

Mapping of Oil Slicks in the Adriatic Sea: Croatia Case Study



Mira Morović, Andrei Ivanov, and Marinko Oluić

Abstract Spaceborne synthetic aperture radars (SAR) are used as major instruments for operational oil spill detection and monitoring, and for this reason attract significant research interest. A large number of SAR images acquired and collected over the Adriatic Sea provided high number of oil slicks to be analysed. These slicks may come from different sources, from natural to anthropogenic, accidental or deliberate. Given are examples of oil slicks detected on the images of the Envisat and Radarsat-1 satellites in the period 2003–2016. The SAR images were obtained mainly through research projects from ESA and other sources. The images were processed via ESA software and integrated using Geo-Mixer by SCANEX RDC (www.scanex.ru). We presented and discussed the most pronounced causes of oil pollution, their sizes, shapes and prevailing locations in the Adriatic Sea as well as oil spill distribution maps. Main sources are considered to be due to routine tank washing operations and illegal discharges. The Adriatic Sea is a small semi-enclosed sea, and oil spill accidents could have far reaching consequences for the encompassing countries. Because of the general regime of circulation and its variability the coast of Croatia is highly vulnerable. Presented are also geographical and geological features and physical properties of the Adriatic Sea, particularly those relevant for transport and dispersions of oil pollution. Discussed are possible threats to the Croatian coastal communities, regarding increased transport in the Adriatic and new investigation and exploration, some of which is about to be

M. Morović (✉)

Institute of Oceanography and Fisheries, PP. 500, 21000 Split, Croatia
e-mail: morovic@izor.hr

A. Ivanov

P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences, Nakhimovsky prospect 36, Moscow 117997, Russia

M. Oluić

Geo-sat, Poljana B. Hanžekovića 31, 10000 Zagreb, Croatia

executed in the Southern and Middle Adriatic, and some are already going on in the west coast.

Keywords Adriatic Sea, Circulation regime, Environmental impact, Marine oil pollution, SAR images, Satellite monitoring

Contents

| | | |
|---|---|-----|
| 1 | Geographical Settings of the Adriatic Sea | 160 |
| 2 | Physical Properties of the Adriatic Sea Important for Dispersion of Oil Pollution | 161 |
| 3 | Causes of Oil Slicks and Look-Alike Signatures | 163 |
| 4 | Available Data and Methods | 164 |
| 5 | Requirements in Support of Operational Monitoring System | 165 |
| 6 | The Concerns of Croatian Coastal Population | 166 |
| 7 | SAR Image Analysis for Oil Spills | 169 |
| 8 | Conclusions | 176 |
| | References | 177 |

1 Geographical Settings of the Adriatic Sea

The Adriatic Sea is a small semi-enclosed sea covering 138,595 km², situated in the Northern edge of the European Mediterranean. Adriatic Basin is surrounded by mountain chains Dinarids–Albanids, Alps and Apennines. Its longer axis is about 800 km and it is up to 200 km wide. It is a relatively shallow marine basin (Fig. 1) with average depth of about 173 m and reaches depths below 1,230 m. Two thirds (2/3) of the Adriatic Sea area is less than 200 m deep, e.g. most of the Adriatic Sea located in shelf area. Usually it is divided into Northern, Middle and Southern parts. The Northern Adriatic is very shallow, reaching 100 m depth and extending to Zadar–Ancona line, from where it extends to the 170 m deep Palagruža Sill. The Middle Adriatic encompasses the 270 m deep Jabuka Pit. The South Adriatic extends over the South Adriatic Pit, 1,267 m deep, to a narrow Otranto Strait, 780 m deep, its connection to the Ionian Sea and the greater Mediterranean. The turnover time for the Adriatic water mass (35,000 km³) is estimated from 1 to 5 years [1, 2] but is usually considered 3.3 years [3]. The west coast is rather smooth contrary to the east coast, being very fractal, containing thousands islands, particularly in the Croatian waters.

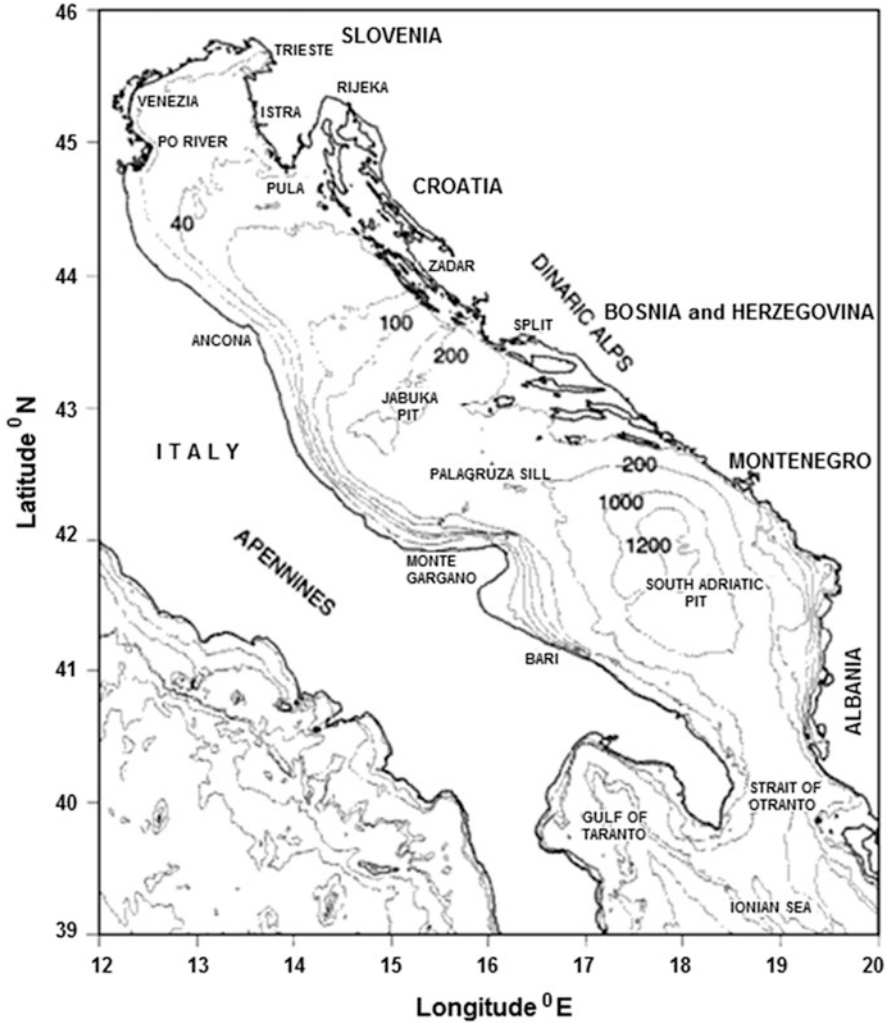


Fig. 1 The Adriatic Sea, coastal features, settlement and bathymetry. *Source:* GEBCO Free Map Data

2 Physical Properties of the Adriatic Sea Important for Dispersion of Oil Pollution

The geographical settlement of the Adriatic Sea is in the zone known for high seasonal mesoscale atmospheric disturbances, governed by solar forcing. In the atmosphere this results in high variability of wind, precipitation and temperature and the response in the sea is high variability of salinity, temperature and currents.

The Adriatic circulation at the surface is generally cyclonic [4, 5], characterized by northwest directed current along the East coast and West Adriatic Current

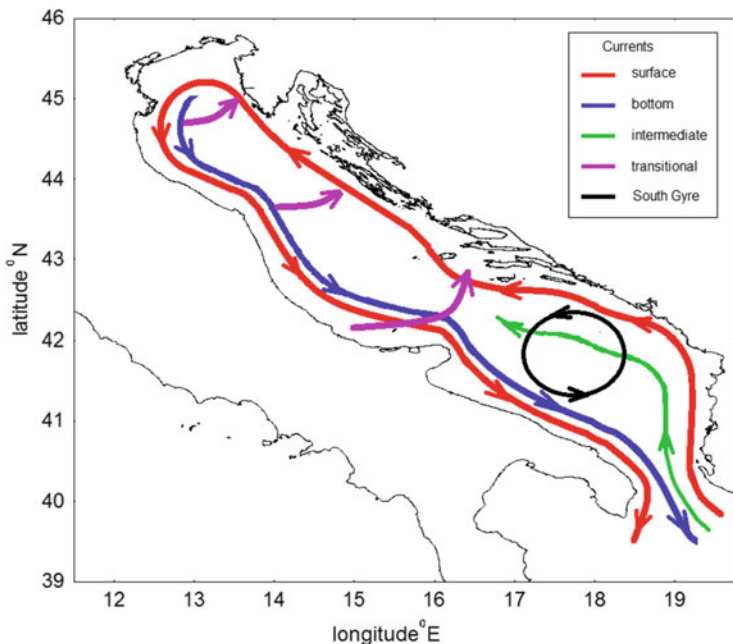


Fig. 2 Main features of the Adriatic general circulation and potential pathways of transitional currents. *Source:* Author's own map

(WAC), flowing southward along the West coast (Fig. 2). Such circulation is a consequence of freshwater input, from Northern Adriatic Rivers, especially the Po River, and of cooling of water in the north Adriatic during winter period. The circulation and winds alternate between winter and summer regimes [6]. Winter cooling is forced by outbursts of cold and dry bora wind which cause water density increase forming North Adriatic deep water (NAdDW). In such periods the South Adriatic deep water (SAdDW) is also formed. NAdDW flows southward along the west coast filling the Jabuka Pit. In harsh winters, when considerable quantity of deep water is formed, it flows further to the south and joins the SAdDW on the way through the Otranto Strait, where both exit the Adriatic Sea in deep layers. This exiting flow of water is compensated by incoming warmer and saltier Mediterranean water from the surface to the intermediate layer.

This process basically drives the Adriatic Sea thermohaline cyclonic circulation but is variable due to stronger or weaker intrusions of Mediterranean waters into the Adriatic [7, 8] and more or less efficient formation of NAdDW. The variability of this processes ranges from annual to decadal scale, depending on climate conditions on a scale larger than the Mediterranean and is also associated with bimodal Adriatic–Ionian oscillation [9, 10]. Generally, warm winters weaken the water exchange and the circulation between the Adriatic and the Mediterranean basin.

In addition to the cyclonic circulation oscillations, which govern the rate of basins exchange, there occur short term phenomena at the scales from days to

weeks, provoked by strong synoptic disturbances which can locally overturn the circulation pattern. Both, strong sirocco and bora winds could force the WAC to change direction and flow towards Croatian coast. This phenomenon is observed in the Adriatic through several investigations detecting directly deviation of currents [11] or salinity decrease at the east coast [12, 13]. These transitional currents occur particularly at the Palagruža Sill and off Ancona.

The frames of the Adriatic Sea vertical dynamic and surface circulation are generally as presented here. However, spreading of potential spills at the sea surface, their dispersion and mixing through the water column largely depend on a number of factors. These are actual local thermohaline conditions, depending on seasons, winds, local currents, tides, free and inertial oscillations that all generate conditions of currents and mixing at shorter time scales.

In the Northern Adriatic, the bora winds force currents towards Italy, but local compensation currents can occur due to differences in topography at the East coast, and the flow from Italian side can reach the coast of Istra Peninsula. The tides can cause very strong variations of currents particularly in the Northern Adriatic [14]. As a result of wind and pressure variability, free oscillations (seiches) can cause strong currents [15]. The phenomenon of resonant energy transfer (meteorological tsunami), when occur, may locally produce flood and strong currents [16].

Taking into account the general circulation, we can suppose that most of the spills which would occur in the Southern Adriatic, closer to the Albania and Montenegro coasts would end to the Croatian coast, and especially at the Croatian South Adriatic islands. This statement is supported by findings of a lot of sewage (accidentally dumped from Albania) found at the Mljet Island, not in one isolated accident.

The Middle Adriatic is potentially endangered from accidents that could occur on the Italian side, or along the main transport routes in the Central Adriatic, since the conditions may evolve to turn the WAC to the east towards the Island Vis or Lastovo.

3 Causes of Oil Slicks and Look-Alike Signatures

As proven by many investigations, detection of oil spills/slicks on synthetic aperture radar (SAR) images is often a problem [17] due to appearance of similar signatures on the sea surface, because certain wind conditions [18] must be fulfilled that allow detection of oil spills. At low wind speed < 2 m/s the scattering radar signal at the sea surface is extremely low, the required contrast is insufficient and the oil slicks are not detectable by SAR. The minimum wind speed of 2–3 m/s allows creation of sufficient roughness on the sea surface and, in turn, backscatter and brightness on the SAR images. As established by [18] optimal wind speed is between 3 and 6 m/s, but oil spills may still be visible at wind speed up to 10–12 m/s [19, 20], while the wind above 12 m/s makes the spills to disappear from the sea surface due to oil film breaking and water mixing.

False observations (and false alarms) may come from hydrodynamic phenomena like current shears, upwelling zones, internal waves and even sea surface temperature variations, which can create a number of ‘thermo-hydrodynamic’ slicks on the sea surface. Manifestations of meteorological phenomena in the lower atmosphere may be also mistaken for slicks, these are calm zones, wind shadows, rain cells, atmospheric gravity waves, etc. Marine biota can create biogenic slicks due to activity of plankton and fishes, algal blooms, floating seaweeds, sperm and eggs of marine animals. Also there may be manifestations of oil seeps of natural origin leaking from the underwater oil deposits, usually triggered by a local seismicity. Existing methods of discovering oil leaks tend to rely on SAR that can detect bottom sources through multi-temporal oil slicks floating on the sea surface [21].

Besides these, a ship-made turbulent wake can give impression of a spill and sometimes even shallow bottom topography in tidal seas. The list of potential look-alikes is not complete yet and experienced expertise is needed to distinguish between real oil spills and look-alikes.

Oil slicks occur on the sea surface in different forms and dimensions, depending on the amount of oil, the strength of winds and currents, and the time passed from a discharge. They could be linear or amorphous, sometimes perturbed with feathered edges or totally diffused. Fresh and old differs as well as the spills caused by different oil products and fractions.

4 Available Data and Methods

The large ESA archive of Envisat SAR images was available for inspection in the frame of the ESA research project #19234. The area of interest was the open sea of the Middle and Southern Adriatic. First, the image quick-looks were examined through the EOLISA on-line catalogue for the period 2003–2010, and the SAR images with pronounced oil spills were ordered from ESA for further analysis. The raster images were imported to the NEST program, processed (geo-referenced) with the NEST ESA SAR ToolBox to geographical grid and exported to geotiff format. Each image was in details analysed with purpose to determine oil slicks and enlarged to get clear view of a particular slick. After analysing the images visually, the properties like size, shape and contrast were considered. The wind conditions during the image acquisitions were also taken into account. SAR images with inappropriate wind conditions (too strong or very low wind) were excluded from analysis. Wind data (10 min averaged wind speed, direction and gust data) were obtained from the State Hydrometeorological Office in Zagreb (for details, see [22]). Also the wind data were available from several weather stations in the Adriatic islands. For more comprehensive analysis we also used Radarsat-1 SAR images acquired in 2011 in the framework of the pilot project with Russian collaborators. Two Sentinel-1A SAR images from 2016 were also used.

After that, all images were imported to the GeoMixer tool (<http://geomixer.ru>). GeoMixer is a GIS technique, on-line API application and interactive tool for storage, integration, visualization, interactive analysis and publishing of satellite

images, other remote sensing and geophysical data and results of analysis using the on-line GIS tool. In it, it is also possible to integrate SAR images with other geospatial data about oceanography, meteorology, bathymetry, offshore oil-and-gas infrastructure, digital nautical charts, marine boundaries, ship lines and other useful information. In the Scanex software the tools are developed to automatically calculate number of detected slicks and determine the areas they cover, which was also utilized in this analysis.

Collection as many data and information about marine basin as possible in such an application allows proper identification of oil spills and discrimination of them from look-alikes, with a very high confidence level, although there may be uncertainties in oil spill identification on SAR images without additional airborne survey or in situ sampling. The SAR images also enable ship detection, as ships appear as small bright spots, and wind speed retrieval using CMOD-type model.

5 Requirements in Support of Operational Monitoring System

Due to fractal coastal geography and a thousand islands the Croatian coast is quite difficult to 'defend' from potential spills. In the present situation with SAR satellite sensors, the protection system cannot be based on real time satellite data.

A well-prepared meteorological and oceanographic system is needed to control and prevent harmful consequences of eventual oil spill accidents. All the mentioned oceanographic processes could be predicted, if the system of adequate monitoring existed. This should include availability of real time satellite data that can provide information about spills. Also meteorological and oceanographic forecasts are needed.

Croatia Hydrometeorological Office (in Zagreb with the branches in Split and Rijeka) is in charge for meteorological measurements and weather forecast and also for weather alarm, including the weather at the sea. Oceanographic measurements are organized mainly through several scientific institutes (in Split, Rovinj, Zagreb and Dubrovnik). These institutes possess the state-of-the-art oceanographic equipment, vessels, buoys and a few coastal stations, most of it operational. However, in Croatia oceanography does not provide a continuous service, neither an operational model (the exception is the State Hydrographic Institute that provides on-line tidal measurements and publishes forecast for astronomical tides). However, the scientists from these institutes are proficient in oceanographic measurements and were experienced in numerical hydrodynamic modelling through several recent projects. Numeric model under the project ADRICOSM (2001–2005) enabled forecasts of short term changes in the circulation of the Adriatic Sea and in the coastal area of the Central Adriatic [23]. Recent modelling simulations on the scale of the Adriatic have been carried within the two phases of the Adriatic Project [24] and numerical simulations have been carried out for a period of 1 year. The results of these studies are available, and can serve for environmental studies and estimates of anthropogenic influence to the marine environment. The mentioned activities and studies of

water dynamics in the Adriatic Sea in which the numerical models have an important role show the potential of the numerical methods for assessing and forecasting the state of the marine environment during the planned exploration and exploitation of hydrocarbons as well.

At the moment in Croatia there is an initiative to connect the activities of oceanography and meteorology and produces coupled oceanographic meteorological model and forecast.

In order to protect very long shoreline, there were activities with intention to lower the damage, if the oil spill accidents occur. In the year 2009 the project took place that has defined the so-called the places of refuge [25, 26] where a leaking ship could eventually hide, to prevent larger damage. These places have been determined considering the position of a ship and supposed trajectory of a spill regarding the meteorological and oceanographic conditions. The estimates for the best places of refuge were based on modelling simulations for prevailing winds.

Recently one of the results of a MONGOOS initiative and through the Copernicus project, presented is oceanographic service [27] that provides oceanographic forecast for various users, from citizens to companies, and such a service can also be used in case of accidents. It is based on model, and a number of fields from satellite data including air and sea temperature and winds.

Although the effort of ESA is huge, to provide SAR images, we are missing an organized service to collect and make available these images at the national level.

6 The Concerns of Croatian Coastal Population

About a million people inhabit the Croatian coast and islands, having on the average half income per capita than the capital city. The economy of this population is directly oriented to the sea and its resources. The main economy branches in the coastal area are tourism, fisheries, aquaculture, shipping, transport, marinas, etc. The tourism is considerably gaining importance lately.

The fear of domestic population from possibility of oil or other large marine accidents is not irrational. There are dozen tankers and other cargo ships travelling along the Adriatic Sea every day from the Otranto to the Northern Adriatic ports. It is estimated that in the Adriatic transported are many million tons of oil per year [28]. Due to ever increasing demands for fuel, such transport has increasing trend.

The transport of passenger ships is especially frequent in warm season and daily several times operate between the coast and islands. Between east and west coasts from May to October on the routes on lines Pula–Venezia, Zadar–Ancona, Split–Ancona, Dubrovnik–Bari, Bar–Bari and Durres–Bari the ships operate several times during a week. The lines between Italian ports Venice, Ancona and Bari to Greek ports of Patras and Igoumenitsa are also intensified in touristic season. Large number of fishing ships, crossing the main transport routes, work in fishing areas. Tankers and cargo ship transport routes concentrate along the long axis of the Adriatic Sea, while fishing areas are dispersed both in the coastal and open sea (Fig. 3).

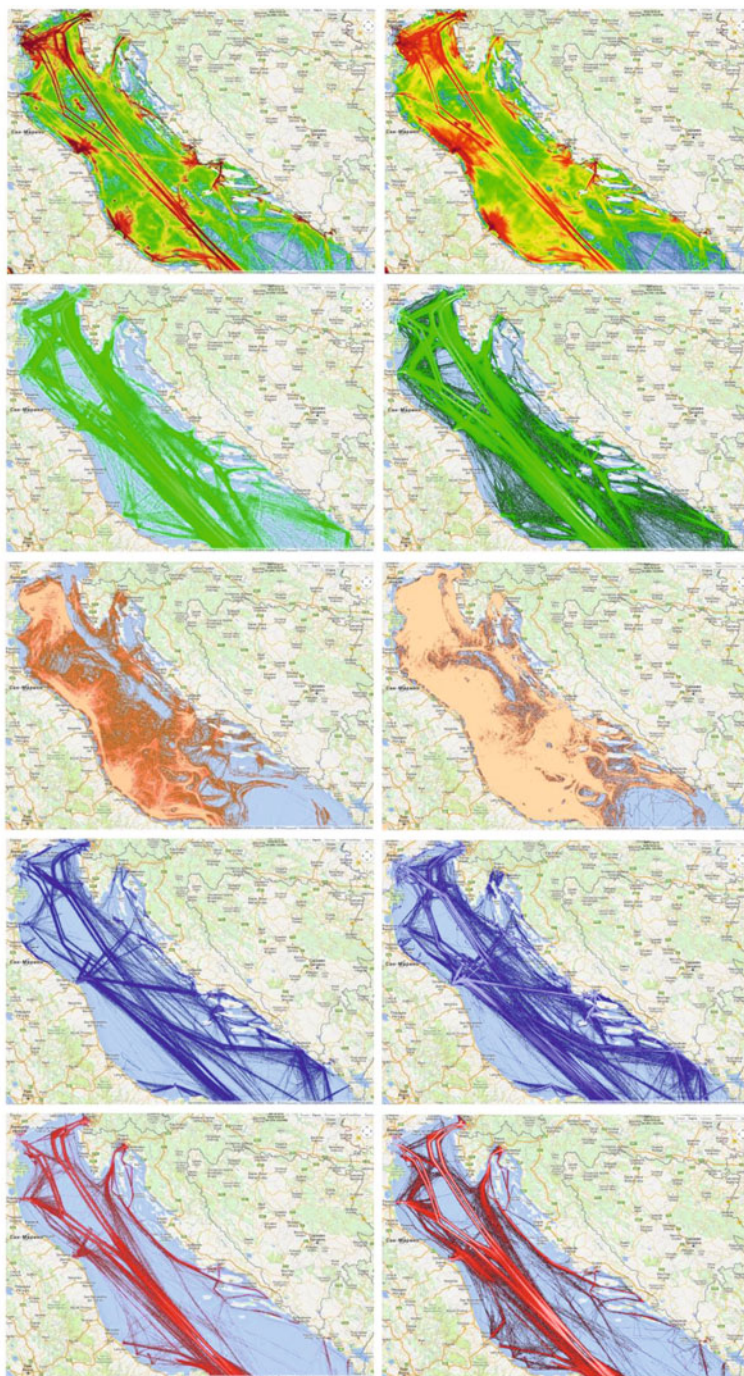


Fig. 3 Density of ship traffic in the Adriatic Sea in 2013 (*left*) and in 2014 (*right*). The all traffic intensity (*first row*) is represented by colour, the most intensive by *red–yellow*, clearly marking the ship routes. Separately the traffic of tankers (*second row*), cargo ships (*third row*), fishing

Although not very large, but there were a few accidents in the Adriatic Sea like *Brigitta Montanari* near Šibenik in 1984, *Val Rosandra* in Brindisi in 1990, *Alessandro Primo* near Molfetta in 1991 [29] and *Und Adriyatik* Turkish-flagged cargo ship in 2008 in the Northern Adriatic. The probability of accidents increase with increasing traffic, and this is a fact in the Adriatic. Increased is not only transport of oil, but also transport in general, which is directly linked to the risk of oil and other pollution.

In the west coast there are about thirty active oil rigs in Elsa, Elsa West, Rospo mare, Ombrina mare, situated off Ancona and further southward. There are also several prospective fields like Tremiti and Pianosa in the Middle Adriatic to be exploited in the future. In the open sea of the South Adriatic, towards the west coast, there are several active oil rigs.

Now, other three nations (Albania, Montenegro and Croatia) are preparing to drill for oil in the Southern and Middle Adriatic. If new oil deposits would be found, this will pose additional risk of oil spill accidents. The consequences of these would be unforeseen for the national economy of Croatia, of which tourism contributes considerably and with increasing trend. Some of the investigations, in spite of given concessions, seem now to be stopped due to the loss of interest of investors. Drilling for oil from the Southern Adriatic is rather expensive, which may not be so profitable with regard to the dumped prices of oil lately. Also, yet undefined borders at the sea between Montenegro and Croatia that encompass potential exploration areas may be part of a problem.

The people are worried what threats future investigation and exploration of oil may bring. Will the prospective oil fields be so close to the islands as to ruin the nice view? The permitted distance for exploration of 10 km from the coast and 6 km from islands is below normally high visibility. The Croatian coasts with its clear and clean sea than may not be so attractive to the tourists, with a view to the oil platforms. Not to mention the possibility that one day an environmental disaster might occur.

Income from fisheries and aquaculture is also important for coastal population, and risk during investigation and exploration is possible. Aquaculture ponds are situated not only in the coastal area but also on the south sides of several east Adriatic islands, making them highly vulnerable to oil pollution. Protection is especially necessary for maintaining normal wild fish reproduction. In the phase of investigation for oil the precautions must be made, since disturbing the fish during spawning and growing could be fatal for young fish. The threat during the oil exploitation phase comes also from a disturbing factor of noise. It is essential to protect the migration locations of different fish species, especially those of commercial interest. However, it is very difficult to find in the Adriatic Sea isolated areas where numerous fish species do not migrate during spawning or growing [30].

Fig. 3 (continued) vessels (*fourth row*) and passengers ships (*fifth row*) are shown in *red, green, light brown* and *dark blue*, respectively. © Marinetrffic.com

7 SAR Image Analysis for Oil Spills

From approximately four hundred examined Envisat SAR images from the period 2003–2010, after careful inspection 29 images showed clear middle and large size oil spill signature and were selected for analysis. Also we used the oil spills detected on 27 Radarsat-1 SAR images in 2011 during the pilot project. Selected Envisat and Radarsat-1 SAR images were integrated in GeoMixer together with geographical maps and other data useful for analysis. The coverage by Envisat SAR images from our analysis is shown in Fig. 4. On 29 archived Envisat SAR images the 380 slicks (from small to large) were detected (and marked) with the total area of about 670 km². On 27 operational Radarsat-1 SAR images 16 slicks were detected with total area of 77.7 km². In total, from this analysis the 396 slicks were observed, covering the area of 457.7 km².

On some SAR images ship wakes and spills (Fig. 5) were visible along the main transport routes that concentrate along the long Adriatic axis, and in fishing areas that are dispersed both in the coastal and open sea. When the spill manifestation is linear like in Fig. 5, it is probably fresh and very likely made by illegal discharges of intentional ships that travelled fairly rapidly through the region. These are not spills from big cargo ships or tankers, but most probably come from small vessels, fishing boats or may have been either caused by accidents or by dumping of oily wastes. The ships could have used different tactics to avoid identification: after discharges

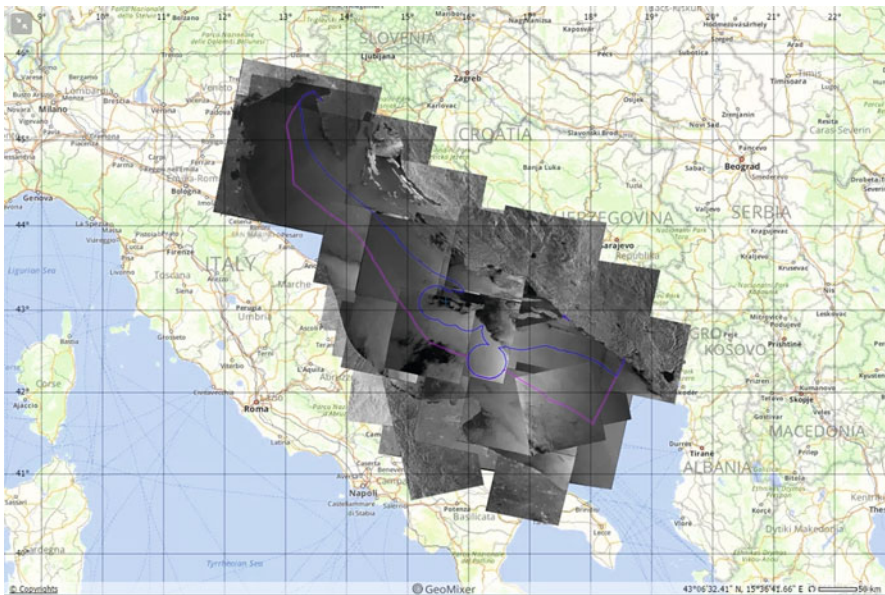


Fig. 4 Coverage of the Adriatic Sea by Envisat SAR images acquired in 2003–2010 and Radarsat-1 SAR images acquired in 2011, selected for analysis in the GeoMixer application. © ESA, MDA, SCANEX

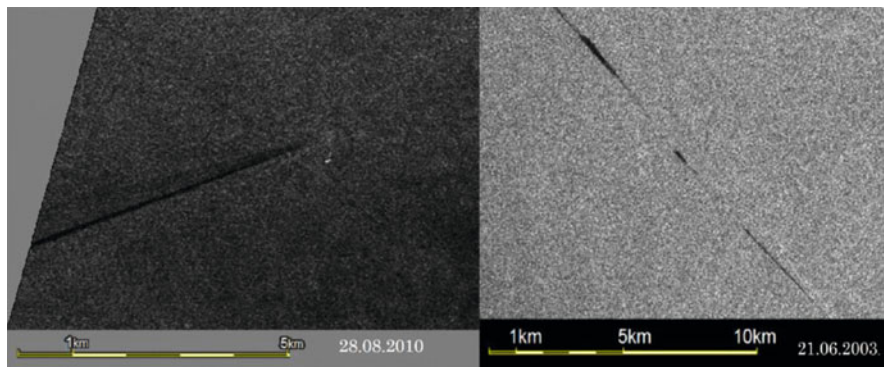


Fig. 5 Subscenes of Envisat SAR images of 28.08.2010 and 21.06.2003 with probable oil spills in the ship wakes. © ESA

they could slow down and turn in the opposite direction, or stop moving for a while and wait until spill origin cannot be connected to them, if currents or winds are strong and move the oil away from them.

In Fig. 6 rather narrow slicks are presented. The manifestation on the image of 10.05.2008 (Fig. 6, left) could be oil spill; the deviation from a straight line may be caused by wind or local differences in the current field. The manifestation on the image of 01.05.2004 (Fig. 6, right) may have similar cause, but is more probably a deliberate oil spill. Here we see that either the ship that was dumping the oil changed direction or there was a divergence in the wind field.

On some SAR images we have found rather large spills (Figs. 7 and 8). We assume all these were definitely caused by dumping of different mixtures with oil and produced by discharges from cargo ships or chemical tankers. For example, ship-generated oil spills can be produced via ballast water discharges, tank washing residues, oily mixtures from the engine room, bilge waters and even oily fish wastes, some of which is produced during routine fishing boats operations. On the SAR image of 19.07.2008 (Fig. 7) feathered edges can be seen, indicating the presence of different oil fractions that have spread the spill under the influence of the wind (Fig. 9).

Summary maps of all large and medium oil slicks having different man-made nature detected in 2003–2011 in the Adriatic Sea, created and analysed using GeoMixer technology, are shown in Figs. 10 and 11.

In Fig. 12 the distribution of the oil spills detected in the central part of the Adriatic Sea appears along the main shipping routes. Here one very large spill of 108 km², the largest observed throughout analysis, is observed. For largest spills date and size are indicated in the callouts. Main ship routes (hatch blue lines), boundaries (shadowed light blue lines) of the territorial waters and ZERP (Zaštićeno ekološko ribarsko područje or Croatian Fishery and Ecological Zone) (dark blue line) are shown.

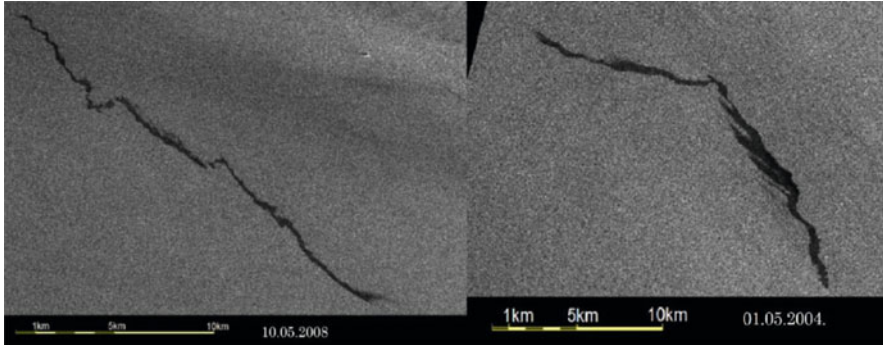


Fig. 6 Subscenes of Envisat SAR images of 10.05.2008 and 01.05.2004 with oil spills modified under action of wind and currents. © ESA

The maps show many large oil slicks especially in the central part of the Adriatic Sea. Large oil spills are mostly found in the ZERP and close to this area. The slicks/spills are as large as 9–108 km². Such slicks may come into the water during routine tank washing operations and illegal discharges, and are dispersed in the course of time and under the action of wind and currents. Most of these oil spills were intentionally released during night, since were detected on the SAR images acquired during descending morning passes of the satellite between 05:00 and 09:00 UTC.

The highest amount of largest oil spills is detected in the open sea, at the boundaries of the Italian and Croatian sectors and along the main ship routes. Although it would be possible to track ships that caused such types of pollution, for example, using data of automatic ship identification system – AIS [31], but there is a problem that the satellite images are not accepted as proves in the court, and it would be difficult to press charges to any suspected ship.

Furthermore, our analysis of Envisat SAR images and oil spill distribution maps for the Adriatic Sea confirmed general conclusion from other seas that most oil pollution occurred along the main ship routes [31]. Analysis of distribution of large oil spills also revealed that tank washing occurs frequently in the Central Adriatic Sea like it does in the Black Sea [32].

Although the tankers claim to have rather strict controls of all waste waters from port to port, it is still possible that some of these spills were produced by multipurpose chemical tankers. They transport liquid substances of different toxicity, including crude oil and oil products of which most are carcinogenic and toxic for marine life. These liquids together with emulsifiers and surface active substances used for tank cleaning can form different surface active films on the sea surface.

Also quantity and quality of spilled oil and oily products remain unknown. Even with the Sentinel-1A, new SAR-equipped satellite with coverage of every second day over the mid-latitudes, a lot of spills would pass undetected due to other



Fig. 7 Subscenes of Envisat SAR images of 21.06.2003, 11.09.2008, 19.07.2008, 04.08.2008 and 23.07.2009, with very large slicks, which are definitely ship-made oil spills. © ESA



Fig. 8 Subscene of Sentinel-1A SAR image (1.02.2016, 04:55 UTC) with oil spills off Italian port of Brindisi (the longest spill is 116 km, start at $41^{\circ}23''\text{N}$, $17^{\circ}35''\text{E}$; end (red circle) at $40^{\circ}41''\text{N}$, $18^{\circ}30.5''\text{E}$). © ESA

reasons, often due to the absence of the favourable conditions in the sea and atmosphere that allow recognition of the oil slick phenomena.

Although the Adriatic Sea is declared as a Special Zone according to the MARPOL Convention, tank washing is sometimes legal under specific conditions [33]. In the Adriatic Sea under Croatian jurisdiction there are protected areas national parks, special reserves, significant landscapes and monuments of nature. The ecological network [34] of marine protected areas is a part of European Union Ecological network, Natura 2000. It encompasses 16.4% of Croatian sea and covers $5,205 \text{ km}^2$. It is composed of hundreds of polygonal or point areas important for the conservation/preservation of species and habitat types. However, these areas count for about only 10% of the total Croatian sea territory and the rate is the same in Italian side. Although human activities are limited in the protected areas, these measures cannot save these areas of accidental oil pollution that could occur nearby.

As a result of undefined marine borders between the republics of the former Federation of Yugoslavia, the agreements are still missing between Montenegro and Croatia in the South Adriatic, and the border is not completely clear between Bosnia-Herzegovina and Croatia in the Neum-Klek Bay. Also the delimitation



Fig. 9 Subscene of Sentinel-1A SAR image (6.04.2016, 05:03 UTC) with recent large oil spill (total area about 16.5 km²) close to the Ancona–Igoumenitsa ship lane. © ESA

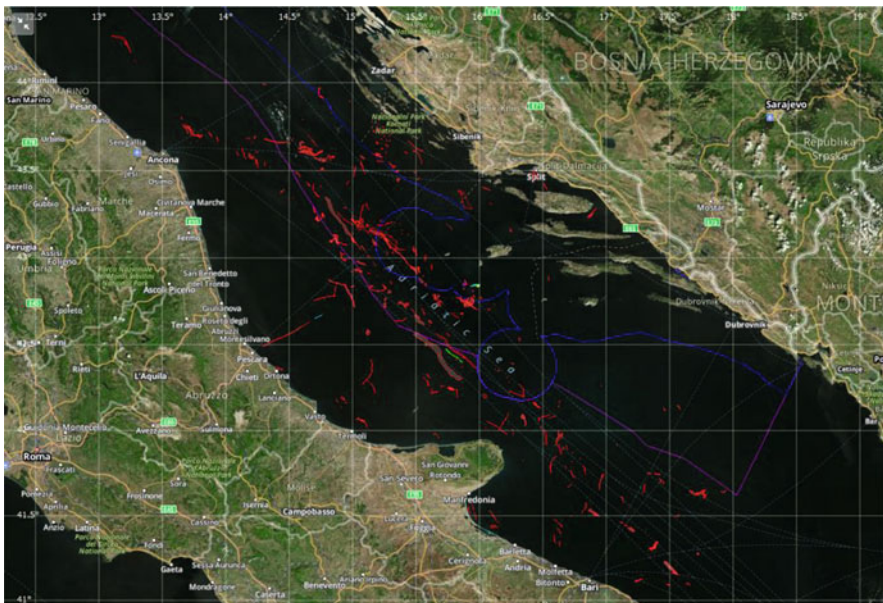


Fig. 10 Summary map of oil slicks of different nature detected in the SAR imagery of the Adriatic Sea. Extent of oil pollution along the main shipping routes is clearly seen. © SCANEX

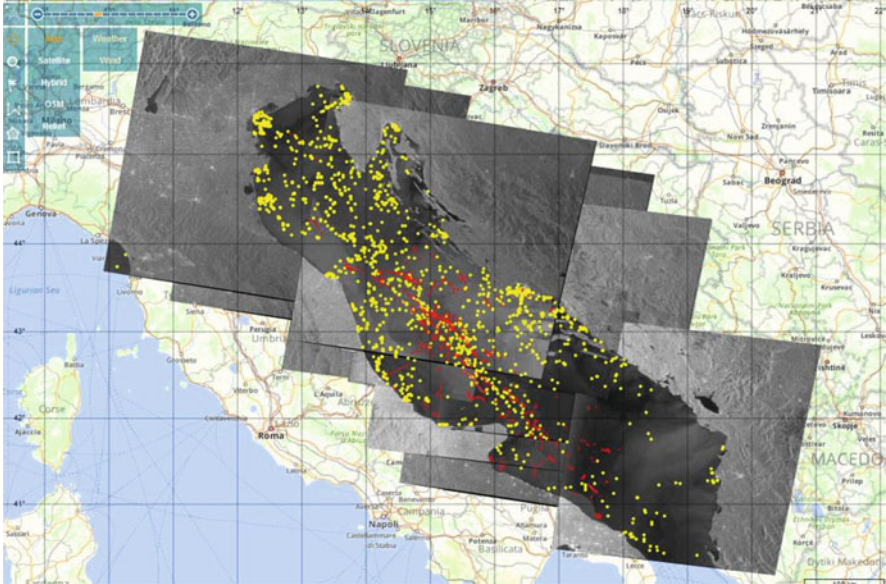


Fig. 11 Map of all oil slicks/spills detected on Radarsat-1 and Envisat SAR images (*red spots*), and collocated with the detected ships (*yellow dots*) from all analysed images. © MDA, ESA, SCANEX

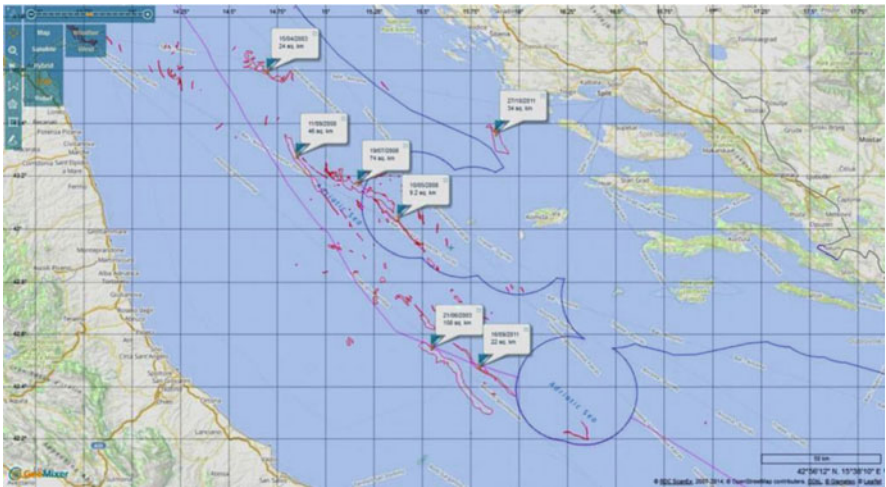


Fig. 12 Distribution of the oil spills detected on the SAR images in the central part of the Adriatic Sea along the main ship routes. For largest spills date and size are indicated in the callouts. Main ship routes (*hatch blue lines*), boundaries (*shaded light blue lines*) of the territorial waters and ZERP (*dark blue line*) are shown. © SCANEX

agreements are still pending, between Slovenia and Croatia about Savudrijska vala (or Piran Bay) and marine border between Croatia and Montenegro.

It is very important to define marine borders of the States surrounding the Adriatic Sea especially not only for their obligations concerning protection, search and rescue, but also for the rights for exploration of underwater oil and gas reserves.

8 Conclusions

Continuous SAR observations from space have significantly contributed in oil spill monitoring and provide a new knowledge on oil pollution. The most important findings from this study can be summarized as follows:

- Most of oil spills were detected along the main international shipping routes at the boundaries of the Italian and Croatian sectors, while large oil spills are mostly observed in the Croatian ZERP.
- The sizes of the detected oil spills varied between 0.1 and 108 km².
- In total, 396 slicks were observed covering the area of 457.7 km².
- Feathered edges of oil slicks indicate heavy and middle fractions of oil in a slick that also can be a sign of routine tank washing operations or illegal discharges.
- The number and the total area of detected oil spills depended on the particular time/season and ship traffic.
- Most of oil spills have been released during night time, and were detected during descending (morning) satellite passes.
- Oil spills have been more often detected on SAR images in the open parts of the sea beyond the territorial waters, rather than in the coastal waters.
- Other, yet not estimated source of oil pollution may be bottom seepage.

As established, prevailing distribution of oil spills in the Central Adriatic is along its longer axis, along the main ship lines, and it may be concluded: the more intensive traffic the more intensive oil pollution. It is also obvious that many detected oil slicks are of anthropogenic origin, caused mostly by deliberate dumping of waste oily waters or oil products from ships of all kinds. Of course, there is a reasonable doubt that oil spills in the Adriatic Sea occur much more frequently than could be detected by satellites.

The Adriatic Sea with increasing frequency of oil tankers, other cargo ships and increased transport in general, is potentially endangered from marine accidents that could result with oil pollution. Being a small semi-enclosed sea with valuable resources concerning biodiversity and importance for economy of surrounding population is in need of additional measures to protect it.

Finally, collection of SAR images, their geospatial analysis is very useful either from practical and scientific points of view, because, first, it clearly shows the sources of oil pollution in the sea, second, reveals a specific pattern of spill distribution that definitely connected with ship traffic in the open sea and, third,

allows finding new, earlier unknown sources. These results increase knowledge about the level of oil pollution and its sources in the Adriatic Sea.

Acknowledgments The Envisat SAR images for analysis were provided by ESA in the framework of the research project 19234 (PI M. Oluić), whereas Radarsat-1 SAR images were provided by RDC SCANEX in the framework of the joint Croatia–Russia pilot project. This work is supported in part by Croatian Science Foundation under the project IP-2014-09-3606 (Marine plankton as a tool for assessment of climate and anthropogenic influence on the marine eco-system), and through the Russian Foundation for Basic Research, project No. 14-05-93084.

References

1. Mosetti F (1983) A tentative attempt at determining the water flow through the Otranto Strait: the mouth of the Adriatic Sea. Criterion for applying the computation of dynamic height anomalies on the water budget problems. *Boll Oceanol Teor Appl* 1:143–163
2. Lušić Z, Kos S (2006) Glavni plovidbeni putovi na Jadranu (The Main Sailing Routes in the Adriatic). *Naše more* 53(5–6):198–205
3. Franić Z (2005) Estimation of the Adriatic Sea water turnover time using fallout ^{90}Sr as a radioactive tracer. *J Mar Syst* 57:1–12
4. Zore M (1956) On gradient currents in the Adriatic Sea. *Acta Adriat* 8:1–38
5. Argegianni A (1996) The Adriatic sea hydrography, the European anchovy and its environment (Palomera, I. and Rubies P. eds.). *Scienza marina* 60(Suppl 2):33–43
6. Argegianni A, Bregant D, Paschini E, Pinardi N, Raicich F, Russo A (1997) The Adriatic Sea general circulation. Part II: Baroclinic circulation structure. *J Phys Oceanogr* 27:1515–1532
7. Buljan M (1953) Fluctuation of salinity in the Adriatic. *Izveštaj Republičke Ribarstveno-biološke ekspedicije “Hvar” 1948–1949*. *Acta Adriat* 2:1–64
8. Grbec B, Morović M, Beg Paklar G, Kušpilić G, Matijević S, Matić F, Ninčević Gladan Z (2009) The relationship between the atmospheric variability and productivity in the Adriatic Sea area. *J Mar Biol Assoc U K* 89(8):1549–1558. doi:[10.1017/S0025315409000708](https://doi.org/10.1017/S0025315409000708)
9. Civitarese G, Gačić M, Lipizer M, Eusebi Borzelli GL (2010) On the impact of the Bimodal Oscillating System (BIOS) on the biogeochemistry and biology of the Adriatic and Ionian Seas (Eastern Mediterranean). *Biogeosciences* 7:3987–3997. doi:[10.5194/bg-7-3987](https://doi.org/10.5194/bg-7-3987)
10. Gačić M, Borzelli GLE, Civitarese G, Cardin V, Yari S (2010) Can internal processes sustain reversals of the ocean upper circulation? The Ionian Sea example. *Geophys Res Lett* 37, L09608. doi:[10.1029/2010GL043216](https://doi.org/10.1029/2010GL043216)
11. Vilibić I, Book JW, Beg Paklar G, Orlić M, Dadić V, Tudor M, Martin PJ, Pasarić M, Grbec B, Matić F, Mihanović H, Morović M (2009) West Adriatic coastal water summertime excursion in-to the East Adriatic. *J Mar Syst* 78:S132–S156
12. Grbec B, Vilibić I, Bajić A, Morović M, Beg Paklar G, Matić F, Dadić V (2007) Response of the Adriatic Sea to the atmospheric anomaly in 2003. *Ann Geophys* 25:835–846
13. Grbec B, Morović M (1997) Seasonal thermohaline fluctuations in the middle Adriatic Sea; *Nuovo Cimento della Società Italiana di Fisica C*. *Geophys Space Phys* 20(4):561–576
14. Malačić V, Viezzoli D, Cushman-Roisin B (2000) Tidal dynamics in the northern Adriatic Sea. *J Geophys Res* 105(C):26265–26280
15. Vilibić I (2000) A climatological study of the uninodal seiche in the Adriatic Sea. *Acta Adriat* 41(2):89–102
16. Šepić J, Vilibić I, Fine I (2015) Northern Adriatic meteorological tsunamis: assessment of their potential through ocean modeling experiments. *J Geophys Res* 120(C):2993–3010
17. Espedall HA, Johannessen OM (2000) Detection of oil spills near offshore installations using synthetic aperture radar (SAR). *Int J Remote Sens* 21:2141–2144

18. Bern T-I, Wahl T, Andersson T, Olsen R (1992) Oil spill detection using satellite based SAR: experience from a field experiment. Proceedings of the 1st ERS-1 symposium, Cannes, France, 4–6 November, 2, pp 829–834
19. Ivanov AY, Litovchenko KT, Ermakov SA (1998) Oil spill detection in the sea using Almaz-1 SAR. *J Adv Mar Sci Technol Soc* 4(2):281–288
20. Litovchenko K, Ivanov A (2006) Oil spills on ALMAZ-1 and ERS-1 SAR images: results from DOSE-91 experiment. In: Gade M, Huhnerfuss H, Korenowski G (eds) *Marine surface films. Chemical characteristics, influence on air-sea interaction and remote sensing*. Springer, Berlin/Heidelberg, pp 299–313
21. Ivanov A (2011) Remote sensing of oil films in the context of global changes. In: *Remote sensing of the changing oceans*. Springer, Berlin/Heidelberg, pp 169–194
22. Morović M, Ivanov A, Oluić M, Kovač Ž, Terleeva N (2014) Distribution and sources of oil slicks in the Middle Adriatic Sea. In: *Proceedings of the 12th Pan Ocean Remote Sensing Conference (PORSEC-2014)*, 4–7 November 2014, Bali, Indonesia, O-109, pp 1–8
23. Orlić M, Dadić V, Grbec B, Leder N, Marki A, Matic F, Mihanović H, Beg Paklar G, Pasarić M, Pasarić Z, Vilibić I (2006) Wintertime buoyancy forcing, changing seawater properties and two different circulation systems produced in the Adriatic. *J Geophys Res Oceans* 111. doi:[10.1029/2005JC003271](https://doi.org/10.1029/2005JC003271)
24. Andročec V, Beg Paklar G, Dadić V, Đakovac T, Grbec B, Janeković I, Krstulović N, Kušpilić G, Leder N, Lončar G, Mara-sović I, Precali R, Šolić M (2009) Coastal cities water pollution control project, Part C1: strengthening of coastal water monitoring network. The Adriatic Sea monitoring program
25. Beg-Paklar G, Dadić V, Grbec B, Ivanković D (2007) Simulations of physical properties in south part of the Croatian Adriatic using numerical model – case study. In: Kereković D (ed) *Richness and diversity of GIS*. Croatian Information Technology Association – GIS Forum, University of Silesia, Zagreb, pp 119–126
26. Bradarić Ž, Mladineo N, Srdelić M (2010) Sensitivity index of the coast of the place of refuge to oil pollution. In: Kereković D (ed) *Space, heritage and future*. Croatian Information Technology Association – GIS Forum, University of Silesia, Zagreb, pp 222–228
27. Coppini G (2016) MONGOOS: Mediterranean operational oceanography in support of sea situational awareness services. Webinar, 13 April 2016
28. OCEANA. <http://eu.oceana.org/en/eu/media-reports/features/oil-slicks>
29. CEDRE. www.cedre.fr
30. Institute of Oceanography and Fisheries (IOF) (2015) Prilozi za dopunu Strateške procjene utjecaja na okoliš, Okvirnog plana i programa istraživanja i eksploatacije ugljikovodika na Jadranu [Contribution to complement the strategic study for environmental impact and framework plan of investigation and exploration program for hydrocarbons in the Adriatic Sea, Institute of Oceanography and Fisheries, in Croatian]. Institut za oceanografiju i ribarstvo, Split, pp 1–191
31. Ivanov AY, Kucheiko AA (2014) Large discharges from ships in the Black Sea studied by synthetic aperture radar with the support of automated identification systems. *Int J Remote Sens* 35(14):5513–5526
32. Morović M, Ivanov A, Oluić M, Kovač Ž, Terleeva N (2015) Oil spills distribution in the Middle and Southern Adriatic Sea and intensive ship traffic. *Acta Adriat* 56(2):143–150
33. International Maritime Organization (2009) International convention for the prevention of pollution from ships, 1973, as modified by the protocol of 1987 (MARPOL 73/78). IMO, London, Available at: [http://www.imo.org/About/Conventions/ListOfConventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-\(MARPOL\).aspx](http://www.imo.org/About/Conventions/ListOfConventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-(MARPOL).aspx)
34. <http://www.dzpp.hr/ekoloska-mreza/natura-2000/ekoloska-mreza-rh-natura-2000-1300.html>, <http://www.biportal.hr/gis/>. Accessed 14 Apr 2016