuznaya str. 84/32

ABSTRACT

Radar manifestations of ship wakes in zones of phytoplankton bloom are discussed. It is shown that these signatures can be regarded as indicators of biogenic activity. The main data are satellite radar images. Satellite visible (VIS) and infrared (IR) satellite data are also analyzed. The large amount of the available data allowed us to make some generalizations and obtain statistically reliable results concerning spatial and temporal variability of certain type of ship wake manifestations in synthetic aperture radar (SAR) images of the sea surface.

Traditional classification of surface ship wakes manifestations in satellite SAR images specifies distinct features such as a dark trailing centreline region (turbulent wake), narrow V-wakes aligned at some angle to the ship's path (the Kelvin wake), and, sometimes, internal wave wakes generated under conditions of shallow stratification. Their characteristic lengths are reported to be up to tens of kilometers and they can last from tens of minutes up to one hour.

Instances of radar signatures of the ship wakes dissimilar to the previously described were detected in radar images obtained in the course of a satellite monitoring campaign of the central and south-eastern Baltic. These ship wakes can be seen in satellite radar images as long bright strips of enhanced backscatter with characteristic length of up to several hundred kilometres lasting more than 5 hours.

A hypothesis is put forward of the coherence of this type of ship wakes detected in sea surface radar imagery and areas of intensive biogenic activity under conditions of low near-surface winds.

Statistics on their seasonal, spatial and year-to-year distribution are drawn. These results are compared with temporal and spatial variations in chlorophyll *a* concentration and intensity of phytoplankton bloom in the area of interest. Chlorophyll *a* concentration maps derived from satellite data are used, as well as those based on *in situ* measurements. The relation between occurrences of this type of ship wake manifestations and areas of algae blooms is established.

Keywords satellite radar imagery, satellite monitoring, sea surface, ship wakes, phytoplankton, the Baltic Sea, algae bloom

1. INTRODUCTION

The possibility of remote detection of ships and ship wakes by means of satellite radar imagery is extremely important for sea transportation, fishery, pollution monitoring etc. The satellite based synthetic aperture radars (SAR's) are the most informative remote sensing tools of sea surface monitoring, providing the possibilities of fast survey of large areas of the offshore and harbor waters with high spatial resolution independently on surface illumination and cloudiness. Radar manifestations of ships and ship wakes were found in the first radar images obtained by SeaSat satellite in 1978[1]. The further development of satellite radar technologies lead to increasing the interest in radar manifestations of wakes produced by moving vessels, referred to as ship wakes[2 3, 4]. The radar images of "traditional" ship wakes are notable for their well-distinguished structure which obeys the expansion law and includes a dark trailing centerline region and V-like structures[5].

The turbulence caused by wave breaking, ship propeller rotation and vessel hull motion results in disturbance and further dumping of short capillary gravity waves behind the moving ship. Immediately behind the ship a turbulence area is created, and, further, a long strip of smooth water extends[6]. The smooth water area is created as a result of relaxation of

Remote Sensing of the Ocean, Sea Ice, Coastal Waters, and Large Water Regions 2014, edited
by Charles R. Bostater Jr., Stelios P. Mertikas, Xavier Neyt, Proc. of SPIE Vol. 9240, 924018
 · doi: 10.1117/12.2067339

the short wavelength part of the surface wave spectrum in turbulent wake due to a viscosity increase, temperature decrease and elasticity and surface tension variations in surface layer. In radar image, wakes of this kind look like dark strips several kilometers long, starting just in the vicinity of the vessel. Ship wakes of this kind are observed in radar images most frequently and are most frequently manifested at moderate wind velocities of 2.5-7 ms^{-1}. A section of an Envisat ASAR image is shown in Figure 1a, where manifestations of turbulent wakes with lengths of 8-10 km are distinctly visible.

V-like structures behind ships are observed less often than turbulence wakes in radar images. The latter are manifestations of Kelvin waves that are wave systems arising from vessel motion and consisting of divergent and transverse waves. The front of the divergent waves is directed at an angle with respect to ship's path. This angle is dependent on the ratio of the vessel speed to sea depth. The front of the transverse waves is perpendicular to the direction of the ship motion. According to the classical theory, the wave area is restricted by a sector symmetrical with respect to the ship motion axis. However, manifestation of Kelvin waves in radar images depends on observation conditions, in particular on mutual orientation of the azimuth angle and ship's path direction, on ship's dimensions, shape and speed[7, 8]. Since the divergent waves are spreading in different directions with respect to the observation direction, they are displayed in radar images in different ways. It very often happens that one arm of a V-like structure is displayed as a bright strip due to an increase of the backscattered signal, while the other arm – as a dark strip due to a reduction of the of the backscattered signal. An example is shown in Figure 1b. Certain combinations of ship direction and radar look-angle exist when radar backscattering from the both arms has more or less equal intensities, but such situations are infrequent. As a rule, Kelvin wake radar manifestations are shorter than those of turbulence wakes. The reason is that Kelvin wakes decay more rapidly and thus have shorter life span. An example of Kelvin wake radar manifestation with two clearly visible bright arms is shown in Figure 1c.

Our observations as well as previously published results of investigations carried out by various scientific groups show that the ship wake manifestations mentioned above are characterized by lengths not exceeding 20 km and life span from tens of minutes up to one hour.

Analyzing radar images obtained in the course of a satellite monitoring campaign of several seas[9, 10, 11, 12] we found numerous instances of ship wake manifestations that are quite different from those described above. In radar images, they appear as long bright strips of enhanced backscattered signal. From remote sensing data, we retrieved their spatial and temporal characteristics. It was found that these wakes have considerably longer life span and their lengths can reach hundreds of kilometers. Joint analysis of satellite radar images and remote sensing data in visible and infrared spectral ranges allowed us to reveal possible factors entailing this type of ship wakes. In particular, a relation was established between occurrence of this type of ship wake manifestations and areas of algae bloom under conditions of weak surface wind.

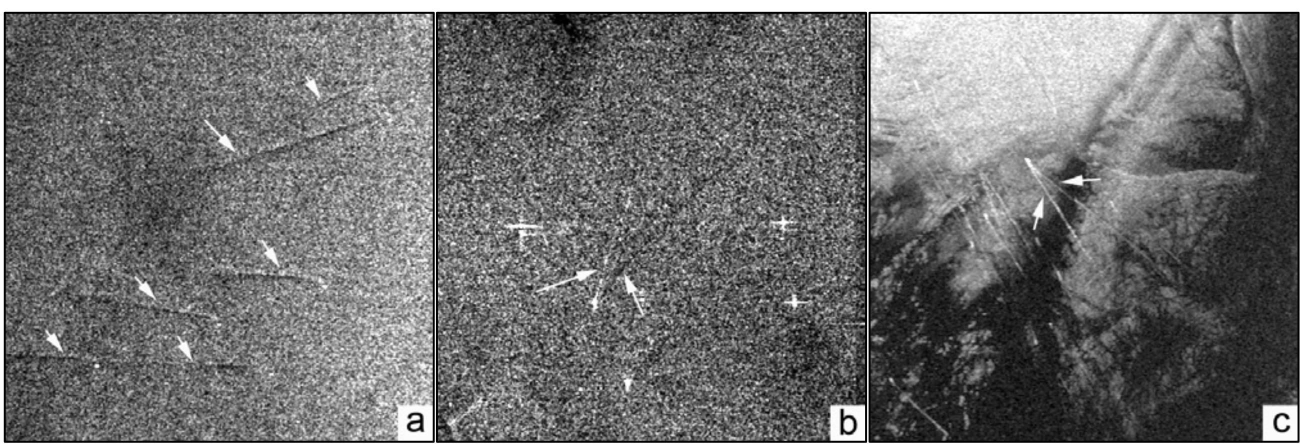

Figure 1. Sections (30 km x 30 km) of Envisat ASAR images showing manifestations of ship wakes: a) turbulent ship wakes with lengths of 8-10 km. Envisat ASAR image acquired on 22.08.2009at 19:57 UTC; b) V-like structure with the length of about 8 km and ship wake angle of about 40°. Envisat ASAR image acquired on 10.09.2009 at 19:59 UTC; c) V-like structure with the length of about 9 km and ship wake angle of about 40°. Envisat ASAR image acquired on 14.04.2011 at 20:39 UTC.

2. SATELLITE DATA USED AND THE AREA OF INTEREST

The main experimental data, that we used in our studies were sea surface radar images obtained by Envisat ASAR and ERS-2 SAR sensors with spatial resolution of up to 25 m. During more than three years, since January 2009 to April 8 2012 (until the failure of Envisat satellite), we carried out satellite monitoring of Baltic, Black and Caspian Seas based mainly on Envisat ASAR and ERS-2 SAR data. The data was obtained from three European receiving stations (MATERA, KIRUNA and ESRIN) in the near real-time. Along with radar data, the data of visible and infrared sensors Terra/Aqua MODIS, Envisat MERIS, Landsat-5 TM and Landsat-7 ETM+ were used. In total, more than 1000 radar images of sea surface were received, archived and analyzed. Practically all of them were accompanied by additional data: satellite IR and VIS range data, data from coastal meteorological stations, etc. A considerable amount of collected experimental data ensured the statistical reliability of our results.

Radar data was used for ship wakes identification. Each image was visually analyzed and structures belonging to either type of ship wakes were outlined and recorded. For each structure, its characteristic dimensions and geographic position were determined. The outlined wakes were put on the map for further analysis using satellite data in visible and infrared spectral ranges. From the latter, the information about the areas of intense algae blooms was extracted and maps of chlorophyll *a* concentration and surface temperature were drawn. This allowed us to estimate the effect of temperature variability on the algae blooming intensity.

Analysis of long term archive of satellite optical data showed that areas of intense phytoplankton bloom are regularly observed over the whole aquatic area of the Baltic Sea. In this paper, we discuss radar signatures of long-lasting ship wakes detected during the periods of phytoplankton blooms in the Baltic Sea. The selection of the area of interest was defined by the following criteria: intense all-season shipping traffic, every-year phytoplankton bloom, including cyanobacteria bloom, a considerable amount of accumulated data concerning the phytoplankton bloom and chlorophyll *a* concentration. All-the-year-round observations of this kind are carried out by Swedish and Finnish scientists in various areas of the Baltic Sea (http://www.helcom.fi/baltic-sea-trends/environment-fact-sheets, http://www.smhi.se/oceanografi/oce_info_data/reports/alg).

3. LONG-LASTING SHIP WAKES AND THEIR MANIFESTATIONS IN SATELLITE RADAR IMAGES

Long-lasting ship wakes are manifested in radar images as relatively narrow strips of enhanced radar signal stretching along the ship track for up to 200 km. At the beginning of the wake, a bright point corresponding to the position of the vessel can be sometimes observed. As a rule, no noticeable expansion of the wake is observed in the direction opposite to the ship motion.

Examples of numerous radar manifestations of long-lasting wakes with the lengths of 65 – 86 km are shown in Figure 2a. In Figure 2b, variations of radar normalized cross-section caused by surface manifestation of the long-lasting ship wake are presented. The enhancement of the intensity of backscattered signal within the wake radar signature is distinctly seen. The width of the wake is 300 m while its visible length is 86 km.

Maps of spatial distribution of the long-lasting ship wakes in the Baltic Sea revealed in radar images in 2009 – 2011 are shown in Figure 3. The data is presented only for the period of April – September because no wakes of the given type were registered in the other months.

A diagram of long-lasting ship wakes' length distribution detected in radar images of the Baltic Sea in 2009, 2010 and 2011 is shown in Figure 4. From the diagram, it follows that the characteristic lengths of this type ship wakes range from 10 to 50 km, while in some rare cases their lengths may exceed 150 km. It should be noted that in some observation geometry cases wakes are not manifested in full length, cut by the image frame borders. On the other hand, in areas with intense shipping traffic the ships may follow each other or they can move toward each other, so there is a possibility of two waves being counted as a single wave. Assuming the average speed of big ships to be 15 knots (27 km per hour), we can calculate the approximate life span of the wakes from their length. Such an estimate produces the lifetime of these long-lasting ship wakes from one to six hours. The year-to-year variability of radar images of long-lasting ship wakes is also observed.

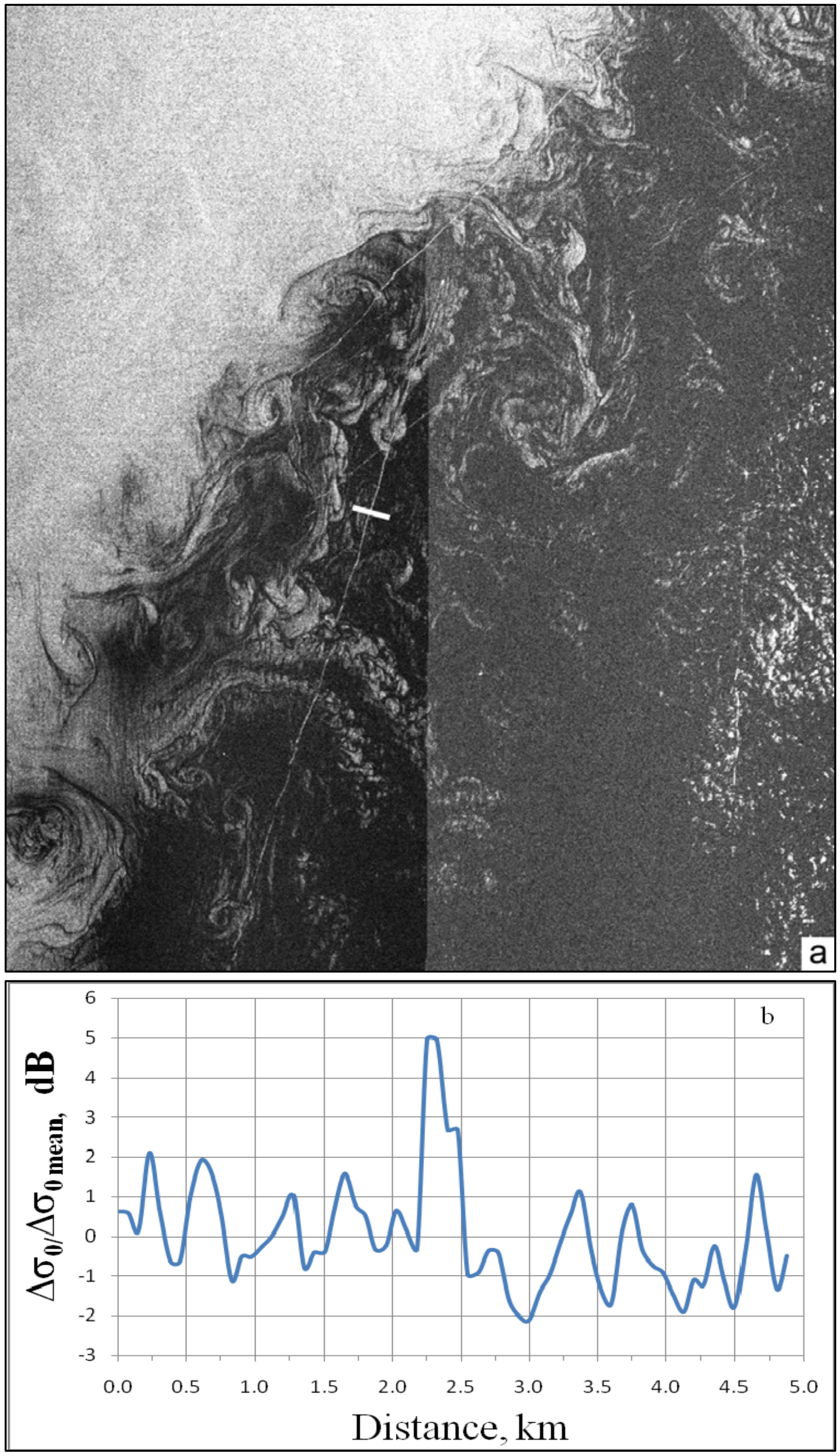

Figure 2. a) Section (105 km x 90 km) of an Envisat ASAR image acquired over the Baltic Sea to the east of the Gotland Island on 20.09.2009; б) Variations of radar signal caused by surface manifestation of the long-lasting ship wake along transect marked in Figure 2a.

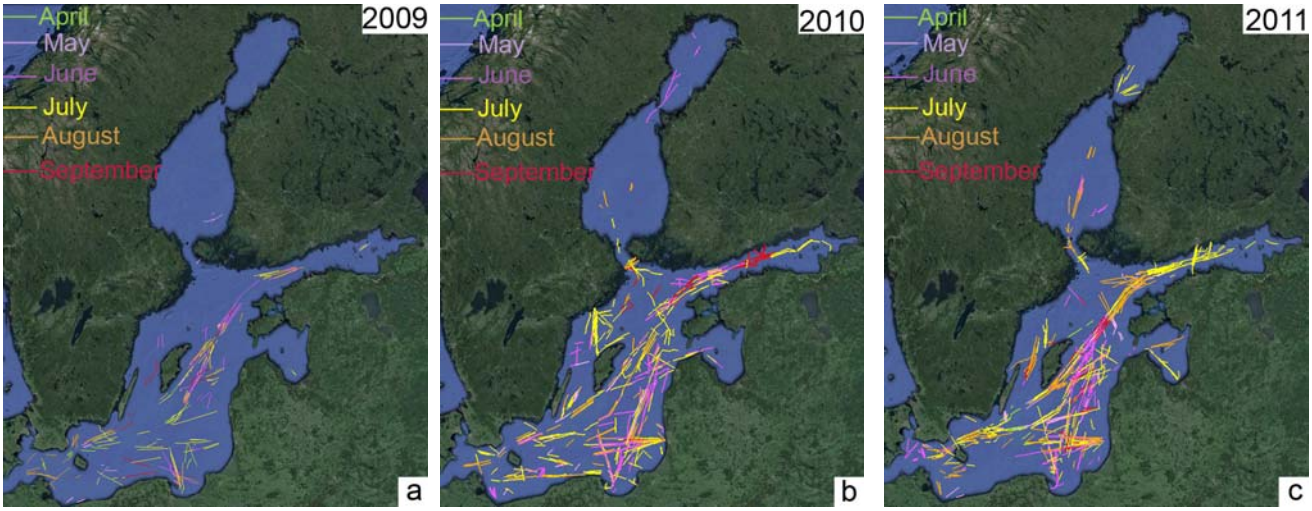

Figure 3. Generalized maps of the long-lasting ship wakes detected in radar images of the Baltic Sea.

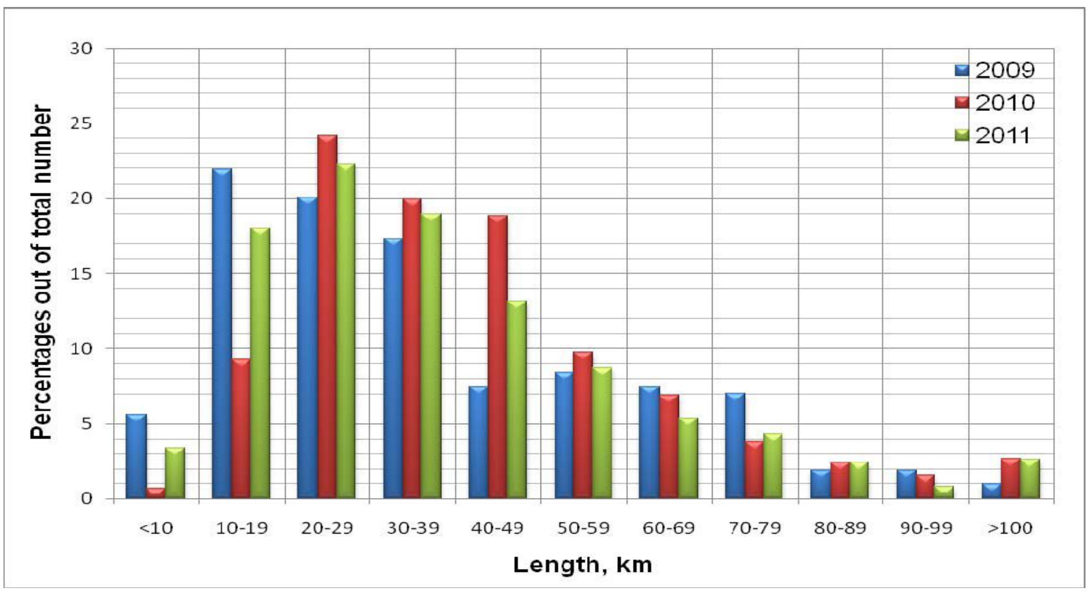

Figure 4. Length distribution of long-lasting ship wakes detected in radar images of the Baltic Sea in 2009, 2010 and 2011.

Joint analysis of the satellite radar and optical data allows us to suggest that the long-lasting ship wakes are most frequently observed in the areas of intense phytoplankton bloom at the time of observation. The Baltic Sea is characterized by two periods of phytoplankton bloom: spring bloom of diatoms and dinoflagellates and summer bloom of cyanobacteria[13, 14]. During the spring diatom and dinoflagellates bloom, large number of cells float at the surface, while during the summer bloom, cyanobacteria are coagulated to aggregates accumulating at the surface or undersurface layers. Occurrence of the long-lasting ship wakes in areas of intense phytoplankton bloom may be explained in the following way. A ship making way through algae leaves a path of clear water behind, resulting in the emergence of short wind waves responsible for the increase in normalized radar crossection. If wind is relatively weak, the wake of this type continues to exist for a long time without significant expansion. In Figure 5a a section of an Envisat ASAR image is shown containing manifestations of long-lasting ship wakes in the area of main shipping route eastward of the Gotland Island. In Figure 5b a corresponding section of an RGB-composite image acquired by sensor TM Landsat-5 over the same area short time after the radar image of Figure 5b was taken.

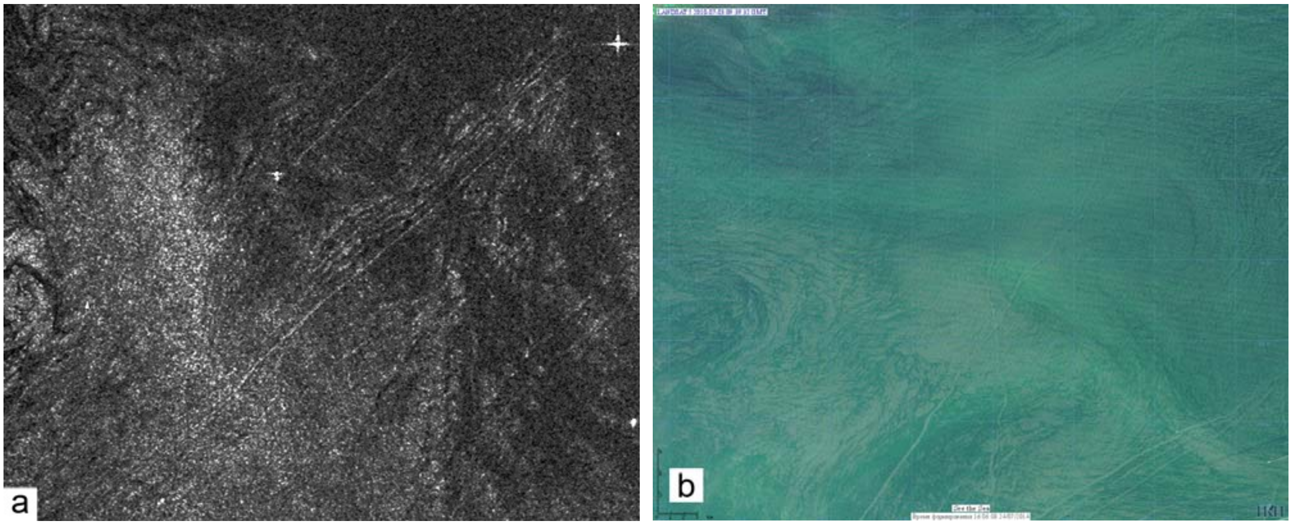

Figure 5. a) Long-lasting ship wakes manifestations in Envisat ASAR image taken over the Baltic Sea on 02.07.2010 at 20:27 UTC ; b) RGB composite of Landsat -5 TM image (3; 2; 1bands) taken over the same area on 03.07. 2010.

Our analysis of the RGB-composite image evidences an intense algae bloom in this area. In summer time, this algae bloom serves as a good tracer, outlining positions of the convergence-divergence zones and, correspondingly, the currents structure. Distinct eddies; filaments and eddy dipoles can be clearly seen, as well as long bright strips corresponding to the ship wakes.

To confirm the hypothesis that long bright ship wakes are observed during period of intense phytoplankton bloom, a statistical analysis of the radar images taken over the Baltic Sea aquatic area from February 2009 to December 2011 was performed. For each month, a percentage of the images containing long ship wakes of enhanced brightness with respect to total number of images taken was determined. The results are presented in Figure 6.

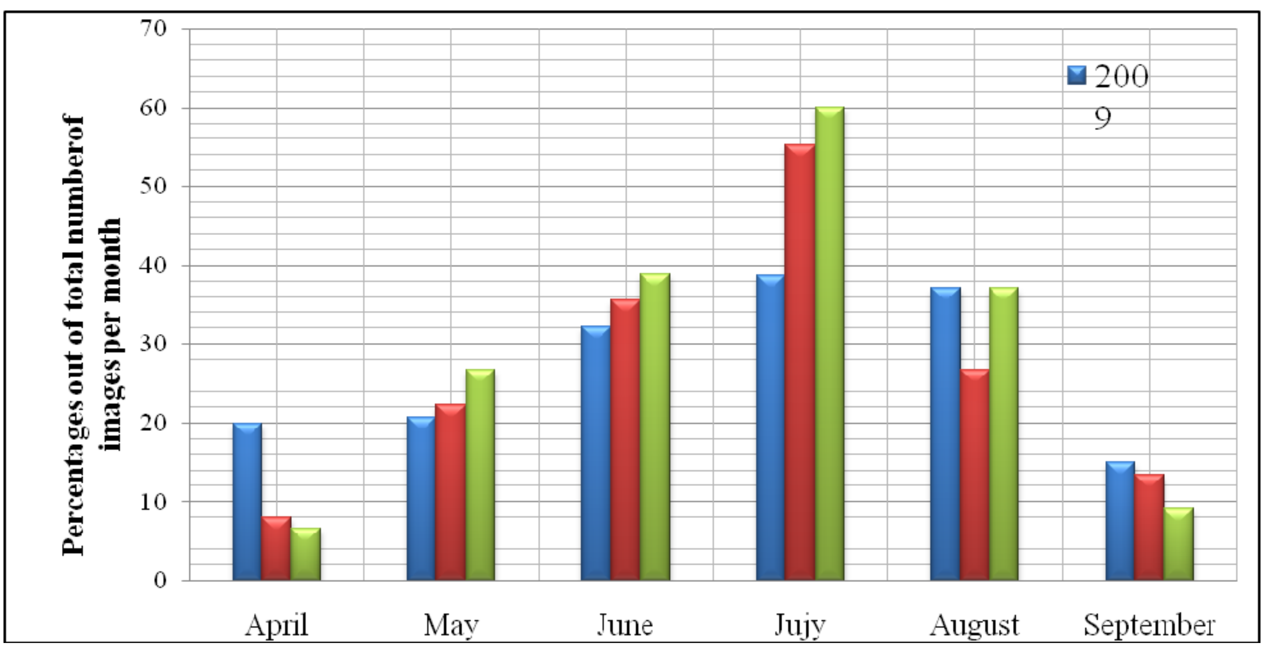

Figure 6. Percentage of radar images containing wakes of enhanced intensity in different months of 2009-2011, with respect to total number of images taken in given month.

The results shown in Figure 6 were obtained for the whole aquatic area of the Baltic Sea including the Gulf of Bothnia and the Gulf of Finland. Please note that the blooms in different areas are observed in different time periods. However, these characteristics seem to be quite informative for understanding a year-to-year variability of the intensity and the duration of the blooming. They are confirmed by published data on quantitative content and specific diversity of phytoplankton in different areas of the Baltic Sea obtained in situ by specialists from Oceanographic Unit of SMHI in the course of monthly cruises of R/S "Argos" [15, 16, 17], as well as by data on cyanobacteria distribution and bloom duration in the Baltic Sea presented in HELCOM reports[18, 19, 20]. In particular, the high percentage of the long-lasting ship wakes revealed in April, 2009 (see Figures 3a and 6) can be explained by the early bloom in the South and West Baltic. In the diagrams of the integral chlorophyll *a* content measured at stations in Hanö Bight and Gotland Basin, a distinct peak can be seen corresponding to April measurements when the blooms of diatoms and dinoflagellates were detected (see Figs 7a, 7b). The summer bloom of cyanobacteria was not intense and was observed all summer in different waters of the Baltic Sea (see Figure 8a). The year 2009 bloom in the Baltic Sea was characterized by large variations, both in time and space. Correspondingly, the diagram of long-lasting ship wakes in 2009 (see Figure 6) is rather smooth and has no sharp peaks.

In 2010, the spring bloom of diatoms and dinoflagellates of moderate intensity was detected practically at all stations (see Figure 7). The peak of cyanobacteria bloom was in July with sharp decrease in August. It follows from the diagram in Figure 6 that in April 2010 a considerable amount of long-lasting ship wake manifestations was revealed in radar images (see Figures 3b, 6). The peak was in July and a sharp decrease was observed in August.

In 2011, as previous years, an intense bloom of diatoms and dinoflagellates was observed in the South Baltic, but it was practically negligible in the western part of the sea (see Figure 7). However, the summer cyanobacteria bloom was observed for a long time and extended over a considerable part of the Baltic Sea, including the Gulf of Bothnia (see Figure 8a). In 2011, summer blooms of cyanobacteria were observed for a period of over two months, covering extended areas. The Gulf of Bothnia, which typically blooms in August, also had an unusually prolonged bloom. Correspondingly, in April 2011 the minimal number of long-lasting ship wake manifestations was revealed in radar images (see Figures 3b, 6) and the diagram shown in Figure 6 features a broad smoothly decaying maximum.

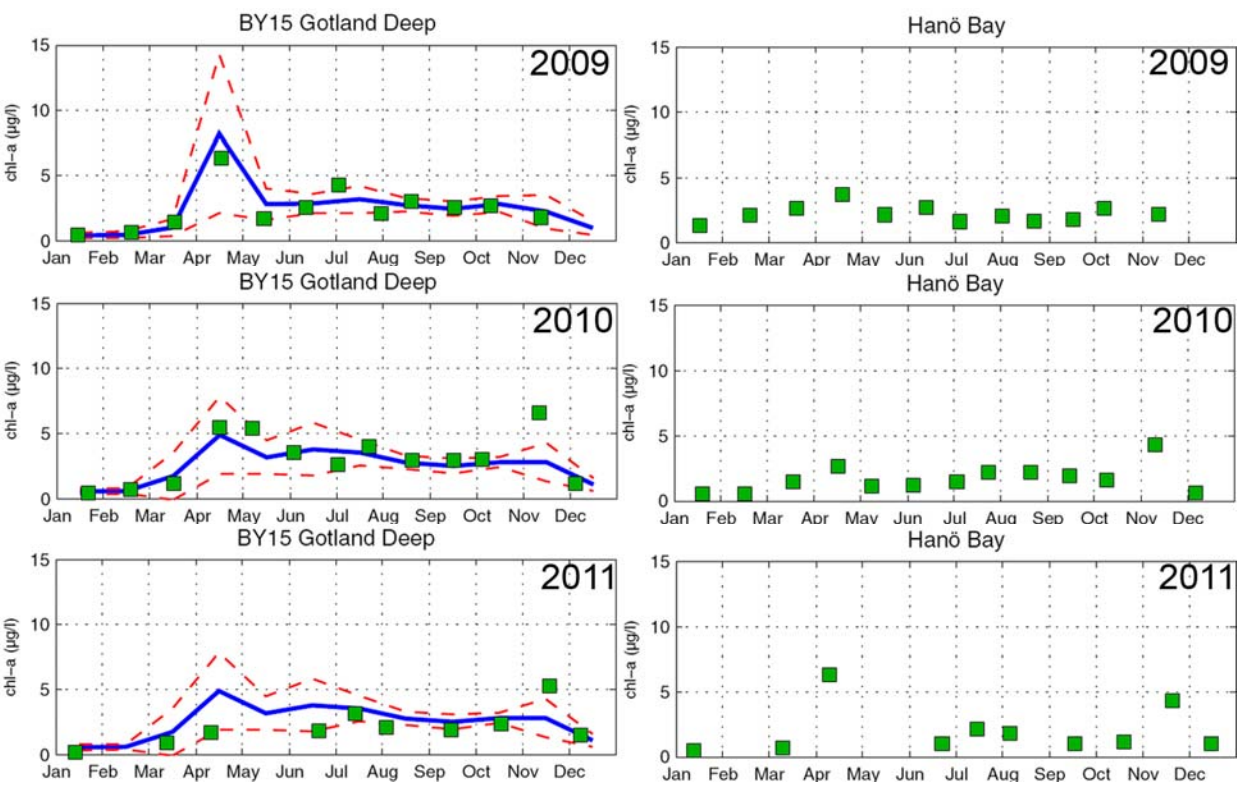

Figure 7. Chlorophyll *a* mean value in the layer from 0 to 20 m: a) during 2009 (after [18]); b) during 2010 (after [19]); c) during 2011 (after [20]).

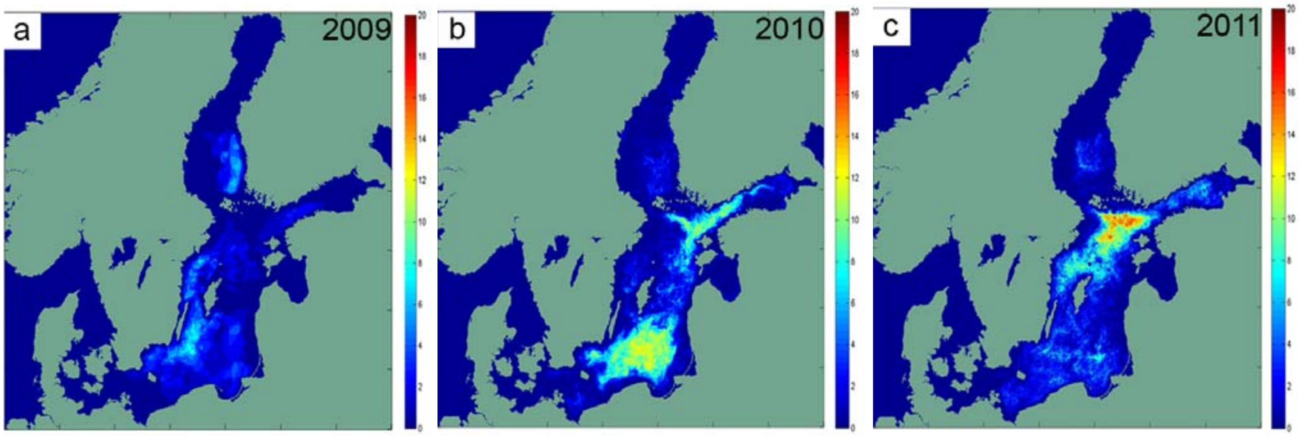

Figure 8. Number of days during with surface accumulations of cyanobacteria observed in each pixel based on NOAA-AVHRR satellite imagery.

The presented above data on spatial and temporal variability of the areas of active phytoplankton bloom are in a good match with the maps of long-lasting ship wake radar manifestations shown in Figure 3 and can explain the year-to-year variability of the long-lasting ship wakes radar manifestations shown in Figure 6.

4. CONCLUSIONS

Numerous manifestations of long-lasting ship wakes revealed in satellite radar images taken over the Baltic Sea were detected and analyzed. It was found that these wakes are displayed as relatively narrow strips of enhanced radar signal with characteristic lengths of 10 – 50 km, but in some cases the wakes of up to 200 km are observed. The hypothesis was put forward and confirmed that this types of ship wakes were observed in periods of intense phytoplankton bloom. It was established that a considerable seasonal and year-to-year variability of the long-lasting ship wake manifestations in radar images was conditioned by the intensity and the duration of a phytoplankton bloom in the areas of observation.

It should be noted that the long-lasting ship wakes are of interest not only not only because they are insufficiently explored to date. In our opinion, the results of radar monitoring of this type of wakes can be helpful in revealing the areas and periods of intense algae blooms. Visible lengths of the wakes can serve as a mediate parameter revealing the area covered by algae bloom. There are natural restrictions for the use of the optical data for detecting the areas of intense bloom, since the Baltic Sea is very often covered by clouds. *In-situ* measurements are conducted regularly but only at several stations. In contrast, radar observations can be carried out independently of cloudiness and solar illumination.

ACKNOWLEDGEMENTS

The work was supported by the Russian Science Foundation under the project # 14-17-00555. Satellite radar data were provided by the European Space Agency in the framework of the C1P.6342, Bear 2775 and C1P.1027 projects.

REFERENCES

[1] Fu,L.-L., and Holt,B., [Seasat views oceans and sea ice with synthetic-aperture radar], JPL Publication 81-120, NASA and JET Propulsion Lab, C.I.T., 1-200 (1982).

[2] Zilman,G., Zapolski,A. and Marom,M., "The speed and beam of a ship from its wake's SAR images," IEEE Transactions on Geoscience and Remote Sensing 42, 2335–2343 (2004).

[3] Soloviev,A., Gilman,M., Young,K., Brusch,S., and Lehner,S., "Sonar measurements in ship wakes simultaneous with TerraSAR-X overpasses," IEEE Transactions on Geoscience and Remote Sensing 48, 841–851 (2010).

[4] Ermakov, S.A. and Kapustin, I.A., "Experimental study of turbulent-wake expansion from a surface ship," Izvestiya - Atmospheric and Ocean Physics 46(4), 524 – 529 (2010).

[5] Pichel,W. G., Clemente-Colón,P., Wackerman,C.C., Friedman, K.S., "Ship and wake detection," Synthetic Aperture Radar Marine User's Manual (Ed. C. R. Jackson J. R. Apel), 277-304 (2004). http://www.sarusersmanual.com/

[6] Peltzer,RD, Griffin,OM, Barger,WR, Kaiser,JAC, "High-resolution measurements of surface-active film redistribution in ship wakes," Journal of Geophysical Research 97(C4), 5231–5252 (1992).

[7] Hennings, I., Romeiser, R., Alpers, W., and Viola, A., "Radar imaging of Kelvin arms of ship wakes," International Journal of Remote Sensing 20(13), 2519–254 (1999).

[8] Reed, A. M., Milgram, J. H., "Ship wakes and their radar images," Annual Review of Fluid Mechanics 34, 469-502 (2002).

[9] Mityagina, MI., Lavrova OYu., "Satellite survey in the Black Sea coastal zone," International Water Technology Journal 2(1), 67 – 79 (2012).

[10] Mityagina, M., Lavrova, O . "Main Results of the Satellite Survey of the Baltic and Caspian Seas: Surface Oil Pollution," ESA - SP-722, (2013).

[11] Mityagina, M., Lavrova, O., and Kostianoy, A., "Long Term Satellite Monitoring of the Oil Spillages in the South-Eastern Baltic Sea," ESA-SP-709, (2012).

[12] Lavrova, O. Yu., Mityagina, M. I., Bocharova, T. Yu. "Manifestation of ship wakes in satellite images in periods of intense algae bloom," Proc. IEEE/OES Baltic Symposium 2014: Measuring and Modeling of Multi-Scale Interactions in the Marine Environment, (2014).

[13] Wasmund, N., and Uhlig, S., "Phytoplankton trends in the Baltic Sea," ICES Journal of Marine Science 60, 177–186 (2003).

[14] Kahru, M. and Elmgren, R., "Multidecadal time series of satellite-detected accumulations of cyanobacteria in the Baltic Sea," Biogeosciences 11, 3619-3633 (2014).

[15] Johansen, M. and Skjevik, A.-T., "Algae report number 11, 2009,", (2009). http://www.smhi.se/en/Publications/algae-report-number-13-2010-1.14326

[16] Johansen, M., "Algae report number 13, 2010," (2010). http://www.smhi.se/en/Publications/algae-report-number-13-2010-1.14326

[17] Skjevik, A.-T., "Algae report number 10, 2011," (2011). http://www.smhi.se/en/Publications/algae-report-number-13-2010-1.14326

[18] Hansson, M. and Öberg, J., "Cyanobacterial blooms in the Baltic Sea," HELCOM Baltic Sea Environment Fact Sheets, 2009, (2009). http://www.helcom.fi/baltic-sea-trends/environment-fact-sheets

[19] Hansson, M. and Öberg, J., "Cyanobacterial blooms in the Baltic Sea," HELCOM Baltic Sea Environment Fact Sheets, 2010, (2010). http://www.helcom.fi/baltic-sea-trends/environment-fact-sheets/

[20] Hansson, M. and Öberg, J., "Cyanobacterial blooms in the Baltic Sea," HELCOM Baltic Sea Environment Fact Sheets, 2011, (2011). http://www.helcom.fi/baltic-sea-trends/environment-fact-sheets/