Main Pattern of the Caspian Sea Surface Oil Pollution Revealed by Satellite Data

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Abstract
Over the years, oil pollution has been the primary environmental problem of the Caspian Sea. In this paper, we present the results of our satellite survey in 2019 of the whole aquatic area of the Caspian Sea. These results reveal the spatial and temporal distribution of hydrocarbon films of various origins on the sea surface. Our primary attention was focused on the main types of petroleum hydrocarbon films polluting the sea surface. They get into the aquatic area via several different ways: (i) from natural marine hydrocarbon emissions from the seabed; (ii) from the mouths of numerous mud volcanoes; (iii) from offshore oil production and transportation; (iv) from oily wastewaters discharged by ships. We mapped the petroleum hydrocarbon pollution of the Caspian Sea surface on the base of satellite data. For each type of pollution, specific manifestation features were revealed, regions of regular pollution occurrence were outlined, and polluted areas were estimated. The relative contribution of every kind of pollution to the total oil pollution of the Caspian Sea is assessed on the base of satellite data. Comparison with the previous results of our long-term survey of the Caspian Sea is made. The problem of reliability of quantitative estimates of surfaced oil volumes on the base of slick areas seen in the satellite images is discussed.

Key words: the Caspian Sea, satellite monitoring, sea surface, oil pollution, ecological risks, natural hydrocarbon seeps, ship spillages.

Introduction
The Caspian Sea is the largest enclosed body of water on Earth, and in terms of its size, the Caspian Sea far exceeds such lakes as Upper, Victoria, Huron, Michigan, and Baikal. According to formal signs, the Caspian Sea is a closed lake. However, given its large size, brackish water, and a regime similar to the sea, this body of water is called the sea. The surface of the Caspian Sea is located below the ocean level and is oscillated around 27-28 m below the mean ocean level.

The Caspian Sea is located at the junction of two parts of the Eurasian continent - Europe and Asia and is surrounded by five countries: Russia, Azerbaijan, Iran, Turkmenistan, and Kazakhstan. The “S”-shaped Caspian Sea is divided traditionally into three large parts: Northern (25% of the sea area), Middle (36 %) and Southern (40%). In the northern part, the seabed is rather flat; the maximum
depth is about 10 m. The southern part is located in the zone of tectonic activity; the maximum depth reaches 1025 m (see Fig.1).

The main industrial activities in the countries of the Caspian region are the oil and gas production, shipping, fishing, the extraction of various salts and minerals. The Caspian Sea pertains to the world largest oil-bearing regions. Total oil reserves of the Caspian Sea region are estimated at above 250 billion barrels (Aliyev, 2010). The explored oil resources in the Caspian Sea amount to about 10 billion tons. Oil and gas are being produced and transported on an ever-increasing scale that gives rise to many serious environmental and water management problems.

![Map of the Caspian Sea](image)

**Figure 1.** Map of the Caspian Sea. Dashed lines indicate the division into Northern, Middle and Southern Caspian.

For many years, the primary environmental problem of the Caspian Sea has been oil pollution, which is associated both with oil production and transportation, as well as changes in sea level, leading to secondary pollution, river runoff and even seismic activity, which provokes natural oil seeps from the bottom of the sea.

Oil pollution inhibits the development of phytobenthos and phytoplankton, reduces oxygen production, and accumulates in the bottom sediments. An increase of an oil film on the water surface up to 0.1 mm interferes the process of gas exchange and threatens the death of hydrobionts. This phenomenon is already observed on reaching 1 g/m² of oil on the water surface. Oil produces a hazardous effect on marine organisms – from bacteria and phytoplankton to fish. A concentration of oil products of 0.01 mg/L becomes dangerous to fish, 0.1 mg/L for phytoplankton, 100 mg/L for macroalgae. It should be remembered that in
combination with other pollutants, the toxic effect of oil becomes stronger (Zonn, 2006). Pollution of the Caspian Sea leads to the death of rare fishes and other living organisms. The sturgeon stocks are steadily declining. Seafowls are affected by oil most drastically. In contact with oil, their feathers lose the water-repellent and heat-insulating properties, which quickly cause birds to die. The impact of oil on other aquatic animals is also significant, although not so obvious.

According to some estimations (Aliyev, 2003), about one million tons of oil is leaked annually to the Caspian Sea. There are several different ways for petroleum hydrocarbon films polluting the Caspian Sea surface to get into its aquatic area:

- from natural marine hydrocarbon emissions from the seabed;
- from offshore oil production and transportation;
- from the mouths of numerous mud volcanoes;
- from oily wastewaters discharged by ships;
- with river runoff.

A long-overdue need exists to assess the relative contribution of each of the sources of pollution of the Caspian Sea, which varies in different periods depending on climatic factors, on the intensity of various hydrodynamic and hydrometeorological processes, on seismic activity and human economic activity. These problems can only be solved by methods of remote sensing from space, which allows for continuous monitoring of oil pollutions over a vast area of offshore water, including territorial waters of neighboring countries. The latter is particularly crucial for monitoring trans-border transport of the pollutions by sea currents.

Environmental research technologies, based on the satellite remote sensing of the Earth, is actively developing nowadays throughout the world. Over the last decade, a large number of studies appeared, devoted to the development of satellite methods of ecological control of the sea surface. European countries are quite successful in preventing significant sea surface pollution and establishing a system for monitoring sea surface using aerial and satellite surveillance (Gade and Alpers, 1999; Lavrova et al., 2011, 2016; Kostianoy and Lavrova, 2014; Carpenter, Kostianoy, 2018a,b).

None of the Caspian countries (except Russia) carry out satellite monitoring of the aquatic area of the Caspian Sea. Publications on satellite observation of the oil pollution of the Caspian Sea surface are scarce and focus mainly on oily slicks around the oil-producing area “Neftyanye Kamni” (translated as “Oil Rocks” in English) in the Middle Caspian (Bayramov et al., 2018; Ivanov et al., 2012). We can point out also one publication on satellite observation of ship spills in the Kazakhstan sector of the Caspian Sea (Holstein et al., 2018a,b) and one paper on satellite observation of oil seeps from the seafloor in the Southern Caspian (Ivanov et al., 2019).

The authors of this article have long-term experience in satellite survey of the Caspian Sea. Our previous results based on satellite data obtained in 2009-2011 and 2014-2015 are published in (Mityagina and Lavrova, 2015; Mityagina and Lavrova, 2016). The present article is based on recently collected satellite data. In this paper, we attempt to fill some gaps in the knowledge of oil pollution patterns in the whole area of the Caspian Sea. Main types of oil pollution characteristic for different parts of the Caspian Sea are outlined, and the main pattern of the surface oil pollution is revealed on the base of satellite data. New results are compared with those obtained in the course of our previous long-term satellite observation of the Caspian Sea. The problem of reliability of quantitative estimates of surfaced oil amounts on the base of the satellite images is discussed.

**Materials and methods**

In 2019 the sea surface oil pollution survey was based on the combined use of satellite imagery obtained by sensors installed on various satellites and operating in different bands of electromagnetic waves. Data in visible and microwave ranges provided the primary material for the analysis.

We used high-resolution radar imagery data obtained by SARs onboard Sentinel-1A and -1B satellites. The oil spills on the sea surface have diverse characteristics and scales, and it is not always possible to pinpoint typical features that would allow us to detect them in satellite images with 100% confidence. For more robust interpretation, the SAR data is complemented by other satellite data on the sea surface and water condition, sea surface temperature, and mesoscale water dynamics. We used data taken in
visible bands by MSI sensors onboard of Sentinel-2A, -2B satellites and by OLI-TIRS sensor of Landsat-8 satellite.

The data were processed and analyzed using the toolkit of the satellite information system developed at the Space Research Institute of the Russian Academy of Sciences (IKI RAS). The system is named “See the Sea” (STS). STS functionality is detailed in (Loupian et al., 2012, Lavrova et al., 2019a,b). STS provides not only instruments for fast and easy access to satellite data and products, but also various tools for specialized data analysis. STS enables easy search of the distributed image archive using a sensor type, a time interval, and a location as search criteria. The selected image is visualized in the map area of the interface, along with its geographic basis and related cartographic data. All information (regardless of sensor type or product) is presented for viewing in the same cartographic projection for a given geographic area facilitating the selection of data for analysis. The combining data of different nature (active/passive microwave, VIS, and NIR), spatial resolution and swath width allows better understanding the complex nature of meteorological and hydrodynamic processes in the study regions, and revealing the factors favoring oil spill drift and spread. The main characteristics of oil spills were determined using the STS interface in an interactive semi-automatic mode. As a result, we have a particularized description of the phenomena stored in the database. The database tools allow storing and visualization of graphical and attributive information, hierarchical classification of observed processes, searching by spatial, time and typological criteria, and mapping oil pollution of different types in the area of interest. A semi-supervised classification tool implemented in the STS was used to trace oil slicks in SAR images. The traced slicks are incorporated into the cartographic interface for further analysis.

Results

Oil pollution in the “Oil Rock” oil-producing area. The most important source of the open sea surface pollutions in the central zone of the Caspian Sea and in the area of Absheron and Baku archipelagoes is the ingress of the oil caused by the oil production and by oil outflow from natural and artificial seepages at the sea bottom. From the late 19th century, Azerbaijan pioneered the development of shelf and offshore oilfields, and it was the first country to suffer from sea surface pollution.

The major shelf oilfield, “Oil Rocks”, located in 35 km off the coast of the Caspian Sea, was discovered and developed in the late 1940s. Nowadays, “Oil Rocks” oil-producing area consists of more than two hundred stationary platforms interconnected by piers with a total length of 350 kilometers. Oil films are always present on the sea surface in that area covering areas of 200 – 1000 km² (Brandon, 1995). Large oil slicks are observed and identified almost in all radar images as well as in “cloudless” images of optical sensors in VIS bands taken over the oil production areas.

Typical examples of the manifestation of oil slicks on the sea surface near the oil-producing area “Oil Rocks” in the satellite images obtained by SAR-C Sentinel-1A and by Sentinel-2A are shown in Fig.2. In the SAR image, the oil slick with the area of about 385 km², is seen as a dark area of reduced backscattered signal (Fig. 2a). A thin layer of oil floating on the ocean came to be called an oil slick because it suppresses surface roughness. Surface films cause a reduced interaction of ocean waves and wind as well as an attenuation of the resonance gravity-capillary component of surface waves. In this case, smooth areas (slicks) appear on the sea surface and form areas of reduced backscattered signal in a radar image. SAR has been used for the detection of oil films on the sea surface for many years (Jenkins and Jacobs, 1997; Mityagina and Churumov, 2006).

In the VIS image obtained in the sunglint area, oil-containing films have increased brightness and appear as light structures surrounded by a dark halo; the polluted area is of about 420 km² in this case (Fig. 2b). Sunglint refers to the reflection of solar radiation from the sea surface observed by optical sensors when sunlight’s incidence angle is equal to the angle of reflection. In the sunglint region, areas covered by films appear brighter because the surface film reduces the sea surface roughness and a higher number of local elements are present, reflecting light to the sensor. It should be added that the oil film on the VIS images may be visible even better than in the radar images since the observed contrasts are caused not only by smoothing surface waves by the oil slick, but also by the differences in the optical characteristics of clean water and the oil film. However, usage of optical data is heavily constrained by illumination and cloud-free requirements, so they lose by far to radar data in application to continual monitoring and gathering statistics. Nevertheless, optical data, especially images with sunglint effect, often help to interpret radar data and
decide on the origin of a slick film: whether it is an oil or biogenic film because oil and biogenic films are manifested differently in optical data. Oil films are brighter and have shiny signatures in color composites. Oil-producing platforms connected by piers are visible in both images.

We should admit that the sea surface pollution near these drilling platforms is caused not only by “dirty” oil production techniques (the oil production and oil well drilling, the underwater oil rig repair, oil outflow during pipeline breaks). Even before drilling started at “Oil Rocks” in 1949, the sea surface in this area was famous for its natural oil slicks. The amount of the oil ingress from the seabed to the sea in this area can vary between 100 and 500 tons per day.

The spread and evolution of the oil patch, which is always present near the oil drilling site, depend on the meteorological conditions. The oil-producing area “Oil Rocks” can be used as a natural laboratory for studying the effect of wind conditions on oil patches as well as on formations of oil slick signatures in radar images (Mityagina and Lavrova, 2015; Mityagina and Lavrova, 2016). Methods of the monitoring of the sea surface oil pollution by means of remote sensing developed here will be applied to other regions.

First of all, virtually all the SAR images taken at moderate wind speeds (3-8 m/s) over the “Oil Rocks” oil production area included oil slicks. The newly taken Sentinel-1 SAR imagery was compared with that obtained in 2015-2018 and with Envisat ASAR imagery taken in 2010-2011. It was found that the amount of surface oil slicks manifestations in radar images remains practically the same during both observation periods. Oily films floating on the sea surface appear in radar images as dark patches occupying large areas among the bright (rough) sea surface and evolve under the influence of currents and local winds. The reduction in the Normalised Radar Cross Section (NRCS) within a slick can reach 2 - 11 dB depending on film thickness, oil concentration, and wind speed as well as on the type of sensor and polarisation. Fig. 3a presents a characteristic example of oil slicks seen in radar images taken over the “Oil Rocks” platforms under moderate winds.

Radar images taken but under less than favorable wind speeds higher than 10 m/s as well as in the presence of active processes in the atmosphere-ocean boundary layer reveal very small (or not at all) dark areas of decreased radar backscatter near the oil rig. This situation occurs because at high wind speeds (exceeding 9-10 m/s) both oil and biogenic polluting films are disrupted by wind and waves, and cannot always be identified in radar images (Mityagina and Lavrova, 2016). A combination of strong wind and waves inhibits the formation of an oil slick. Moreover, considerable variations of NRCS caused by atmospheric signatures can sometimes cover the significant part of a radar image. It sometimes makes it impossible to identify oil patches on the sea surface under such conditions. All the factors mentioned above lead to the high probability of the underestimation of the polluted area size under high winds and disturbed atmospheres. A Sentinel-1 SAR image taken over the oil-producing area “Oil Rocks” is depicted in Fig. 3b. Wind field variations caused by convective processes in the near-surface atmosphere produce prominent cellular structure in the radar image, and oil slick cannot be easily identified in this image.
On the other hand, a large number of low backscatter areas are seen in radar images obtained under low near-surface wind that are not related to the presence of oil-containing films on the sea surface. The capillary-gravity component of the sea surface wave field may not develop under weak-to-no-wind conditions. Low wind areas seen in radar images in the vicinity of oil drilling platforms can be misinterpreted as oil slicks. The existence of these low scattering (dark) areas in radar images increases the “false alarm” probability in oil pollution monitoring. Hence sizes of polluted areas derived from radar data taken at low winds can be overestimated. Fig. 3c illustrates this situation. Vast dark areas of decreased NRCS are seen in the Sentinel-1A SAR-C image taken over the central part of the Caspian Sea. Areas marked by “A” and “B” represent low-wind areas. Elongated areas covered by oil film are present on the sea surface near the oil-producing platform resulting in significant attenuation of short gravity-capillary waves and formation of slicks (marked by “C”). The interpretation of the area “D” where the sea surface is smooth can lead generally speaking, to ambiguous results.

Figure 3. a) A part of a VV-polarized Sentinel-1 SAR image of 27 March 2019, 14:37 UTC, showing oil patches near the oil platform. Total area of the oil slick is 375 km²; b) a part of a VV-polarized Sentinel-1 SAR image of 01 July 2019, 14:37 UTC, showing the sea surface near the oil platform; c) a part of a VV-polarized Sentinel-1 SAR image of 14 January 2019, 14:37 UTC, obtained at low wind.

For the study, we examined all Sentinel-1A and 1-B images of the Caspian Sea over the «Oil Rocks» area for the year 2019 obtained to the data of this paper writing (August 2019). It was found that 65% of radar images taken over the oil-producing area “Oil Rocks” bore signatures of oil patches near the oil platforms. No slicks were found in the remaining images because high/low winds prevented them from being detected. These results were compared with those based on ASAR Envisat imagery for the period from January 2010 to December 2011 and on Sentinel-1 SAR imagery taken from October 2014 to June 2015 (Mityagina, Lavrova, 2015). It was found that 69.3% of radar images of the test area contained signatures of oil patches near the oil rigs. No slick structures were seen in the remaining images because high/low winds prevented them from being detected by SAR. The corresponding statistics are shown in Fig. 4.

Figure 4. Statistics on the frequency of detection of oil patches in the “Oil Rocks” oil producing area in SAR images in dependence on near-surface winds.
Oil pollution due to natural hydrocarbon showings from the seabed. Two regions of the Caspian Sea attracted our attention because the slick patterns remarkably different in structure from ship spills, widespread slicks of biological origin, and vast slicks around the “Oil Rocks” area were regularly observed there during our satellite survey. These regions are: (i) the part of the Caspian Sea westward of Cheleken Peninsula which belongs administratively to Turkmenistan, and (ii) the part of the Caspian Sea off the southwestern coast in the Gilan Province of Iran eastward of the Sefid Rud Cape.

The principal feature of the slicks under discussion is their fixed link to specific geographical locations. In both areas, we detected many slicks with distinctive active emission points. The recurrence of slicks in the same place is considered as the main criterion of their belongings to the class of natural oil slicks (MacDonald, 1998, Mityagina and Lavrova, 2016) due to natural hydrocarbon seeps at the seafloor. Seafloor hydrocarbon seeps are sites of natural leakages of hydrocarbons in liquid and gaseous forms. These leakages are fed by underground deposits of oil and gas. Faults or fractures in the seabed provide natural pathways through which gas bubbles coated with oil are released into the water column.

Surface manifestations of oily slicks from hydrocarbon seepages at the seafloor are easily recognizable in satellite images. As a rule, oil leaks from a vent or a group of vents on the seabed and reaches the surface not far from the underlying source point. We can say that the persistent occurrence of slicks emanating from a stable emission point serves as an indicator of a natural seep located on the seafloor. Oil slicks from a natural seep appear in satellite images as elongated strips that look as “foreign bodies” in the background of the overall structure of an image and evolve under the influence of currents and local winds. Natural oil slick includes oil near the emersion point that has newly arrived at the surface and oil at the opposite end of the slick, and the most substantial oil film thickness is present at the point of emersion. Examples of manifestation of surface oil slicks from natural seepages on the seafloor in satellite images are depicted in Figs. 5-6. The seeps under discussion are active sources of hydrocarbons. Emissions are frequently observed, which can serve as evidence of intensive geological and geophysical processes in the modern system of accumulation and migration of hydrocarbons of the Caspian Sea. We present below fragments of SAR images taken in different years to stress the persistence of the phenomena observed. Asterisks mark the oil slicks origin location.

Figure 5. Examples of the manifestations of oil slicks from a natural seep on the seafloor in the Cheleken area in satellite images. Parts of SAR-C Sentinel-1A images: a) September 16, 2017, 14:28 UTC; b) July 25, 2018, 14:28 UTC; c) June 8, 2019, 02:36 UTC. Parts of OLI-TIRS Landsat-8 images (color composites of 4, 2 and 1 spectral channels): d) June 28, 2013, 07:09 UTC; e) June 15, 2014, 07:07 UTC; August 14, 2016, 07:13 UTC.
Figs. 5a, 5b, 5c and 6a, 6b, 6c show examples of radar signatures of oil slicks typical for the continental slope off the Cheleken Peninsula and off the Iranian coast correspondently. On the sea surface, slicks are shaped by winds and currents.

Figs. 5d, 5e, 5f and 6d, 6e, 6f show color composites derived from data taken in VIS bands in a sun glint area. We see bright bands surrounded by a dark halo that broadens with film spreading.

**Figure 5**. Examples of the manifestations of oil slicks from natural seeps on the seafloor in the Sefid Rud Cape area in satellite images. Parts of SAR-C Sentinel-1A images: a) February 16, 2015, 14:36 UTC; b) August 9, 2016, 14:36 UTC; c) October 27, 2017, 14:36 UTC. Parts of MSI Sentinel-2A images (color composites of 4, 3 and 2 spectral channels): d) September 14, 2015, 07:39 UTC; e) May 28, 2016, 07:29 UTC; f) June 25, 2019, 07:38 UTC.

In the case of Turkmenistan shelf, the site of seep source is located in the oil-producing area and is surrounded by oil-drilling platforms seen in the satellite data as bright dots. Nevertheless, the source of these oil slicks is a natural seep on the sea bottom tied to the oil-bearing structure. It is possible, however, that the active oil-producing in the area can affect the frequency and intensity of oil emission from the source on the seafloor. Over the past years, the daily oil production at the Cheleken area increased from about seven thousand barrels per day up to one hundred thousand barrels per day. More than one hundred new wells have been drilled here (Caspian Barrel, 2018).

Analyzing the slicks locations in satellite images taken over the Sefid Rud Cape region, we associated the slick patterns with the two closely located vents. A common feature characteristic of natural oil showings in this area can be seen in satellite radar and VIS images, namely, the striped pattern of the slicks. At both emersion points, two or more distinct slick bands can be observed because both seep vents have more than one channel through which oil can migrate from the seafloor to the surface. The southern vent appears to be less intensive, than the northern one, because releases are observed with lesser frequencies and have lower volumes.

The estimation of the location of the oil seeps from natural oil slicks detected in satellite images requires the availability of a large dataset of satellite data. New satellite data obtained this year were analyzed jointly with the previous years’ data. Satellite images were analyzed to detect structures belonging to the natural oil slick class. The slicks extracted from satellite data were incorporated into the map, which allowed us to locate the seep sources on the Turkmenian shelf off the Cheleken Peninsula and on the Iranian shelf near the Sefid Rud Cape. The seep on the seafloor in the Cheleken area was documented as the persistent location of origins of 254 oil slicks detected in satellite images taken over the region of interest in
years 2009-2019. Our results indicate that the point with coordinates 52°36.2’E, 39°32.9’N appeared a “source” of the natural oil slicks origin. This point can be recognized as a point of location of an offshore seep at the seafloor at a depth about 1000 m. A cumulative map of the sea surface pollution by natural oil films in the region off the Cheleken Peninsula is presented in Fig. 7a. The area exposed to potential oil pollution due to natural hydrocarbon showings from the seafloor is about 260 km².

In the case of Iranian shelf, two seeps located close to each other on the sea bottom are documented as the persistent location of origins of 173 and 198 oil slicks correspondently. The points with coordinates 50°24.4’E, 37°23.4’N and 50°28.9’E, 37°20.4’N are points of location of offshore seeps at the seafloor. A map of sea surface pollution by natural surface oil slicks in the continental shelf area off the Sefid Rid Cape is shown in Fig. 7b. High risk of the sea surface pollution due to natural hydrocarbon showings from the seafloor is attributed to the area of 620 km². The aquatic area near the Sefid Rud Cape (the Sefidrud River Delta) is an important feeding and spawning site for numerous species of fish, including some endangered sturgeon species. It serves as a refuge for more than 100 thousand waterfowl and is an important area of migration and wintering for numerous migratory waterfowl species. This is why the critical need exists in the regular satellite monitoring of the surface oil pollution in this area.

![Consolidated maps of oil slicks due to natural seepages on the seafloor revealed from SAR imagery: a) in the Cheleken area; b) in the Sefid Rud Cape area.](image)

**Figure 7.** Consolidated maps of oil slicks due to natural seepages on the seafloor revealed from SAR imagery: a) in the Cheleken area; b) in the Sefid Rud Cape area.

**Oil pollution in the Southern Caspian due to offshore mud volcanoes activity.** More than one thousand mud volcanoes are known to exist all over the world, and they can be found onshore and offshore. Nevertheless, their largest concentration is in the Caspian region, and more than 160 mud volcanoes are located on the Southern Caspian Sea bottom. Mud volcanoes differ from magmatic volcanoes on activity area astonish by their beauty, but their direct connection with oil and gas system attracts the most significant attention for study (Guliyev and Feizullayev, 1997). The size of mud volcanoes is generally smaller than that of magmatic volcanoes, but varies over a wide range, from tens of centimeters to several hundred meters in height and tens of kilometers in diameter (Kopf, 2002; Dimitrov, 2002; Mazzini and Etiope, 2017). Among fluid venting structures, mud volcanoes are the most important phenomena related to natural seepages from the Earth's surface (Mazurenk and Soloviev, 2003).

Mud volcanoes can serve as indicators of underground oil and gas deposits. Big oil and oil-gas-condensate fields exist in the Southern Caspian Basin. Natural hydrocarbon showings in the form of mud volcanoes appear here in abundance. The maximum number of mud volcanoes and most of the biggest ones are concentrated at the north-western edge of the South-Caspian Depression. The majority of the South-Caspian Depression mud volcanoes are in the seepage stage of the evolution discharging the mud, hot water, rock fragments, gas, and oil. These products form the specific surface manifestations, which can be identified on satellite images. Some characteristic examples of satellite signatures of surface oil pollution due to seabed mud volcano activities in the south-western part of the Caspian Sea are shown in Fig. 8. The total areas of oil manifestations caused by mud volcanic activity, identified in a single satellite image, vary from several tens to one hundred and fifty square kilometers.
It is clear that surface manifestations of oil slicks due to seabed mud volcanoes activity drastically differ from any other, either ship spills or natural hydrocarbon seeps described in this paper above. Numerous ring, crescent, and spiral structures are seen in satellite images. These structures are formed by products discharged by mud volcanoes on the seafloor and are evidence of presently ongoing fluid release.

The fluid dynamics of mud volcanoes affect the Caspian Sea ecology sufficiently. The problem of the estimation and prediction of sea surface pollution during the mud volcanoes eruptions and their "quietness" is of great importance. The pieces of evidence exist that mud volcanic activity in the Southern Caspian Basin is related to seismic and solar activity, and maybe even to moon phases. The ability to test these hypotheses based on remote sensing data would be a big step forward. Long-time series of satellite data taken over the Southern Caspian Basin should be collected and analyzed jointly with seismological and geophysical data.

Oil pollution due to ship spillages. The anthropogenic pollution caused by oil-containing wastewater discharges from ships is also detected in satellite images of the Caspian Sea surface. The Caspian Sea carries heavy marine traffic (Marine Vessel Traffic, 2019). The shipping activities, including oil transport and oil, handled at ports and terminals, have many negative impacts on the marine environment. Routine activities on ships often cause oil contamination of the sea surface. Ship-related operational discharges of oil include discharge of bilge water from machinery spaces; operational discharges of oil from machinery spaces to the sea; discharge of tank-washing residues and oily ballast water. Spillages of oil-containing waters cause all these events from moving ships. The satellite data analysis showed that the concentration of spots delineates the main navigable routes. As one might expect, discharges from ships are concentrated along the main routes of the oil transportation in the Caspian Sea in the directions of Aktau–Makhachkala, Aktau–Baku, Aktau–Turkmenbashi, and Aktau–Neka.

When the release of oil is done from a moving ship, an oil slick in the absence of strong wind and waves is displayed on a radar image in the form of a narrow band of a lower signal, repeating the route of the ship. If release occurs during radar imaging or occurred just before it, the band is narrowing toward the ship, and, as a rule, it is possible to identify the ship-culprit, which looks like a bright white dot on the radar image. Ships may discharge oil for several tens of kilometers of their way, i.e., during several hours. Ship discharges along the main shipping routes are numerous and differ in size. The most massive spills are detected on the approach routes to the Caspian ports of Russia and Kazakhstan. The areas of individual spills detected in satellite images are usually less than 10 km². We can confirm that for now ship discharges in the Caspian Sea are less frequent and have smaller areas than, for example, in the Black Sea. As opposed to what was observed in other enclosed seas (Kostianoy and Lavrova, 2014; Lavrova and Mityagina, 2013; Kostianoy et al, 2006; Carpenter and Kostianoy, 2018a,b), illegal discharges in the Caspian Sea are not the primary source of sea surface film pollution, although unfortunately, their amount grows year-to-year. In recent years, the intensity of shipping has increased dramatically in the Caspian Sea due both to the rapid development of oil fields and to the fact that the Caspian Sea became part of the south-north transport corridor (the marine part of the route from southern Asia through Iran to the port of Astrakhan passes through it). Currently, tankers in the Caspian Sea transport more than 15 million tons of oil annually and
make more than 3000 passages. Such heavy traffic, especially in the conditions of severe winter storms and poor technical condition of vessels, significantly increases the likelihood of oil spillages.

A good illustration is the case of the major oil pollution detected on 7 June 2019 in the northern part of the sea is depicted in Fig. 9.

Figure 9. Fresh oil spill from a moving vessel seen in SAR imagery of the Caspian Sea. SAR Sentinel-1A, 7 June 2019, 14:38 UTC. Length of oil spill - 89 km.

In the radar image, a distinct black band of a decreased radar signal is seen. This is an example of “ideal” fresh discharge by a moving ship. The radar image was acquired in conditions of moderate wind and small waves. The dark band depicting the spillage becomes narrower to the south-east, which indicates that the ship - culprit discharged wastewaters moves in this direction. Bright white dot in the south-eastern end of the stripe demonstrates the present locations of the ship. The length of the detected oil slick is 89 km. This is the longest ship spillage we registered over ten years of our satellite survey of the Caspian Sea.

Oil pollution in offshore oil-producing areas. Azerbaijan became the first country, which began to exploit the offshore deposits of oil and gas. Now, Russia, Kazakhstan, and Turkmenistan are also developing offshore oil fields in the north-western, north-eastern and eastern parts of the Caspian Sea correspondingly. Only Iran has not yet exploited oil deposits in the Caspian Sea.

This year, only several single oil slicks of the small area were detected in the Cheleken oil production area, owned by Turkmenistan. These slicks were located near the shipping routes and occurred most likely during the oil overload.

No films of crude oil were detected in satellite data taken over the northern part of the Caspian Sea, where a current production of oil takes place. Nevertheless, the growing rate of oil production and transportation as well as the development of new oil fields, especially on the shelf lead to an increase in the probability of oil pollution despite new technologies (zero recovery, plans for the prevention and elimination of emergency oil and oil products etc.) and all the measures taken. One should be conscious on the fact that the specific and particular features of the Caspian, especially its shallow northern part, are such that one serious oil spill is enough to inflict a fatal blow on sturgeon flocks and bird nests. In general, oil pollution can be associated with any operations for the extraction and transportation of oil, its scale can be either minor or catastrophic.

Unfortunately, accidents regularly occur on the oil-producing sites in the Caspian Sea, the details of which are not always known to the public (Zhiltsov et al., 2016). In this regard, it is necessary to note the role of satellite remote sensing, which allows for continuous monitoring of areas of accidents and for revealing aftereffects. For example, an intense fire occurred on December 4, 2015, on the offshore stationary platform in the Azerbaijani part of the Caspian Sea at the Guneshli field. The fire was caused by a rupture of a high-pressure gas pipeline due to storm conditions which lead to depressurization of the oil well.
In the satellite true-color image (Fig. 10a) taken over the area of interest on December 8, 2015, the plume of smoke from the burning platform is seen. The smoke can be traced to the center of the Southern Caspian throughout almost 170 km. The burning lasted 13 days till December 17, 2015. Oil pollution in the adjacent water area was observed in SAR images as an aftereffect of the fire (Fig. 10b).

Figure 10. Manifestations of the fire aftereffects in satellite images: a) the smoke plume from a burning platform. A part of a color composite (R: 620-670 nm, G: 545-55 nm, B: 459-479 nm) MODIS Aqua image of 8 December 2015, 09:00 UTC; b) sea surface oil pollution caused by the accident at the platform. A part of SAR Sentinel-1A image of 13 December 2015, 14:37 UTC. The area of oil pollution due to the accident is 263 km².

Discussion

The results of our satellite monitoring have made it possible to retrieve the persistent pattern of the Caspian Sea surface oil pollution. This pattern is determined by the ways through which petroleum enters the aquatic area of the Caspian Sea. The main elements of this pattern are depicted in Fig.11. Regions of regular occurrence of specific types of oil pollution are outlined where continuous satellite monitoring should be implemented. The Absheron Sill and the Baku Archipelago - natural leakages of liquid hydrocarbons fed by underground deposits occurs here. According to modern concepts, the contemporary process of oil and gas formation occurs in the Absheron Sill area.

1. The western part of the Southern Caspian - a large number of mud volcanoes is located on the seabed here. According to published data (Zonn et al., 2010), millions of tons of oil and billions of cubic meters of gas are emitted annually through the mouths of mud volcanoes into the waters of the Caspian Sea. Natural hydrocarbons are partially dispersed in seawater, partially evaporated into the atmosphere.
2. Natural hydrocarbon seafloor seeps off the south-western coast in the Gilan Province of Iran eastward of the Sefid Rud Cape.
3. Natural hydrocarbon seafloor seeps westward of Cheleken Peninsula which belongs administratively to Turkmenistan.
4. The south-eastern shelf - There is a risk of oil pollution in case of accidents on offshore oil-producing platforms of Turkmenistan and underwater oil pipelines.
5. The north-eastern shelf - There is a risk of oil pollution in case of accidents on offshore oil-producing platforms of Kazakhstan and underwater oil pipelines.
6. The north-western shelf - There is a risk of oil pollution in case of accidents on offshore oil-producing platforms of Russia and underwater oil pipelines.
7. Ship discharges along main shipping routes. The bulk of international oil shipments is carried out by oil tankers. Each of the Caspian countries makes efforts to create and develop its tanker fleet and port infrastructure. Most of the oil is transported through the seaport of Aktau (Kazakhstan) to the Port of Baku (Azerbaijan) and the Port of Makhachkala (Russia). It is planned to expand tanker shipments of oil from the eastern coast of the Caspian Sea (Kashagan oil field) to the west to the Baku-Tbilisi-Ceyhan oil pipeline within the framework of the projected Kazakhstan Caspian Transportation System (Zhiltsov et al., 2016).

The monitoring of sea surface oil pollution by conventional in situ sensors is not efficient. At the same time, remote sensing of the Caspian Sea shows that pollution of the sea with oil products can be detected in almost every radar image. Benefits from satellite remote sensing for the Caspian Sea are
undeniable. Data from satellite sensors have the unique capability of collecting data over the whole aquatic area of the Caspian Sea. The continuous use of these data allows to assess the relative contribution of each of the oil pollution sources of the Caspian Sea and reveal main ecological risks caused by sea surface oil pollution.

**Figure 11.** Main pattern and sources of sea surface oil pollution of the Caspian sea, revealed on the basis of satellite remote sensing data: 1 – Natural leakages of liquid hydrocarbons; 2 – Seabed mud volcanoes; 3 – Natural hydrocarbon seafloor seeps off the Sefid Rud Cape; 4 – Natural hydrocarbon seafloor seeps westward of Cheleken Peninsula; 5 – offshore oil-producing platforms in the Cheleken oil field; 6 – Kashagan oil field; 7 – LUKOIL oil-producing area. Main shipping routes depicted by green lines.

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