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Chronic Oil Pollution from Vessels and Its Role in Background Pollution in the Southeastern Baltic Sea

Elena V. Krek 1, Alexander V. Krek 1 and Andrey G. Kostianoy 1,2,*

1 P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences, Nakhimovsky pr. 36, 117997 Moscow, Russia; elena.krek@atlantic.ocean.ru (E.V.K.); av_krek@atlantic.ocean.ru (A.V.K.)
2 Laboratory for Integrated Research of Water Resources, S.Yu. Witte Moscow University, Second Kozhukhovsky pr. 12, Build. 1, 115432 Moscow, Russia
* Correspondence: kostianoy@ocean.ru

Abstract: The results of long-term satellite monitoring of oil pollution of the sea surface in the southeastern Baltic Sea (SEB) are discussed in this paper. From June 2004 to December 2020, in total, 2780 Synthetic Aperture Radar (SAR) images from different satellites were received and analyzed. There were 788 oil spills detected in the study area. The oil spills were concentrated along the main shipping routes in the SEB. The volume of the detected oil spills was estimated. The average size of the spill was about 2 km² or 0.8 m³. Seasonal variability of oil pollution shows a decrease in the number of oil detections in the autumn–winter period, which is associated with the prevalence of unfavorable wind conditions that limit the use of SAR technology for oil spill detection and navigation for small ships. In situ measurements show that seasonal variation in the concentration of oil products in seawater is characterized by a maximum in April and a minimum in July. Since 2007, a decrease in oil detections has been observed for the entire Baltic Sea, including the study area. The interannual variability also shows a decrease in the concentration of oil products in the water column. In the southeastern Baltic Sea, the volume of oil products released yearly to the sea surface from ships does not exceed 0.1% of the average instantaneous presence of oil products in the water column.

Keywords: oil spill; chronic pollution from vessels; anthropogenic impact; concentration of oil products; satellite remote sensing; SAR images; in situ data; the southeastern Baltic Sea

1. Introduction

Ships impact the marine environment in multifarious ways. The main transport mode for global trade is ocean shipping. Around 90% of goods are carried by sea [1]. The production and transportation of oil by sea accounts for about 20% of the total supply of oil to the world ocean. At the same time, accidental spills are not the main source of oil pollution of the marine environment. Their contribution is 10% of the total (global) oil flow into the marine environment [2]. Oil pollution of the sea surface, in most cases, is from deliberate dumping of waste oil. Chronic oil pollution is the result of the illegal “operational” discharges of relatively small volumes of oily waste waters from vessels. Shipping accidents resulting in large spills receive the most attention [3,4], while chronic oil pollution is a constant threat leading to greater damage to the vulnerable marine environment [5]. The Baltic Sea is one of the busiest seas in the world, with about 40 large ports and oil terminals. Nine percent of the world’s trade and 11 percent of the world’s oil transportation pass through the Baltic Sea [3].

The HELCOM Automatic Identification System (AIS) network has hosted all the AIS signals received by the Baltic Sea states since 2005. The AIS dataset represents the density of all IMO registered ships operating in the Baltic Sea. Density is defined as the number of ships crossing a 1 × 1 km grid cell monthly (HELCOM). According to the HELCOM AIS for monitoring maritime traffic, there are about 2000 ships in the Baltic marine area at any given moment [6].
The Baltic Sea area is a special area where any discharge of oil or oily mixtures is strongly prohibited [7]. Despite the restrictions, illegal oil discharges have been observed yearly during aerial surveillance conducted by the HELCOM Contracting Parties since 1988 [6] (Figure 1). Most of the observed oil spills do not result from accidents but from intentional discharges. According to the HELCOM data for the whole Baltic Sea, data of other authors, and our own data for the southeastern Baltic Sea, oil spills are mainly located along the main shipping routes in the Baltic Sea (Figure 1) [3,6–17]. The concentration of oil spills close to the shore in the Exclusive Economic Zone (EEZ) of Latvia is the result of aerial observations predominantly within its territorial waters [6] (Figure 1). There are no aerial observations performed by Russia and Lithuania, which explains the clean water area of the mentioned countries (as seen in Figure 1). Since 1993, Russia has not performed any aerial surveillance of its waters for oil pollution in the southeastern Baltic Sea or in the Gulf of Finland [3,6].

Figure 1. Monthly average traffic density of the HELCOM AIS signals for 2016, volume of illegal oil discharges observed during aerial surveillance flights by HELCOM Contracting Parties during 1998–2017, and accidental oil pollution observed during the period from 1989 to 2017 (Courtesy: E.V. Krek based on statistical data published by HELCOM).

Synthetic Aperture Radar (SAR) for monitoring oil pollution of the sea surface can provide broad ocean area coverage independent of weather and light conditions. Satellite observation in the Baltic Sea has been intensified since 2007 due to the CleanSeaNet service.
provided by the European Maritime Safety Agency (EMSA) [18]. The combined use of satellite-based SAR images and airborne surveillance is a cost-effective way to monitor deliberate oil spills in large ocean areas [19]. The satellite images are delivered in near real time to provide the first warning of possible oil slicks to be checked by aircraft on the spot.

Aircrafts are more suitable to identify the oil film thickness and type of spilled oil product and to identify the polluter. Best practice examples of aerial surveillance among HELCOM contracting parties are German, Danish and Swedish coast guards. Aircrafts carry the following sensors: Side-Looking Airborne Radar (SLAR), Infrared/Ultraviolet Line Scanner (IR/UV), Laser Fluorescence Sensor (LFS), Microwave Radiometer (MWR), VIS Line Scanner, Active Television, and Aerial Reconnaissance Camera. SLAR locates oil discharges, IR/UV scanning is used to quantify the extent of the film, MWR is used to quantify the oil film thickness, and LFS is used for oil type classification [20]. The HELCOM data of oil thicknesses was used to evaluate the volume of spills detected using SAR in the present work.

Airborne surveillance is limited by its high costs and is less efficient for wide-area surveillance. The SAR instrument has therefore become one of the most important sensors for operational monitoring of the marine environment.

In June 2003, LUKOIL-KMN Ltd. organized comprehensive in situ environmental monitoring in the southeastern Baltic Sea in relation to the forthcoming start of oil production at the D-6 offshore oil platform in March 2004 (see Figure 2 for the D-6 platform’s location). In June 2004, satellite monitoring of oil pollution of the sea surface of the southeastern Baltic Sea as an important component of environmental monitoring of the Kravtsovskoe oilfield (D-6 oil platform) started [8,21].

![Figure 2. Study area with bottom topography (white lines). Legend: 1 = area of satellite monitoring; 2 = boundaries of the Exclusive Economic Zones (EEZs); 3 = D-6 oil platform; 4 = Butinge oil terminal.](image)

During the past 17 years, several satellite sensors have been used for oil spill monitoring of the southeastern Baltic Sea, such as ASAR-ENVISAT (European Space Agency,
ESA, Paris, France), SAR-Radarsat-1 (Canadian Space Agency, CSA, Longueuil, Quebec, Canada), SAR-Radarsat-2 (MacDonald, Dettwiller and Associates, Ltd., MDA, Brampton, ON, Canada), SAR-Cosmo-SkyMed-1–4 (Italian Space Agency, ASI, Rome, Italy), SAR-TerraSAR-X/TanDEM-X (German Aerospace Centre, DLR, Cologne, Germany), and SAR-Sentinel-1A/B (ESA). A near real-time (NRT) oil spill detection service was provided by Kongsberg Satellite Services (KSAT, Tromsø, Norway, www.ksat.no (accessed on 25 October 2021)) within 30–60 min after the satellite passed over the southeastern Baltic Sea under the contract with LUKOIL-KMN Ltd. To reduce gaps in satellite data related to the periodical shift of the satellite orbits, leading to 2–3 days without SAR data, additional Sentinel-1A/B data provided by ESA via the Copernicus Open Access Hub were analyzed in non-NRT mode [22].

Since 2004, our team has participated in integrated satellite and in situ monitoring of oil pollution in the southeastern Baltic Sea. The authors of this paper have developed a unique satellite monitoring system for the LUKOIL Company. The monitoring was performed yearly during the past 17 years, as well as in situ oil pollution observations. We have to note that we elaborated and established this near real-time monitoring system 3 years before the EMSA established its CleanSeaNet service in Northern European waters (16 April 2007) [23]. At present, this pioneering oil pollution satellite monitoring operational service is the only one established in the Russian Federation. Analogs of this system do not exist for other seas of the Russian Federation. Since 2004, the data obtained within the framework of this satellite monitoring is the only source of continuous information on the sea surface oil pollution in the southeastern Baltic Sea [9–12,15–17].

The authors of this paper regularly publish the spatial and temporal characteristics of oil pollution in the southeastern Baltic Sea, revealed from the results of yearly satellite and in situ monitoring [9–12,15–17], and inform others about the unprecedented cases of oil pollution [24]. The last update of this information was published 5 years ago [11,12]. The aim of this paper is to present the updated (up to December 2020) statistical information on oil pollution in the southeastern Baltic Sea resulting from illegal discharges from vessels detected using SAR, as well as to estimate the percentage of such oil pollution in the total background oil pollution.

2. Study Area

The satellite monitoring area is a part of the southeastern Baltic Sea (SEB), which includes the Lithuanian and Russian EEZs and a part of the Polish EEZ up to 18° E. The study area is covered with about 80% of the analyzed Synthetic Aperture Radar (SAR) satellite images (see Figure 3 in [12]).

The monitoring area is located at a distance from the main shipping route in the Baltic Sea, passing south and east of Gotland Island (see Figure 1). Nevertheless, shipping routes to major ports in the SEB such as Gdynia (Poland), Gdansk (Poland), Kaliningrad (Russia), Klaipeda (Lithuania), and the Butinge oil terminal (Lithuania) cross the monitoring area and have potential for chronic oil pollution from vessels, as is evident from aerial surveillance flights by the HELCOM Contracting Parties over the main shipping routes in the Baltic Sea (see Figure 1).

The D-6 offshore oil platform is situated 22.5 km from the shore of the Curonian Spit (Natural and Cultural Heritage of UNESCO) and 8 km from the Lithuanian EEZ at a depth of about 30 m (see Figure 2).

The transformation and migration of oil pollution is determined by the hydrological and meteorological features characteristic for the SEB. The horizontal migration of pollution is mainly determined by wind speed and direction as well as the resulting surface currents, in addition to depending on specific meteorological conditions (e.g., sea surface temperature, air temperature, rain, snow, and algal bloom) [25].

Seasonal variability of meteorological conditions over the SEB seriously impacts “visibility” of oil spills on the sea surface in SAR images. Usually, in autumn and winter, strong winds and stormy conditions prevent oil spills from being detected due to the
known limitations of SAR technology. Thus, during this period of the year, we observe fewer oil spills than in spring and summer when meteorological conditions favor oil spill detection in SAR imagery. Seasonality is of great importance for vertical migration of oil pollution, as well as formation, depression, and destruction of the thermocline (pycnocline) in the region of the Kravtsovskoe oilfield where, since 2003, seasonal observations of the parameters of the marine environment and characteristics of oil pollution in the water column and bottom sediments have been carried out [10,16,26].

Seasonal stratification of the water column occurs with the onset of spring warming and the appearance of a seasonal thermocline (in March). By August, the water column warms up to the bottom, and stratification in August–September may appear at depth due to the rise of colder waters from the cold intermediate layers during upwellings [27]. Autumn–winter convection begins to develop in October, which leads to vertical mixing of the water column to the bottom.

The bottom layer in the deep-water part of the Gdansk Basin (more than 60 m) is much less influenced by the surface processes, where the main hydrological processes are determined by the advective bottom water exchange of the transformed North Sea waters [28,29].

3. Data and Methods

Synthetic aperture radar (SAR) has been successfully used for oil spill monitoring in the world ocean and inland seas [30–48], as well as in the Baltic Sea [3,9–17,49–55]. Its main advantages are a wide swath and independence of sun light and clouds. A limitation of the SAR method of detecting oil spills on the sea surface is a wind speed range from 3 to 10 m/s [48,54,56–60].

Oil slicks on the sea surface appear as dark areas in SAR images. This is due to the dampening effect the oil has on the short capillary waves normally found on the ocean surface. Dark areas identified as possible oil slicks are subject to detailed analysis, and each slick is analyzed with respect to its physical properties and in context with its surroundings. An oil spill is classified by relating these two important aspects together.

State-of-the-art operational satellite SAR-based oil spill detection in the world ocean includes two main approaches: manual (expert evaluation) and semi-automatic or automatic approaches to discriminate between oil slicks and look-alikes [61]. During manual inspection, contextual information is an important factor in classifying oil spills and look-alikes [58].

The oil spill analysis used in our research relies upon the sophisticated European methodology of an interactive manual interpretation approach developed and used by KSAT (www.ksat.no (accessed on 25 October 2021)). From 2004, KSAT was responsible for oil spill detection under yearly contracts with LUKOIL KMN Ltd. for 14 years. Classification of dark features in SAR images as a suspicious slick is performed by using a set of decision criteria. Analysis of the predicted winds and wind history, shape, and image texture was performed. The applied wind information was obtained from the Norwegian Meteorological Institute (www.met.no (accessed on 25 October 2021)).

Information about oil rig and pipeline locations, national territory borders, and coastlines could also be overlaid on the image to assist in the analysis. After oil pollution was detected, it was classified as high, medium, or low confidence. The levels are listed in Table 1 together with the main guidelines used to determine the probability level of an oil slick.

After receiving the oil report from KSAT, further analysis was performed for the case of low- and medium-confidence oil spills. Meteorological information from the Warsaw Meteorological University was involved in the analysis (www.meteo.pl (accessed on 25 October 2021)), as well as wind data from the D-6 oil platform, the bottom topography map [62], and additional satellite infrared and optical information. The features of the hydrological regime were also taken into account, such as zones of frequent recurrence of upwellings, river plumes, outflow from the Vistula and Curonian Lagoons, wastewater
discharges, and other factors to exclude natural slicks. After detailed analysis, the final decision on the origin of the slick was made.

Table 1. Confidence levels for oil spill detection.

| High Confidence                                      | Medium Confidence                                      | Low Confidence                                      |
|------------------------------------------------------|-------------------------------------------------------|----------------------------------------------------|
| The slick has a large contrast to gray-level surroundings | The slick has a diffuse or low contrast to the gray-level surroundings in moderate to high wind speed | Low-wind areas are located nearby                   |
| The surroundings are homogenous, with a constant gray-level. | The wind speed is moderate to low, (i.e., approximately 3–6 m/s) | Natural slicks (e.g., biological, algae, or fractal streaks at very low wind) are located nearby |
| The wind speed is moderate to high, (i.e., approximately 6–10 m/s) | The shape of the slick is irregular (i.e., the edges are not smooth) | The slick has diffuse edges or an irregular shape |
| Ship or oil installation directly connected to the slick |                                                       |                                                    |

Slick analysis was carried out on a full-resolution satellite image and was characterized by several features, such as size, shape, and contrast, among others.

In our study, special attention was paid to the shape of the slick. Shape is an important parameter to distinguish between oil slicks and natural phenomena. Therefore, elongated spills, in which the length significantly exceeded the width, were assigned to the tail-shaped form (Figure 3). Moreover, if a spill consisted of several fragments, regardless of their shapes, located along one straight or curved line, then it was considered as one spill and was also classified as tail-shaped (Figure 3a). This made it possible to separate obvious discharges from ships that were chronic polluters. The remaining spills were attributed to spills of another shape (Figure 4).

All detected oil spills were digitized using ArcGIS 10.0 software, where their areas were calculated. The following data were entered into the attribute table for each oil spill: date and time of oil spill detection, satellite, coordinates of the spill, length and width of the spill, calculated area of oil pollution, number of fragments, confidence level, and coordinates of possible polluters, if any. These data were used for further spatial, temporal, and statistical analysis.

One of the major issues related to correct interpretation of SAR images for oil spill detection concerns the so-called look-alikes, which look like oil spills (dark patches on SAR images) but are caused by different natural hydrodynamic, atmospheric, or biological phenomena. Organic films, algal bloom, some types of ice and snow on the sea surface, water areas shaded by land topography, rain cells, upwelling zones, internal waves, and calm water are among many radar similarities to oil spills on the sea surface [48,54,57,60]. In the SEB, during the spring and summer seasons, the probability of the so-called “false alarms” increases due to yearly algal bloom [54,57,60,63]. In winter, grease ice may take a shape similar to oil discharge from the moving vessel, or it may look like a huge oil spill (Figure 5). For the SEB, such ice phenomena are concentrated mainly in the coastal zone or near the canals connecting the SEB with the Curonian and Vistula Lagoons [63–65]. As an example, two slicks were reported as oil spills, and later it was proven that they were of natural origins (see Figure 5). To reduce the number of such “false alarms”, high- and medium-resolution optical images from MSI-Sentinel-2, OLI-Landsat-8, and MODIS-Terra/Aqua were used to discriminate between these natural phenomena and oil pollution.
Figure 3. Examples of tail-shaped oil spills. Oil spills are shown with white arrows. A black arrow points to the polluter. (a) COSMO-SkyMed-4 11.11.2014 (04:09 UTC); (b) Sentinel-1A 21.04.2020 (04:59 UTC); and (c) Sentinel-1A 23.07.2016 (04:59 UTC).

Figure 4. Examples of oil spills of other shapes. Oil spills are shown with white arrows. (a) Radarsat-1, 26.04.2012 (16:12 UTC) and (b) Radarsat-2, 20.06.2013 (16:15 UTC).
Figure 5. Grease ice propagation along the shore of the Curonian Spit and Sambia Peninsula (ASAR-ENVISAT, 11 February 2012). Arrows show grease ice propagation. A red dot shows the location of the D-6 platform.

From June 2004 to December 2020, 2780 SAR images were received and analyzed (Figures 6 and 7). In different years, a combination of data from different satellites was used. For example, from June 2004 to April 2012, we used mainly the ENVISAT data, and the gaps between consecutive SAR images were filled by the RADARSAT-1 data. Since April 2012, we used mainly RADARSAT-1 and RADARSAT-2 data and filled the gaps by other available satellite data. The main characteristics of SAR images are presented in Table 2. The spatial resolution of SAR images varies from 100 m$^2$ for Sentinel-1A/B to 22,500 m$^2$ for ENVISAT, or in the range of 0.0001–0.0225 km$^2$. Thus, the accuracy of oil spill surface detection is very high and of the same order. In our investigation, we used the median value of an oil film thickness of 0.2 µm, observed during aerial surveillance in the Baltic Sea for the period of 1998–2017 calculated using the HELCOM dataset [66].

The shortest time interval between two successive acquisitions was available for ENVISAT and equaled 12 h. During the day, satellite images from one satellite were analyzed. The longest time gap between acquisitions reached 72 h. Thus, annually, on average, we had 1 SAR image every 2 days, which covers the monitoring area shown in Figure 2. Considering the wind speed limitations of the SAR method and the number of processed SAR images, which varied from 100 to 214 per year (Figure 7), the estimates of oil pollution corresponded to the lower value of the actual oil pollution of the sea surface.

Table 2. Main characteristics of SAR images used.

| Satellite                | Usage Period               | Scene Size (km) | Spatial Resolution (m) | Band |
|--------------------------|----------------------------|-----------------|------------------------|------|
| ENVISAT                  | from June 2004 to April 2012 | 400 × 400       | 150 × 150              | C    |
| RADARSAT-1               | from January 2005 to March 2013 | 300 × 300       | 50 × 50                | C    |
| RADARSAT-2               | from December 2008 to December 2020 | 300 × 300       | 50 × 50                | C    |
| COSMO-SkyMed-1,-2,-3,-4  | from April 2013 to December 2015 | 200 × 200       | 100 × 100              | C    |
| TerraSAR-X/TanDEM-X      | from February 2015 to January 2018 | 300 × 300       | 40 × 40                | X    |
| Sentinel-1A/B            | from January 2016 to December 2020 | 250 × 250       | 10 × 10                | C    |
Figure 6. Summary map of oil spills detected from June 2004 to December 2020 within the study area. The color bar shows the monthly average ship traffic according to HELCOM AIS in 2016.

Figure 7. Interannual variability of the analyzed number of SAR images and detected oil spills in 2004–2020.

To investigate the oil product (OP) concentration in the water column, in situ water sampling was performed from the D-6 oil platform (see Figure 2 for the location) regularly in different hydrological seasons (Table 3) and since 2011 (monthly, which made it possible to trace the seasonal and interannual variability of oil pollution in the water column).

Table 3. Frequency of in situ water sampling for determination of OP concentration near the D-6 oil platform.

| Year | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 |
|------|------|------|------|------|------|------|------|------|
| Month | 7, 11 | 3, 5, 7, 10 | 3, 5, 7, 10 | 3, 7, 10 | 3, 7, 10 | 3, 7, 11 | 4–10 | 4–10 |
| Year | 2011 | 2012 | 2013 | 2014 | 2015 | 2017 | 2018 | 2019 | 2020 |
| Month | 1–12 | 1–12 | 1–12 | 1–12 | 1–12 | 1–12 | 1–12 | 1–12 | 1–12 |

Samples were taken from three depth levels—surface, intermediate (10 m), and bottom (about 30 m)—with a HYDROBIOS plastic bottle. The concentration of OP in the seawater
was determined by the fluorometric method on a Fluorat-02 liquid analyzer [67, 68]. The OP concentration measurement ranged from 0.005 to 50 mg/L. The results of the long-term research of oil pollution showed that the concentration of OP near the D-6 oil platform over the entire observation period was similar to the values typical for the entire study area [10, 16]. All drilling, pumping, and technical operations at the D-6 oil platform are performed in compliance with the zero-discharge principle. This means that all industrial and residential waste is transported onshore for recycling and disposal [69]. The influence of oil production on the oil pollution level was not recorded. Therefore, the data obtained from the D-6 oil platform reflected the natural variability of oil pollution in the upper 30-m layer of the water column in the SEB. On the other hand, satellite monitoring of oil pollution showed numerous oil spills related to different types of shipping activity in the region (Figure 6).

4. Results

4.1. Satellite Observations

We have to note that SAR frames periodically and partially covered water areas west and north of the research area, sometimes reaching Gotland Island and the Gulf of Riga to the north. In the present paper, we will discuss the characteristics of oil pollution detected only in the limits of the monitoring area shown in Figure 2 and will leave outside the scope of the paper those cases which were detected outside of this region. Some of these results concerning a much larger water area have been published in our previous publication [12].

During the period of satellite observations from June 2014 to December 2020, there were 788 oil spills detected within the study area (Figures 6 and 7). The number of SAR images from year to year varied from 100 to 214. In 2004, we analyzed only 88 SAR images because satellite monitoring started in June 2004. Concerning the number of yearly detected oil spills, this varied from a maximum of 113 in 2006 to a minimum of 17 in 2018. A negative trend in oil spill detection in the study area occurred from 2006 (113) to 2011 (21), which was consistent with a negative trend in oil spills detected by aerial surveillance in the whole Baltic Sea (Figure 8) [3, 6]. From 2011 to 2020, the number of oil spills detected with SAR varied from 17 to 56 and tended toward 20–30 oil spills per year (Figure 7).

Figure 8. Number of confirmed oil spills per HELCOM country, 2000–2019. Note that the total number of spills is indicated on the vertical axis on the right, which uses a different scale (Figure 3 from [6]).
Figure 6 shows an accumulated map of all oil spills (with a real form and size) detected in the study area from June 2004 to December 2020. It was noted that most of the spills were mainly concentrated in close proximity to the main shipping routes of the southeastern Baltic Sea leading to the ports of Gdynia, Gdansk, Baltiysk (the entrance to the Kaliningrad Sea Canal), and Klaipeda. It is interesting to notice that the concentration of oil spills even highlighted several shipping routes coming to the ports from different destinations, such as the six lines to the Port of Klaipeda (see Figure 6). Large spills mainly occurred outside the territorial waters of Poland, Russia, and Lithuania [17,24]. The most polluted area was located in Gdansk Bay, with a concentration of oil spills in its eastern part offshore of Baltiysk. This is explained by a large number of anchored vessels waiting for entrance to the Kaliningrad Sea Canal. The concentration of oil pollution offshore of Port Pionersky is likely explained by fishery activity on small boats which are not equipped with the AIS [9]. The area around the D-6 oil platform and along the coast of the Curonian Spit was free from oil spills, which was proven by 17 years of satellite observations (see Figure 6). This is explained by the absence of any kind of shipping activity in this region. Additionally, during this time period, we did not detect any case of oil pollution released from the D-6 platform.

It is well known that oil spills released from moving vessels have the form of lines with different lengths, depending on the time of discharge and velocity of the ship. On SAR images, freshly released oil spills look like a “tail” connected to a moving vessel. Stationary ships, as well as oil platforms, produce oil patches slightly elongated with time due to wind forcing and advection by the currents. It was interesting to discriminate between these two shape types of oil spills detected and show their spatial distribution. More than 64% (506 spills) of the detected oil spills were tail-shaped, which indicates more frequent discharge of oily waters from moving vessels (Figure 9). The total area of the detected oil spills was 2193.3 km\(^2\), from which tail-shaped oil spills accounted for 1467.4 km\(^2\) or 67% of the total area of the oil spills. The average area of an oil spill did not depend on its shape. For tail-shaped spills, the average area was 2.1 km\(^2\), but for other shapes it was 2 km\(^2\). The spatial distribution of tail-shaped spills better fit the main shipping routes, as displayed by the AIS, while the spatial distribution of spills with other shapes seemed to be irregular, except for their concentration offshore of Baltiysk, where anchored vessels release oil spills very often (see Figure 9).

![Figure 9](image-url)

**Figure 9.** Spatial distribution of spills detected during 2004–2020 in the study area: (a) tail-shaped oil spills and (b) oil spills of other shapes.
To estimate the interannual variability of the level of oil pollution in the study area, we had to normalize the observed number of oil spills and their area by the number of SAR images, as this changed significantly from year to year (see Figure 7). To do this, we used the Pollution per Satellite Image (PI) index for the normalized number of oil spills and the Pollution Area per Image (PAI) index for the normalized area of oil pollution (Figure 10). The following formulas were used to calculate the indices:

$$PI = \frac{N_s}{N_i},$$  \hspace{1cm} (1)

where PI is the Pollution per Satellite Image index, $N_s$ is the number of detected oil spills, and $N_i$ is the number of satellite images:

$$PAI = \frac{S_s}{N_i},$$  \hspace{1cm} (2)

where PAI is the Pollution Area per Satellite Image index, $S_s$ is the area of the oil spills, and $N_i$ is the number of satellite images.

![Figure 10. Interannual variability of the PI and PAI indices for 2004–2020.](image)

We observed a maximum PI (0.61) in 2006 and two minima of 0.11 in 2011 and 2018. This variability fits well with the PAI index, with a maximum of 2 km$^2$/image registered in 2006 and a minimum of 0.17 km$^2$/image observed in 2018. Steady decreasing trends of the PI and PAI indices were observed from 2006 to 2020. An increase in the PI and PAI indices in 2012 was associated with large individual oil spills detected in this particular year [15,17].

In the seasonal dynamics, an increase in the number of oil spills and their area was noticed in March–September, which was expected, and this was caused by more favorable wind conditions for detection of oil films on the sea surface in SAR images (Figure 11a). From October to February, the winds were stronger, which prevented identification of oil spills in SAR images, and the number of oil spills and their area dropped by an order. For the same reason, in autumn–winter, the average area of an individual oil spill was two times less than during spring and summer (Figure 11b).

### 4.2. In Situ Measurements

Figure 12 shows the interannual variability of the average concentration of oil products in seawater, detected in situ near the D-6 oil platform. In 2003, the value of the OP concentration was much higher than in other years, which was related to the accidental pollution from the Chinese bulk carrier “Fu Shan Hai” [12] (Figure 12a). On 31 May 2003, she collided with the Cypriot container ship “Gdynia” 3 nm northwest of Bornholm Island, and that same evening, “Fu Shan Hai” sank to the bottom of the Baltic Sea. The highest OP concentrations near the D-6 oil platform were recorded in July 2003 (0.073 mg/L). By November, the concentration had decreased to 0.026 mg/L but remained above the
average value (0.018 mg/L) (Figure 12a). The most representative period was 2009 onward, where the regularity of observations was increased. A decrease in the concentration of oil products was noted after 2014. In general, the average concentration of OP, with the exception of the anomalous 2003, did not exceed 0.03 mg/L, and from 2017 onward, it did not exceed 0.015 mg/L.

Figure 11. Seasonal variability of the oil spill number and area of oil pollution for 2004–2020 (a) and the seasonal variability of the average area of oil spills for 2004–2020 (b).

Figure 12. Interannual variability of the average concentration of oil products in the water column at the D-6 oil platform (a) and seasonal variability of the concentration of oil products averaged over the months from 2011 to 2020 for layers of 0, 10, and 30 m (b). The numbers above the columns indicate the mean squared error.

In seasonal variability, the maximum OP concentrations were observed in April (average value for three layers of 0.020 mg/L), which decreased by July, when the minimum was noted (0.012 mg/L) (Figure 12b). In August, the second maximum of the OP concentration is usually recorded. From November to January, the OP concentrations were at the average annual level. In February and March, the average OP concentration decreases slightly against the background of winter [16]. The OP concentrations near the sea surface were slightly higher than those in the water column. Only in August was the OP concentration higher at the bottom than at the surface (see Figure 12b).

5. Discussion

The oil spill number detected in the study area has been constantly decreasing since 2006. The same trend was observed for the entire Baltic Sea based on the HELCOM data on aerial surveillance [3,6]. On the one hand, this is a result of intensive aerial surveillance in the Baltic Sea, which means that ships are potentially watched by patrol aircrafts [6]. On the other hand, this is due to the European satellite-based oil spill monitoring and vessel detection service CleanSeaNet, which was set up for the Baltic Sea and has been operated
by the EMSA since April 2007 [18]. Within the framework of the EMSA service, oil pollution detection is in operation, using images from both SAR and optical satellite missions as well as the identification of possible polluters and the spread of oil spills. Unfortunately, the EMSA service does not operate over Russian waters.

To estimate the volumes of oil spills detected by satellites in the study area, the median value of the oil spill thickness observed during aerial surveillance in the Baltic Sea (0.0000002 m or 0.2 µm) was used [66]. The volume of an oil spill was calculated as the spill area multiplied by the median value of the oil spill thickness. Most of the detected oil spills were less than 1 m$^3$ (Figure 13). Attention is drawn to the accumulation of “small” spills within the territorial waters of Russia west of the Sambia Peninsula and north of the Port of Pionersky. In the areas with low AIS signal density, the pollution sources are mainly small- and medium-sized fishing vessels that are not equipped with the AIS equipment [9].

![Figure 13. Volume of illegal oil discharges observed during aerial surveillance flights by the HELCOM Contracting Parties during 2004–2017 and the estimated volume of oil discharges revealed by satellite data during 2004–2017 in the study area. The intensity of the ship traffic is shown in blue, based on the AIS signals in 2016 according to HELCOM data.](image)

The absence of satellite detection of oil spills in the roadstead of the Port of Gdynia is also noteworthy, while according to aerial observations, oil spills periodically occur in this area [66]. The clean waters adjacent to the Curonian Spit are about 20 km wide. No single oil spill originating from the D-6 oil platform was detected from the beginning of satellite monitoring in June 2004. Relatively large spills with volumes of 1–10 m$^3$ were located mainly outside of the territorial waters of Poland, Russia, and Lithuania. The largest spill volume was 15 m$^3$, which was detected in the Russian EEZ in September 2013 [17].
In comparison with Figure 1, Figure 13 shows the most likely pattern of spatial distribution of oil slicks. Satellite data filled the data gaps for areas lacking aerial surveillance as well as providing supplementary information on oil pollution for regions surveyed from aircrafts. The high density of oil spills in the Polish, Russian, and Lithuanian EEZs is explained by the high frequency of the study area’s coverage with satellite data in comparison with aerial surveillance, which is also quite different in terms of flight hours among the Baltic Sea countries, such as between Sweden and Latvia [3,6]. All these factors should be taken into account when analyzing the density of oil spills on the accumulated map of oil spills in the Baltic Sea (Figure 13).

Based on in situ measurements, it is interesting to estimate the total volume of oil products contained in the water column in the study area. An approximate estimate was made based on an average OP concentration of 0.016 mg/L and the volume of the water for the study area, calculated from the topography dataset [62]. In total, the seawater in the monitoring area, on average, contained 28,000 tons of OP. Nevertheless, even with such a rough estimate, the role of chronic pollution from vessels was negligible for the study area, and, on average, was less than 0.1% per year of the average instantaneous presence of OP in the water column.

The volumes of the oil supplies from ships and the average concentration of OP in the water decreased since 2006 and 2003, respectively. However, there was no statistical relationship between them (correlation coefficient was −0.1), which confirms a negligible role of chronic pollution from vessels in the total content of OP in the water column. Accident-free discharges or chronic pollution from ships have an insignificant effect on the formation of the natural-anthropogenic background of oil pollution. On the contrary, major accidents, such as “Fu Shan Hai” on 31 May 2003, can multiply the natural-anthropogenic background of the OP content. The general decrease in the concentration of petroleum products in the whole Baltic Sea and, in particular, in the Russian waters is apparently associated with the general strengthening of environmental control in recent years, including in the Russian Federation.

To estimate the seasonal changes in the number of oil spills, it was necessary to take into account the limitation of the used SAR method leading to a decrease in oil spill detections in autumn and winter, when strong winds are often observed. Strong winds limit the navigation of small- and medium-sized vessels, such as fishing vessels, and practically do not affect large-capacity vessels. This can reduce the number of small oil spills in autumn–winter but not the large ones, because large-capacity vessels in particular are the sources of large oil discharges. Thus, with a uniform density of shipping throughout the year (the study area was an ice-free region), the number of illegal discharges in the autumn–winter period should have been within the same values as those for April–September, but their “visibility” in the SAR images was significantly reduced due to the SAR method’s limitations. That aside, the lifetime of oil spills is also reduced under the wind–wave action.

The seasonal variability in the concentration of OP near the D-6 oil platform was rather uniform. A little increase in the concentration of OP was noted in April and in August–September which, apparently, was associated with the phytoplankton bloom. Plankton blooms are especially pronounced in April in the surface layer, when the seasonal thermocline is just forming and the water column is strongly stratified. If we assume that the peak in April was associated with the spring bloom of phytoplankton, then its maximum contribution in the background could be estimated to be 40% of the increase in the concentration of OP relative to the average values. The July minimum in the OP concentration could be associated with the summer succession of phytoplankton. The decrease in OP concentration was 25% of the average annual values. Nevertheless, phytoplankton can be one of the determining factors for the hydrochemical background during periods of hyper-bloom. For the rest of the year, including the winter months, when the role of phytoplankton is insignificant, there was a uniform, stable background in the OP concentrations. At the first glance, this might have been a coincidence, but we have to remember that during phytoplankton bloom, algae can release oily substances,
which are different from mineral oil but can contribute to the OP concentration in seawater, depending on the analytical methods of laboratory analysis. All this requires further specific biochemical investigations.

It is probable that the key role in the hydrochemical background (more than 50%) belonged to the supply of OP with the runoff of large rivers (Vistula, Pregolya, and Neman) and transboundary transport with currents from the west, since other sources of oil near D-6 were unknown, including oil seeps from the bottom.

Our estimates did not take into account the solubility of OP or the rate of other oil degradation processes, including biodegradation, which proceed much faster in summer due to the high temperature of the seawater. However, the seasonal variability in the concentration of OP indicates that these processes can be neglected in such an analysis. For example, the warmest month is August, when the rate of chemical processes is at its maximum, but the concentration of OP is relatively high.

The Baltic Sea has its own resources to fight against oil pollution. Microbes play a significant role in the degradation of oil in seawater, often being the dominant factor controlling the fate of toxic hydrocarbons in aquatic environments. All together, they can degrade from 40% to 80% of an oil spill. Several factors influence biodegradation rates, such as oil composition, water temperature, nutrient availability, oxygen levels, and salinity [70]. The total amount of hydrocarbons, which the bacterioneuston can oxidize during the vegetation period in the Baltic Sea, is estimated to be 1200–5000 tons [71]. This estimate shows the capability of the sea to completely clean itself from anthropogenic oil pollution by natural processes. This fact may explain why, in general, we do not observe the accumulation of oil pollution in the sea, because the above-mentioned values are equal or exceed the estimates of the oil volume coming to the Baltic Sea yearly from different sources, as discussed in [4,72].

6. Conclusions

Every ship entering the Baltic Sea must comply with the anti-pollution regulations of the Helsinki Convention and MARPOL Convention. Even though strict controls over ships’ discharges were established by the Baltic Sea countries, illegal oil spills and discharges still happen. The number of illegal oil spills has been reduced significantly over the last 30 years, from 763 spills in 1989 to 52 spills in 2017, and this is an evident and positive tendency resulting from the long-term efforts of HELCOM and the Baltic Sea countries [3].

However, the actual total number of oil spills and their volume seem to be unknown, because these values significantly contradict (100–1000 times) the estimates of different organizations and authors [4,72], as well as the results of our own almost daily satellite monitoring of oil pollution performed since 2004 over the southeastern Baltic Sea. The contradictions are related to the different methods and irregular data used for such types of estimates. Anyway, the performed satellite and in situ monitoring of the study area for oil pollution made a significant contribution to understanding the real spatial, seasonal, and interannual variability of oil spills in the Polish, Russian, and Lithuanian EEZs and to fill the gap for this region in the HELCOM maps of oil pollution based on aerial surveillance, which have existed since 1993.

We detected 788 oil spills over 17 years of satellite observation in the study area, and most of them were localized along the main shipping routes in the SEB. The tail-shaped form of oil spills is prevailing over the other shapes, which proves that ships of different types are responsible for oil pollution. The average spill area is about 2 km$^2$. A significant decrease in the number of oil detections during October–February is explained by the following two factors. During autumn and winter, the area has strong winds, with speeds of more than 10 m/s. This first makes the SAR method inapplicable for detection of oil spills, and second, it leads to considerable mixing and breaking of oil films. Thus, the real values of oil spills and their volume could double if we could correctly measure oil pollution in the autumn and winter, and they could triple if we could have daily SAR images for the SEB. The number of processed SAR images is a very important factor,
keeping in mind that about 50% of oil spills resulting from chronic pollution evaporate from the sea surface during the first 12 h.

We observed a steady decrease in the number and volume of oil spills in the study area since 2006 according to satellite observations which, paradoxically, does not affect the concentrations of oil pollution in the water column. This is explained by the fact that the volume of oil supplied from the surface (discharges from ships) is a small fraction (0.1%) of the formed natural-anthropogenic oil background in the SEB. Chronic oil pollution from ships does not significantly contribute to the pollution of the water area, providing a temporary and local impact. Most likely, the main factor of such an impact is the originating of an additional barrier between the ocean and the atmosphere, which provokes a change in the rate of biogeochemical processes and heat and mass transfer, and this is reflected in changes in the food chain. The strongest anthropogenic impact on ecosystems is observed only as a result of an accidental large oil spill, when significant areas are exposed to oil pollution or oil spills cover the coastal zone.

Regular well-equipped aerial surveillance is very expensive, and it is clear that countries in economic recession reduce their aerial and in situ monitoring. For example, since 1993, Russia has not carried out aerial surveillance in the Gulf of Finland or in the southeastern Baltic Sea. According to HELCOM data, Lithuania (since 1994) and Latvia (since 2005) seem to have had no regular aerial surveillance of oil pollution. With the annual decrease in the number of discovered oil spills in the Baltic Sea, the effective cost of aerial surveying is increasing dramatically. It can be assumed that in different countries, the question will arise soon about the expediency of conducting aviation control of water areas. Paradoxically, the decision to stop aerial surveillance under these improving conditions may be a negative result of the reduction of oil pollution in the Baltic Sea. It is interesting to contemplate whether this will lead to an increase in oil pollution again if polluters get to know that they are no longer observed. Daily satellite monitoring of all parts of the Baltic Sea may partially solve this problem, because satellites simultaneously cover very large areas of the Baltic Sea, and this method is less expensive. The existing satellite monitoring has been performed on a regular basis since 2004 only in the southeastern Baltic Sea and by the private company Lukoil-Kaliningradmorneft. The extension of our experience to the entire Baltic Sea area would unify observations and make it possible to more accurately establish the level of oil pollution, which is still unknown.

The formation of the Baltic International Satellite Monitoring Center in HELCOM could solve many problems in the operational monitoring of oil pollution in the Baltic Sea. This idea was proposed by Kostianoy and Lavrova [72] 8 years ago, but until today, there have been no steps in this direction. As already mentioned in [72], this could accomplish the following:

- Ensure full and uniform coverage of the Baltic Sea area by remote sensing control;
- Reinforce aerial surveillance and improve oil pollution monitoring;
- Establish daily satellite monitoring for the countries where it has not been yet applied;
- Remove duplication of satellite monitoring for the same area performed by neighboring countries;
- Reduce the total cost of operational satellite monitoring for all countries;
- Provide data to all the Baltic Sea states in the same format;
- Solve the problem regarding different technologies, methods, and algorithms used for the analysis of satellite data in different countries and in the EMSA CleanSeaNet;
- Solve the problem of “night” oil spill pollution, which is getting more and more acute;
- Stimulate the exchange of data and cooperation between countries;
- Solve the problem of transboundary oil pollution and contribute to early warnings in this case;
- Improve the ecological state of the Baltic Sea, coastal zones, and shores of the Baltic Sea states;
- Stimulate the organization of analogous operational monitoring centers for seas with a high density of shipping or oil, gas exploration, or production industries (e.g., the North
Sea, the Mediterranean Sea, the Black Sea, the Caspian Sea, the Gulf of Mexico, the coastal zone of Nigeria, and the Barents Sea).

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