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Oil Pollution in the Baltic Sea

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Volume 27

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Volume Editors: Andrey G. Kostianoy · Olga Yu. Lavrova

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Aims and Scope

Since 1980, *The Handbook of Environmental Chemistry* has provided sound and solid knowledge about environmental topics from a chemical perspective. Presenting a wide spectrum of viewpoints and approaches, the series now covers topics such as local and global changes of natural environment and climate; anthropogenic impact on the environment; water, air and soil pollution; remediation and waste characterization; environmental contaminants; biogeochemistry; geoecology; chemical reactions and processes; chemical and biological transformations as well as physical transport of chemicals in the environment; or environmental modeling. A particular focus of the series lies on methodological advances in environmental analytical chemistry.

Series Preface

With remarkable vision, Prof. Otto Hutzinger initiated *The Handbook of Environmental Chemistry* in 1980 and became the founding Editor-in-Chief. At that time, environmental chemistry was an emerging field, aiming at a complete description of the Earth's environment, encompassing the physical, chemical, biological, and geological transformations of chemical substances occurring on a local as well as a global scale. Environmental chemistry was intended to provide an account of the impact of man's activities on the natural environment by describing observed changes.

While a considerable amount of knowledge has been accumulated over the last three decades, as reflected in the more than 70 volumes of *The Handbook of Environmental Chemistry,* there are still many scientific and policy challenges ahead due to the complexity and interdisciplinary nature of the field. The series will therefore continue to provide compilations of current knowledge. Contributions are written by leading experts with practical experience in their fields. *The Handbook of Environmental Chemistry* grows with the increases in our scientific understanding, and provides a valuable source not only for scientists but also for environmental managers and decision-makers. Today, the series covers a broad range of environmental topics from a chemical perspective, including methodological advances in environmental analytical chemistry.

In recent years, there has been a growing tendency to include subject matter of societal relevance in the broad view of environmental chemistry. Topics include life cycle analysis, environmental management, sustainable development, and socio-economic, legal and even political problems, among others. While these topics are of great importance for the development and acceptance of *The Handbook of Environmental Chemistry,* the publisher and Editors-in-Chief have decided to keep the handbook essentially a source of information on "hard sciences" with a particular emphasis on chemistry, but also covering biology, geology, hydrology and engineering as applied to environmental sciences.

The volumes of the series are written at an advanced level, addressing the needs of both researchers and graduate students, as well as of people outside the field of "pure" chemistry, including those in industry, business, government, research establishments, and public interest groups. It would be very satisfying to see these volumes used as a basis for graduate courses in environmental chemistry. With its high standards of scientific quality and clarity, *The Handbook of*

Environmental Chemistry provides a solid basis from which scientists can share their knowledge on the different aspects of environmental problems, presenting a wide spectrum of viewpoints and approaches.

The Handbook of Environmental Chemistry is available both in print and online via www.springerlink.com/content/110354/. Articles are published online as soon as they have been approved for publication. Authors, Volume Editors and Editors-in-Chief are rewarded by the broad acceptance of *The Handbook of Environmental Chemistry* by the scientific community, from whom suggestions for new topics to the Editors-in-Chief are always very welcome.

Damià Barceló
Andrey G. Kostianoy
Editors-in-Chief

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Introduction

Andrey G. Kostianoy and Olga Yu. Lavrova

Abstract This book presents a review of knowledge on oil pollution in the Baltic Sea. The publication is based on observational satellite, airborne and in-situ data, scientific literature, technical reports, and long-standing experience of authors of the chapters from several Baltic Sea countries in this field of science. Special attention is paid to national practices, HELCOM and EMSA CleanSeaNet activities in oil pollution monitoring in the Baltic Sea. Different applications of the Seatrack Web model for oil spill prediction and identification of illegal polluters, as well as for Environmental Risk Assessment are shown. Some of the results on satellite monitoring of the Nord Stream gas pipeline construction in the Gulf of Finland are given. This book is addressed to the specialists working in various fields of environmental problems, ecology and oil pollution in the Baltic Sea.

Keywords Environmental risk assessment, Marine environment, Nord Stream, Oil pollution, Satellite monitoring, Seatrack Web, The Baltic Sea

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Petroleum or crude oil and its refined components (petrochemicals) are crucial resources for the economy of all countries. Crude oil originates from fossilized organic materials (zooplankton and algae), which via geochemical processes convert into oil. Oil reserves are distributed on the land, on the shelves of the ocean, and in the inland seas. Crude oil is pumped from the ground or the ocean bottom and is transported via pipelines or shipped with oil tankers to oil refineries for production of benzene, diesel fuel, fuel oils, jet fuel, kerosene, ethane, and other petrochemicals. The top five oil producing countries are (in 2011): Saudi Arabia (517 million tons), Russia (511), the USA (346), Iran (215), and China (203). The top five offshore oil producers are (in 2009): Saudi Arabia (124 million tons), the USA (117), Norway (116), Mexico (115), and Brazil (99) [1].

Transportation of oil across the ocean and production of oil at offshore oil platforms are inevitably related to the risks of catastrophes which may result in release of oil or oil products into the sea. These reasons include collisions and grounding of the ships, fires and explosions of tankers and offshore platforms, severe storm conditions with high waves, leakages due to technical problems and use of old equipment, and even sabotage, terrorism, and war actions. The term "oil spill" is usually applied to release of liquid petroleum products into the marine environment due to human activity or natural seepage from the bottom of the ocean and is a form of chemical pollution of the sea. Oil spills may also occur on land, but normally this is less dangerous to the environment because they do not spread so much on the land surface as they do on the sea surface.

In the sea, oil pollution may result from releases of crude oil and oil products from tankers, offshore platforms, drilling rigs, wells, pipelines as well as from releases of bunker fuel, waste oil, and bilge water from other types of ships (cargo, ferry, tourist, military, fishery, and even submarines). This oil pollution may occur as a result of accidents or during routine operations in the sea or in ports. Releases of oil products into the sea may be legal, illegal, or accidental. Oil comes to the sea also with river runoff, from the atmosphere, and from the ocean bottom due to natural seepages (some estimates give from 0.45% up to 46% [2] from the total ocean pollution to natural seeps worldwide). Oil pollution of the ocean is often divided into the chronic (permanent pollution by small portions due to anthropogenic or natural causes) or accidental (rare, but strong pollution due to a catastrophe of a ship, offshore platform, or pipeline).

The share in percentages of these sources/reasons varies significantly (10–100 times) between scientific publications, regions of the world ocean, and different time periods, but one of the largest belongs to different kinds of shipping activities – 20–50% [2–9], which have a number of negative impacts on the marine environment and coastal zone. Oil contamination of seawater, bottom, shores, and beaches may persist for several months and even years and represent a threat to marine ecosystems and resources, fishery, recreation, and tourism [2, 4, 8, 10].

According to the International Tanker Owners Pollution Federation (ITOPF), over the period of 1970–2009, spillages resulting from collisions, groundings, tanker holes, and fires amounted to 52% of total leakages during tanker loading/unloading and bunkering operations [11]. In the category 7–700 tons, some 38% of spills occurred during routine operations, most especially loading or discharging (31%). Accidents were the main cause of large spills (>700 tons), with groundings and collisions accounting for 65% of the total during the period 1974–2009 [11].

From archeological records it is known that for over 6,000 years people have used petroleum in the form of asphalt, bitumen, and liquid oil as building cement (e.g., Tower of Babel), for caulking boats, lighting, warfare, fuel, ornamental, medicine, and funeral purposes [4]. Herodotus, an ancient Greek historian (484–425 BC), probably was the first who recorded the cases of natural oil seepages from the sea bottom, when he wrote about "black mucus in the sea" [3]. In ancient times, sailors used to spill oil (including vegetable) into the sea to damp waves around the boat in a rough sea. Probably, these were the first cases of anthropogenic pollution.

It is believed that the first accident with tankers was a wreck of *Thomas W. Lawson*, a seven-masted, steel-hulled schooner used to haul coal and oil along the East Coast of the United States. Built in 1902, it was the largest schooner and the largest pure sailing vessel (without an auxiliary engine) ever built. *Thomas W. Lawson* was destroyed off Annet Island, in the Scilly Isles, at the entrance to English Channel, in a storm on 14 December 1907. Her cargo of 8,900 tons of light paraffin oil caused, probably, the first large oil spill from a ship in modern history [3].

On 18 March 1967, due to a navigational error, supertanker *Torrey Canyon* struck Pollard's Rock on Seven Stones reef between the western coast of Cornwall, England, and the Scilly Isles, causing an environmental disaster. *Torrey Canyon* was a supertanker capable of carrying 120,000 tons of crude oil, at that time it was the largest tanker ever to be wrecked. Mystically, but 60 years after the *Thomas W. Lawson* wreck, almost at the same place, it opened a count of the largest catastrophes related to oil pollution of the sea [3, 4].

The world's dozen worst oil spills by amount of oil released into the environment (ocean and land) is listed below [3, 4, 12]:

1. *Gulf War oil spill*: Persian Gulf, Kuwait, 19 January 1991, oil spilled – 0.8–1.9 million tons. Iraqi forces attempted to stop a potential American troop landing by dumping oil from several tankers in the Persian Gulf.
2. *Lakeview Gusher*: Kern Country, California, March 1910–September 1911, oil spilled – 1.4 million tons. The worst accidental oil spill in the USA, when uncontrolled oil geyser continued during 18 months.
3. *Deepwater Horizon oil spill*: Gulf of Mexico, USA, 20 April–15 July 2010, oil spilled – 492,000–627,000 tons. Explosion of the *BP Deepwater Horizon* oil platform during drilling operations.
4. *Ixtoc 1 oil spill*: Bay of Campeche, Gulf of Mexico, Mexico, 3 June 1979–23 March 1980, oil spilled – 454,000–515,000 tons. A blowout at an offshore oil well, oil was gushing out for more than 9 months.
5. *Atlantic Empress/Aegean Captain oil spill*: Off the coast of Trinidad and Tobago, 19 July 1979, oil spilled – 287,000–330,000 tons. Collision of two oil tankers during a tropical storm.

6. *Kolva River oil spill*: Kolva River, Russian Arctic, 8 September 1994, oil spilled – 309,000 tons. A ruptured oil pipeline was leaking for 8 months, but the oil was contained by a dike, which collapsed, and millions of gallons of oil spilled into the Kolva River.
7. *Nowruz Oil Field oil spill*: Persian Gulf, Iran, 10 February–18 September 1983, oil spilled – 260,000–294,000 tons. During the Iran–Iraq War, an oil tanker crashed into an offshore oil platform at the Nowruz Oil Field in the Persian Gulf.
8. *Castillo de Bellver oil spill*: Saldanha Bay, South Africa, 6 August 1983, oil spilled – 252,000–290,000 tons. The oil supertanker *Castillo de Bellver* caught fire about 70 miles northwest of Cape Town, South Africa, then drifted before finally breaking apart 25 miles off the coast, presenting South Africa with its worst-ever marine environmental disaster.
9. *Fergana Valley oil spill*: Fergana, Uzbekistan, 2 March 1992, oil spilled – 285,000–324,000 tons. The Mingbulak oil spill or Fergana Valley oil spill was a massive terrestrial oil spill that started on 2 March 1992 at the Mingbulak oil field in the Fergana Valley, Uzbekistan, when a blowout occurred at the well N5. It was the worst oil spill in the history of Asia. The oil coming out of the well caught fire and was burning for 2 months.
10. *Amoco Cadiz oil spill*: Portsall, France, 16–17 March 1978, oil spilled – 223,000–254,000 tons. The oil supertanker *Amoco Cadiz* was caught in a violent winter storm, damaged, grounded, broke apart, and the entire crude oil cargo spilled into the English Channel.
11. *ABT Summer oil spill*: 1,300 km off the coast of Angola, 28 May 1991, oil spilled – 188,000–260,000 tons. The oil supertanker *ABT Summer* exploded, caught fire, and sank 1,300 km from the coast of Angola.
12. *M/T Haven oil spill*: Genoa, Italy, 11 April 1991, oil spilled – 165,000 tons. The oil supertanker *M/T Haven* was unloading a cargo of 230,000 tons of crude oil at the Multedo platform, about 13 km off the coast of Genoa. The ship exploded, caught fire, broke into two parts and sank. For the next 12 years, the ship continued to pollute the Mediterranean coasts of Italy and France.

All these cases, as well as many other largest oil spills (more than 10,000 tons) occurred since the beginning of the twentieth century in the ocean, inland seas, and land are shown in Fig. 1.

Total yearly oil pollution of the world ocean from all sources is estimated as 1.7 to 8.8 million tons (the more realistic value was about 3.2 million tons) in 1970s [3, 8], 0.47–8.3 (1.3) million tons in 1990s [2], and 2.6–4.8 million tons in 2000s [13], which is about 0.05–0.1% from the world oil production (4.76 billion tons in 2011). Almost a half of the world oil production is transported by tankers – 2.4 billion metric tons or 11,705 billion metric-ton-miles taking into account a distance of oil transport (2005). This volume almost doubled since 1970 when it was 1.44 billion metric tons or 6,487 billion metric-ton-miles [14]. Global oil pollution due to tanker transport is estimated from 0.1% [3, 8] to 0.01% [2] from the transported volume, what gives 0.24–2.4 million tons. If we divide 221.2 million tons of oil

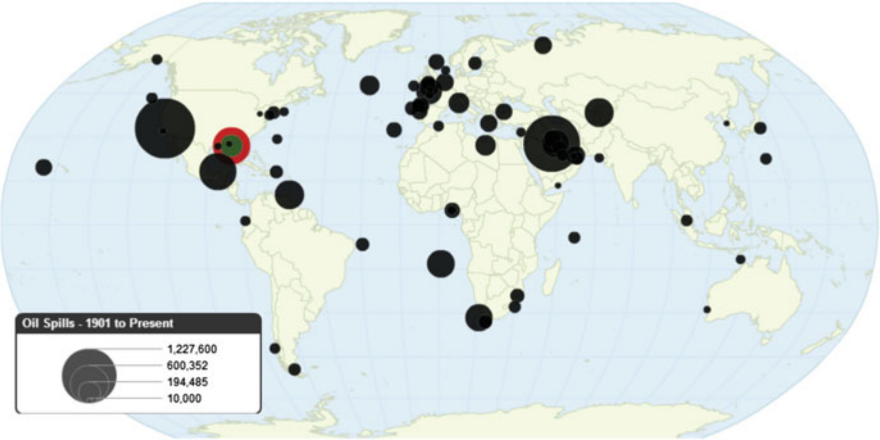

Fig. 1 Location of the largest oil spills in modern history (from 1901 to present) resulted from tanker accidents and drilling operations, as well as a number of other notable spills on land. A relative size of the spills is shown by *circles* with numbers in tons (the original interactive map can be found here: http://chartsbin.com/view/mgz)

transported in the Baltic Sea in 2005 [15] by 2.4 billion tons, we will get 9.2% of the world oil transport, and about 22,000–220,000 tons as oil pollution, which is an unrealistic value of pollution for the Baltic Sea. If we take into account a length of the ship route in the Baltic Sea, we will get a more realistic value of 4,000–40,000 tons, which corresponds to the published estimates given below.

As highlighted by Oceana in its report “The Other Side of Oil Slicks,” chronic hydrocarbon contamination from washing out tanks and dumping bilge water and other oily waste represents a danger at least three times higher than that posed by oil slicks resulting from oil tanker accidents [16, 17]. For example, in the North Sea the volume of illegal hydrocarbon dumping is estimated at 15,000–60,000 tons/year, added to which are another 10,000–20,000 tons of authorized dumping. Oil and gas platforms account for 75% of the oil pollution in the North Sea via seepage and intentional release of oil-based drilling muds [18]. In the Mediterranean Sea it has been estimated as 0.4–1.0 million tons a year. Of this about 50% comes from routine ship operations and the remaining 50% comes from land-based sources via surface runoff [18].

The application of satellite synthetic aperture radar (SAR) technology to the investigation of oil pollution in the Mediterranean, Black, North and Baltic seas was done in the OCEANIDES Project (Harmonised monitoring, reporting and assessment of illegal marine oil discharges, 2003–2005), which was an EC fifth Framework project and corresponded to the theme “Environmental Stress in Europe.” The aim of OCEANIDES was to understand the number, location, and impact of oil slicks deposited annually in European waters and to lay the foundation for a monitoring system that will provide this information in a continuous manner.

In the Black Sea there were detected about 200–250 oil spills yearly (in 2000–2002), in the Mediterranean Sea – 1,700 oil spills yearly (1999–2002), and in the North Sea – 520 oil spills in 2000 [19].

Despite the fact that the Baltic Sea has only 0.1% of the world's ocean surface, in 1970s it got approximately 2.8% of the total oil pollution of the oceans [3]. In 1970s–1980s, some estimates of oil pollution in the Baltic Sea gave a value of about 40,000–50,000 tons a year, from which 20,000–40,000 tons belong to chronic pollution and 5,000–10,000 tons – as a result of accidents [3, 8]. In the beginning of 2000s, the oil pollution volume was estimated from 1,750–5,000 tons [16, 17] to 35,000–60,000 tons a year [2]. According to Finnish Environment Institute [20], the total annual number of oil spills in the Baltic Sea 10 years ago could potentially reach 10,000 and the total amount of oil running into the sea could be as much as 10,000 tons which is considerably more than the amount of oil pouring into the sea in accidents. Recently, new estimates based on the analysis of satellite data showed 1,100–1,300 oil spills (1,100–1,300 tons) for the whole area of the Baltic Sea yearly [9]. HELCOM [21] reported that in 2011, 122 confirmed oil spills were observed with a total volume of 24 m^3 or about only 20 tons, which is a minimal estimate of oil pollution for the Baltic Sea ever found in the literature.

It is clear that thanks to the efforts of the European Union's (EU's) Integrated Maritime Policy and Baltic Sea Strategy, HELCOM's Baltic Sea Action Plan, MARPOL Convention, European Maritime Safety Agency (EMSA) CleanSeaNet satellite service, governments of the Baltic Sea countries, NGOs, shipping companies and port authorities, during the last three decades we observe a significant reduction in the number of oil spills in the Baltic Sea. But the total value of oil pollution is still unclear because of 100–1,000-fold difference in the estimates. Also, it seems too optimistic to think that since 1970s a real volume of oil pollution in the Baltic Sea has decreased from the estimated 50,000 to only 20 tons. As usual, the truth has to be somewhere in the middle.

Today, the Baltic Sea is one of the world's busiest waterways. It has about 40 ports and oil terminals. An estimated 9% of the world's trade and 11% of the world's oil transportation pass through Baltic waters. It is estimated that this will increase by 64% between 2003 and 2020. For example, oil transportation has increased by 133% between 1997 and 2008 and is now over 250 million tons per year. Besides, there are around 130 accidents each year, with ten of these leading to oil pollution [15].

Crude oil and petroleum products account for about 40% of total exports of Russia. The Russian Federation stands as one of the leading operators in the international oil business, being the largest oil exporter after Saudi Arabia. In 2000, Russia exported approximately 145 million tons of crude oil and 50 million tons of petroleum products. Since 2000, exports of petroleum and petroleum products began to grow and virtually doubled for the period from 1996 to 2005 [9]. According to the Federal Customs Service of Russia, in 2004–2012 Russia yearly exported 240–260 million tons of crude oil. Ports on the Baltic Sea play a huge role in the export of oil from Russia. The main oil terminals here used to be the Latvian port of Ventspils and the Port of Tallinn, Estonia. In the last 10 years, a number of new oil terminals have been built in the Baltic Sea area, resulting in increased transport of oil by ships and, consequently, an increased risk of accidents and increased risk of pollution of the marine environment. Today, in the Gulf of Finland, there are more than 18 oil terminals in Russia, Finland, and Estonia [22]. The following are the major Russian existing and projected oil terminals in the Gulf of Finland: Primorsk, Vysotsk, Big Port of St. Petersburg, Ust-Luga, Batareinaya, Vistino, Gorki, and Lomonosov [23, 24]. The last one was set into operation on 23 March 2012 in Ust-Luga, Gulf of Finland, Russia.

Primorsk is the largest Baltic oil terminal located on the Russian territory. In 2008, 75.6 million tons of oil products were exported from Primorsk, 13.6 million tons from Vysotsk, and 14.4 million tons from the St. Petersburg oil terminal. By 2015, the maximum export possibility of the Primorsk terminal is estimated as 120 million tons, while that of Vysotsk is as 20.5 million tons. In November 2000, Lukoil opened an oil terminal in Kaliningrad. In 2001, the company built another terminal in Kaliningrad with a declared capacity of 2.5 million tons. These terminals can overload up to 3–5 million tons of oil annually [9].

According to estimates of the Centre for Maritime Studies at the University of Turku (Finland), in 2007, 263 million tons of cargo was transported through the Gulf of Finland, of which the share of oil is 56% [24]. Russian ports handled 60% of goods, Finnish ports handled 23%, and Estonian ports handled 17%. The share of import was 22%, that of export was 76%, and that of local transportation was 2%. Russian ports held 68.6% of the total turnover of petroleum products, Estonian ports held 17.2%, and Finnish ports held 14.2% [24]. The major ports are the following: Primorsk (74.2 million tons), Saint Petersburg (59.5 million tons), Tallinn (35.9 million tons), Skoldvik (19.8 million tons), Vysotsk (16.5 million tons), and Helsinki (13.4 million tons). In 2007, the ports of the Gulf of Finland carried out about 53,600 ship calls, most of which were in St. Petersburg (14,651), Helsinki (11,727), and Tallinn (10,614). In 2009, vessels entered or left the Baltic Sea via Skaw 62,743 times; this is 20% more than in 2006. Approximately 21% of those ships were tankers, 46% were other cargo ships, and 4.5% were passenger ships [25].

Forecasts of the Finnish Centre for Maritime Studies for the year 2015 according to the three basic scenarios of economic development in Russia, Finland, and Estonia give a value of 322.4–507.2 million tons of cargo to be transported in the Gulf of Finland, which is 23–93% more than in 2007, and under any scenario, growth in turnover will occur mainly due to Russia. In addition, the share of oil and petroleum products among other goods will be an even greater increase in absolute terms – it can reach 158–262 million tons. For transportation of petroleum products, 6,655–7,779 tankers will be used [24].

The growth of oil and other cargo through the terminals and the Baltic ports inevitably leads to an increase in the number of tankers and other types of vessels, which then leads to an increase in chronic sea pollution and a higher probability of ship accidents. According to statistics, shipping accounts for 20–50% of oil pollution in the ocean, while oil production at the shelf accounts for only 2%. In the Baltic Sea, about 2,000 large ships and tankers are at sea every day; thus, shipping, including oil transport, has a major negative impact on the marine environment and

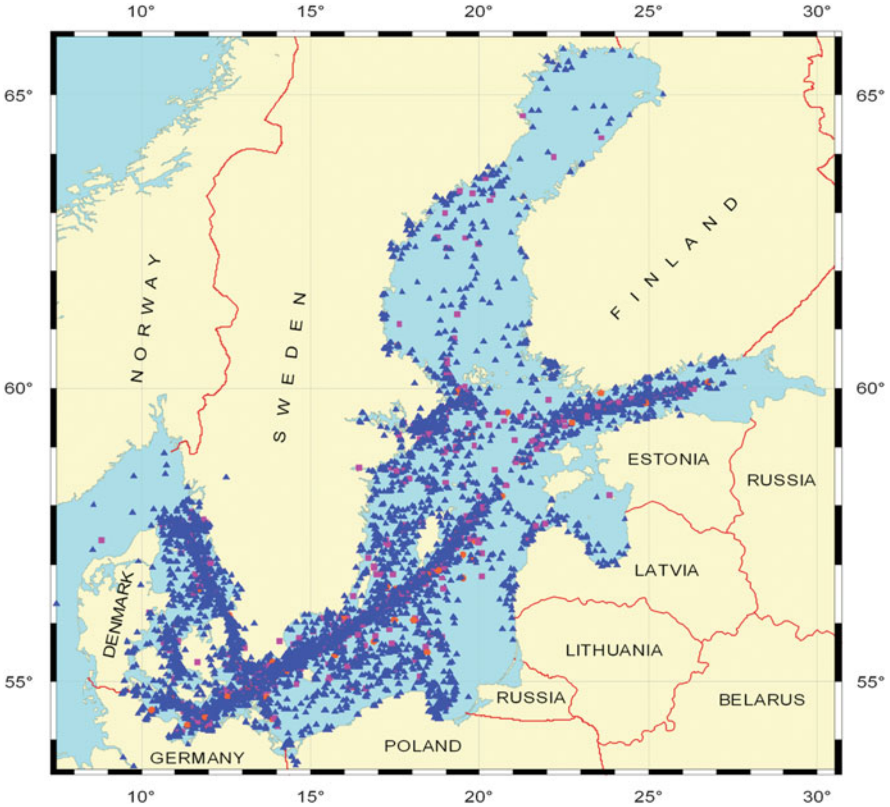

Fig. 2 Oil spills detected in the Baltic Sea by aerial survey in 1988–2002 based on HELCOM data [27]

coastal zone. Illegal discharges of oil and petroleum products from ships, ship accidents, collisions, and groundings represent a significant threat to the Baltic Sea [9]. Fig. 2 proves that ships are primarily responsible for oil pollution in the Baltic Sea. In order to obtain the geographical distribution of oil spills, we put the confirmed oil spills registered by HELCOM in 1988–2002 on the same map. Traces of oil spills in Fig. 2 show the main ship routes in the Baltic Sea, as well as approaches to the major sea ports and oil terminals.

According to Global Marine Oil Pollution Information Gateway [26] and other sources [e.g., 2, 15], the major oil spills resulted from ship accidents in the Baltic Sea in 1970–2007 are listed below in the chronological order:

1970: *Othello* (Tralhavet Bay, Sweden, spill of 60,000 tons),
1977: *Tsesis* (off Nynäshamn, Sweden, spill of 1,000 tons),
1979: *Antonio Gramsci* (off Ventspils, Latvia, spill of 5,500 tons. Another incident in 1985, off Porvoo, Finland, spill of 580 tons),
1981: *Jose Marti* (off Dalarö, Sweden, spill of 1,000 tons),

1981: *Globe Asimi* (off Klaipeda, Lithuania, spill of 16,000 tons) [3],
1984: *Sivona* (in The Sound, Sweden, spill of 800 tons),
1990: *Volgoneft* (off Karlskrona, Sweden, spill of 1,000 tons),
2001: *Baltic Carrier* (international waters between Denmark and Germany, spill of 2,700 tons),
2003: *Fu Shan Hai* (between the Danish island of Bornholm and coast of Sweden, spill of 1,200 tons),
2003: *Haaga* (St.-Petersburg port, Russia, spill of 1,300 tons),
2007: *Golden Sky* (off Ventspils, Latvia, spill of 25,000 tons).

Since 1969 till 2011, in the Baltic Sea there were recorded about 20 other oil spills with a volume of 100–600 tons, and this occurred quite regularly during the last 40 years [15].

As far as oil exploitation at sea and on the coast is concerned, offshore operations have been taking place for some years in Polish waters (Baltic Beta, Petro Baltic and PG-1 platforms) [15]; two decades ago Germany operated two platforms very close to the coast; in March 2004 Russia started to drill for oil in the waters between the Kaliningrad area (the Russian Federation) and Lithuania, as well as there are Latvian plans to drill for oil in the waters between Latvia and Lithuania [26].

In June 2004 we (in cooperation with teams from P.P. Shirshov Institute of Oceanology, Russian Space Research Institute, Geophysical Center of Russian Academy of Sciences, and Russian Research Institute for Space Instrument-Making, Atlantic Research Institute for Fishery and Oceanography, and Marine Hydrophysical Institute of National Academy of Sciences of the Ukraine) organized daily service for monitoring oil spills in the southeastern Baltic Sea based on the operational receiving and analysis of data from the Advanced Synthetic Aperture Radar (ASAR) on board the *Envisat* satellite (European Space Agency), and from the Synthetic Aperture Radar (SAR) on board the *Radarsat* satellite (Canadian Space Agency) as well as of other satellites infrared (IR) and optical (VIS) data, metocean information and operational numerical modeling (Seatrack Web) of oil spill drift. This work was initiated by "Lukoil-Kaliningradmorneft" Company (Kaliningrad, Russia) in connection with the start of oil production from the continental shelf of Russia on the Lukoil D-6 oil platform in March 2004 [27–34]. The principal difference from the above-mentioned OCEANIDES Project was: (1) an operational regime of monitoring 24 h/day, 7 day/week during 18 months and (2) a multisensor, multiplatform, and multidiscipline integrated approach to oil spills detection and forecast of their drift.

The idea of this book came to us by the end of 2005, when in the framework of this monitoring contract with Lukoil Company, during 18 months we had received and analyzed the largest ASAR data set that anyone had ever had, as well as other satellite and in-situ information on oil pollution in the southeastern Baltic Sea, including waters of Russia, Lithuania, Latvia, and partially Poland, Sweden, and Estonia. We have to note that we had elaborated and established this operational monitoring system 3 years before EMSA established its CleanSeaNet service for the Baltic Sea countries (16 April 2007) [35]. Also, this was a pioneering oil pollution satellite monitoring operational service established in the Russian Federation. It is well known that since 1993 there has not been any regular aerial surveillance of oil spills in the Russian sector of the southeastern Baltic Sea and in the Gulf of Finland. Unfortunately, there is no aerial surveillance up to now not only in the Baltic Sea, but in all other Russian seas [36]. This is partially compensated by satellite monitoring performed mainly by several academic institutions and private companies.

The book addresses the main question: What do we know about oil pollution in the Baltic Sea? To answer this question we invited specialists and experts in oil pollution from all the Baltic Sea countries, as well as from HELCOM and EMSA, to write "national" chapters in the form of a review of knowledge on oil pollution. Unfortunately, we could not get representatives of all the Baltic Sea countries in the book team due to different reasons, but anyway we are very thankful to those who agreed to write a chapter and to those who did not, but with whom we had a pleasure to negotiate from several months to 2 years. Also, we would like to fill the gap in knowledge on oil pollution in Russian waters in the Baltic Sea, as well as to share our experience in operational satellite monitoring of oil pollution, which is little known in Western countries but can be successfully applied in other Baltic Sea countries, as well as to other inland and coastal seas in the world.

The book contains twelve chapters including Introduction and Conclusions written by the volume editors. This introduction to the book and the problem of oil pollution in the seas is followed by a chapter on HELCOM actions related to prevention of illegal and accidental oil pollution from ships in the Baltic Sea. The next chapter is devoted to the European Maritime Safety Agency CleanSeaNet activities in the Baltic Sea. Then the book has five chapters describing the state of oil pollution and monitoring systems in waters of Finland, Germany, Latvia, Lithuania, and Russia. This is followed by two chapters devoted to the Seatrack Web model – the HELCOM tool for oil spill prediction and identification of illegal polluters. The first one describes the model and examples of direct application of the model. The second is focused on the new capabilities of the model related to the Environmental Risk Assessment in the Baltic Sea. We could not pass up such a large project as the Nord Stream gas pipeline construction in the Baltic Sea and have included a chapter on satellite monitoring of its construction in the Gulf of Finland. The book ends with our conclusions.

The book is addressed to specialists working in different fields of marine, environmental, and remote sensing sciences. We hope it will serve as a useful handbook on oil pollution for international and governmental agencies, and policy makers who plan and manage oil and gas projects, construction of ports and terminals, shipping, fishery, recreation, and tourist activities in the Baltic Sea. Graduate and undergraduate students in marine and environmental sciences will find this book as a valuable resource of knowledge, information, and references on oil pollution in the Baltic Sea.

We were able to start working on this book in May 2010, when we signed a contract with Springer-Verlag and began negotiations with potential authors. During these 3 years till the publication of the book, there were several big accidents in the ocean, which resulted in serious oil pollution of the marine environment: the *BP* oil platform *Deepwater Horizon* in the Gulf of Mexico (20 April 2010, oil spill up to 627,000 tons and 23,000 km^2) [1, 37]; the Mumbai oil spill offshore India (7 August 2010, oil spill of 800 tons); the MV *Rena* grounding offshore New Zealand (5 October 2011, oil spill of 350 tons); the *Chevron* oil platform offshore Brazil (7 November 2011, oil spill up to 400 tons); the *Shell Bonga* oil spill offshore Nigeria (20 December 2011, oil spill of 5,500 tons and 923 km^2) [38]; the *Total* gas/oil platform *Elgin* in the North Sea (25 March 2012, oil spill of 89 km^2); the Arthur Kill storage tank spill (Sewaren, New Jersey) after hurricane Sandy (29 October 2012, oil spill about 1,100 tons). In total, in 2010–2012 20 oil spills of more than 100 tons occurred in the sea and on the land throughout the world.

Fortunately, no serious accidents occurred in the Baltic Sea during this time, but the resonance from the above-mentioned catastrophes in different parts of the world at the public, governmental, and international levels was so high that there are no doubts that a series of such kind of books devoted to oil pollution in the inland and coastal seas is required. We are very thankful to Springer-Verlag (The Handbook of Environmental Chemistry book series) that supported our idea, and we are glad that our initiative will be followed by the next volume “Oil pollution in the North Sea” which is under preparation. We have our own plans to continue this book series with the next two volumes on the Black and Caspian seas where we have put a lot of efforts in the monitoring of the marine environment since 2000 [34, 39, 40].

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HELCOM Actions to Eliminate Illegal and Accidental Oil Pollution from Ships in the Baltic Sea

Anne Christine Brusendorff, Samuli Korpinen, Laura Meski, and Monika Stankiewicz

Abstract The Baltic Sea countries have been quite successful in preventing major pollution spills from shipping, and establishing a system to monitor ship traffic and detect illegal oil spills using aerial and satellite surveillance. The regional cooperation is carried out in the framework of HELCOM, an intergovernmental organization of the nine coastal states and the European Union. Ships operating in the Baltic Sea have to follow strict global and regional anti-discharge regulations, and the number of illegal, deliberate oil discharges has decreased since 1980s substantially. While the risk of large accidental spills is constantly present, requiring that sufficient response capacities are available in the region, smaller oil discharges also pose a threat to, and have an impact on the marine environment of the Baltic Sea.

Keywords Baltic Sea, HELCOM, Impact of oil, Response to oil spills, Shipping accidents

Contents

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1 Introduction to HELCOM

For close to four decades the Baltic Marine Environment Protection Commission (the Helsinki Commission/HELCOM) has acted as the main environmental policy maker for the Baltic Sea area by developing specific measures to protect and conserve the unique Baltic marine environment, taking into account its sensitivity and the impacts of different pressures.

The work is based on the Convention on the Protection of the Marine Environment of the Baltic Sea Area [1], made up in 1974 and revised in 1992, following political changes and developments in international law. All countries surrounding the Baltic Sea as well as the European Union (EU) are parties to the HELCOM work.

The Convention takes a comprehensive approach to the protection of the Baltic marine environment in addressing all sources of marine pollution, be it from land, at sea, or in the air, and also includes the cooperation to improve response to accidents at sea.

This work is prepared and carried out in expert subsidiary groups, assisted by the HELCOM Secretariat, and political and strategic decisions are taken by high-level representatives of the ten Contracting Parties on an annual basis by the governing body, HELCOM. On a regular basis HELCOM meets at ministerial level, to get guidance and input on its further work from environmental ministers as well as ministers of other sectors.

Decisions are taken unanimously, meaning that all countries and the EU have to agree in order to further proceed with an issue.

In 2007 HELCOM, at a ministerial meeting in Krakow, Poland, adopted the HELCOM Baltic Sea Action Plan (BSAP), embracing an ecosystem approach to management of human activities impacting the marine environment. Within an overall vision of a healthy Baltic Sea, the ministers and the EU representative decided on goals for the main environmental challenges to the marine environment, on indicators for how to measure the progress in reaching these goals as well as importantly, on actions to be implemented on a Baltic wide scale in order to reach the goals.

Acknowledging the steadily growing maritime transportation and the thus growing environmental risks, a goal to achieve an environmentally sound maritime transportation in the Baltic was established. And two of the decided indicators were “No illegal discharges” as well as “Safe maritime traffic without accidental pollution”.

Prevention of pollution from maritime traffic has been a major item for the Baltic coastal countries since the beginning of their environmental cooperation in the 1970s. To ensure maritime safety in the Baltic Sea region, which is well-known for its narrow straits, shallow waters, archipelago areas, and ice coverage during winter time, HELCOM has decided on a great number of measures over the last more than 35 years.

HELCOM, working through intergovernmental cooperation between all nine coastal countries and the European Union, has produced many environmental gains. These gains validate the belief that the deterioration of one of the most polluted seas in the world can be arrested and the state of the marine environment improved.

2 International Regulations for Shipping

The international character of shipping strongly influences the elaboration of regulatory measures. This is firstly due to the fact that the regulations have to be applicable to the whole of the Baltic Sea, including internal waters, the territorial seas, and the exclusive economic zones, and secondly, due to the fact that the regulations have to be applicable to all ships entering and leaving the Baltic Sea, and not only those sailing under the flag of one of the Baltic Sea States.

The legal regime to be followed is laid down in the United Nations Convention on the Law of the Sea, 1982, the UNCLOS Convention [2], which balances the rights and duties between flag, coastal, and port states. With the granting of the overall right of freedom of navigation, including transit passage in international straits and the right of innocent passage through the territorial seas, the UNCLOS Convention correspondingly states the obligation of the flag state to, as a minimum, adopt laws and regulations, established by the International Maritime Organization (IMO), and to ensure, through enforcement, that its ships are complying with relevant rules.

The right of the coastal/port states to adopt rules to reduce and control pollution to the marine environment from ships is limited by the above rights of the flag state. Thus, in the territorial seas the right of the coastal state to adopt laws and regulations is restricted by the right of ships to innocent passage and these may in any case not apply to the design, construction, manning, or equipment other than giving effect to generally accepted international rules or standards. In international straits the right of the coastal state is generally limited to giving effect to the applicable/generally accepted international regulations. In the Exclusive Economic Zone, apart from particularly and clearly defined areas, the right of the coastal state is restricted to generally accepted international rules and standards established by IMO.

The right of the coastal state to enforce infringements of pollution prevention control measures depends on the spatial zone where the infringement took place as well as the gravity of the offence. These measures include physical inspection, at first limited to examination of certificates required to be carried by generally accepted international rules and standards, and only in case of substantial non-correspondence, or need of additional information to verify a suspected violation enlarged to a further physical examination. In case of violations having taken place in the Exclusive Economic Zone, the measures are restricted to requiring the vessel to give information, *inter alia,* regarding the last and next port of call.

Only in case of casualties where there are grounds to expect they might result in major harmful consequences, is the coastal state entitled to take and enforce measures even beyond the territorial seas. As a general rule, however, proceedings in respect of violations beyond the territorial seas have to be suspended in case the flag state institutes proceedings within six months.

Therefore, the IMO is the most appropriate international forum to seek regulations on environmental protection and safety measures for ships, including ensuring their harmonized implementation in the Baltic Sea area. The above overview also emphasizes the importance of the cooperation between the Baltic Coastal States in promoting and reaching decisions at the international level in the interest of the protection of the Baltic Sea environment.

Also within the EU a large number of pollution prevention and maritime safety measures have been adopted covering the key aspects of the IMO Conventions, thereby ensuring a harmonized and effective implementation within the EU. In 2002 the EU established the European Maritime Safety Agency (EMSA) as a major source of support to the European Commission and the EU Member States in the field of maritime safety and prevention of pollution from ships, with its mandate further refined and enlarged to cover assisting the Commission in monitoring the implementation of the EU legislation, developing maritime information capabilities at the EU level and establishing marine pollution preparedness, detection, and response capabilities. Regarding the latter one, EMSA has established a European network of stand-by oil spill response vessels, to top-up the existing national resources, as well as established a European satellite oil spill monitoring service (CleanSeaNet).

When it comes to response to pollution incidents at sea and the national and trans-national response to such incidents, this issue needs to be dealt with at the regional level. This is due to the fact that there is a need to consider the national capability as a precondition to be able to cooperate at the trans-national level in case of bigger accidents. For this reason HELCOM measures (see Sect. 5.2) have been put in place:

- To establish the national response capacity;
- To guide the trans-national cooperation (HELCOM Response Manual);
- To practice the cooperation in real-time, including both aerial surveillance operations and response exercises.

The work of HELCOM in the field of pollution prevention and safety of navigation as well as response to incidents at sea is carried out in accordance with these principles and has paved the way for a very effective and close regional coordination.

Such cooperation in the Baltic Sea is especially needed due to the intense shipping and the steadily increasing oil transportation, which raises the risk of a large oil spill, caused by grounding or a collision. Ensuring maritime safety and preventing pollution from ships is an aim which can only be achieved by a continuous process of improvement.

3 Oil Spills in the Baltic Sea

3.1 Shipping Activities

The Baltic Sea has always played an important role to people living in the surrounding countries. The sea is used for a multitude of maritime activities like commercial fishing, leisure boating, and extraction of sea-floor resources. For the future there are also extensive plans for offshore wind parks and gas pipelines in the area. Additionally and most importantly, the Baltic Sea is a very busy traffic route for shipment of goods and passenger traffic.

Due to its narrow straits, winding passages, shallow waters, and vast labyrinths of skerries and islands, the Baltic Sea is a difficult area for ships to navigate. Winter conditions in the northern Baltic Sea, where waters freeze up every winter, make navigation even more challenging. The busy waters where shipping lanes cross, and many fishing vessels operate, also result in increasing risks of major pollution accidents, which could have a devastating impact on the marine environment, especially in the coastal waters.

During the last decade shipping has steadily increased in the Baltic Sea, reflecting intensifying international cooperation and economic prosperity. Since mid-2005 the Baltic Sea countries are able to monitor maritime traffic with the use of the Automatic Identification System (AIS), invented for the exchange of information between ships, and between ships and shore-based stations. The data derived from this monitoring system provides for annual reports and statistics on ships' traffic in the Baltic Sea area as well as trends compared to earlier years.

At any time around 2,000 sizeable ships are normally at sea in the Baltic and each month around 3,500–5,000 ships ply the waters of the Baltic. In 2010, vessels entered or left the Baltic Sea via Skaw 56,564 times (Fig. 1). This figure has increased by more than 10% since 2006 (51,628 crossings). Approximately, 19% of those ships were tankers, 44% other cargo ships, and 4% passenger ships. Additionally, 31,933 ships passed through the 98-kilometer long Kiel Canal (in 2010).

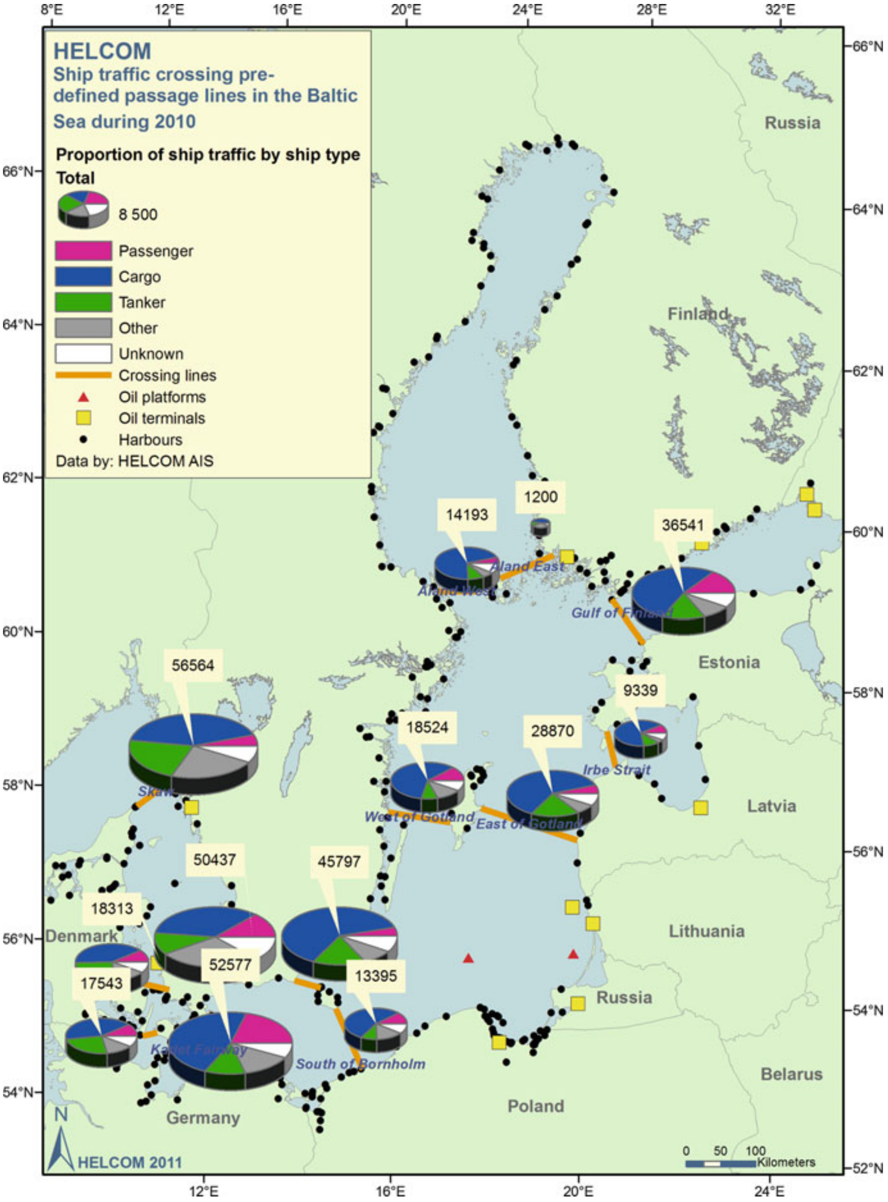


Fig. 1 Number of ships crossing Automatic Identification System (AIS) fixed lines in the Baltic Sea according to the type of the vessels, 2010

Following the increase between 2006 and 2008, an overall traffic in the Baltic Sea has declined in recent years (Fig. 2), which is related to the economic downturn in the region.

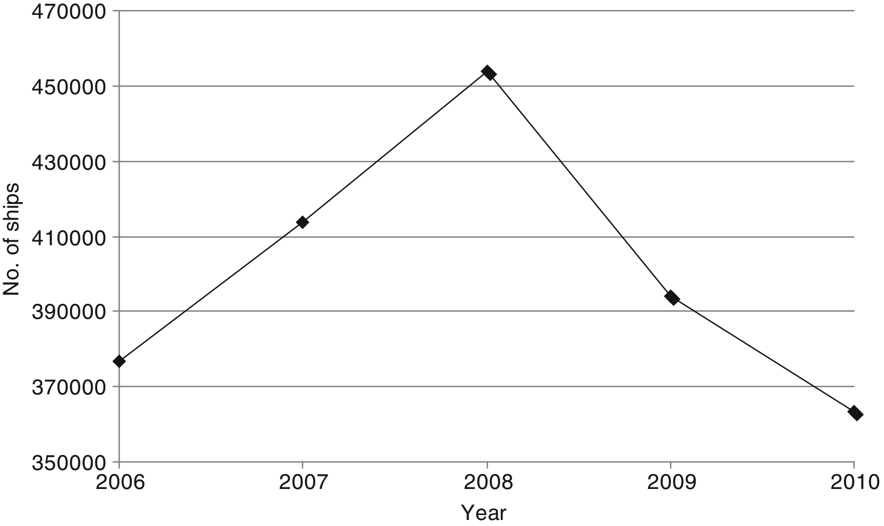


Fig. 2 Overall traffic in the Baltic Sea, 2006–2010, based on HELCOM AIS data

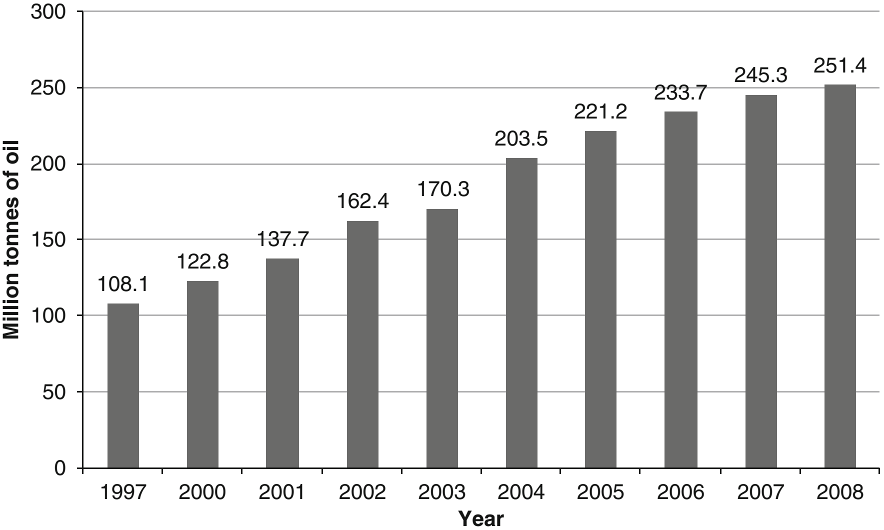


Fig. 3 Amount of oil transported via the 16 largest oil terminals in the Baltic Sea area during 1997, and 2000–2008. Data source: HELCOM MARIS

The Baltic Sea accounts for around 9% of total cargo and 11% of oil transportation in world traffic. The amount of cargo shipped on the Baltic in 2008 was 822.4 million tonnes, with the fastest annual growth taking place in Russia [3]. In 2008, over 251 million tonnes of oil were shipped on the Baltic, more than double of the shipment in 2000 (Fig. 3). The use of much bigger tankers is also expected, meaning that there will be more tankers in the Baltic carrying 100,000–150,000 tonnes of oil.

3.2 Shipping Accidents

Maritime transportation is generally one of the most environmentally friendly ways of transporting goods, but there are also potential negative impacts like ship-generated wastes, air pollution, releases of alien species in ballast water, accidental, and illegal pollution. A number of shipping accidents, of which groundings and collisions are the most common, occur every year in the Baltic. Only a few of these incidents have so far resulted in serious pollution. The last major oil spill (more than 100 tonnes of oil) in the Baltic Sea happened in 2003 as a result of the bulk carrier “Fu Shan Hai” colliding with the container ship off Bornholm Island in Denmark.

Overall, there is a slightly decreasing trend in the number of shipping accidents in the Baltic Sea (Fig. 4) [4]. A more profound decreasing trend is observed in busy waters of the Gulf of Finland for groundings and collisions, and in the southwestern part of the Baltic Sea, including Danish straits, for groundings. On average there are about 130 accidents per year in the Baltic Sea, mostly occurring very close to shore or in harbors.

The number of shipping accidents in the Baltic Sea resulting in some kind of pollution, usually containing not more than 0.1–1 tonnes of oil, ranges from zero to 13 annually (Fig. 4). Although most of the shipping accidents in the Baltic Sea do

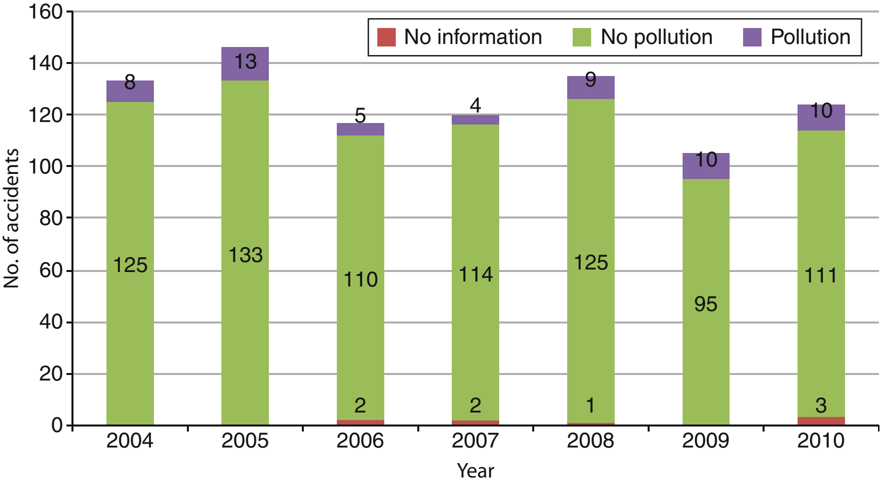


Fig. 4 Number of reported shipping accidents in the Baltic Sea during the period 2004–2010, with and without causing pollution

not result in any pollution, the risk of a major spillage of oil or hazardous substances is profoundly present due to heavy traffic and the large amount of tankers in the Baltic Sea.

Overall, the launch of HELCOM AIS, the traffic separation schemes and the ship reporting systems introduced in the Baltic, e.g., the Gulf of Finland Reporting System (GOFREP), have had a positive effect on the safety of navigation and have contributed to the reduced number of accidents over the recent years.

3.3 Assessment of Risk of Major Oil Pollution

One way of dealing with risks of shipping activities is to conduct a formal safety assessment (FSA), an IMO process which assesses the risks and evaluates the costs and benefits of different risk control options. A region-wide risk assessment, with a character of FSA has been carried out within an EU-funded project called BRISK (Subregional risk of spill of oil and hazardous substances in the Baltic Sea), with the main purpose to optimize the coastal countries' resources to respond to pollution at sea.

The BRISK assessment indicates hot spots for accidents and spills as well as estimates the so-called return period – expected intervals between spill events. According to BRISK, the total number of accidents in the Baltic Sea corresponds to approximately 44 groundings and 4 collisions with ships of 300 gross tonnage and above per year. Based on the estimated risks of accidents, the risk of spills has been analyzed, covering all size classes of spills, up to 150,000 tonnes.

The spills of 5,000 tonnes of oil and above are estimated to occur once every 26 years for the whole Baltic Sea, whereas the spills of 300–5,000 tonnes are expected once every four years. According to the assessment, the risk of spills of up to 300 tonnes is dominated by illegal discharges, and accidental small spills play a minor role in this size category.

There are also substantial differences in the intervals between possible spills in the two biggest size ranges in different subregions of the Baltic Sea area (Table 1).

Table 1 Estimates of expected intervals between spill events

Subregion	Large accidents: 300–500 tonnes spilt (years)	Exceptional accidents: 5,000 tonnes and more (years)
1. Gulf of Bothnia	36	600
2. Gulf of Finland	39	255
3. Northern Part of the Baltic Proper	30	175
4. Southeastern Baltic Proper	140	1,060
5. Southwestern Baltic Proper	17	97
6. Sound and Kattegat	11	65
Entire Baltic Sea	4	25

These intervals are the shortest in the Sound and the Kattegat, closely followed by the southwestern Baltic Sea, and the longest in southeastern Baltic Proper. Spills are expected to be also less frequent, in the Gulf of Finland and Gulf of Bothnia (more than four times) and northern part of the Baltic Proper (almost three times), than in the Sound and Kattegat.

3.4 Illegal Oil Discharges

Deliberate, illegal discharges from ships are observed each year by national surveillance aircrafts and satellites over the Baltic Sea area. The number of detected oil spills in the Baltic Sea has been decreasing over the past years, even though the density of shipping has grown and aerial surveillance in sea by the countries has increased. In 2010 a total of 149 illicit oil spills were detected (Fig. 5), which is one third of the spills observed a decade earlier [5].

The size of slicks is also declining, the majority being smaller than a cubic meter, or even less than 100 L. Of the total 149 oil discharges detected in 2010, 136 (91%) were smaller than 1 m^3, and of these oil spills as much as 97 were even smaller than 0.1 m^3 or 100 L. Two oil spills were over 10 m^3 in size and the total estimated volume of oil spills observed in 2010 amounted to 49 m^3. The share of each size category of oil spills is presented in Fig. 6. The trend of the spill sizes for the years 1998–2010 is presented in Fig. 7. Figure 8 further illustrates the trend in total

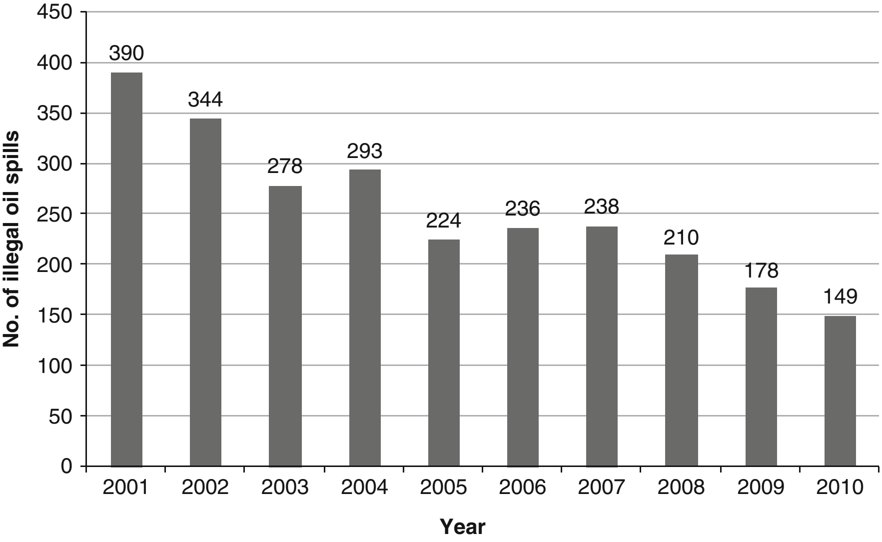


Fig. 5 Number of detected illegal oil spills in the Baltic Sea area, 2001–2010

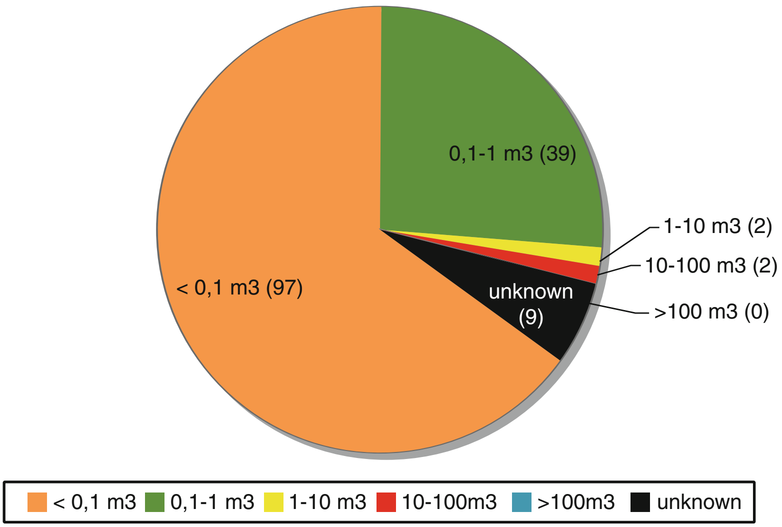
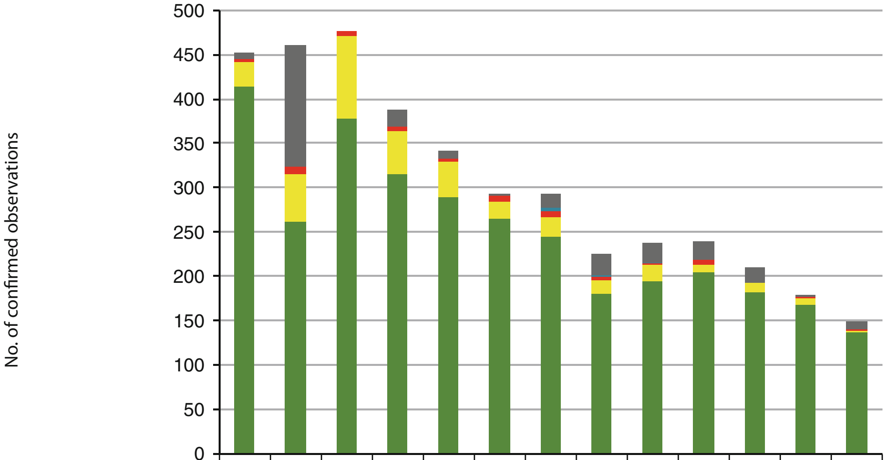


Fig. 6 Illegal oil discharges detected in the Baltic Sea during aerial surveillance in 2010 according to size of spill



	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
⬛ unknown	7	138	0	19	9	2	17	23	21	21	18	2	9
🟦 >100 m3	0	0	0	0	0	0	2	2	1	0	0	0	0
🟥 10-100 m3	3	8	6	5	4	6	8	4	2	4	0	1	2
🟨 1-10 m3	28	54	93	50	40	20	22	16	18	9	10	7	2
🟩 < 1 m3 (incl. < 0,1 m3)	414	261	377	314	288	264	244	179	194	204	182	168	136

Fig. 7 Illegal oil discharges by spill size observed during aerial surveillance in the Baltic Sea, 1998–2010

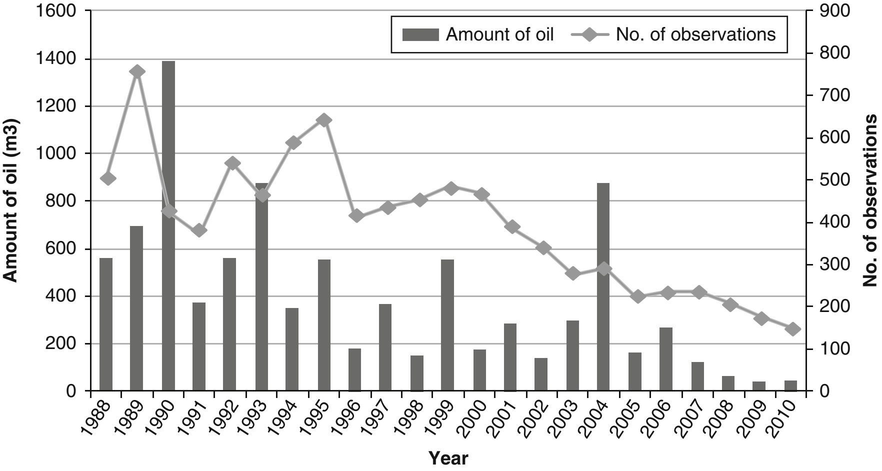


Fig. 8 Total estimated amount of oil detected versus number of observations, 1988–2010

amount of oil detected and the number of spills observed in 1988–2010. Most illegal oil discharges are detected along major shipping routes (Fig. 9).

Regular aerial surveillance flights (see Sect. 5.3) have contributed significantly to the decrease in illegal discharges because ships are aware that their illicit polluting activities can be detected.

4 Impact of Oil on Marine Environment and Its Assessment in the Context of Good Environmental Status

Maritime traffic inflicts multiple pressures on the Baltic Sea biodiversity including noise, release of nutrients, coastal erosion, disturbance of seabed, oil spills, and spreading of alien species. Impacts of this array of pressures on the marine ecosystem are wide, affecting not only species but also quality of habitats and the marine environment in general. One of the major oil accidents globally – the Prestige oil spill in the Atlantic coast of Spain in 2002 – caused significant short-term reduction in phyto- and zooplankton biomass [6], reduced abundance and species richness of littoral invertebrates [7] and severely affected fish reproduction [8]. It killed or harmed about 200,000 birds [9], caused stranding of marine mammals and turtles [10] and significant egg and adult mortality of peregrine falcons [9]. Long-term chronic effects of such large-scale environmental catastrophes are well known from the tens of studies after the Exxon Valdez oil spill in Alaska in 1989 (e.g., [11]).

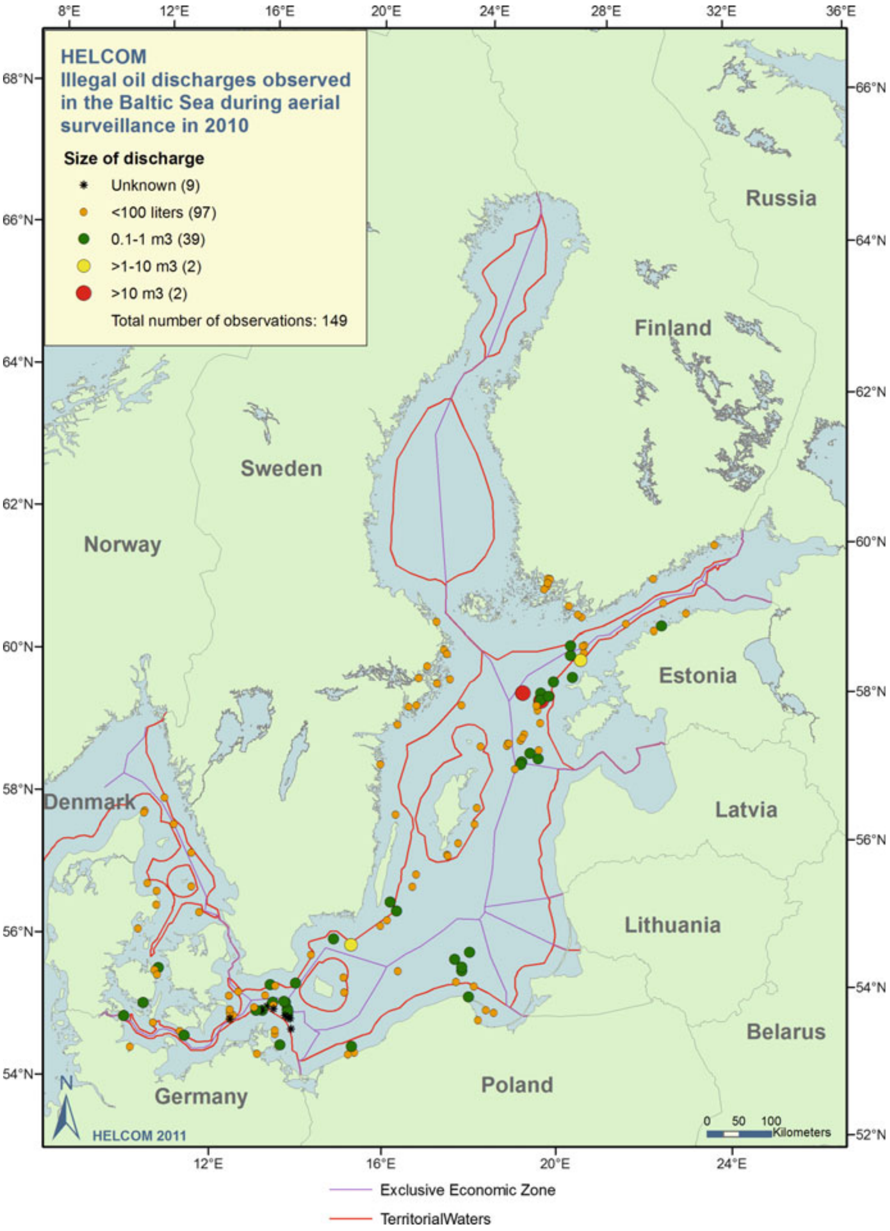


Fig. 9 Spatial distribution of illegal oil discharges in the Baltic Sea during aerial surveillance in 2010

The Baltic Sea has avoided a large-scale oil spill despite the high volume of the transported oil and the shallow and narrow navigation routes. There have, however, been small oil spills in the sea, which show – in addition to the experience from other sea areas and experimental science – the impacts of oil spills in the Baltic Sea.

4.1 Impacts on Lower Trophic Levels

Species in the lower end of the trophic chain, such as plants (phytoplankton, periphyton, and macrophytes) and invertebrate fauna (zooplankton and zoobenthos), form the basis of the functioning marine ecosystem. Increased mortality or intoxication of these species cause not only decreased food availability to higher trophic levels but also biomagnification of several hazardous substances from the oil in sea birds and marine mammals and degradation of habitat quality and several crucial ecosystem services, which are operated by the organisms at the lower trophic levels [12, 13].

The exposure of molluscs to crude oil in vitro has been shown to cause mainly sublethal effects [14]. The clam *Macoma balthica* buries deeper to sediment as a response to oil exposure and the mussel *Mytilus edulis* detaches from hard substrata. The gastropod *Theodoxus fluviatilis*, which is an abundant epiphytic grazer in the littoral zone, was shown to slow its crawling, ending to total immobilization after 2 h of exposure time [14]. A dominating littoral crustacean *Gammarus oceanicus* was shown to suffer from impaired swimming performance, reduced egg production, and increased mortality after experimental exposure to crude oil and refined oil [15]. In the studies outside the Baltic Sea, soft-bottom amphipod species have been suggested to be particularly sensitive to impacts of oil spills [16].

Field sampling after the Tsesis oil spill in October 1977 on the Swedish east coast (Baltic Proper) revealed that the abundance of amphipods (*Pontoporeia femorata*) and polychaetes (*Bylgides sarsi*) was reduced to less than 5% of their pre-spill abundance and the meiofauna species (ostracods, harpacticoids, Turbellaria, and kinorhynchs) showed clear reductions in abundance [17]. Indirect impacts of the Tsesis oil spill were seen for example as a high frequency of malformed embryos of *P. femorata*. Reproduction rate of the affected species returned to normal levels after two years of the spill, but the authors estimated that the full recovery of the local ecosystem may take a decade. The Tsesis oil spill was only 1,000 tonnes, but it happened within an archipelago area, which increased its impacts on the littoral zone. Similar effects were seen after the Antonio Gramsci oil spill in 1979 with 5,000–6,000 tonnes of crude oil spilled in the eastern Baltic Proper [18]. In the studies after the Antonio Gramsci oil spill, it was also noticed that the zone of the perennial alga *Fucus vesiculosus* was impacted more severely than the hydrolittoral zone of ephemeral seaweeds [18].

4.2 Oil Spills Destroy Fish Larvae

Light oil and crude oil have been shown to cause malformations and death to hatched larvae of Baltic herring in laboratory conditions [19]. Likewise, exposure of the Pacific herring to low concentrations of polynuclear aromatic hydrocarbons (PAHs, 0.7 ppb) caused malformations, genetic damage, mortality, and decreased size and inhibited swimming [20]. PAH concentrations as low as 0.4 ppb caused sublethal responses such as yolk sac edema and immaturity consistent with premature hatching. Field estimates of the effect of the Exxon Valdez accident on the mortality of herring larvae in the Prince William Sound (Alaska) reached a loss of 52% of larvae.

4.3 Seabirds Are Sensitive to Small Oil Spills

Seabirds are very sensitive to the effects of oil in the sea. Even small amounts of oil on the sea surface absorbs to the plumage causing hypothermia. Oiled birds suffer also from intoxication. Especially, wintering populations in the offshore areas have been shown to be heavily affected by the oil spills [21]. Annually, 100,000–500,000 ducks, guillemots, and other bird species are estimated to die due to small oil spills in the Baltic Sea [22]. Long-tailed Duck (*Clangula hyemalis*) is a species of worldwide concern for which the Baltic is of special importance. The species has been the most numerous bird wintering in the Baltic Sea, but is now most likely rapidly decreasing in numbers, because of chronic oiling [23]. An important shipping route from the southern Baltic Sea to the Gulf of Finland with approximately 22,000 ship passages per year passes through the Natura 2000 site Hoburgs Bank (south of Gotland). Around 150–200 oil spills, most of them less than 1 tonne, are registered along the route each year. Weekly winter surveys of oiled birds at southern Gotland between 1996/1997 and 2006/2007 have shown that several tens of thousands of Long-tailed Ducks are annually killed by oil in the central Baltic Sea [24, 25]. Furthermore, analyses of Long-tailed Ducks drowned in fishing gear at Hoburgs Bank showed that a large proportion, about 12% of the birds, had oil in the plumage [25]. Encouragingly, oil spills seem to have decreased during the recent years, possibly due to better enforcement.

The oil spills have also intoxicating impacts on sea birds. In the northwestern Spain, embryos and adults of peregrine falcon died due to toxic concentrations of PAHs from the Prestige accident [9]. In Alaska, the hepatic activity in Harlequin ducks was significantly higher in the oil area than elsewhere [26]. In contrast, heavy metal concentrations in sea birds in the northwestern Spain, some years after the Prestige oil spill, were not higher than in other areas of the North Atlantic coast [27].

4.4 Marine Mammals Accumulate Hazardous Substances from Oiled Prey

Marine mammals do not seem to suffer from the acute effects of oil exposure [28], except in the case of very large oil spills such as the Exxon Valdez [29]. However, in a review paper of the effects of the oil on grey seal Jenssen [28] suggested that chronic effects as a result of bioaccumulating of organochlorines (PCBs and DDTs) from the oil may cause greater concern than the exposure to the oil itself. The concentrations of organochlorines are high in the marine mammals in the Baltic Sea, but the main source of the compounds has been judged to be pulp industry [30].

4.5 Ecosystem Effects

The impact of a large oil spill on the Baltic marine and coastal ecosystem is difficult to predict because of the differences between the Baltic Sea and the oceanic ecosystems which have experienced large oil spills. The Baltic food web consists of fewer species than oceanic ecosystems, being probably less intricate as regards the interspecific relationships but, on the other hand, risking the loss of all food sources for a predatory species. The cascading effects of the decreased abundance of a prey species are well documented in the Baltic Sea [31, 32].

The degradation of habitats in the water column, seabed or shore is a serious consequence of oil pollution. In the Prince William Sound, Day et al. [33] noticed a clear initial decrease in the habitat suitability of oiled breeding habitats for 42 species of birds. Coastal habitats are breeding and feeding areas of many terrestrial and marine species that spend most of their life cycle in the open sea. Hence, the effects of oil pollution – either degraded habitat quality or increased exposure to hazardous substances – spread further than the oiled area.

4.6 How to Measure the Good Environmental Status as Regards the Oil Pollution?

Maritime traffic is addressed by one of the four main segments of the BSAP. A number of management objectives have been set in order to point out the main areas of concern (see [34]). The management objectives represent normative definitions to reduce anthropogenic pressures to reach the Good Environmental Status (GES). There are two BSAP management objectives for the oil spills: “No illegal discharges” and “Safe maritime traffic without accidental pollution,” which both are clearly more linked to the human activities than the environmental status or even impacts of the pressures. A step closer to the status objectives would be to define an objective for the *impacts* of the oil spills, such as “No oiled sea birds” or

"No petrogenic PAHs in mussels," which could be used indirectly to estimate GES in an area.

Objectives more directly linked to GES should define the *status* of the environment and not the pressures or their impacts. In the case of the impacts of the oil spills, an objective for the environmental status could be "Viable sea bird populations" or "Reproduction of predatory birds at natural levels." The European Marine Strategy Framework Directive (MSFD) sets clear normative objectives for GES [35]. The 11 objectives are called qualitative descriptors for GES and they define the status of the marine environment as regards its biological diversity, eutrophication, hazardous substances, condition of seabed and hydrography, and introduction of noise and litter. Assessment of GES as regards the impacts of oil spills can be linked directly or indirectly to at least five GES descriptors:

D1: Biological diversity is maintained. The quality and occurrence of habitats and the distribution and abundance of species are in line with prevailing physiographic, geographic, and climatic conditions.
D4: All elements of the marine food webs, to the extent that they are known, occur at normal abundance and diversity and levels capable of ensuring the long-term abundance of the species and the retention of their full reproductive capacity.
D6: Sea-floor integrity is at a level that ensures that the structure and functions of the ecosystems are safeguarded and benthic ecosystems, in particular, are not adversely affected.
D8: Concentrations of contaminants are at levels not giving rise to pollution effects.
D9: Contaminants in fish and other seafood for human consumption do not exceed levels established by Community legislation or other relevant standards.

The EU MSFD requires the Member States to assess each of the GES descriptors by the use of associated criteria and indicators [36]. The criteria and indicators for each of the descriptors are given in Table 2. The descriptors 1 (distribution, abundance and condition of populations, habitats, and the functioning of the ecosystem), 4 (functioning of the food web), and 6 (sea-floor integrity) are status objectives for biodiversity, whereas the descriptors 8 and 9 (hazardous substances) are status objectives for water quality and contamination. Pressure indicators can be used indirectly to measure the status objectives or directly the impact of management measures. Thus, the assessment of GES in the MSFD is not done solely on the basis of status objectives (i.e., measuring the actual status), but also by measuring pressures (i.e., measuring the progress toward the good status).

The GES criteria and indicators in the EU MSFD are indicative in the sense that more specific indicators can be used to assess the state of the ecosystem. For example, the impacts of oil spills can be seen in the polychaete/amphipod ratio in soft-bottom communities, in the nematode/copepod ratio in the meiobenthos [16], in the extent of oiled habitats or abundance of oiled sea birds, or by specific measurements of petrogenic contaminants in organisms. The tendency in the marine assessments is currently, however, not in separate assessments, but in the development of methods to integrate indicators, which measure GES from different aspects [23, 30, 37, 38], and in holistic assessments [38], which include not only status indicators but also indicators for impacts, pressures, drivers, and management responses.

Table 2 Descriptors, criteria and indicators for good environmental status in the EU Marine Strategy Framework Directive related to impacts of oil spills

Criteria	GES indicator
Descriptor 1.	
1.1 Species distribution	1.1.1 Distributional range
	1.1.2 Distribution pattern within the latter
	1.1.3 Area covered by the species (for sessile/benthic species)
1.2 Population size	1.2.1 Abundance and/or biomass
1.3 Population condition	1.3.1 Population demographic characteristics: (body size or age class structure, sex ratio, fecundity rates, survival/mortality rates)
	1.3.2 Population genetic structure
1.4 Habitat distribution	1.4.1 Distributional range
	1.4.2 Distributional pattern
1.5 Habitat extent	1.5.1 Habitat area
	1.5.2 Habitat volume
1.6 Habitat condition	1.6.1 Condition of the typical species and communities
	1.6.2 Relative abundance and/or biomass
	1.6.3 Physical, hydrological and chemical conditions
1.7 Ecosystem structure	1.7.1 Composition and relative proportions of ecosystem components
Descriptor 4.	
4.1 Productivity of key species or trophic groups	4.1.1 Performance of key predator species using their production per unit biomass
4.2 Proportion of selected species at the top of food webs	4.2.1 Large fish (by weight)
4.3 Abundance/distribution of key trophic groups and species	4.3.1 Abundance trends of functionally important selected groups/species
Descriptor 6.	
6.1 Physical damage, having regard to substrate characteristics	6.1.1 Type, abundance, biomass and areal extent of relevant biogenic substrate
	6.1.2 Extent of the seabed significantly affected by human activities for the different substrate types
	6.2.1 Presence of particularly sensitive and/or tolerant species
6.2 Condition of the benthic community	6.2.1 Presence of particularly sensitive and/or tolerant species
	6.2.2 Multi-metric indexes assessing benthic community condition and functionality, such as species diversity and richness, proportion of opportunistic to sensitive species
	6.2.3 Proportion of biomass or number of individuals in the macrobenthos above some specified length/size
	6.2.4 Parameters describing the characteristics (shape, slope and intercept) of the size spectrum of the benthic community

(continued)

Table 2 (continued)

Criteria	GES indicator
Descriptor 8.	
8.1 Concentration of contaminants	8.1.1 Concentration of the contaminants mentioned above, measured in the relevant matrix (such as biota, sediment and water) in a way that ensures comparability with the assessments under Directive 2000/60/EC
8.2 Effects of contaminants	8.2.1 Levels of pollution effects on the ecosystem components concerned, having regard to the selected biological processes and taxonomic groups where a cause/effect relationship has been established and needs to be monitored
	8.2.2 Occurrence, origin (where possible), extent of significant acute pollution events (e.g. slicks from oil and oil products) and their impact on biota physically affected by this pollution
Descriptor 9.	
9.1 Levels, number and frequency of contaminants	9.1.1 Actual levels of contaminants that have been detected and number of contaminants which have exceeded maximum regulatory levels
	9.1.2 Frequency of regulatory levels being exceeded

5 Regional Work to Prevent and Combat Oil Spills

5.1 Safety of Navigation

While recognizing that the IMO is a global regulator of shipping, also regional measures to increase the safety of navigation are undertaken by the Baltic Sea countries. The most voluminous set of such measures were adopted by the ministers of the environment and of transport in the form of the Copenhagen Declaration [39], covering new and improved routing measures, improved hydrographic services, AIS, phasing out the use of single hull tankers, port State control, places of refuge, safety of winter navigation, and adequate response capacities. The ministers also agreed to investigate the benefits from designating parts of the Baltic Sea as a Particularly Sensitive Sea Area (PSSA).

PSSA is an area that needs special protection through action by the IMO because of its significance for recognized ecological, socio-economic or scientific reasons and because it may be vulnerable to damage by international shipping. The Baltic Sea is such an area with the special attributes, like unique biodiversity, which are at risk of damage arising from the heavy and increasing international shipping activities. Following a proposal in 2002, the Baltic Sea area, except for the waters of the Russian Federation, has been decided in 2005 to become a PSSA.

The PSSA is linked to associated protective measures (APM) by the IMO to prevent, reduce, or eliminate risks from shipping activities. The available APM include:

- To designate an area as a Special Area and/or as an Emission Control Area under MARPOL Annexes [40] or application of special discharge restrictions to ships operating in a PSSA;
- To adopt ships' routing and reporting systems near or in the area, under the SOLAS Convention [41];
- To develop other measures, such as a compulsory pilotage schemes or vessel traffic management systems.

Until now numerous ship routing systems have been established in the Baltic Sea area, including a number of traffic separation schemes and deep water routes, ship reporting, recommended pilotage, measures related to safety of winter navigation. Mariners' Routeing Guide for the Baltic Sea has been prepared and is available in a form of a chart serving as a single source of navigational information for ships sailing in the Baltic Sea. Web-based version of the Mariners' Routeing Guide for the Baltic Sea has also been produced.

The Baltic Sea has also been designated, among others, as a Special Area under MARPOL Annex I prohibiting the discharge of oil from ships.

5.2 Response to Oil Pollution

To ensure the safety of navigation, various measures have been adopted at the global level by the IMO, at the regional level by HELCOM, and at the national level by the Baltic Sea States. But even though all safety of navigation measures would be in place and as long as ships ply the waters of the Baltic Sea, the risk of oil spills exists.

The cooperation in combatting spillages of oil in the Baltic Sea area is based on the Helsinki Convention and HELCOM Recommendations on combatting matters, adopted by the Helsinki Commission.

Regional principles and procedures for international response operations in the Baltic Sea have been laid down in the HELCOM Response Manual. The Manual is a framework guiding the nine nations how to act in case of major oil pollution, starting from alerting the neighboring countries and exchanging the details on an accident to requesting foreign assistance and solving the related financial matters.

HELCOM Recommendations determine the required minimum national ability to respond to pollution incidents threatening the marine environment of the Baltic Sea, including adequate equipment, ships, and manpower prepared for operations in coastal waters as well as high seas.

Likewise, HELCOM has agreed on guidelines for how to designate places of refuge, in case of accidents, on an overall Baltic scale, irrespective of in whose waters the accident has occurred (HELCOM Recommendation 31E/5).

Overall, the national resources to respond to pollution at sea are substantial, with more than 70 oil combatting vessels on stand-by located around the Baltic Sea. Six new oil combatting ships will become operational within the next three years. Additionally, three oil spill recovery vessels are chartered by the EMSA in the Baltic Sea to top-up the HELCOM response resources. These vessels are in principle able to reach any place in the region within some hours of being notified of an oil spill accident.

An important aspect of maintaining the readiness to respond to pollution is exercising. Several kinds of exercises are conducted under the HELCOM flag, including the annual BALEX DELTA exercises, which test the alarm procedures and response capability of the coastal countries in case of a major accident. The general objective of the BALEX DELTA exercises is to ensure that every Contracting Party is able to lead a major response operation.

5.3 Enforcement of Anti-discharge Regulations

One of the tools to enforce the existing anti-discharge regulations is aerial surveillance for illegal oil spills from ships.

According to the Helsinki Convention and the HELCOM Response Manual, the Baltic Sea countries shall develop and ply individually or in cooperation, surveillance activities covering the Baltic Sea area in order to spot and monitor oil and other substances released to the sea, using, *inter alia*, airborne surveillance equipped with remote sensing systems.

The purpose of aerial surveillance is to detect spills of oil and other harmful substances which can threaten the marine environment of the Baltic Sea area. These spills caused by accidents or made in contravention of international Conventions will be registered and, if possible, sampled from both the sea surface and on board the suspected offender.

The aerial surveillance is complemented by satellite surveillance to enable bigger area coverage and optimization of flight effectiveness.

Within the framework of the Helsinki Convention close cooperation on airborne surveillance has been established through:

- Regular National Flights;
- Setting up special flights such as CEPCO Flights (Coordinated Extended Pollution Control Operation Flights);
- Standardization of reporting formats and exchange of information;
- Working together in improving existing systems and developing new techniques to enhance the information obtained.

The Baltic Sea countries have conducted national airborne surveillance since late 1980s. The HELCOM states aerial surveillance fleet comprises more than 25 aircrafts and helicopters, the majority of which are equipped with remote sensing

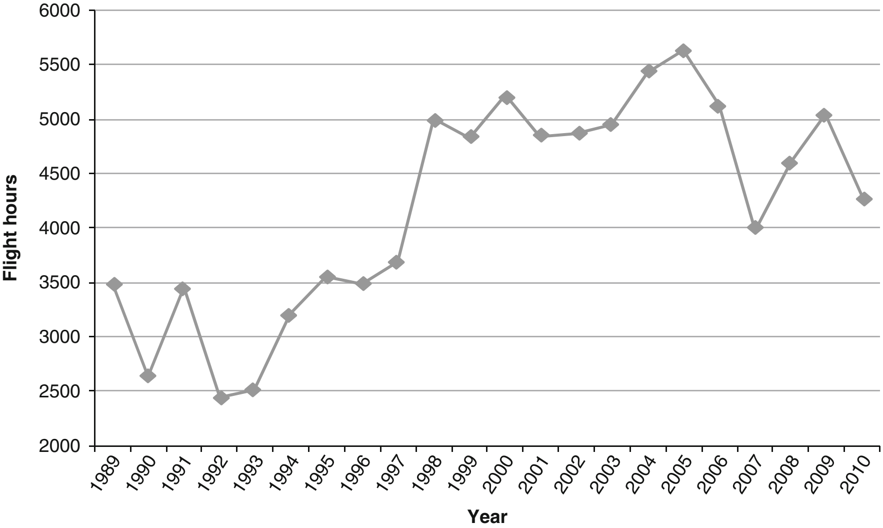


Fig. 10 Total number of flight hours in the Baltic Sea area during aerial surveillance, 1988–2010

equipment such as side-looking airborne radar (SLAR), infrared (IR) and ultraviolet (UV) cameras, and photo and video equipment.

In 2010, a total of 4,279 surveillance flight hours were carried out by the Baltic Sea countries, which is 23% more than in 1989 when the surveillance started (Fig. 10). A certain flight proportion is ensured for detections in darkness, when deliberate discharges are more likely to occur. In 2010, 12% of all flight hours were at night [5].

Apart from regular national surveillance, twice per year the Baltic Sea countries jointly undertake CEPCO flights to monitor main shipping routes for 24 h or more. The first Baltic SuperCEPCO, where aircrafts from several countries maintained continued surveillance for several days, was held in 2009 and the second Baltic SuperCEPCO was arranged in 2011.

In addition to the aerial surveillance the Baltic Sea countries utilize satellite images to detect illegal discharges of oil. Satellite surveillance in the Baltic Sea area has been intensified since 2007 thanks to the CleanSeaNet satellite surveillance service, provided by the EMSA. The satellite images are delivered in near real time to provide first indication of possible oil slicks to be checked by aircraft on a spot.

Altogether, EMSA provided 647 satellite scenes for the users of CleanSeaNet in the Baltic Sea in 2010 (608 in 2009), indicating 186 possible detections (280 in 2009). In the HELCOM area, 44% (82) of the spill indications were checked and out of these 15% (12) were confirmed to be mineral oil (21% in 2009) (Table 3).

These activities by the coastal states have proved to be effective and have led to a decreasing number of illegal oil spills in the Baltic Sea, which can be demonstrated

Table 3 Satellite detections of oil spills in HELCOM countries waters provided by European Maritime Safety Agency (EMSA), including verified detections in 2010

		Verified satellite detections					
Country waters	Satellite detections	Confirmed mineral oil	Confirmed other oil, chemical, sewage or garbage	Confirmed natural phenomena	Unknown substance	Nothing foumd	Not checked
Denmark	40	4	0	6	1	9	20
Estonia	18	2	1	3	0	0	12
Finland	13	3	1	0	1	4	4
Germany	15	1	0	2	2	7	3
Latvia	3	1	0	0	0	0	2
Lithuania	0	0	0	0	0	0	0
Poland	47	0	6	3	1	12	25
Russia	3	0	0	0	0	0	3
Sweden	47	1	0	1	4	6	35
Total	186	12	8	15	9	38	104

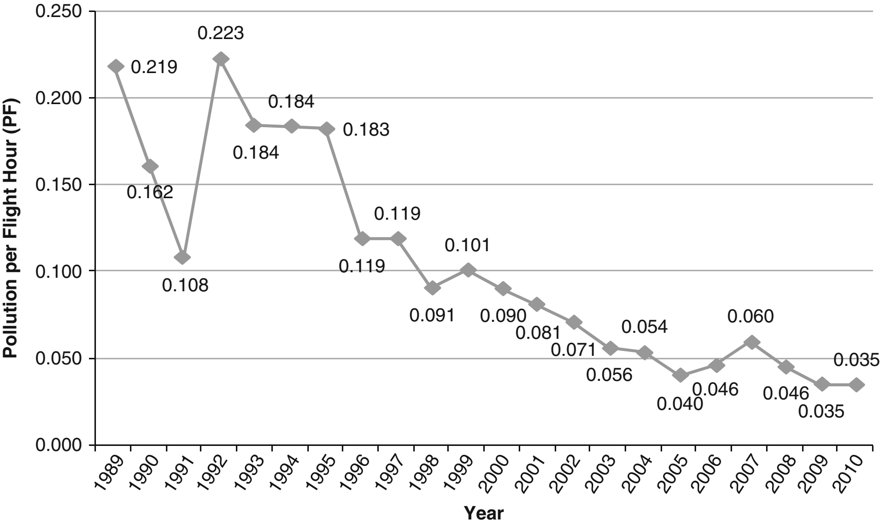


Fig. 11 Pollution per Flight Hour (PF) Index for the Baltic Sea, 1989–2010

by a Pollution per Flight Hour (PF) Index, comparing the total number of observed oil spills to the total number of flight hours (Fig. 11). A decreasing PF Index over the years indicates less oil spills or/and increased surveillance activity. The PF Index for the whole Baltic Sea in 2009 and 2010 was 0.035, the lowest recorded so far.

6 Conclusions

The dense shipping and the rapidly rising amounts of oil being transported by the Baltic Sea mean that the risk of an accident involving serious oil pollution increases correspondingly, unless counteractive measures are implemented. The Baltic Sea region can serve as a model for cooperation on increasing the safety of navigation whereby new risk reduction measures are discussed, coordinated, proposed to the IMO, and applied jointly by several neighboring or all Baltic Sea countries. Likewise, the cooperation among the HELCOM countries to build capacities to respond to major accidental pollution by oil, has led to the high level of preparedness in the region and clear operational routines in place to follow when conducting an international response operation.

Enforcement of existing anti-discharge regulations is crucial for preventing illegal oil discharges from ships, and the monitoring and enforcement system implemented in the Baltic Sea region, consisting of both aerial and satellite surveillance, proves to be efficient, resulting in decreasing number and size of illicit discharges.

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European Maritime Safety Agency CleanSeaNet Activities in the Baltic Sea

Samuel Djavidnia and Jorge Del Rio Vera

Abstract The European Maritime Safety Agency has been providing the CleanSeaNet oil spill monitoring and vessel detection service to all Baltic Sea states since 2007. This operational service was set up to support EU and EFTA member states' actions to combat deliberate or accidental pollution in the marine environment in the framework of Directive 2005/35/EC "on ship-source pollution and on the introduction of penalties, including criminal penalties, for pollution offences". The service is based on the Near Real Time analysis of synthetic aperture radar (SAR) satellite images for both oil pollution monitoring and vessel detection. This service has proven to be a valuable tool at EU level and specifically in the Baltic Sea basin as it has brought together even more the different Baltic Sea maritime administrations in the planning and monitoring of oil spill monitoring activities. The latest results stemming in the period February 2011 to June 2012 confirm the reduction of overall oil spill detections and highlight the deterrent effect provided by a guaranteed sustainable service such as CleanSeaNet.

Keywords CleanSeaNet, Earth observation, EMSA, Oil spill monitoring, Satellite remote sensing

Contents

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1 Introduction

European citizens have been affected by major oil spills on a regular basis. The raised awareness of the socio-economic and environmental impacts of oil spills has been one of the driving forces in the evolution of preparedness and response structures of costal states and industry as a whole, particularly in the Baltic Sea. While the number of major accidents is relatively low – Fu Shan Hai (in 2003) and the Baltic Carrier (in 2001) – the increase in traffic of oil tankers has intensified the risk of accidents and has marked the public conscious.

Founded in the aftermath of the Erika (1999) and Prestige (2003) disasters, the European Maritime Safety Agency (EMSA) legal basis includes the following tasks:

- Provide member states and the Commission with technical and scientific assistance in the field of ship-sourced pollution
- Support on request with additional means in a cost-efficient way the pollution response mechanisms of member states

In September 2005 the European Parliament and the Council adopted Directive 2005/35/EC, since amended by Directive 2009/123/EC, on ship-source pollution and on the introduction of penalties, including criminal penalties, for pollution offences [2005/35/EC: Directive 2005/35/EC of the European Parliament and of the Council of 7 September 2005 on ship-source pollution and on the introduction of penalties for infringements]. The Directive states that EMSA shall:

> (a) 'work with the Member States in developing technical solutions and providing technical assistance [...] in actions such as tracing discharges by satellite monitoring and surveillance';
>
> (b) 'assist the Commission in the implementation of this Directive' including, if appropriate, by means of visits to the Member States, in accordance with Article 3 of Regulation (EC) No 1406/2002'.

In early 2006, EMSA consulted industry and the national authorities of the EU member states and coastal EFTA states in order to collect information on existing operational surveillance resources and further requirements for oil pollution monitoring. EMSA also obtained considerable feedback from other relevant organisations, such as the European Space Agency, all of which was used as input for the development of the CleanSeaNet service, which became operational in April 2007. CleanSeaNet is now considered the most comprehensive oil spill monitoring and vessel detection service in Europe, supplying over 2,000 services a year to its 26 participating states.

In addition to the regular monitoring service, the Agency also provides assistance to EU and EFTA states during emergency situations. This is usually requested by member states through the Monitoring and Information Centre of the European Commission in Brussels, which coordinates the assistance during emergencies. In relation to CleanSeaNet, it usually takes the form of additional services over an area where an incident or accident has occurred, in order to monitor the extent of a spill and its changes over time (e.g. direction of drift).

2 Oil Spill Monitoring and the CleanSeaNet Service

The CleanSeaNet service is based on radar satellite images, which are analysed to detect possible oil spills on the sea surface as well as the vessels. The service, which is integrated into national and regional pollution response chains, aims to strengthen operational responses to accidental and deliberate discharges from ships, and assist member states to locate and identify polluters in areas under their jurisdiction. CleanSeaNet supplements the existing surveillance systems, strengthens member state responses to illegal discharges, and supports response operations to accidental spills.

From 2007, CleanSeaNet uses three polar orbiting synthetic aperture radar (hereafter SAR) satellites: ENVISAT, RADARSAT-1 and RADARSAT-2 to provide its services. Since 8 April 2012, ENVISAT is no longer available but regular services continue to be provided by the other two satellites. The satellite image size can be up to 500×500 km^2.

It is the users within the different national maritime organisations who define their service coverage requirements. Thereafter, in close cooperation with the users, EMSA plans and orders satellite images to meet these requirements. Satellite data are acquired via a network of receiving stations, and operators analyse and assess the images, together with supporting meteorological, oceanographic and ancillary information (e.g. AIS, vessel detection), to determine the likelihood of the presence of oil on the sea surface and to assist in identifying the source of the pollution. The results of the analysis, together with all the satellite and satellite-derived data/ information, are sent in real time to EMSA for immediate alert generation and data dissemination. If a potential spill is detected, it is of utmost importance that coastal state administrations are immediately alerted by phone and email with the aim of increasing the likelihood of catching a polluter red-handed.

As time is critical for confirming a possible spill and catching polluters in the act, the shortest possible delay between satellite detection and alert is essential for a rapid response by coastal states. Due to this fundamental aspect CleanSeaNet provides its services in near real time. Detection results are reported to the affected coastal state approximately 30 minutes after satellite image acquisition (the exact time varies according to the size of the image) (see also Fig. 1).

Each coastal state has access to the CleanSeaNet service through a dedicated user interface. Users can access a wide range of information through the interface, such as satellite images, Electronic Nautical Charts, vessel traffic information, oil spill polygons, oceanographic and meteorological information. All data and information are provided to the users also as “web services” following the standards and recommendations of INSPIRE (Infrastructure for SPatail InfoRmation in Europe) and OGC (Open Geospatial Consortium) with regard to architecture, catalogues/ metadata, sensor planning, ordering, web mapping services, data access and dissemination amongst others.

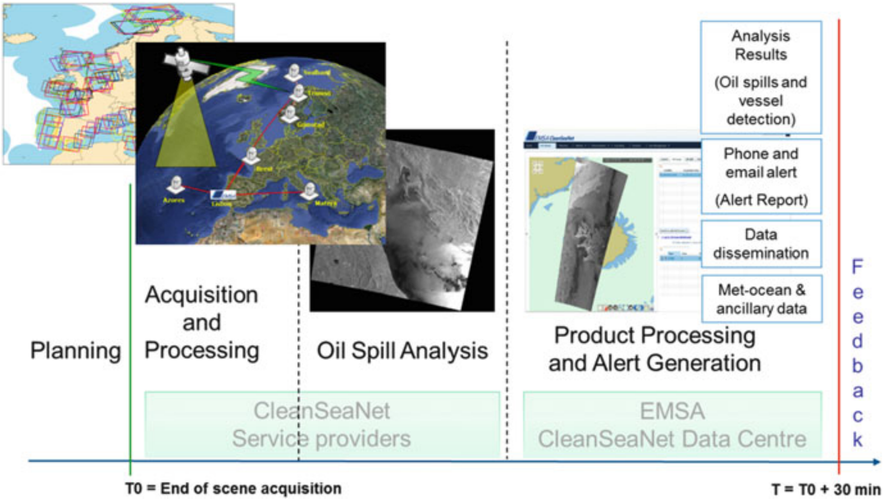

Fig. 1 CleanSeaNet service flow: from planning to alert generation and dissemination

The Baltic Sea member states represented in CleanSeaNet are the following: Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Poland and Sweden. In the spirit of collaboration that has distinguished the work of these states within HELCOM, the Baltic Sea basin has been divided into four areas, and the coverage requirements have been provided by area as opposed by country. This is in contrast with the other EU and EFTA member states whose coverage requirements represent only their own needs.

The geographical extent of the aforementioned four areas, Helcom-A, Helcom-B, Helcom-C and Helcom-D, is shown in Fig. 2.

For 2012 the total annual coverage requirements for the complete Baltic Sea basin have been of approximately 900 images. The annual breakdown per area is summarised in Table 1.

It is important to note that the monthly distribution of images per area in the Baltic Sea basin is not equal throughout the year, since issues such as seasonal blooms and ice coverage are taken into account by the users when requesting the services. Figure 3 shows the total distribution of requested satellite images per month for the complete Baltic Sea area basin for the period February 2011 to June 2012.

For the period running from February 2011 to June 2012, the total satellite imagery coverage provided to the Baltic Sea states by CleanSeaNet has been in the order of 138 million square kilometres. The density of the services (and therewith also of the delivered satellite imagery) for the period February 2011 to June 2012 is visible in Fig. 4.

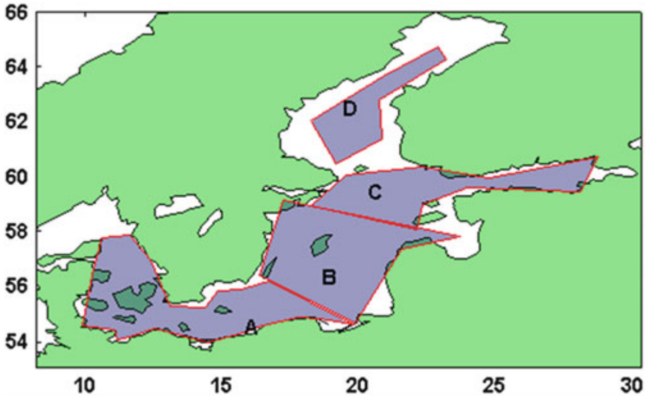

Fig. 2 Baltic Sea state coverage requirement areas

Table 1 2012 Baltic Sea state coverage requirements per area

Area	Total requested images for 2012
Helcom-A	360
Helcom-B	270
Helcom-C	212
Helcom-D	24
Total	*866*

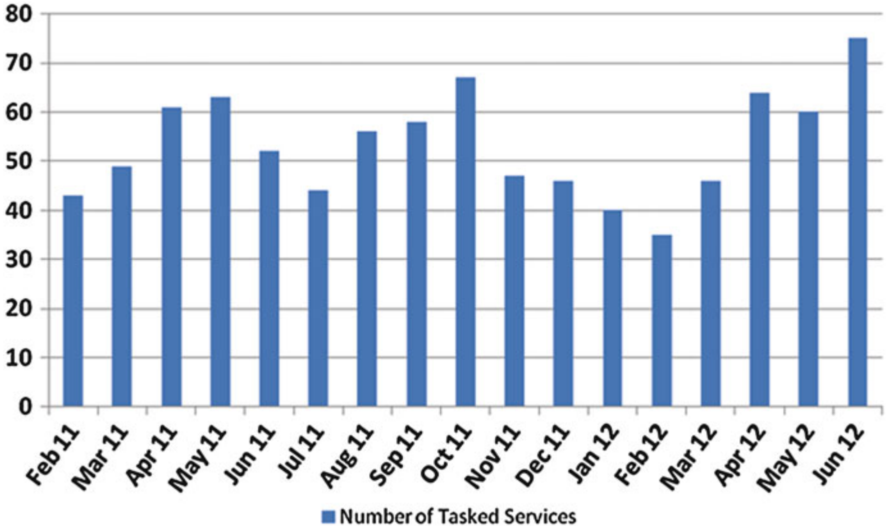

Fig. 3 Number of services tasked during the period February 2011 until June 2012. A service is defined as a satellite image with the value added service (oil spill plus vessel detection) requested by the CleanSeaNet users

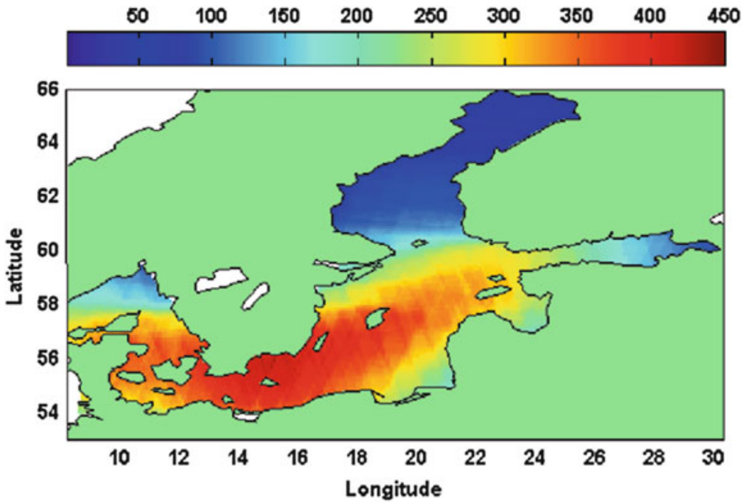

Fig. 4 Density of services (and associated satellite imagery) delivered to the users within the Baltic Sea states during the period February 2011 until June 2012

3 The Use of SAR Images in the Baltic Sea

3.1 Environmental Considerations

The use of SAR images to detect oil spills has steadily increased in the past years. SAR sensors send electromagnetic pulses and measure the pulse travel time and the backscattered signal. The travel time is used to compute the distance to the sea surface while the backscattered signal is used to create the intensity and phase variations across the image. The backscattered signal is mainly proportional to the surface roughness within the order of magnitude of the SAR wavelength (Bragg scattering) [1]. The principle of detection of oils spills is very simple; oil dampens the sea surface capillarity waves caused by the wind, and hence, the incident signal bounces away from the satellite, implying the lack of backscattered signal which is seen in the SAR image as a dark patch.

The dampening of the surface waves may also be caused by other phenomena such as algae bloom, fish oil and wind sheltering due to islands or coastal features and boundaries of water masses. Sea Ice also increases the difficulty of detecting spills from satellite. The following two sections focus on the analysis of the impact of algae bloom and sea ice phenomena in oil spill detection in the Baltic Sea.

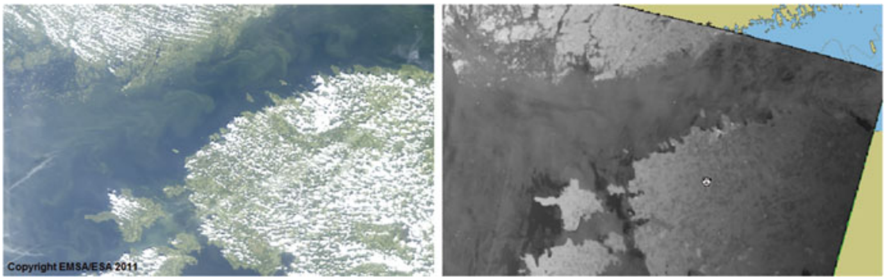

Fig. 5 MERIS optical image (*left*) on 08/07/2011 at 09:00 UTC and simultaneous ASAR SAR image (*right*). Dark patches in the SAR image are typically caused by algae on the surface, and the lack of correspondence is due to the fact that while the SAR sensor is only measuring at surface level (surface roughness) the optical sensor (MERIS) measures reflected light at certain wavelengths which may account for a layer of tens of cm. ASAR and MERIS were sensors on board Envisat, copyright 2011, EMSA/ESA

3.1.1 Algae Bloom

"Algae bloom" is the term used to describe the rapid multiplying of phytoplankton on or near the surface of the sea. Floating freely in the water, phytoplankton is sensitive to sunlight and local environmental variations such as nutrient levels, temperature, currents and winds. Conditions which favour the occurrence of algae blooms in the Baltic Sea are warm temperatures, sunshine, little wind and an increase of nutrients from run-off following the ice season.

Algae blooms impact the ability of SAR sensors to detect oil spills because their presence produces a similar dampening effect on the water's surface. Therefore, in order to provide consistent and correct information to its CleanSeaNet users, it is important to know when algae blooms appear to avoid false positive detections. Figure 5 shows the comparison between an optical image and a SAR image acquired at the same time. Algae bloom areas can easily be discriminated within both optical and SAR images. In the latter the signature is defined by a black patch, which may indeed cause false positive oil spill detections. To avoid this, the CleanSeaNet service incorporates chlorophyll-a layers that are an indicator of potential algae blooms, and this layer can be compared with the SAR image to discard false positives.

3.1.2 Sea Ice

Sea Ice typically backscatters more signal than the ocean surface. This effect is due to a combination of factors including:

- A different dielectric constant than sea water (due to the lack of salt)
- Surface roughness/volume scattering (linked to the compactation of the sea ice)
- Discrete scatterers
- Sea ice surface orientation

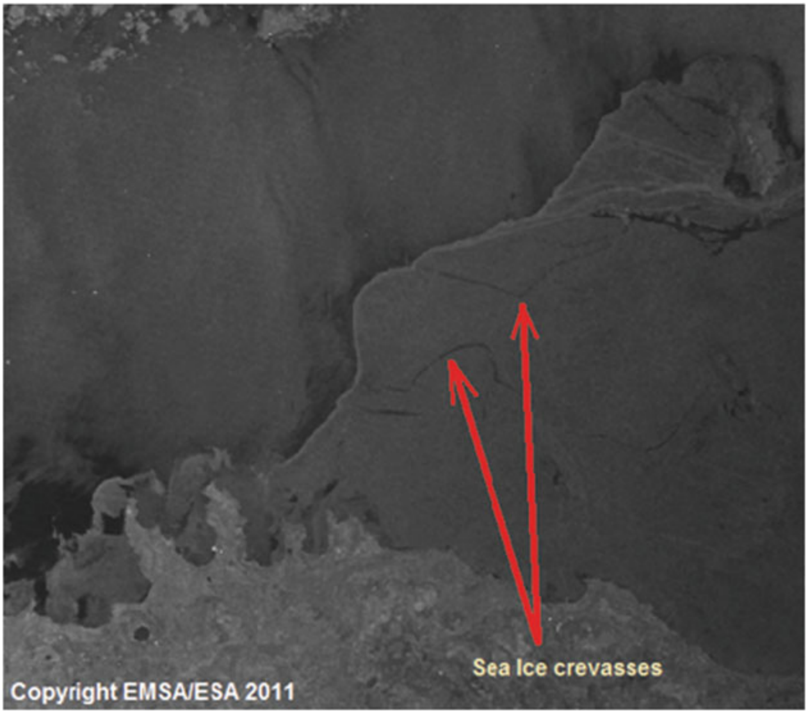

Fig. 6 Envisat ASAR image on 20/04/2011 at 08:56 UTC over the Gulf of Finland. In this case the dark patches pointed by the *arrows* are a low backscatter area inside a block of sea ice. It is important to locate the sea ice areas to avoid misclassification. The boundary between the sea ice and the open sea offers a bright feature that turns into dark in the open water

When sea ice is breaking dark patches in the SAR image can be mistaken as oil spills. This is due to either the lack of wind or the sinking of the fresh water effects. It is therefore important to know where the sea ice is located to be able to discriminate these areas. In addition, sea ice crevasses can be mistaken as potential oil spills due to their contrast with the more reflecting ice. Figure 6 shows the typical features that can be found in ice waters: sea ice crevasses and the interface between the open water and the sea ice.

Sea ice is also limiting the ship traffic (but not stopping it completely). In this case, it is impossible to detect the spills as the paths created by the icebreakers contain sea ice. Within this context, due to the limited ability of SAR to detect potential oil spills in sea ice infested areas, the number of services provided by CleanSeaNet is reduced during the ice season.

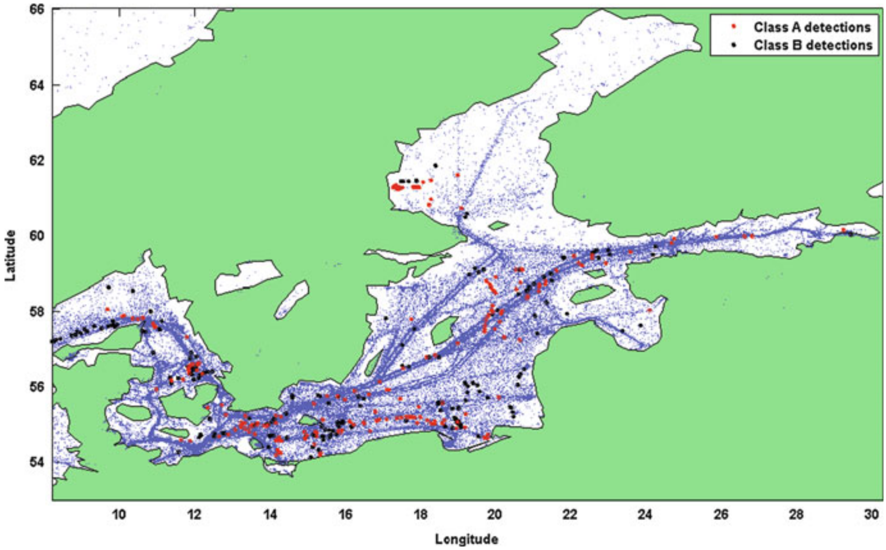

Fig. 7 CleanSeaNet potential satellite-derived oil spills and detected vessels in the period from February 2011 to June 2012. The *black* and *red dots* indicate potential oil spill detected by satellite

4 Potential Oil Spill Statistics

As shown in Fig. 4, the density of tasked services (satellite images) for the period February 2011 to June 2012 varies in accordance with the spatial and temporal coverage requirements as defined by the users. This density coverage must be taken into consideration when analysing the number of spills which are detected within the Baltic Sea basin.

Figure 7 shows both the distribution of CleanSeaNet potential spill detections and the detected vessels within the Baltic Sea basin for the period February 2011 to June 2012. The large (black and red) dots represent the potential oil spill detections provided by the CleanSeaNet service, divided into two separate categories. Red dots correspond to Class-A detections, which are defined as high confidence possible spills, while black dots correspond to Class-B detections, which are defined as low confidence possible spills. The violet dots represent satellite-derived detected vessels and can be used as an auxiliary proxy to analyse the traffic and movements of the vessels during the period February 2011 to June 2012. It is worth mentioning that the main shipping traffic routes in the Baltic match the oil spill pattern generated by the CleanSeaNet Service.

Figure 8 shows the monthly distribution of all CleanSeaNet detected spills during the period February 2011 to June 2012 in the Baltic Sea. In these 17 months, a total of 324 potential oil spills were detected and reported, 171 (53%) of which were verified in situ by the CleanSeaNet users within the Baltic Sea maritime

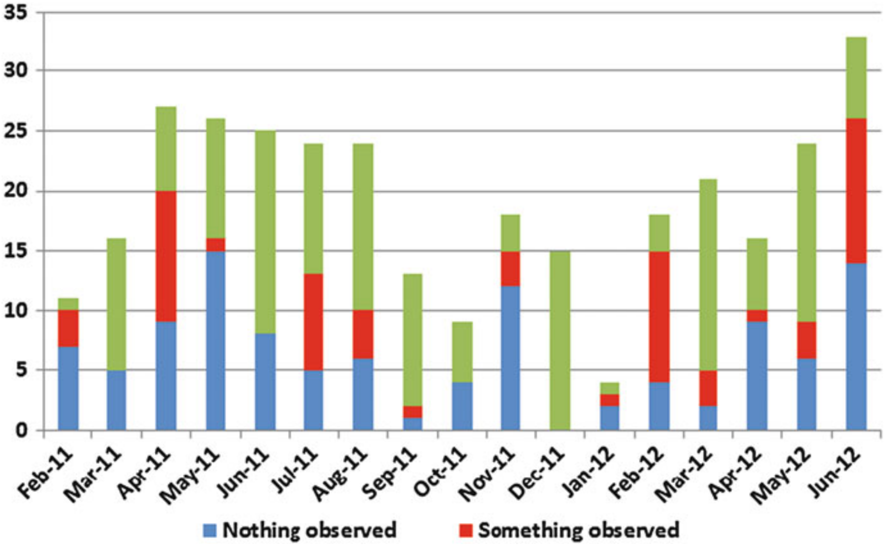

Fig. 8 Monthly distribution of CleanSeaNet potential oil spill detections. Total (*green*) – Verified but nothing observed (*blue*) – Verified and something observed, e.g. mineral oil, natural substance and other substances (in *red*)

authorities. Of these 171 verifications (respectively 88 of Class A and 83 of Class B), 62 (37%) confirmed the presence of a potential polluting substance in the water, although this was not always mineral oil.

More specifically, of the 62 confirmed spills 37 (60%) are of Class A and 25 (40%) are of Class B. For what concerns the remaining 109 non-confirmed spills, 51 (47%) are of Class A and 58 (53%) are of Class B. While the overall confirmation rate is higher for Class A type of spills, the distribution seems to suggest that there is no clear false positive alerting dependency on the Class type. We can speculate that this is probably due to the time taken by the maritime authorities to verify the presence of the oil spill (which invariably varies for each oil spill detection), but is not taken into account in the statistics.

5 Conclusions

A recent report from Helcom has shown that there has been a dramatic decrease in the number of oil spills in the last 10 years [2]. The report states that the reduction of oil spills in the Baltic Sea is related to the increase of time spent conducting aerial surveillance by coastal states. In addition to this EMSA’s CleanSeaNet service provides a sustainable source of satellite monitoring capability, which due to its timely and quality characteristics has proven to be a valuable asset in deterring illegal oil spill discharges from sea.

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Oil Pollution in Waters of Finland

Heli Haapasaari and Kati Tahvonen

Abstract The whole of the Baltic Sea is a vulnerable sea area. Through the narrow Gulf of Finland, 155 million tonnes of oil is transported and also other maritime traffic is remarkably dense leading to a high risk for accidents. Finnish strategy for responding big accidental oil pollution is to act as fast and efficiently as possible on the sea. Mechanical oil recovery is the key. Also, oil pollution from operational discharges is observed on a regular basis. In Finland, operational discharges are monitored mainly by aircraft and satellite. During the last decade, legislation of these discharges has been revisited and updated several times. The polluters may be imposed by an administrative penalty fee. Additionally, a criminal investigation can be carried out. The number and total volume of operational oil discharges has been decreasing during the last 20 years.

Keywords Aerial surveillance, Discharges, Environmental impact, Legislation, Oil, Oil response, Pollution, Satellite

Contents

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1 Geography and Maritime Traffic

Finland, located in the Northern Europe between latitudes 60°N and 70°N, has a 1,200 km long Baltic Sea coastline, without taking into account islands, capes and bays (Fig. 1). The coastline is very scattered with fragmented archipelago, and, taking this into consideration, the total length of the shoreline that can be affected by an oil spill lies around 16,000 km or even close to 20,000 km. Descriptive to Finnish waters are also the narrow fairways which make navigation difficult, especially in the wintertime and in high sea conditions.

The Gulf of Finland is a major ship route in the northern Baltic Sea. It is very narrow and the distance between Finnish and Estonian coastline ranges from 50 to 110 km. In east–west direction, the distance between the entrance to Gulf of Finland and the Kronstad in Sankt Petersburg, Russia, is about 350 km.

During the past 15 years several new oil terminals have been opened in the Gulf of Finland area. With the new terminals the amount of oil transported through the Gulf has increased rapidly. In 1995, total of 20 million tonnes of oil was transported in the Gulf of Finland and in 2011 the amount was about 155 million tonnes, according to Finnish Environment Institute statistics. Also the other maritime traffic such as the number of cargo vessels as well as passanger ferries is high in this region. Unlike in many other sea areas in the world, there are no oil rigs in the Finnish Exclusive Economic Zone (EEZ).

The Bay of Bothnia – the northernmost sea area of Finland – is connected to the rest of the Baltic Sea by a narrow water passage between Åland archipelago and Sweden. Maritime traffic in the Bay of Bothnia is remarkably lower than in other sea areas around Finland. Oil transportation in the Bay of Bothnia is relatively low and there are no oil refineries.

Maritime traffic is crucial for Finland since about 90% of export and 70% of import is transported by sea. However, Finland's northern location creates considerable challenges for the maritime traffic. Unique in the world, during a typical winter, all Finnish ports freeze. Thick layers of ice cover the sea areas in the southern Finland for few months and in the northern Finland for several months every winter. Consequently well-established navigation routes and Traffic Separation Schemes (TSS), Vessel Traffic Services (VTS), efficient ice breaking service, reliable ice mapping and forecasting system together with adequate ability to respond oil and chemical spills at any time of the year and in any kind of weather conditions are necessities for Finnish authorities. Additionally, the importance of good cooperation with neighbouring countries cannot be highlighted enough.

Fig. 1 Map of the Baltic Sea

2 Pollution Response Authorities and Their Roles

2.1 Organization of Pollution Response in Finland

In Finland, the Ministry of the Environment (ME) has the supreme responsibility for the management and supervision of the oil pollution response. The Finnish Environment Institute (SYKE), operating under the Ministry, is the competent governmental oil and chemical pollution response authority. SYKE is in charge of measures against pollution incidents at open sea and, if necessary due to severity of an accident, also in the coastal waters. Additionally, SYKE acts as the nationally appointed competent authority empowered to request and give international assistance in combatting marine pollution caused by oil or other harmful substances [1].

On a regional level, the Rescue Services Regions are responsible for the combatting of oil spills in their coastal and land areas. Altogether, there are ten Rescue Service Regions that have Baltic sea coastline.

Several organizations are liable to assist SYKE in pollution response actions. These organizations include governmental authorities such as the Finnish Transport Safety Agency (TraFi), the Finnish Border Guard (FBG), the Finnish Defence Forces (especially the Navy) and the Centres for Economic Development, Transport and the Environment (ELY). Also private sectors, e.g. oil companies, ports, salvage and shipping enterprises, are liable to assist with the resources at their disposal. Furthermore, the owners of different kinds of facilities handling big amounts of oil shall have a limited oil spill response ability of their own.

Each of Finland's 22 Rescue Services Regions prepares its own oil pollution response contingency plan which is updated every 5 years. These plans are approved by ELY-centres. Additionally, geographically wider contingency plan is made separately for three coastal sea areas and for one inland watercourse area. These plans define, among other things, the cooperation between several Rescue Service Regions in case of an extensive oil pollution incidence.

Where it comes to funding oil response activities, Finnish national Oil Pollution Compensation Fund plays a key role. The Fund is financing the purchases of Rescue Service Regions' response equipment and it can be used as a buffer to finance oil spill response costs. The capital for the fund is raised by a levy that is collected for each ton of oil imported to, or transported through, Finland. Rescue Services Districts have legal right to get compensation from the fund for purchases of the equipment which is mentioned in their approved contingency plans. Also, the governmental authorities are entitled to reimbursement of equipment from the fund. However, the compensation for governmental purchases is always considered on a case-by-case basis.

2.2 *Surveillance of Pollution from Ships*

According to the Finnish national legislation, the Finnish Transport Safety Agency (TraFi) is responsible for the monitoring of the enforcement of the legislation on the protection of the marine environment [2].

The Finnish Environment Institute (SYKE) has the main responsibility for surveillance of discharges from ships to water in the Finnish sea areas, i.e. in the territorial sea and in the EEZ. However, TraFi has the surveillance responsibility in the inland waters, i.e. on lakes and rivers [2].

Additionally, the Finnish Border Guard (FBG) is responsible for the investigation, as well as for imposing an administrative fee for oil discharges. FBG also conducts the criminal investigation in cases where the ship crew is suspected of violating Finnish criminal law [2].

3 Oil Pollution Monitoring Practice and Existing Systems

3.1 Aerial Surveillance

Since 1995, Finland has had two surveillance aircrafts that are equipped with special equipment to detect oil spills. The Dornier 228–212 surveillance aircraft are owned and operated by the Finnish Border Guard. According to the cooperation agreement between SYKE and the Finnish Border Guard, the surveillance aircraft crew monitors the environment for oil spills whenever they patrol over the Baltic Sea. Further on, the cooperation agreement defines SYKE to be responsible for the oil spill surveillance equipment and also for the pollution surveillance training for the aircraft crew members.

In 2009 SYKE bought new oil spill monitoring equipment from the Swedish Space Corporation (SSC) for the surveillance aircraft. Further on, during 2012 the FBG updated the rest of the equipment onboard. After these two updates, Finland now has a state-of-the-art sea surveillance system with a high level of integration.

The most important surveillance equipment for oil pollution monitoring is Side Looking Airborne Radar (SLAR). With SLAR oil can be detected as far as 20 nautical miles distance from the aircraft route. This means that the narrow Gulf of Finland can be covered from Finnish to Estonian coast with one flight. In many cases the surveillance aircraft crew members will receive a first indication of oil from SLAR image.

After indicating an oil spill the oil covered area as well as the thickness of the slick can be measured by IR/UV (infrared/ultraviolet) scanner providing that the slick is thick. To be able to estimate the volume of a thin oil slick, it is crucial that the aircraft crew members are specially trained in order to define different oil thickness layers on the sea surface by the appearance of the discharge.

The Forward Looking Infra Red (FLIR) camera is often used for receiving for more information on the suspected vessel and possibly on the oil slick as well. With a FLIR the crew members can see details from relatively far distances.

An important feature of the surveillance aircraft equipment is a high level of system integration. All the instruments, including video and voice recording, can be operated via the same user interface and will, furthermore, be saved in the same system. If needed the data can be transferred via a satellite communication system immediately after an oil spill has been documented. An important new equipment that was integrated into the aircraft's surveillance system in 2009 is AIS (Automatic Identification System) receiver which enables vessel identification data to be displayed together with oil slick detection data on operators graphical user interface.

Annually, Finnish surveillance aircraft carries out 600–700 pollution surveillance flight hours in the Baltic Sea area. Additionally, Finnish Border Guard helicopters are monitoring the marine environment always when patrolling over the Baltic Sea waters. Especially, due to their good availability and fast alert time, the helicopters are used for verifying oil spill indications made from satellite images. In case of red-handed polluters helicopters play a key role in taking oil samples from the sea.

3.2 Satellite Monitoring

During the last decade, satellite monitoring has become an integral part of oil pollution surveillance. However, the first tests with Synthetic Aperture Radar (SAR)-images were carried out already in 1995 together with Tromso Satellite Station (current name is Kongsberg Satellite Service). Since then Finland has used the satellite images in several oil spill detection pilot projects where the reliability and usefulness of satellite monitoring of oil have been further tested and evaluated.

In 2002–2003, Finland and Sweden carried out a joint evaluation campaign on the use of SAR satellite imagery for oil spill detection. The development work continued with a EU project "Oceanides" (2003–2006) with a focus on enhancement of the reliability of the SAR-based oil detections. In 2004, Finland signed an agreement with the Canadian Space Agency on the use of Radarsat-scenes for Finnish Government purposes including oil spill monitoring. This contract was effective till 2008.

In April 2007, European Maritime Safety Agency (EMSA) launched the European satellite-based oil spill detection service, CleanSeaNet. EMSA provides oil spill satellite surveillance free of charge to the European Union coastal states. Finland has been a user of the CleanSeaNet system since the beginning and, at the moment, receives annually 250–300 satellite scenes from EMSA.

Satellite images can be considered as an important supplementary tool for aerial surveillance activities. However, all the satellite-based detections have to be checked by either an aircraft, helicopter or a vessel. As a rule of a thumb, it has been estimated that about 50% of the possible oil spills detected by the satellite service are identified as oil by the verification flight [3].

4 Amount of Oil Pollution

4.1 Maritime Accidents

SYKE has a 24-h on-duty officer who receives information on marine pollution incidents and accidents, illegal discharges as well as land-based pollution. Additionally, SYKE duty officer acts as a focal point for other environmental accidents and anomalies such as flooding. In 2010, for example, the duty officer received 171 phone alerts. Out of these 58 concerned oil pollution or ship distress situation at sea. In 37 cases the alert was about oil pollution detection at sea and 42 oil spill incidents at shore. Fortunately only in one case oil pollution response actions were needed.

4.2 Operational Discharges from Vessels

During the 15 years that Finland has had the special equipment for aerial surveillance of oil spills, the number of oil spills has varied greatly. As a general trend, the number

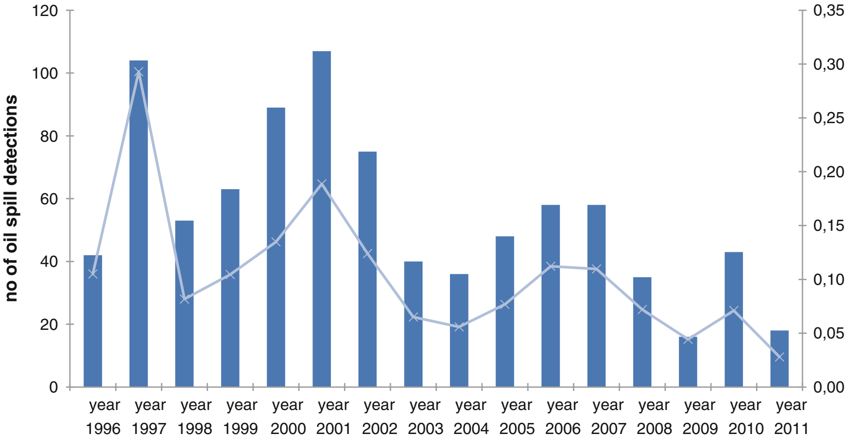

Fig. 2 Statistics on the oil spills detected by the Finnish surveillance aircrafts in 1996–2011

of oil spills detected has been declining for the last decade (Fig. 2). Also the average volume of detected oil spills has got smaller: in 2005 the total estimated volume of the detected oil spills was 29.2 m^3 while in 2010 the amount was estimated to be 5 m^3.

In order to ensure the best use of resources, Finland, Estonia and Sweden cooperate in marine pollution surveillance. These neighbouring countries exchange their flight plans and carry out surveillance activities also in the neighbouring countries' waters. A good indication of this is that out of the 43 oil spill detections that Finnish Dorniers made in year 2010 only 20 were in Finnish water area and 23 in neighbouring countries' EEZ.

Majority of the oil spills detected in the Finnish EEZ are located in the Gulf of Finland waters along the main shipping lanes (Fig. 3). Gulf of Finland has ship routeing systems that collect the traffic to central Gulf area where also majority of the discharges are discovered. There are at least two reasons for less oil discharges in the Bay of Bothnia area. Firstly, the traffic density in the Bay of Bothnia is much lower than in the Gulf of Finland area which mean that the risk to get caught for the illegal act. Secondly, ships entering or exiting the Bay of Bothnia have to enter the territorial waters of either Finland or Sweden which means that the vessels can be easily stopped and inspected by the authorities.

In addition to the oil spills detected along the busiest shipping routes, annually several oil spills are detected near the shoreline, originating both from ships and from land-based sources.

4.3 Penalties for Oil Discharges

In Finland, the legislation governing oil discharges has undergone a major revision during the last decade. In 2005, Finland declared its Finnish EEZ, extending beyond

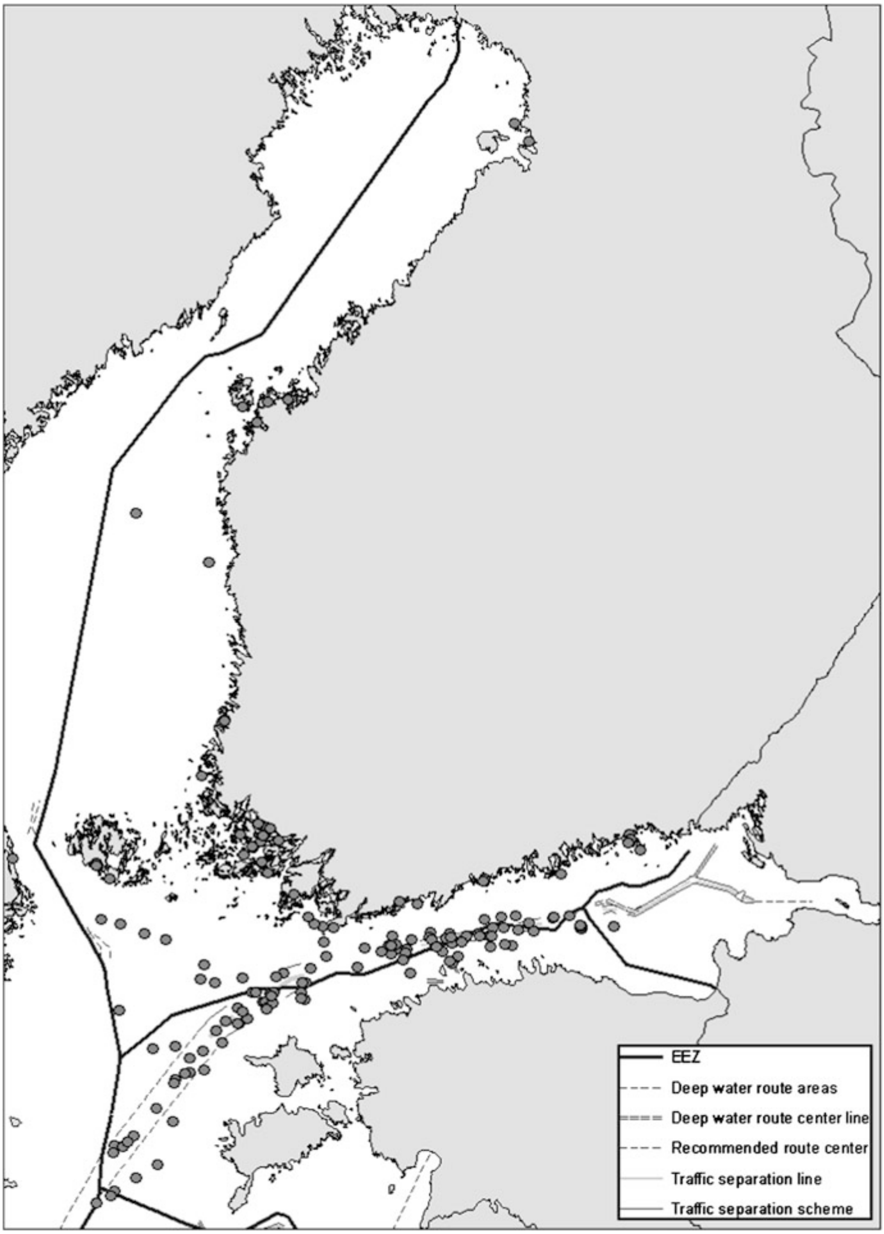

Fig. 3 Oil spill detections by Finnish aerial surveillance assets from 2006 to 2010. Note the low number of detections in the Bay of Bothnia area

the Finnish territorial waters. After the declaration of the EEZ the Finnish authorities investigate and prosecute the violations of the antipollution regulations for the area that extends from the Finnish coastline to the EEZ border – before the EEZ was declared such cases were forwarded to the flag states [4].

Further on, an amendment to the *Act on the Prevention of Pollution from Ships* came in force in 2006. This amendment introduced a new enforcement tool for the authorities and gave the opportunity to impose a fast “oil pollution fee” on polluters. The Finnish Border Guard can impose this administrative penalty fee on the ship owner or on the shipping company. The amount of the fee depends on both the estimated amount of oil spilled into the sea and the gross tonnage of the ship. The gross tonnage is taken into account because it is assumed that the owner of a bigger vessel enjoys better financial circumstances than the owner of a smaller vessel. The amounts of the fees are about the same as in Sweden, the lowest fee being €4000. The law does not define any upper limit of the fee [5].

The most recent law update entered into force in 2010. *Act on the Protection of the Marine Environment (1672/2009)* and reform of the legislation on pollution from ships made it possible for the Finnish Border Guard to submit further complaint if it is dissatisfied with the decisions issued by the Maritime Court or the court of appeals in cases of oil pollution fees. Also, these new regulations extended the scope of the Finnish regulations concerning oil pollution fee to cover the territory of Åland [6].

In case of violation to antipollution regulations in Finnish waters, in parallel with the administrative oil pollution fee investigation, the Finnish Border Guard carries out a criminal investigation of an environmental crime.

5 Impact on the Environment

Oil spills can have very wide-ranging impacts on the marine environment and human activities – reducing the scope for recreational activities and tourism at sea or along the coast, harming fish farms and sea fisheries, and limiting the use of sea water in industrial processes. Oil spills also have many serious impacts on ecosystems.

Even if an accident happened out in the open sea, oil slicks could easily drift onto the shores of the Gulf of Finland within a day of any accident involving a spillage. A major oil spill could pollute numerous stretches of shoreline all around the Gulf to varying degrees. This means that pollution control measures must begin immediately after any accident. Cleaning up oil that has drifted onto shores is extremely difficult, laborious, and ten times as expensive as cleaning up oil slicks at sea.

The Gulf of Finland and the Archipelago Sea are particularly sensitive to pollution. The concentrations of hazardous substances are persistently high in the Gulf and in the Baltic Sea as a whole for the following reasons:

- The low volumes of water.
- The slow rate of exchange of water with the open seas.
- Low temperatures and winter ice slow the evaporation or decomposition of pollutants.
- Stratification of the water into layers with different temperatures and salinities restricts the dispersal of pollutants through the sea.

Oil pollution prevention is further hampered by the intricate shape of the coastline with its many islands and narrow channels, as well as by darkness, cold and icy conditions in the winter.

The consequences of an accident vary greatly according to the season. Oil spills in the winter or spring are the most destructive. Spills in the spring particularly affect the functioning of entire ecosystems and natural habitats by disrupting the breeding season. During winter conditions, the clean-up operations are extremely challenging and the nature may be affected by oil for a relatively long time.

6 Principles of the Oil Pollution Response Activities

Finnish Environment Institute is responsible for marine pollution response in open sea. In the coastal waters the Regional Rescue Services have the responsibility to combat oil. Finnish response strategy is based on the mechanical recovery of the oil and dispersants are not used. These principles follow the HELCOM recommendations [7].

Finland has a total of 16 oil recovery vessels and more than 30 boats that are equipped with mechanical oil recovery equipment. All the ship-sized vessels are multipurpose, i.e. they have other tasks that they carry out when not used for pollution response.

In Finland, oil combatting strategy includes prevention of further damages when an accident has taken place, restriction of damages, recovery of the material causing the damage, and, after that, cleansing of the dirt. The overall aim in all actions is to minimize the damage to the environment and to society.

The key principle in Finnish pollution response thinking is that the duty officer always anticipates the worst possible outcome of an maritime accident. This means that when an accident has happened the Finnish Environment Institute duty officer alerts several vessels and other assets. It is always better to ask a recovery vessel to turn back than to realize that one has alerted too few resources to the accident site.

The first actions on board the vessel are crucial because this can, in many cases, limit the outflow of the oil to the environment. The second priority is to restrict the spreading of oil and to collect the oil from the sea. The least efficient option is to clean the shores since destruction has then already taken place and not even speed is of much use in cleansing. Cleaning the shoreline is also very time-consuming and extremely expensive.

7 Way Forward

In the northern Baltic Sea, most of the ship traffic sails through the narrow Gulf of Finland and then heads to the Baltic Sea Proper. These areas have been identified as a potential places for operational oil discharges from the ships. Finnish opinion is that the surveillance cooperation with neighbouring countries is the key to minimize oil pollution and to maximize the risk of getting caught red-handed, i.e. while still polluting. Effective surveillance cooperation would comprise of good planning of the flights, smooth exchange of evidence gathered during surveillance flights, streamlined legislation in cases of antipollution regulation violations together with best use of available surveillance technologies.

The reliability of the satellite-based oil spill detection should be enhanced – perhaps by evaluation campaigns that are similar to those carried out during the Oceanides project.

The aim is to have zero illegal oil spills and while working to reach this goal it is important that the surveillance and law enforcement actions are effective.

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The German Operational Monitoring System in the Baltic Sea: Sensors, Methods and Example Data

Martin Gade and Björn Baschek

Abstract Operational oil pollution surveillance has been performed in Germany for almost 30 years. Sophisticated state-of-the-art sensors are being used for frequent airborne surveillance, while satellite data are used as additional information input on a routine basis. Basic research on the imaging of marine oil pollution by synthetic aperture radar (SAR) has been performed in Germany since the early 1980s, and a basic understanding of the imaging of biogenic and anthropogenic marine surface films by active microwave sensors has been developed. In this paper, we provide an overview of the current operational surveillance system, and we give some historical background summarising some of the results of the research conducted during the past decades.

Keywords Aerial surveillance, Drift modelling, Germany, Infrared, Oil pollution, Satellite services, Synthetic aperture radar, Ultraviolet

Contents

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1 Introduction

The operational surveillance of oil pollution on German coastal waters is an important part of the duties and responsibilities of the German Central Command for Maritime Emergencies. Since parts of the Baltic Sea (namely its south-western part, the Belt Sea, and the western part of the Baltic Proper) belong to German territorial waters and the exclusive economic zone, they are frequently overflown by German aircraft carrying a selection of sophisticated sensors, which are especially designed, or optimised, for the use on oil surveillance aircraft. Not only that oil pollution monitoring is an important aspect, because of the high vulnerability of the German coasts (with a total of five national parks), but also the scientific research focussing on the signatures oil films cause on SAR imagery has been pushed forward by German researchers. In this paper, we summarise both the application aspect and the research aspect, with special emphasis on the German waters in the Baltic Sea.

1.1 The German Part of the Baltic Sea

German waters comprise parts of the south-western Baltic Sea, mainly the Belt Sea, between Denmark, Germany, and the Darß Sill in the east, and the south-western Baltic Proper (Arkona Basin), between Sweden, Germany, the Darß Sill and the line Szczecin Lagoon–Island of Bornholm. In general, the mean water depth in the German part of the Baltic Sea is rather small, with the Arcona Basin and the Kadett Trench being the deepest parts, where the water depth is up to 40 m.

The German Exclusive Economical Zone, EEZ, includes only coastal waters, see Fig. 1. However, one of the main traffic routes in the Baltic, connecting the Kiel Canal in the west with the Baltic Proper in the east, leads partly through and partly along the border of the German EEZ.

Figure 2 visualises the ship traffic within the southern Baltic on the basis of monthly average of the signals of the Automatic Identification System for ships. Major traffic routes within the Baltic Sea are leading through German waters, connecting the Baltic Proper and the eastern countries with the western straits

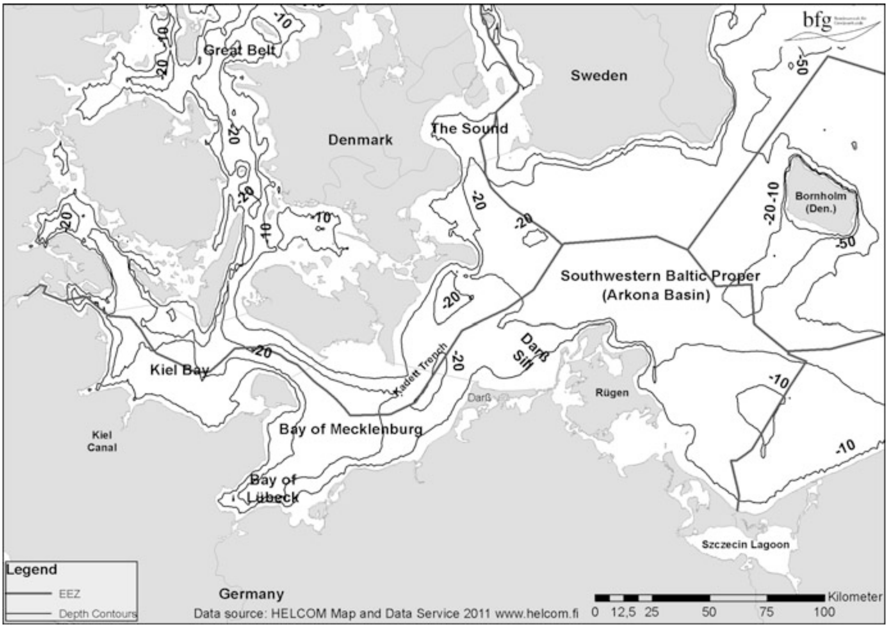

Fig. 1 The German Exclusive Economical Zone, EEZ, in the Baltic. Map produced by BfG with the HELCOM Map and Data Service (www.helcom.fi) as data source

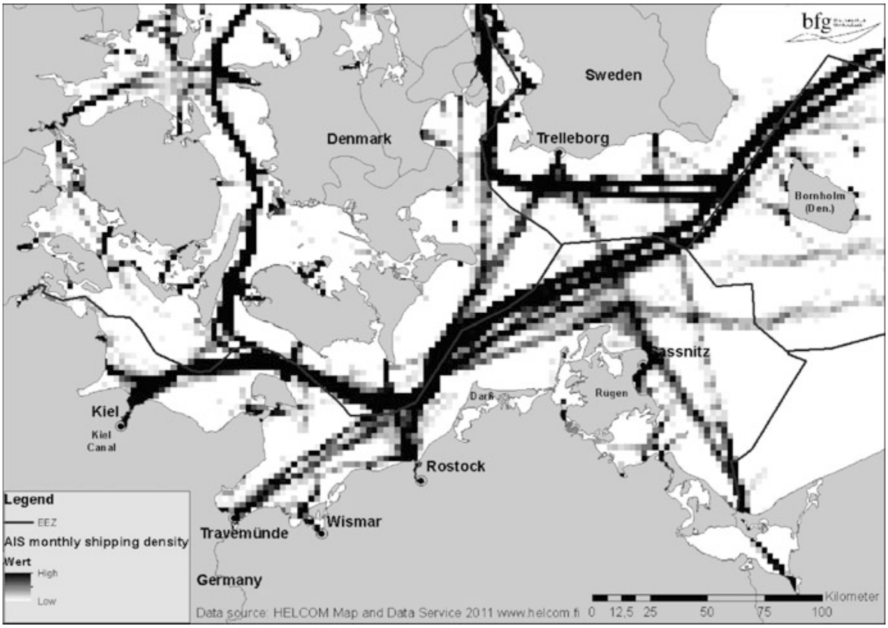

Fig. 2 Monthly average of ship traffic basing on the signal of the Automatic Identification System. Map produced by BfG with the HELCOM Map and Data Service (www.helcom.fi) as data source

leaving the Baltic and with the Kiel Canal as a direct connection to the North Sea. It can clearly be recognised that the points of origin of the ships tracks are mainly built by the main harbours, Kiel (including the Kiel Canal), Travemünde, Wismar, Rostock and Sassnitz as well as by the estuary mouth of the river Oder.

2 History and Projects

In Germany, remote sensing data for monitoring oil pollution on sea surfaces is used operationally since the mid-1980s. Especially radar techniques, if optimised for oil spill detection, are useful for the surveillance of large areas and for night-time or foul weather work [1]. Side-looking airborne radar (SLAR) and synthetic aperture radar (SAR) systems allow a permanent and inordinate observation, because they are independent of atmospheric and weather conditions [2].

For a long time, only airborne radar sensors were available for operational maritime surveillance. In Germany, the operational aerial surveillance started in 1984 with a rented Cessna 406 aircraft (with radar, infrared and ultraviolet sensors) and proceeded in 1986 by using a Dornier Do 28 aircraft (with equipment from the Swedish Space Corporation). Here, radar was the far-range sensor for localising possible oil spills. Only four years later, the newer Dornier Do 228 was introduced as a platform and the sensor system was extended. At the end of 2011, one of the two existing surveillance aircraft will be exchanged by a Do228 New Generation.

The use of satellite data for the detection of marine oil pollution and its discrimination from natural surface films was topic of a number of research projects at the University of Hamburg, starting in the 1980s: after theoretical and experimental laboratory studies, during the joint U.S.-German project SAXON-FPN (“SAR and X-Band Ocean Nonlinearities – Forschungsplattform Nordsee”) first experiments with an airborne scatterometer on the reduction of the radar backscattering by marine surface films were conducted [3, 4]. In 1994, during the SIR-C/X-SAR (“Spaceborne Imaging Radar–C / X-Band SAR”) campaigns, field experiments with quasi-biogenic and anthropogenic surface films were carried out in the German Bight of the North Sea. The aim of the experiments was to investigate whether active microwave sensors are capable of discriminating between the different kinds of surface films [5]. Main finding of those comprehensive studies was that multi-frequency radar techniques have the potential for being used to discriminate between biogenic and anthropogenic surface films, but only at low to moderate wind speeds [6].

In the late 1990s, in the frame of the European project “Clean Seas”, ERS SAR images of three regions within the European marginal seas, including the Baltic Proper, were analysed on a routine basis. For the first time, spatial and temporal statistics were performed to investigate the use of routinely acquired SAR imagery for the monitoring of European waters. Main results of those statistical analyses will be presented hereafter.

In the beginning of satellite-based oil pollution monitoring, the operational use of satellite sensors was hampered due to the long gross processing time of several weeks per image. Later on, in the frame of the European projects OCEANIDES (a follow-on project of “Clean Seas”) or MarCoast, SAR data from satellites such as ENVISAT, Radarsat-1 and Radarsat-2 were available at near-real-time and were introduced to operational pollution monitoring. From 2007 on, CleanSeaNet (CSN) of the European Maritime Safety Agency (EMSA) is acting as a support service for member states for their marine pollution control.

3 Monitoring System and Sensors

Today, 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 [24]. In Germany, the use of satellite services and multi-sensor aircraft is enhanced by a numerical oil spill drift model to form a combined operational monitoring system, whose individual parts are highlighted in the following.

3.1 Airborne Sensors

The German oil pollution surveillance system is primarily based on two Do 228 aircraft, which are operated by the Naval Air Wing 3 “Graf Zeppelin”, on behalf of the Central Command for Maritime Emergencies (CCME) and of the German Federal Ministry of Transport, Building and Urban Development (BMVBS). As one of the two aircraft – the Do 228 with call sign 57+01 as shown in Fig. 8 – will be exchanged shortly, this chapter focuses on the multi-sensor system of the type MEDUSA of the more modern Do 228 with call sign 57+04 (for more details, the reader is referred to, e.g. Trieschmann et al. [7], Zielinski et al. [8] and Robbe [9], and for a general review of airborne remote sensing of oil spills to 1], Fingas [10] or Bonn [11]).

The multi-sensor mission system comprises, among others, a SLAR, which acts as a “far-range sensor”, thus allowing for the detection of possible pollutions at distances up to 30 km – depending on the wind conditions – on either side of the aircraft. Thanks to its wide range this sensor is essential for finding and localising possible pollution. Besides, the extension of a surface slick can be determined. As the sensor emits high-frequency pulses in the X-Band (9.4 GHz), the detection of the smoothing of sea surface by oil (or look-alikes) is possible through clouds and at night-time, but requires intermediate wind conditions.

In addition, a number of “near-range sensors” are used at low altitudes (approx. 1,000 ft), having a viewing range of up to 250 m on either side. With their help, a closer investigation is performed and operationally important additional information (compared to the radar alone) is gained in order to confirm the detected spill as a pollution caused by mineral oil or not.

Fig. 3 View of the interior of the Do228 57+04. All sensors are controlled by an operator from the central computer console (© BfG, CCME)

All sensors of the Do 228 are operated in flight via a central computer console with real-time data viewer and near-real-time analysis software. A qualitative and quantitative judgement of observed features of any kind is ensured through a thorough analysis of all available data and through experienced operators. The set of remote sensing sensors is accomplished by photo and video documentation tools. Figure 3 shows the interior of the Do228 with an operator sitting at the central computer console and with the laser fluorescence sensor placed opposite to the entrance door.

The main characteristics of the sensors, the applied physical principals and their abilities with respect to oil spill monitoring, are summarised in the following:

The infrared channel (IR) is a passive channel that uses the thermal infrared radiation (8.5–14 μm wavelength). It visualises the measured radiation temperature that yields from a combination of kinetic temperature and emissivity. As this combined property is usually different between oil and surrounding water surface, the two parts can be separated. In addition, it allows for the localization of thicker patches of oil if they are warmed up by the sun. This channel has a high spatial resolution of ~3.5 m (at 1,000 ft flight altitude and a velocity of 70 m/s) and works at night-time but is impaired by clouds.

The ultraviolet (UV) is a second passive channel of the same sensor as the IR channel. It detects the ultraviolet radiation part (0.32–0.38 μm wavelength) of the sun light reflected from the sea or oil surface, respectively. As oil has a high reflectivity in the ultraviolet, this channel allows for a high resolution visualisation of even very thin oil layers (<0.1 μm [10]).

The microwave radiometer combines three passive microwave channels at 18.7 GHz, 36.5 GHz and 89.0 GHz, plus a zenith radiometer for atmospheric correction. An interference phenomena for layer thicknesses in the cm or mm range, comparable to “colour iridescence” of thin oil films in the visible [7], allows for the visualisation of thick patches of oil and for the estimation of thickness for thicker oil (between ~0.05 mm and ~3 mm) and thus of volume. This is the main sensor for detecting thick patches of oil as it works also at night-time and even through clouds.

The Laser fluorescence sensor is an active channel, emitting the 308 nm wavelength light of an XeCL excimer laser. The excited fluorescence is measured at 12 different detection wave lengths. Its main purpose is the characterization of oil types and discrimination of look-alikes by comparing the received fluorescence spectra with a reference library. This sensor works at night-time but is impaired by clouds [12].

3.2 Spaceborne Sensors

The detectability of marine oil pollution depends, among others, on the local wind speed, and thus, wind velocity vectors from numerical models and/or satellite sensors are used as supporting information for the classification of the detected SAR image features. Together with the features’ geometrical parameters such as their shape, orientation, or the form of their edges some information on their vicinity in the SAR image is also used as major classification criteria. A review of actual classification systems, seen from a European perspective, was recently provided by Ferraro et al. [13].

The main limitation of spaceborne optical sensors is the need of daylight and cloud-free weather conditions, but they have some potential to discriminate between oil and algal blooms [24].

3.3 Combined Monitoring System

The individual parts of the monitoring system have all their strengths and weaknesses. By combining them, an optimised benefit is received. This chapter summarises this aspect of the interplay and synergetic effects of the monitoring tools.

A (low resolution) radar satellite has the main advantage to deliver a partly automatic first alert and a good overview over a large sea surface of up to 400 km × 400 km that is independent from cloudiness. This output can be achieved in near-real-time for modern processing chains, i.e. within less than half an hour after satellite overpass. This technique is limited due to repetition times and the need of intermediate wind conditions. Further, it does not provide a direct indicator for oil, but only for the lack of capillary waves on the sea surface. Therefore, it is prone to look-alikes and can only deliver indications for possible pollution. Thus, satellites deliver a good overview and first alerts, which then need to be checked by aerial surveillance. Besides, they can help with monitoring in case of known hotspots, as e.g. spills that happened after an accident.

As described in the respective chapter, an aircraft that is equipped with a modern sensor system delivers a variety of add-on information about a surface slicks. Combined with the experienced operators on board, in many cases the discrimination between oil and look-alike can be made. Further, it allows for a high resolution routine surveillance or for monitoring in case of an accident. As a pollution response assistance and assessment tool, aircraft are more flexible and deliver much more information than radar satellite services. In addition, they can – especially if combined with in-situ samples – be used for preservation of evidence in case of deliberate pollution.

Though the information content of aerial surveillance data is much higher, the endurance and coverage of the aircraft are limited. Therefore, the effectiveness is increased, if the aircraft routes can be re-directed following the satellite information: either to specifically check possible pollutions detected by satellite for verification or to reduce the attention on areas reported as clean.

The question how the satellite service information should be prepared for optimal operational use and for the planning of follow-up actions is subject to on-going discussions and research [13]. Next to the operational use, the combination of satellite and aircraft is a valuable tool for validation – either of the satellite service or also for drift models – and thus for improvement of the existing tools.

In Germany, the operational oil spill drift model is operated by the German Federal Maritime and Hydrographic Agency (Bundesamt für Seeschifffahrt und Hydrographie, BSH). The basic circulation model, called BSHcmod, provides a 78 h forecast once a day, which covers the North Sea and the Baltic Sea with focus on, and therefore with higher resolution in, the German Bight and the western Baltic Sea. The model system is operational since 1999 [14] with the latest major update in 2008. Meteorological forcing (with forecasts up to 7 days) is provided four times a day through the meteorological forecast model of the German Weather Service (Deutscher Wetterdienst, DWD) and wave forcing through DWD's wave models. The model results' temporal resolution is 15 min. The drift model considers the most important weathering processes such as evaporation, dispersion, and emulsification, and drift and spreading forecasts serve as decision support for the contingency planning of the operational agencies. In addition, the model is capable of backtracking pollutants and, thus, is used to derive the likely origin of the observed pollution [15].

If a possible marine pollution is detected by remote sensing sensors, drift model runs are started at BSH. Results of prognostic drift model runs are important as support for pollution response on sea or land. It helps to decide if response units are required and where to place them. Besides, in hindcast mode, the back tracking results can – possibly combined with AIS (automatic ship identification system) information – help to find the origin of pollution.

As a part of the DeMarine-project (www.demarine.de, accessed 3 June 2011), a prototype for a processing chain has been developed to partly automatically implement remote sensing information by satellite or aircraft as input into the operational BSH drift model. In this way, position, area and distribution of remotely sensed oil spills can – after manual selection – be automatically processed and a provisional model output is generated to be reviewed by the model operators. This includes a gain of information content and quality as well as saving of time [16].

4 Example Data

In this chapter, we present some examples of remote sensing data showing marine oil pollution in the western Baltic Sea. Historically, only mono-frequent (C-band) SAR data were used for spaceborne oil pollution surveillance, and only during two short (10-days) space-shuttle missions in 1994, multi-frequent SAR sensors were in orbit. However, recently, SAR sensors working at L- and X-band have been placed in orbit, thus giving the opportunity to benefit from previous research on the use of multi-frequency SAR sensors for oil pollution monitoring [17].

4.1 Mono-frequent SAR Data

The capability of SAR sensors of detecting marine oil pollution has been known for decades [2]. SAR images acquired from the First and Second European Remote Sensing Satellites, ERS-1 and ERS-2, have been used to demonstrate this capability and to compare SAR signatures of marine oil pollution with those from other features ("look-alikes") that also cause a reduced radar backscattering from the sea surface and, thus, dark patches on the SAR images [18].

As an example, Fig. 4 shows an ERS-1 SAR image acquired on 16 April 1994 at 21:04 UTC (i.e. well after sunset) over German waters in the western Baltic Sea. Dark areas in the lower (southern) part of the image are due to low wind and to natural surface films, which manifest in large black areas and thin dark patches following the local currents, respectively. In the upper (northern) part of the image, closer to the Swedish coast and just outside of German waters, an elongated dark patch can be delineated, with a bright spot on its right (eastern) end. This feature is likely to be caused by mineral oil freshly spilled from a ship travelling eastbound. This example demonstrates not only the strength of spaceborne SAR sensors for oil pollution detection, but also the danger of misinterpretation of dark features seen on the SAR imagery.

Figure 5 gives an example of the same confirmed oil spill that is shown once by satellite-based SAR (left, ENVISAT-ASAR (ESA, EMSA 2008)) and once observed by air-based SLAR (right, three hours later, BfG, Central Command for Maritime Emergencies (CCME), 2008).

4.2 Multi-frequent SAR Data

In 1994, during two 10-day missions, a multi-frequency SAR system, the "Spaceborne Imaging Radar C / X-Band SAR", SIR-C/X-SAR, consisting of an L-, C- and X-band SAR was flown on the space-shuttle "Endeavour". SIR-C/X-SAR images of biogenic and anthropogenic marine surface films at different places on the world's oceans were

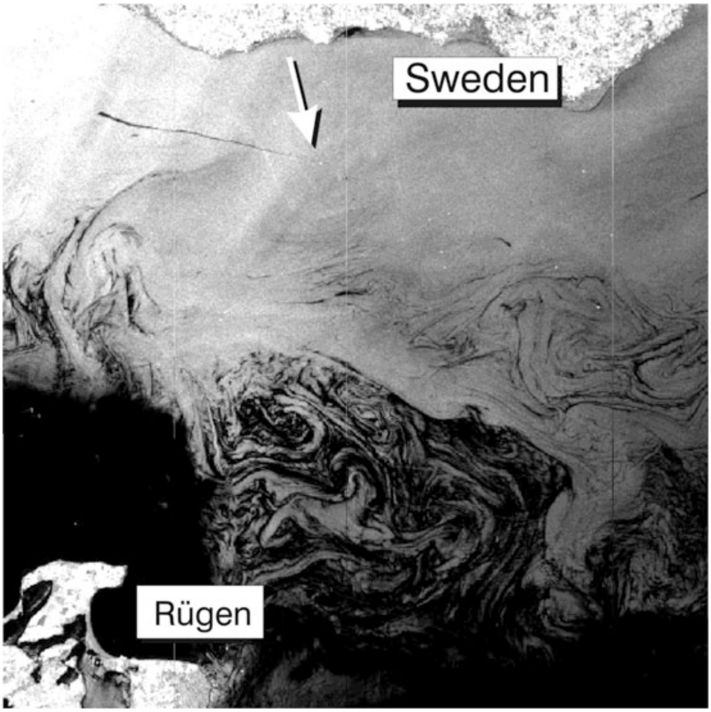

Fig. 4 ERS-1 SAR image of the western Baltic Sea, between the German island of Rügen and Sweden, acquired on 16 April 1994 at 21:04 UTC. The lower (southern) part of the image is dominated by natural surface films, while in the upper (northern) part a single elongated dark line can be delineated, which is due to freshly spilled oil. The causing ship manifests as a bright spot on the eastern edge of the spill and is marked by the *white arrow*. Taken from Gade [19]

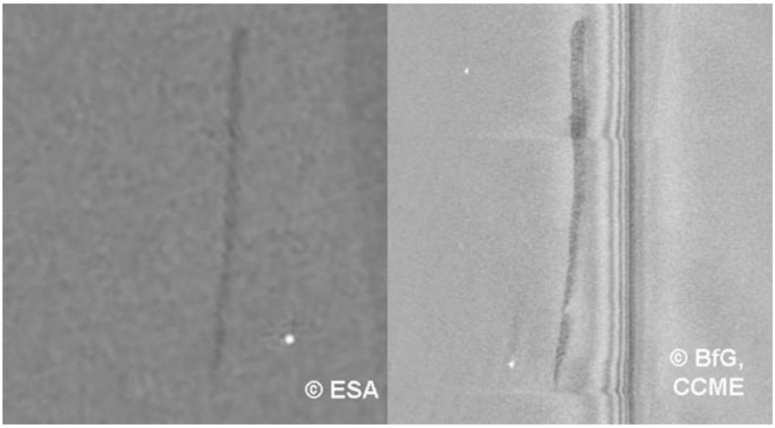

Fig. 5 Example of a confirmed marine oil pollution. *Left*: oil spill causing an elongated dark patch in an ENVISAT-ASAR image (© ESA, 2008). *Right*: the same oil spill detected three hours later by a Side-Looking Airborne Radar (SLAR) (© BfG, CCME, 2008; also published in [16])

acquired during the two missions in April and October 1994. In the mid-1990s, those images were analysed to investigate whether or not a multi-frequency SAR system such as SIR-C/X-SAR is capable of discriminating between biogenic and anthropogenic oceanic surface films [5]. Results obtained from those SAR images of various biogenic and anthropogenic surface films are shown in Figs. 6 and 7, respectively. Note that the classification between biogenic and anthropogenic surface films was made by an operator and was based on the shape and the size of the observed features. For example, the SAR images shown in Fig. 6 show typical signatures of biogenic surface films: during on-going algal blooms, surface-active material accumulates on the water surface and the long, narrow, dark streaks follow the surface currents. On the other hand, signatures caused by mineral oil spills (Fig. 7) can often be identified

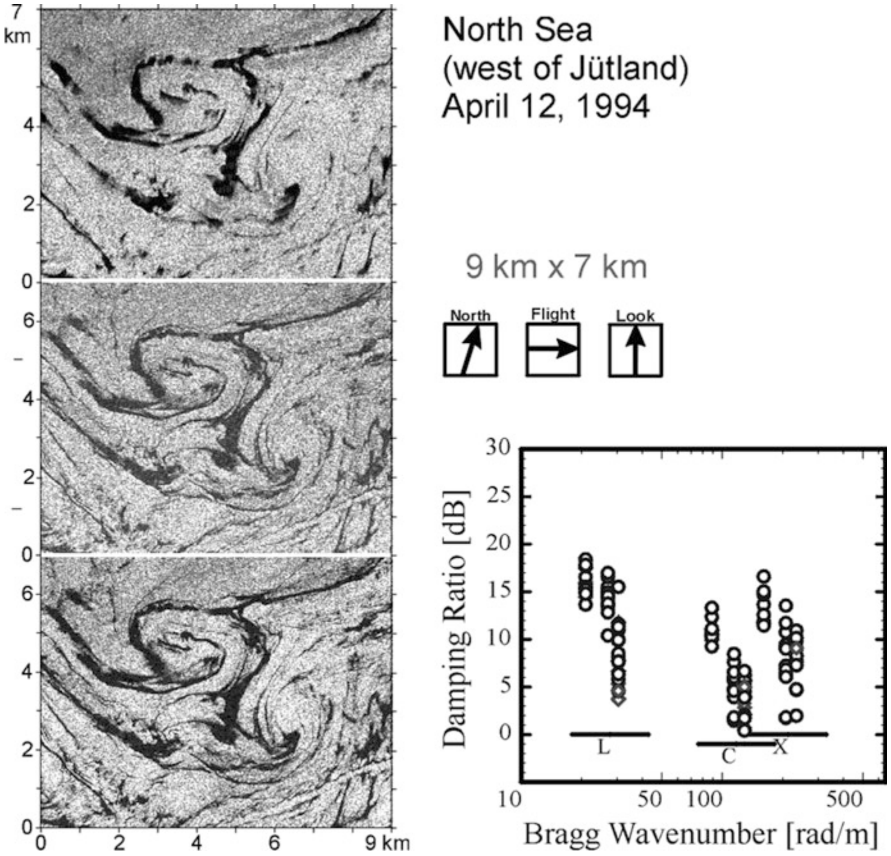

Fig. 6 *Left column*: SIR-C/X-SAR images (9 km × 7 km) of the same spot of the North Sea acquired on 12 April 1994 and showing signatures of natural surface films. The images were acquired at L-, C- and X-band (from top to bottom), VV-polarisation. *Bottom right*: damping ratios obtained from SIR-C/X-SAR images of various natural slicks at low to moderate wind speeds ($<7\ \mathrm{m\ s^{-1}}$). Diamonds and circles denote HH and VV-polarisation, respectively. Taken from Gade [20]

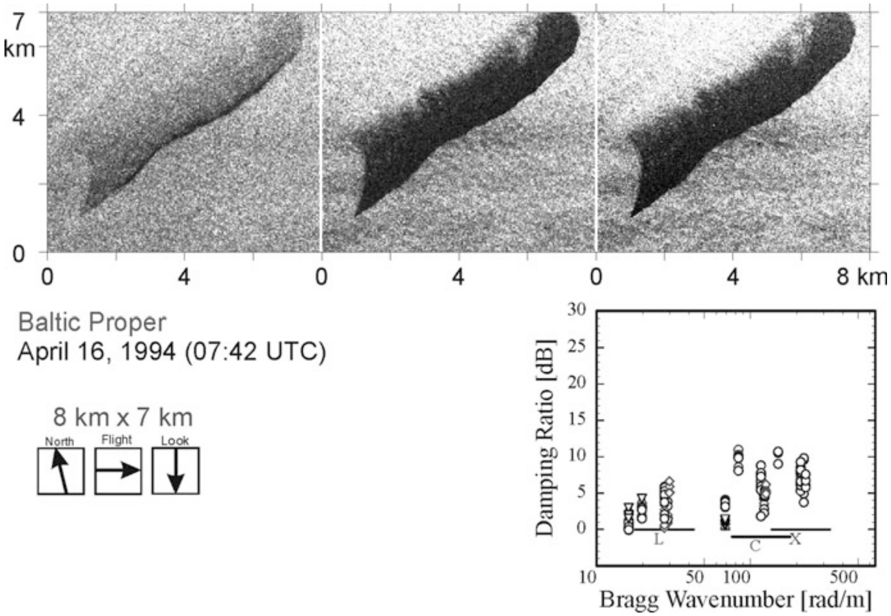

Fig. 7 *Upper row*: SIR-C/X-SAR images of the same spot of the Baltic Proper acquired during the first shuttle mission on April 16th, 1994, and showing signatures of a mineral oil spill (image dimensions 8 km × 7 km). The images were acquired at L-, C- and X-band (from left to right), VV-polarisation. On the *bottom right*, damping ratios obtained from SIR-C/X-SAR images of various mineral oil spills at low to moderate wind speeds (<7 m/s) are shown. *Diamonds*, *circles* and *triangles* denote HH, VV and HV/VH polarisation, respectively. Taken from Gade [20]

because of their irregular shape and the fact that their contrast is often independent of the different wind speed on its either sides [5].

In the early 1990s, scientists of the University of Hamburg performed surface film experiments in the German Bight of the North Sea, which were particularly designed to investigate whether active multi-frequency microwave systems (scatterometers or radars) can be used to discriminate between natural surface slicks and mineral oil spills. Using SIR-C/X-SAR images of those surface film experiments, it was found that the measured damping ratio (i.e. the ration of the radar backscattering from a film-free and a film-covered sea surface) strongly depends on wind speed, which is in accordance with results obtained in parallel by the helicopter-borne scatterometer HELISCAT of the University of Hamburg.

The results show evidence that biogenic sea slicks cause a strong damping also at L-band (Fig. 6), whereas anthropogenic oil spills cause damping ratios increasing from L-band to X-band (Fig. 7). We note that the observed damping ratios from biogenic and anthropogenic surface films at C- and X-band are similar. Particularly at C-band, this is due to the insufficient signal-to-noise ratio of the SIR-C/X-SAR system. The results from Gade et al. [5] show that multi-frequency SAR imagery yields more information on the damping characteristics of oceanic surface films than single-frequency SAR imagery, which is needed for a better discrimination between different kinds of surface films, particularly under low to moderate wind conditions. Particularly, L-band data seems to be crucial for a successful discrimination of different surface films.

The evidence shows that under low to moderate wind conditions, multi-frequency radar techniques are capable of discriminating between the different kinds of surface films, whereas at high wind conditions a discrimination (on a basis of damping measurements) is impossible (for examples for high wind speed, see Gade et al. [6]).

4.3 Airborne Surveillance Data

In this section, we present a few examples of sets of images taken by the sensor system aboard the Do228 57+04 (Fig. 8).

In Fig. 9, a pollution event is shown that has been confirmed as mineral oil. The oil originates from a platform (not within the Baltic). The SLAR image (to the left, different scale) gives an overview: The black area in the middle of the stripe originates from the reduced backscattering due to the lack of capillary waves that is caused by the oil spill. The IR highlights the thicker parts of the oil (here: green and black); whereas the UV shows the maximum extend of the slick. The MWR images points out the thickest parts (in this case sparse; in green at the lower end of the stripe) of the slick and allows for an estimation of thickness. The laser fluorescence sensor sees the rather thin and thicker oil parts (here in green): in a much smaller scanning stripe and gives a classification of the oil (here: crude oil).

Fig. 8 German pollution control aircraft Do228 57+01 (© CCME; Source: www.havariekommando.de)

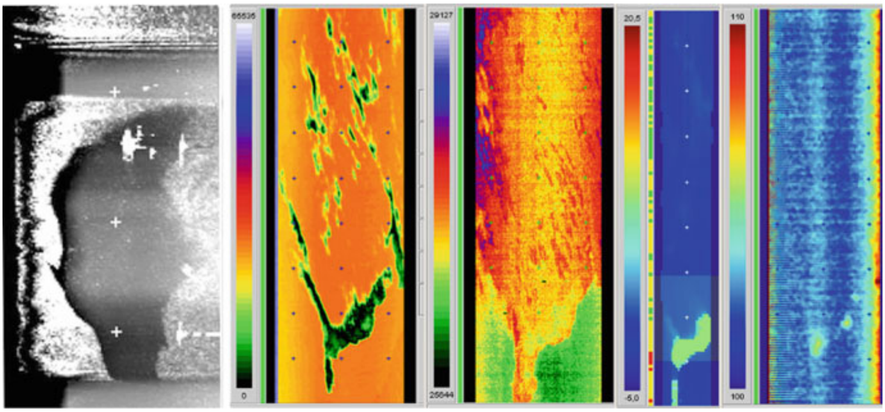

Fig. 9 Example data of a confirmed oil pollution event observed by the sensor system of the Do228 57+04. From left to right: SLAR, IR, UV, LFS, MWR (© BfG, CCME 2011; in similar form in [21])

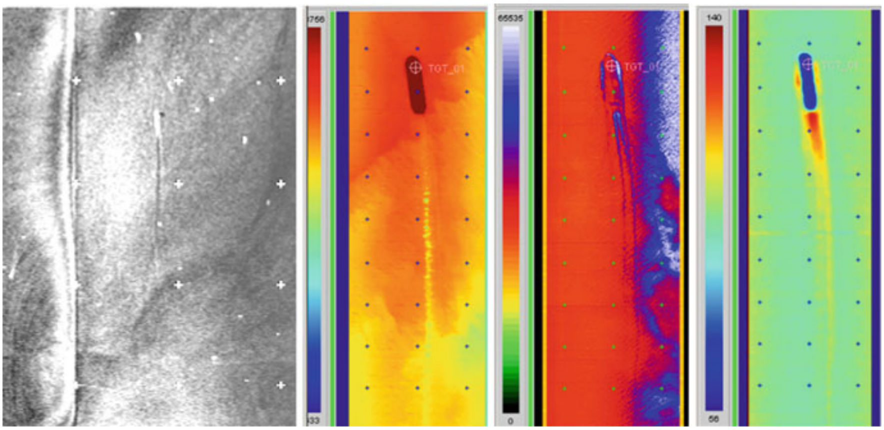

Fig. 10 Example data of a ship track observed by the sensor system of the Do228 57+04. From left to right: SLAR, IR, UV, MWR (© BfG, CCME 2011)

For comparison Fig. 10 shows a set of images of a ship track, where the signature is a mixture of surface effects and temperature differences of water originating from deeper water layers.

4.4 Statistics

Statistical analyses of detected oil pollution incidences have been a key element of the scientific evaluation of the processed SAR data. This chapter contains some main findings of those analyses that were performed at the University of Hamburg in the late 1990 and that can be seen as a basis for those routine analyses performed later.

4.4.1 "Clean Seas" Statistics

Gade and Redondo [22] analysed more than 700 ERS SAR images of European marginal waters (acquired between December 1996 and November 1998 over the Baltic Sea, the North Sea, and the north-western Mediterranean Sea) with respect to the detectability of marine oil pollution. Example results are shown in Fig. 11.

Gade and Redondo [22] were the first to derive from satellite imagery areas of mean oil pollution. They took into account those dark patches in the SAR images that show a significant reduction in the radar backscatter (Fig. 11). In all regions of interest, they found a larger amount of oil pollution during summer (April–September) than during winter (October–March), which they explained by the overall higher wind speeds in all test areas during wintertime. Moreover, the Baltic Proper seemed to be the test area with lowest detected oil pollution, whereas the pollution seemed to be highest in the north-western Mediterranean Sea. They suggested the difference in mean wind speed in those areas to be the main reason for the observed differences, since wind speed differences cause a different visibility of oil pollution in SAR images.

Gade et al. [23] used model wind speeds of the German Weather Service (Deutscher Wetterdienst, DWD) to estimate the influence of the local mean wind speed on the overall detectability of marine oil pollution. The model results for the

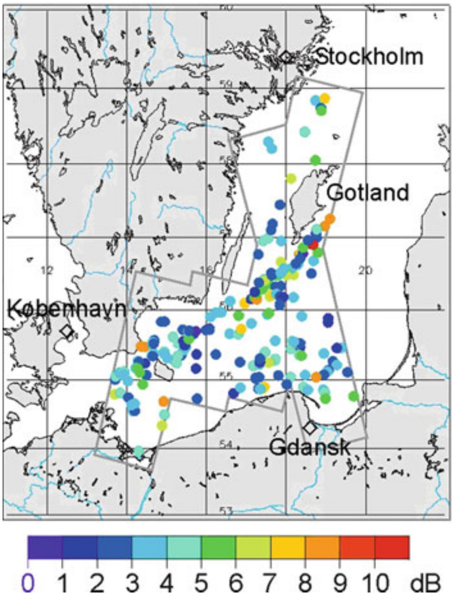

Fig. 11 Results of the analyses of 220 ERS-2 SAR images of the Baltic Proper. Each *dot* denotes the location of a detected possible oil spill, the *colour coding* denotes the measured reduction in the radar backscatter (damping ratio)

Baltic Proper for the entire period of interest (December 1996 until November 1998) are shown in Fig. 12. The left panel contains the values calculated for summer (April–September) and the right panel contains those for winter (October–March). Note that the maximum mean wind speed in the Baltic Proper during summer is just above 8 m/s, whereas it is just below 10 m/s during winter.

Gade et al.'s [23] improved statistical analyses included the mean local wind speed from the DWD model for the three European test sites (Fig. 13, middle panel). Calculating the distribution of the detected oil spills with wind speed (left panel of Fig. 13), they showed that most oil spills were detected at mean (modelled) local wind speeds between 3 m/s and 4 m/s. The maximum of the wind speed distribution (middle panel of Fig. 13) lies between 5 m/s and 6 m/s. The right panel of Fig. 13 shows the "normalised oil spill visibility" (NOSV) Gade et al. [23] calculated as the (normalised) ratio of the two former.

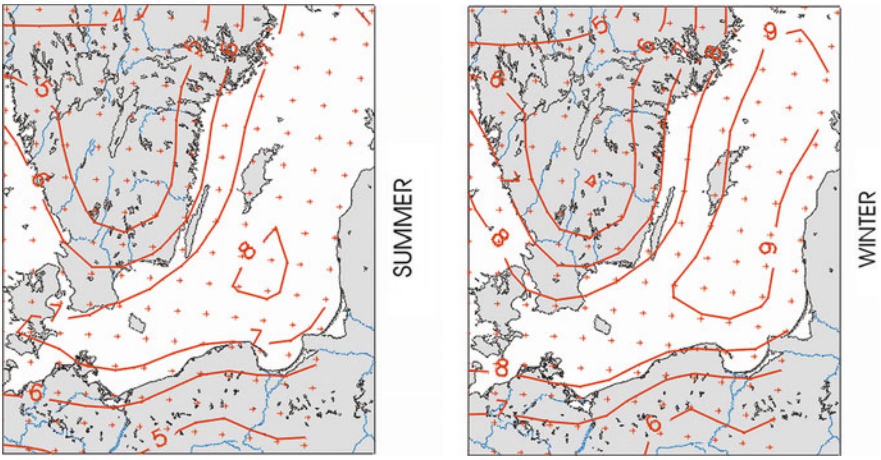

Fig. 12 Mean wind speeds for the Baltic Sea for December 1996 through November 1998, as derived from a numerical model driven by the DWD. *Left*: mean wind speeds for summer periods (April–September), *right*: mean wind speeds for winter periods (October–March). Taken from Gade et al. [23]

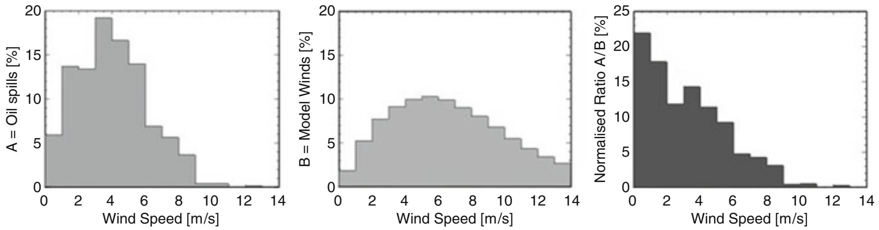

Fig. 13 *Left*: distribution of detected oil pollution with wind speed; *middle*: frequency of the DWD model winds; *right*: "normalised oil spill visibility" calculated as the ratio of the oil spills distribution and model wind speed distribution. Taken from Gade et al. [23]

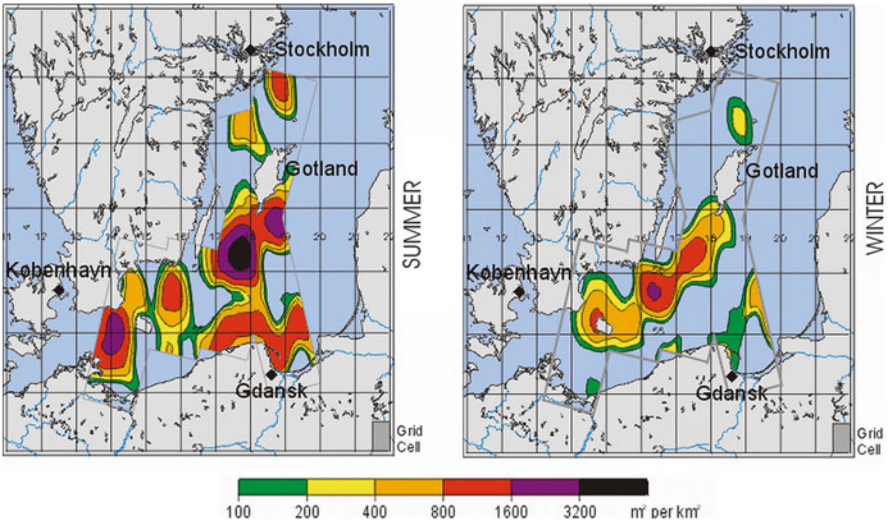

Fig. 14 Density maps of (detected) oil pollution in the Baltic Proper, as derived from 220 ERS-2 SAR images between December 1996 and November 1998. *Left*: Summer months (April–September), *right*: winter months (October–March). The maximum pollution density was found along the main ship traffic route through the Baltic Proper. Taken from Gade et al. [23]

For the first time, the NOSV gave a clear quantitative estimate of the detectability of marine oil pollution. The results of Gade et al. [23] prove that higher wind speeds cause lower detectability of oil pollution, and vice versa. A simple (spline) fit to the NOSV distribution reveals that oil spill detection in European coastal waters is possible only at wind speeds below 10 m/s and that the definite detection of marine oil pollution at higher wind speeds seems to be almost impossible. Gade et al. [23] used these results to explain why less oil pollution was detected in the northern test areas during wintertime, and they were the first to produce density maps of oil pollution for European marginal seas (Fig. 14).

Figure 14 clearly shows that less pollution was found during wintertime (right panel) and that throughout the year, the highest pollution density was found along the main ship traffic route through the Baltic Proper (cf. Fig. 2). Gade et al. [23] concluded that it is unlikely that less pollution occurs during winter months, but that the overall higher wind speed results in a lower detectability of that pollution. This also means that the overall higher ship traffic during summer does not manifest in higher oil pollution of the Baltic Sea (we note that only a limited number of SAR images were used for those statistics, and that the inflexible acquisition times may also have biassed the presented results).

4.4.2 Combined Statistics

Figure 15 shows a map of the possible pollutions in the Baltic part of the German Exclusive Economic Zone (EEZ) originally reported by the satellite service in the

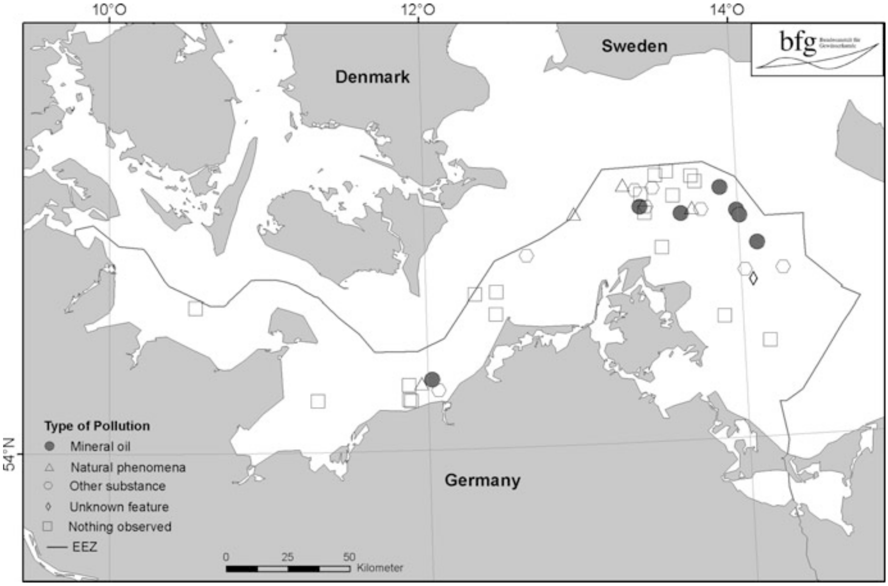

Fig. 15 Results of aerial surveillance of possible oil spills reported by the satellite service in 2007–2010

years 2007–2010 that have been checked by aerial surveillance. The results of the checks are displayed in the map, divided into the classes: confirmed as mineral oil, natural phenomena, other substance, unknown feature and nothing observed. This shows that the detections based on satellites alone have to be taken with care – though there can be a time lag of some hours between satellite overpass and check.

The aerial surveillance is performed on a regular basis but with changing schedules at any day of the year and at day and night-time, partly combined with satellite overpasses and partly independently. As an example, in 2010 there were 235 aircraft missions in the Baltic Sea, thereof 174 during daylight and 61 during night-time. With nearly 600 flight hours on task in the Baltic, this makes an average of 1.6 h monitoring time per day; 19 oil spill pollution events were detected in the German territorial waters and EEZ. Also including pollution events detected by the German aerial surveillance in waters of neighbouring countries, the total oil-covered area in 2010 was 92.2 km^2. According to the Bonn Agreement Oil Appearance Code [11], this area corresponds to 3.3 m^3 floating oil. On a temporal basis, 0.07 pollution events per flight hour were detected (Source: CCME 2011, unpublished material).

5 Summary

The German part of the Baltic Sea is being frequently monitored with respect to possible oil pollution both from aircraft and from space, and from patrol vessels. We have introduced the combined German oil monitoring system using satellite services, aerial surveillance and drift modelling. The sensor system on board of the oil surveillance aircraft of type Dornier228 is presented as well as some images. Further, SAR imagery examples show marine oil films in the western Baltic Sea.

Basic research on the visibility of marine oil pollution and of natural surface films has been performed in Germany, and some fundamentals on the discrimination of anthropogenic oil films and biogenic sea slicks were given.

Acknowledgements The authors are grateful to Susanne Kranz for her support in producing maps and statistics, to the staff of the Naval Air Wing 3 “Graf Zeppelin”, who operate the German surveillance aircraft, and to the Central Command for Maritime Emergencies, who coordinate the German operational oil spill surveillance.

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Oil Pollution in Waters of Latvia

Juris Aigars, Evija Šmite, Juris Skrube, and Ojārs Gerke

Abstract Although oil pollution accidents were quite numerous in the past, the accident frequency has substantially decreased since 2005 both in ports and in the Latvian exclusive economic zone and territorial waters most likely due to the introduction of no-special-fee system in the ports. Furthermore, absolute majority of registered oil spills were small scale. Therefore, no significant impact on the environment could be expected, which was confirmed by the results of limited investigation.

Keywords Baltic Sea, Gulf of Riga, Oil, Oil pollution

Contents

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Hdb Env Chem (2014) 27: 85–100, DOI 10.1007/698_2011_113,

1 Introduction

Latvia, with a coastline of about 497 km, exact coastline length slightly varies in different sources, is located on the eastern shore of the Baltic Sea. Latvia borders with Lithuania from south and with Estonia from north. Latvia has also marine border with Sweden from west. Along Latvia coastline altogether ten ports are located. Three of them (Liepaja, Ventspils, and Riga) qualify as big ports and seven (Skulte, Mersrags, Salacgriva, Pavilosta, Roja, Kuivizi, and Engure) as small. From the point of view of oil pollution, mostly ports with substantial cargo and ship turnaround are of interest. Therefore, of all Latvia's ports, eight commercial ports located along Latvia coastline and on average ranging from 1 thousand tons to up to 30 million tons in annual cargo turnover will be discussed in this chapter (Fig. 1).

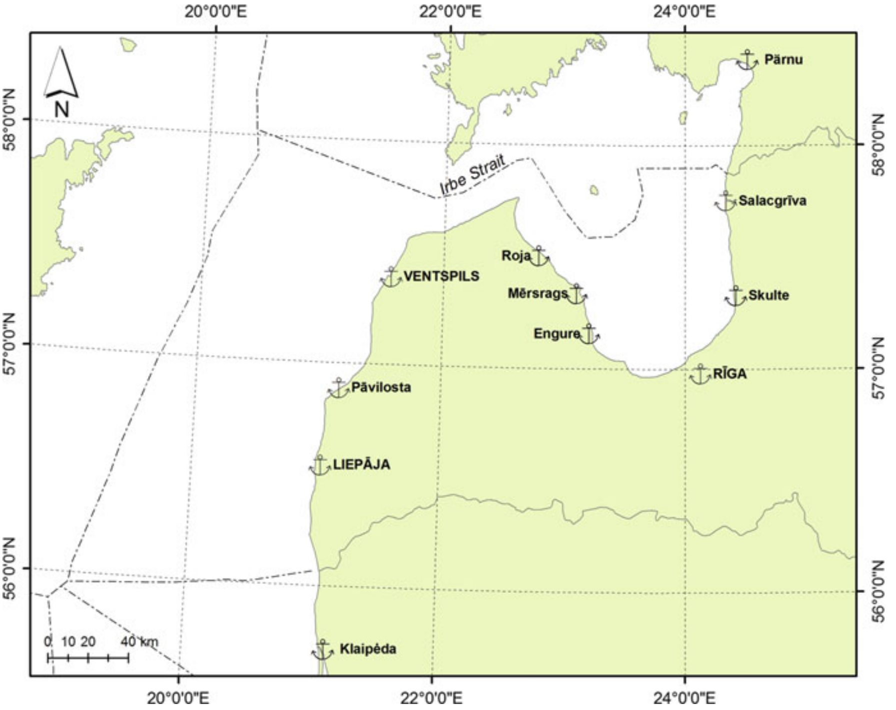

Fig. 1 Distribution of ports along Latvia coastline

Table 1 Average annual cargo turnaround and number of port visits by ships for period 2005–2008. (Data from port statistical overviews)

Port	Cargo turnaround (thousands tons)	Fisherman vessels	Cargo vessels
Liepaja	4,000	–[a]	1,508[b]
Ventspils	29,632	–	2,124[c]
Roja	40	5,500	16
Mersrags	380	–	120
Engure	1	400	–
Riga	26,321	–	3,884
Skulte	461	–	163
Salacgriva	379	–	175[d]

[a] Included in cargo vessel statistics

[b] Data only from 2007

[c] Data from Informative report for 2006 "Par brīvostu un speciālo ekonomisko zonu darbību 2006.gadā un 2007.gada I pusgadā," http://www.em.gov.lv/em/2nd/?cat=30110 (viewed 14.03.2011)

[d] Data from 2005–2007

Main ship route is in Swedish waters so passing Latvia, however, according to HELCOM AIS, substantial number of ships not bound for Latvian ports enter Latvian EEZ and territorial waters.

2 Anthropogenic and Natural Sources of Oil Pollution

2.1 Oil Terminals and Ports

The major share in cargo turnaround of Latvia's ports (Table 1) is taken up by dry bulk and general cargo. Only three biggest ports, Ventspils, Riga, and Liepaja, provide oil and its products loading/unloading services, e.g., in Ventspils more than 60% of cargo is oil and oil products, while in Riga and Liepaja only around 20%. Therefore, it could be expected that oil pollution events would be located only in these three ports or their vicinity. At the same time, very intensive small (up to 100 GT) fisherman vessel traffic observed at ports with very modest cargo turnaround (Table 1) indicates relative importance of these ports too due to statistically large probability of small or medium-sized leakages during servicing of these ships. Furthermore, intensive traffic increases probability of collisions which might result in ship fuel discharge too.

Annually, 10–19 oil pollution events, ranging from less than 1 kg and up to more than 5,000 kg, are reported and acted upon in port territories. Mostly, these events are accidents that can be attributed to ship-based or port facility-based activities (Fig. 2). At the same time, the data indicate that separately accounted deliberate discharge of oil products in port territories, such as bilge waters, have been declining (Fig. 2) and since 2005 no deliberate discharge of bilge waters has been recorded. The most likely reason for this decline is no-special-fee system introduction in ports, which means that ships have to pay certain fee covering the costs of

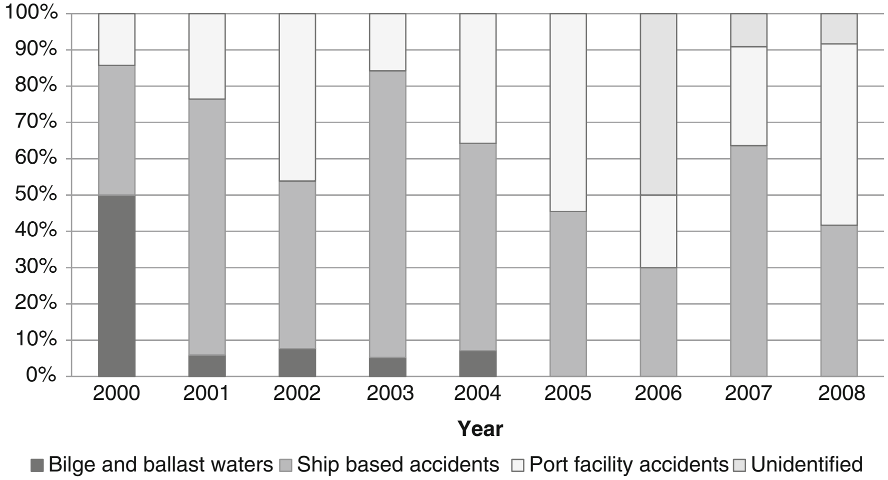

Fig. 2 Relative distribution of oil pollution accidents in ports by categories

reception, handling and disposal of ship-generated waste irrespective of whether or not ship-generated wastes are actually delivered. At the same time, recently the number of pollution events of unidentified source has been observed in port territories. One explanation might be that historically polluted ground waters enter port waters. However, it cannot be excluded that some of these cases are oil products discharged on ground and carried to the port aquatorium by rain water.

2.2 Ship Routes

According to HELCOM AIS, ship traffic in the Baltic Sea is steady growing, e.g., the number of ships crossing fixed AIS lines in the Baltic Sea has increased from 376,671 in 2006 to 453,698 in 2008 [1]. At the same time, it is recognized that part of this increase in numbers should be attributed to increase in number of ships registered in the AIS system. Substantial part (e.g., 33,978 in year 2008) of these ships is crossing fixed AIS line from Liepaja to Gotland [1]. Although most of them are passing by or through Latvian EEZ waters, significant number are bound to Latvia's ports. So, for example, in 2008, AIS has recorded 9,907 ships going through Irbe strait in or out of the Gulf of Riga. Majority of the ships entering the Gulf of Riga are bound to Port of Riga (Table 1). In addition to ship routes, ship waiting areas should be considered. As can be seen from AIS snapshots [1], areas close to ports are exhibiting substantial ship concentrations.

The observed number of oil spills varied widely from 73 in 1990 to 0 in 1994–1997 and 2006. As could be expected, the oil spills are mostly concentrated along the most intensively used ship routes, e.g., Irbe strait, and in port vicinity areas used as ship waiting areas (Fig. 3).

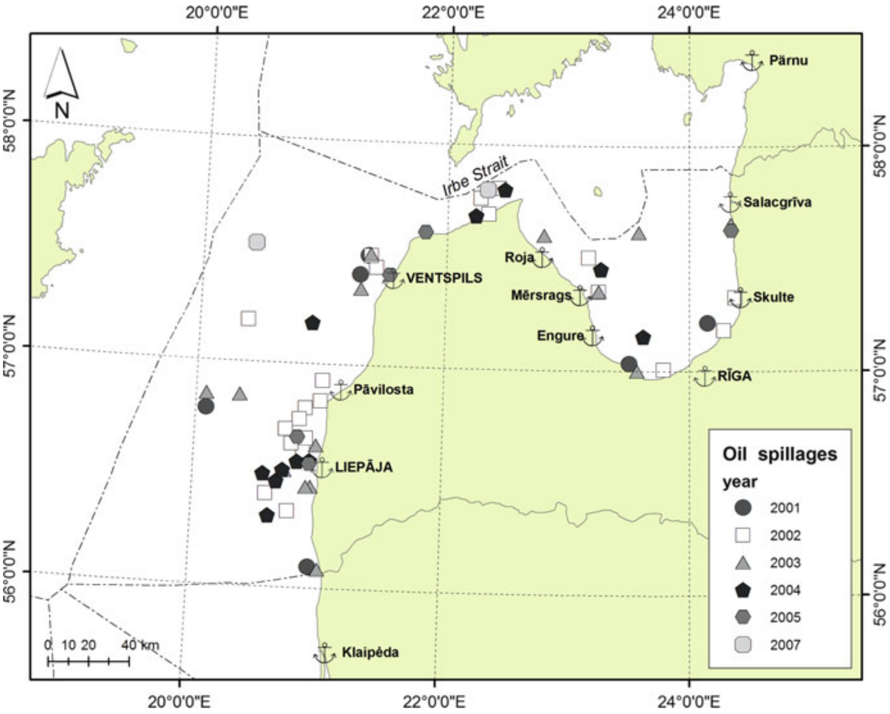

Fig. 3 Location of the oil spills observed in Latvian marine waters in 2001–2007

Since flight hours also varied widely from 8 in 1995–1996 to 577 in 1998 and the number of detections is dependent on the number of flight hours; the Pollution per Flight Hour (PF) index is usually used to describe changes in oil pollution. Similar to most countries around Baltic Sea, the PF calculated for Latvia's waters exhibits clear decrease [1]. However, unlike total Baltic wide PF index, which exhibits clear but gradual decrease [1], the PF index calculated for Latvian waters (Fig. 4) exhibits very sharp decrease in 1993, which can mostly be attributed to drastic decrease in the number of flight hours. Nevertheless, after regular flight system was reestablished in 1998, two distinct periods, 1998–2004 and 2005–2008, can be distinguished. During the first period, on average 416 (range 320–577) flight hours revealed regular oil spills in Irbe strait, in the Gulf of Riga on ship route to Riga and close to Liepaja and Ventspils harbors (Fig. 5a), and resulted in average PF index value 0.042. During the second period, on average 334 (range 298–384) flight hours revealed only occasional oil spills in Irbe strait, close to Liepaja and Ventspils harbors (Fig. 5b), and resulted in average PF index value 0.009. The most likely explanation is the same as to decrease in oil spills in port areas that is no-special-fee system introduction in ports.

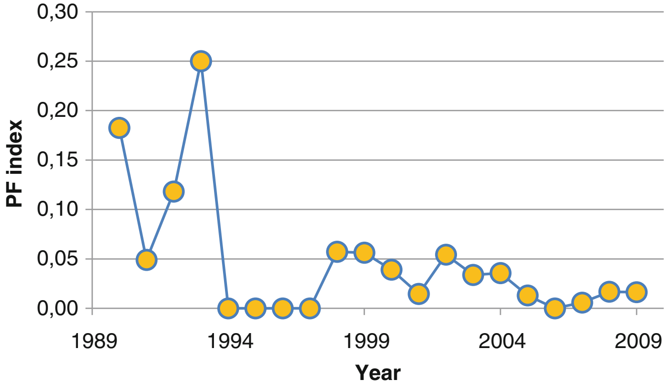

Fig. 4 PF index changes in Latvian territorial and exclusive economic zone waters

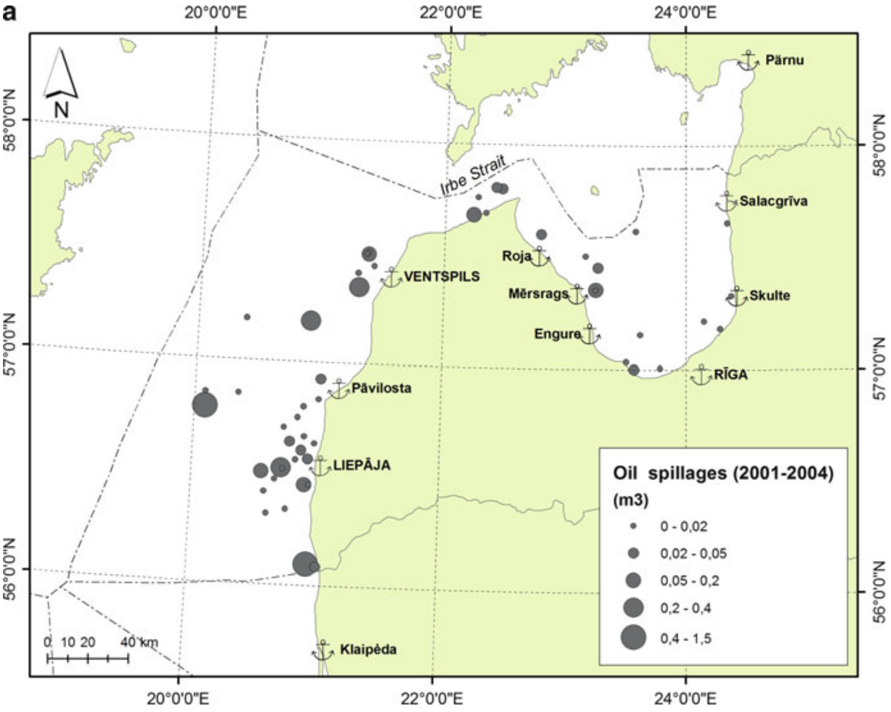

Fig. 5 (Continued)

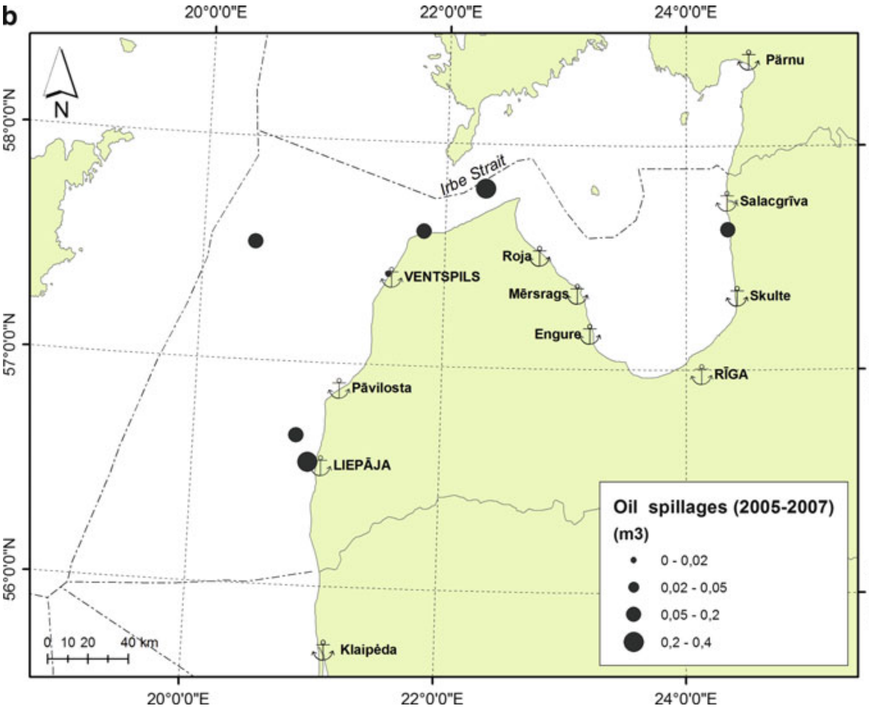

Fig. 5 Location and amount of oil spills in Latvian territorial and EEZ waters from (**a**) 2001 to 2004, (**b**) 2005 to 2007

2.3 Trans-Boundary Pollution

Latvia's marine border is with Lithuania in south, Estonia in north, and Sweden in west. The likely trans-boundary pollution vectors are from ship traffic in Sweden's waters east of Gotland and from ships entering the Gulf of Riga and bound to Pärnu port. However, the most likely trans-boundary pollution can be expected from very busy Klaipeda port, e.g., 8,348 ships serviced in 2008, and in function since 1999 Butinge oil terminal located between Klaipeda and Latvia border, especially taking into the account dominant northward water flux along East-Baltic coast.

Because Lithuanian aerial surveillance reported no oil spills since 1993 [1], it could have been assumed that activities of Klaipeda port, Butinge oil terminal, and Lithuanian waters visiting ships have been resulting in no oil discharges. However, Latvian aerial surveillance has occasionally recorded oil spills, which most likely are of trans-boundary origin (Fig. 3). Furthermore, substantial number of oil spills observed in the vicinity of Liepaja port was located south of it. Although most likely observed oil spills were originating from ships entering or leaving Liepaja port, the possibility of northward transport from Lithuania waters cannot be excluded either. However, to draw more definite conclusion, additional research on weather conditions prior to sighting of oil spills would be needed.

3 Oil Pollution Monitoring Practice and Existing Systems

Up to 2007, Marine and inland waters administration (MIWA) of State Environmental Service had been organizing oil spill observations in the sea by conducting 1–2 flights per week depending on the available financing and weather conditions since flight services were carried out only in weather conditions, which permit visual observations. Since 2007 Latvia in person of Coast guard, National Armed Forces, and MIWA is using satellite ENVISAT and RADARSAT SAR pictures on oil product observation in the sea. The satellite pictures after pretreatment are available to respective country 30 min after satellite has crossed the respective area. In case of identification of possible oil product spill, relevant contact persons are informed by e-mail and SMS. Similar to other coastal states, Latvia has access to CleanSeaNet (CSN) services, which include access to satellite pictures, spill analysis results, wind information, and other relevant information.

Receiving satellite observation on possible oil spill, the information is checked at sea by a ship of Coast guard or aerial surveillance flight by MIWA inspectors (until July 2009). Thereafter, response activities can be initiated (e.g., Fig. 6).

During period 2007–2010, Latvia has received 878 satellite pictures. In 249 of them, indications of possible oil product spills were present, and 33 of them in Latvian EEZ.

Since ship captains, terminal owners, and port pilots are obliged to inform port captain if any oil pollution is sighted, no regular systematic survey system has been

Fig. 6 Oil spill in the Baltic Sea

in place. The port captain upon receiving report on oil pollution immediately informs MIWA which in turn sends inspector to investigate.

4 Amount of Oil Pollution

4.1 Oil Pollution in Port Areas

Altogether 127 oil pollution events were registered in Latvian port territories during 2000–2008. Mostly, 84 cases, oil spills were originating from ships, e.g., discharges of bilge waters, fuel and lubricants during small accidents, and black fuel oil, while port infrastructure objects accounted for 36. In addition to that, seven oil spills of unknown or historical origin were registered. Usually when oil spills are registered, the area and description-appearance is registered. Thereafter, the oil spill volume is calculated according to commonly accepted Bonn agreement oil appearance code.

Mostly registered oil spills were small, less than 0.1 m^3 (Fig. 7); however, substantial number of oil spills in range of 0.1–1 m^3 have been observed as well. No seasonal or spatial pattern in occurrence of oil spills could be distinguished. Oil spills bigger than 1 m^3 originating from ships were registered only occasionally and were caused by various circumstances, e.g., discharge of bilge waters in 2000 or ship fire in 2007. Similar to that, oil spills bigger than 1 m^3 originating from port facilities were caused by accidents or deliberate actions, e.g., in 2008 undiscovered persons unscrewed pipeline connection in result of which around 4 t of diesel was discharged on ground and subsequently polluted nearby port aquatorium.

The oil spills of unknown origin were mostly smaller than 0.1 m^3 and most likely were either entering port waters along with rainwater either as historical pollution washed out from soil or as oil products initially deposited at road and other surfaces from atmosphere and thereafter washed away by rain. Since this type of oil spills was observed only since 2006 (Fig. 2) then it can be assumed that either hydro-engineering constructions were in better shape or pollution events of unknown source were not registered prior to 2006. Only one oil spill exceeding 1 m^3 of unknown origin was registered, e.g., in 2006 Port of Riga and adjacent water bodies were covered (approximately 20,000 m^2) with oil products. Pollution was cleaned up; however, pollution source was undiscovered.

4.2 Oil Pollution in the Sea

The oil spills observed from 2001 to 2007 in Latvian territorial and EEZ waters although numerous can be characterized as small scale (Fig. 5a, b). Only on one

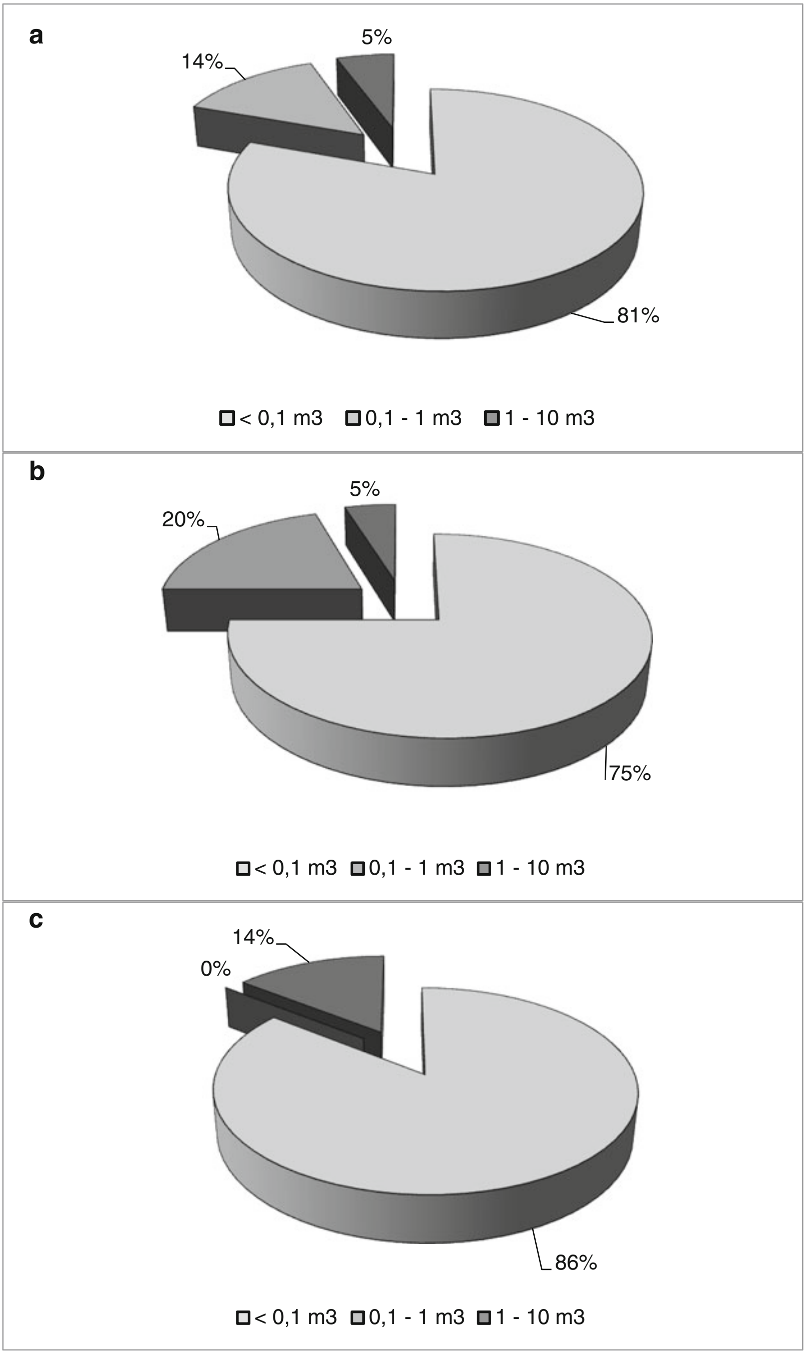

Fig. 7 Percentage distribution of oil spill size in ports. (**a**) Oil spills originating from port infrastructure objects, (**b**) oil spills originating from ships, (**c**) oil spills originating from unknown sources and historical pollution

occasion, in August 2001, registered oil spill exceeded 1 m^3. As discussed earlier, the pollution events mostly occurred in the vicinity of ports of Liepaja, Ventspils, and Riga as well as on the ship routes to these ports. The vicinity of port of Liepaja seems to have been most affected. However, since only rarely pollution source was identified, it is not possible to hypothesize on reason.

5 Impact on the Environment

The largest accidents involving oil discharge in region were the accident of the oil tanker “Antonio Gramschi” near Ventspils in 1979 resulting in 6,000 t discharge of oil and oil tanker “Globe Assimi” accident in Klaipeda port in 1981 resulting in discharge of 16,500 t of heavy oil products, 4,000 t of that remained uncollected. It was speculated that significant decrease (more than 2.5-fold) of *Furcelaria lumbricalis* observed during the period from 1981 to 1986 along Latvia’s East-Baltic coastline could have been caused by impact of oil discharged during the above-mentioned accidents [2]. Although investigations conducted elsewhere concluded that macrophytes after oil pollution accidents can accumulate and retain for long time oil hydrocarbons (e.g., [3]), that discharged oil can affect their health (e.g., [4]), and that worst affected organisms are those inhabiting shallow coastal areas (e.g., [5]), the evidence of macrophyte bed complete disappearance was documented only if beds were completely covered with oil [6]. The poor documentation of direct oil impact on coastal habitats after “Antonio Gramschi” and “Globe Assimi,” only *Furcelaria lumbricalis* distribution was assessed, does not give a possibility to estimate habitat area completely covered by oil hydrocarbons. Therefore, it cannot be confirmed that observed decrease in *Furcelaria lumbricalis* beds during 1981–1986 was only due to oil pollution as assumed by Korolev et al. [2]. More plausible explanation is that observed decrease of *Furcelaria lumbricalis* was due to combined effect of more than one factor, eutrophication included.

Smaller scale accidents were recorded more frequently after Butinge oil terminal started function in 1999, e.g., around 4 t in 1999, 3 and 2 t in 2001, with presumable impact on coastal area covered by macrophytes north of terminal, but no immediate follow-up studies were initiated. Therefore, it was not possible to assess impact of these discharges on environment. Only in 2005, Life project “Marine protected areas in the Eastern Baltic Sea” (Ref. Nr. Life05NAT/LV/000100) attempted to assess oil pollution impact on coastal area potentially influenced by the above-mentioned accidents. Since the project aim was not to conduct full-scale impact assessment, the data gathered in frame of project were very limited. Nevertheless, acquired total oil hydrocarbon concentration distribution [7] along with mapped macrophyte and other benthic fauna and flora distribution strongly suggest that oil pollution accidents that occurred at Butinge oil terminal have left no obvious visible impacts on coastal area north of it. Similar to that, it can be assumed that small size registered oil and its products discharges (Fig. 5a, b) have no visible effect on ecosystem too. At the same time, studies performed along the East Baltic coast of Latvia so far have not been designed to register more subtle impacts as reported elsewhere (e.g., [4–6]), so we cannot exclude possibilities of negative impacts.

6 Combating Oil Pollution Practice

Although major accidents at sea are not frequent, the Latvian Coast Guard (CG) has to keep readiness and capacity to respond to oil spills according to IMO MEPC 58/7 Manual on Assessment of Oil Spill Risks and Preparedness and Helsinki Commission recommendation 31/1 Development of National Ability to Respond to Spillages of Oil and Other Harmful Substances. The oil spill combating procedures are described in the Latvian National Oil Spill Contingency Plan, which has been updated in 2010 when response procedures to hazardous and noxious substances (HNS) have been included.

In order to comply with these requirements, Latvian Coast Guard operates two seaworthy naval vessels (A-90 Varonis and KA-14 Astra) and one nonpropelled barge, each of them fitted with oil spill response equipment, such as brush-type skimmer systems, open sea boons, and submersible skimmers. Recently, Latvia has built a new multipurpose CG patrol ship (SKRUNDA) to be used for oil combating at sea as well (Fig. 8).

Latvian response area is divided into three subareas, thus there is one response vessel per area, based in the major ports – Riga, Liepaja, and Ventspils. Additional supply vessels may be chartered by the Latvian Coast Guard Service from Latvian Port Authorities.

Fig. 8 Multipurpose CG patrol ship “SKRUNDA” built in 2011

Also, oil combating stockpiles are located in the same ports of the three response subareas in Riga, Liepaja, and Ventspils. All the national oil spill response equipment of the Latvian Coast Guard is stored in these stockpiles and in total consists of:

- 2,200 m of open sea boom
- 120 m of coastal boom
- 500 m of harbor boom
- 5,400 m of absorbent boom
- 6,000 kg of absorbent granules
- 4 brush-type skimmer systems for a vessel of opportunity
- 3 submersible skimmers
- 9 high capacity oil/water transfer pumps
- 8 floating oil bags with total capacity of 110 m^3
- 1 dispersant spray system with 2,000 l of dispersant concentrate
- 1 steam generator
- 1 oil trawl system

Additional oil spill response equipment is operated by Latvian Port Authorities and State Boarder Guard.

The estimated capacity of all response equipment is considered to be able to deal with 800 t of oil at sea, which is based on the provisions of the National Oil Spill Contingency Plan and the first version of Oil Spill Risk Assessment for the Baltic Sea.

In practice combating oil pollution at sea has occasional character in Latvia, which is defined in each case by the amount and type of oil discharged. At sea usually there are few cases per year when insignificant (maximum 0.2–0.4 m^3) oil pollution is observed by the Clean Sea Net satellite service. Each of these cases is investigated by CG and MIWA and duly reported, but due to quick weathering of oil on the sea surface, no oil combating operations have been considered as appropriate.

During the last 20 years, no serious oil spills have happened either within the Latvian territorial waters or Exclusive Economic Zone. Nevertheless, there have been few cases, when due to prevailing current and wind toward the Latvian coast of the Baltic Sea, oil patches have been observed on the coastline after accidents outside the Latvian waters.

Recently, full-scale oil combating operation at sea has been carried out in 2007 caused by the grounding of dry bulk cargo ship m/v Golden Sky (Fig. 9) on the Latvian coastline approx. 10 miles northwards from Ventspils port. During the oil combating operation at sea, 3 tons of heavy fuel IFO-380 was collected on the sea surface by the Latvian Coast Guard ship KA-14 Astra using Lamor brush-type skimmers and oil collection bags. About 1 ton of oil was collected on the coastline. In total during the salvage operation of m/v Golden Sky, 598 tons of oil was removed from the ship. Total costs of oil combating operation and damage to the environment claimed by the Latvian government compiled 1.3 million EUR.

Fig. 9 Grounded m/v Golden Sky on the Latvian coastline in 2007

7 Unsolved Problems

There are few issues to be solved on a short time span (2012–2014):

1. In order to strengthen the co-operation between the Baltic Sea countries in the field of oil spill response at sea Latvia is looking forward to conclude tri-lateral regional oil spill response agreement with Sweden and Estonia (SWE-EST-LAT).
2. Due to lack of airborne surveillance means Latvia is falling behind other countries in the oil pollution observation efficiency and therefore is heavily relying on participation in HELCOM Coordinated Extended Pollution Control Operation (CEPCO) flights, as well as reserved to check satellite images obtained through Clean Sea Net service.
3. Improvement of oil spill response capacity and equipment at the Latvian Coast Guard is an ongoing issue to hold to the growing shipping density trend.

8 Conclusions

The most recent observations indicate that current level of oil pollution accidents does not cause visible impact on Latvian marine ecosystem, although in the past oil pollution was at least potential threat to it due to frequent small-scale oil spills as well as occasional big accidents. The observed improvement can mostly be attributed to the very successful implementation of no-special-fee system.

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Oil Pollution in Waters of Lithuania

Algirdas Stankevičius and Galina Garnaga

Abstract The Lithuanian seaside is famous for its sandy beaches as well as for Palanga town and the Curonian Spit, a UNESCO protected site, which are all enjoyed by the locals and holiday guests. Potential contamination of Lithuanian sea water is possible from three oil companies, apart from the discharges of passing tankers and other ships. In Lithuania, the responsibility for works involving the clean-up of marine incidents lies with the Maritime Rescue Coordination Centre of the Naval Forces.

Total oil hydrocarbons (THC), polycyclic aromatic hydrocarbons and oil-oxidizing bacteria indicate considerable pollution in some areas of the Lithuanian part of the Baltic Sea. THC concentrations in water frequently exceed the Maximum Permissible Level; long-term studies show increasing trends of THC concentrations in some areas of the Lithuanian part of the Baltic Sea. Būtingė oil spill (31 January 2008) caused significant increase of micronuclei and other nuclear abnormalities in mussels; elevated environmental genotoxicity and cytotoxicity responses were observed in mussels even 6 months after the oil spill.

Keywords Environmental monitoring, Evaluation of the environmental state, Oil- polycyclic aromatic hydrocarbons, Oil spills

Contents

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1 Introduction

The Lithuanian seaside is famous for its sandy beaches as well as for Palanga town and the Curonian Spit, a UNESCO protected site, which are all enjoyed by the locals and holiday guests.

Europe is the largest crude-oil importer, consuming about one third of the global production. About 90% of oil and oil products reach and leave Europe by sea. Some of it gets into the marine environment during marine accidents or illegal discharges.

The Baltic Sea accounts for about only 0.1% of the total area of the world's oceans and seas, but it is responsible for almost 3% of all the oil that gets into the water. With its many sources of pollution and very slow water renewal, the Baltic Sea is considered one of the worst polluted areas in the world.

Approximately 10% of all oil hydrocarbons in the Baltic Sea turn up due to deliberate illegal discharges of contaminants from sailing ships. Surveillance by aircraft shows that approximately 400 illegal oil discharges have been recorded per year. The automatic identification system records 51,000 ships navigating in the Baltic Sea per year. About 17–25% of all these ships are tankers [1].

While the Lithuanian coastline is about 90 km in length, the Lithuanian economic zone only accounts for about 8% of the total area of the Baltic Sea. The entire Lithuanian segment of the Baltic coast is distinguished by its high biodiversity and richness of biological resources.

Risk factors that increase the probability of oil products spilling into the marine area of Lithuania are as follows: import and export of oil products, economic activities of oil companies, the number of tankers and ships visiting the Port of Klaipėda, and transit of tankers carrying oil products to the neighboring port as well as extreme weather conditions (stormy winds, poor visibility, sudden water level fluctuations, heavy seas, the complicated water current system, ice packs, icing on ships, etc.) [2].

Potential contamination of Lithuanian part of the Baltic Sea is possible from three oil companies – Būtingė oil terminal, Stock Company "Klaipėdos Nafta," and D-6 "Kravcovskoje" oil platform, apart from the discharges of passing tankers and other ships (Fig. 1). In the southern area there is the "Kravcovskoje" oilfield situated within the Russian territory. At present, this "Kravcovskoje" oilfield is being exploited by the Russian "Lukoil" company. Oilfield reserves are estimated to be 21–24 million tons. The sea depth here is around 27–30 m. It is at a distance of just about 20 km from the Curonian Spit coast and only 7 km from the Lithuanian

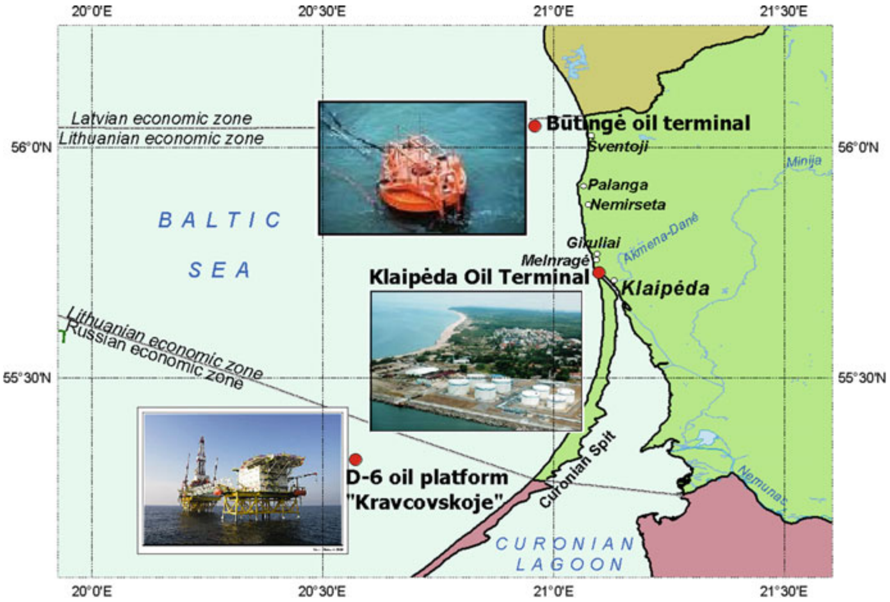

Fig. 1 Location of oil terminals

and Russian border. The Lithuanian seacoast experiences predominantly West (18%), Southwest (14%), and South (13%) winds, which determine the spreading of oil toward the Lithuanian coastline. The strongest winds in these directions are during autumn and winter. Our estimates, based on the SEATRACK WEB oil drift model developed by the Swedish Meteorological and Hydrological Institute (SMHI), have shown that, given the West wind blowing at 20 m s^{-1}, oil from the D-6 oil platform can reach the Lithuanian coastline in only 20 h. If 10 tons of oil was to be spilled at the D-6 oilfield and the Southwest wind blew at 20 m s^{-1}, it would show up at Klaipėda after 36 h.

In the northern section of the economic zone, we have the Būtingė Terminal, which started its operation on the 22nd of July, 1999. Inland and within an area of 63 ha, storage facilities have been positioned. From there, an oil pipeline stretching almost 92 km in length has been laid down by the "Orlen Lietuva" petroleum refining company in Mažeikiai. At the seacoast, a buoy-type oil transshipment terminal is located, the only such one in the Baltic Sea. The terminal's capacity is 12–14 million tons per year. The Būtingė Terminal can operate both for oil export and import. In Būtingė, ships and tankers with a tonnage of up to 150,000 tons are serviced. For oil reception from tankers, a single-point mooring buoy is used, which is installed offshore about 7.3 km from the coastline. An underwater pipeline of 914 mm in diameter runs out to the buoy. The distance from the buoy to the Lithuanian–Latvian border is one nautical mile to the North. The terminal's water area encompasses an area with a radius of 1,000 m around the buoy, and an area of 300 m on either side of the pipeline safety zone. Navigation, fishing, and the anchoring of unauthorized ships within the terminal's water area are strictly forbidden.

Dangers arising while operating the terminal are: performance of stevedoring works relating to tanker mooring, direct oil loading/stevedoring, impermissible operations for which the single point mooring (SPM) buoy is not adapted, errors in equipment maintenance and service, and wrong decisions while carrying out stevedoring works under unfavourable meteorological conditions.

Joint-stock company "Klaipėdos Nafta" is located in the middle of the coastline. Facilities of the Oil Terminal complex located on a 37.4 ha area allow handling 9 million tons of export/import oil products and crude oil per year. The Klaipėda Oil Terminal has been in operation for about 40 years. Reconstruction of the Oil Terminal started in 1995 with demolition of the old facilities and construction of new objects. The reconstruction was completed in 2002. Today SC "Klaipėdos Nafta" is one of the most up-to-date terminals in Europe. Oil products are delivered to the Terminal by railway cars, unloaded into storage tanks, and after accumulation of the required cargo batch are loaded into tankers [3].

The Lithuanian coast has suffered the consequences of oil spills more than once. The largest and most severe event was the accident of a British tanker "Globe Assimi" flying the flag of Gibraltar within the approaches of Klaipėda. On the 21st of November, 1981, a tanker of 170 m in length, carrying fuel oil loaded at the Klaipėda Oil Terminal, ran aground over the northern breakwater of Klaipėda Port. The hurricane wind, whose speed was reaching up to 30 m s^{-1}, broke the tanker into three parts. 16,493 tons of fuel oil spilled into the sea. The waves and wind took the spilled fuel oil farther along the seacoast and drove it into the Klaipėda Strait, the northern part of the Curonian Lagoon. Heavy seas rendered boom defenses (oil-retaining equipment) ineffective. The consequences for the Lithuanian coastal ecosystem were very negative. Strong winds, which were prevalent at the end of November, brought fuel oil to the shore and to the North from Klaipėda Port. In this way, 90 km of beaches were polluted with fuel oil, and the penetration of the inland area affected by the oil products varied from 5 to 15 m, and in some places up to 100 m [4]. Fuel oil penetrated into the beach sand down to 0.4–0.6 m, and in some places down to 0.8–1 m. The most extensive penetration of the oil occurred in areas of weak or medium accumulation from Melnragė to Giruliai, and between Nemirseta and Šventoji. In these areas, beaches are composed of fine or medium-sized sand fractions. Part of the fuel oil had apparently sank and was sanded over, and during a larger storm, portions of fuel oil were again thrown out onto the beaches. They needed to be cleared, and the contaminated sand was disposed of. It is believed that about 600,000 tons of sand contaminated with fuel oil was removed from beaches within the Lithuanian territory. Unfortunately, we can now see that such a large-scale removal of sand has had negative consequences. Mechanical clearing has destroyed the natural dynamic coastline base, and the sand deficit has led to a washed-away destruction of the coast [4].

The oil spill had negative consequences for sea hydrobionts as well. Surveys conducted [5] after the accident resulted in the conclusion that the reserves of mussels within the Klaipėda–Liepaja range had decreased by 30%, whereas the reserves of Black Carrageen (lot. *Furcellaria lumbricalis*) – by up to 50%. During the first 3 years, fish catches in the Curonian Lagoon had decreased by 11% on the average.

The negative consequences were mitigated by the low water temperature, and where the waves caused by western winds had thrown the fuel oil onto the coast, it was expeditiously collected. This partially helped to prevent a secondary contamination.

Two years had not yet passed, when on the 25th of June, 1983, about 70 tons of oil erupted from the D-6 test drill hole of "Petro Baltic" in the Russian territory, and the oil spot quickly reached Lithuania and its nicest beaches in Nida within several hours. Oil granules covered an entire coastal range of 20 km in length and 5 m in width, of which 14 km lied within Lithuanian territory.

During the period from 1999 to 2008, 54 notifications were recorded in the waters belonging to Lithuania with regard to contamination with oil products. In the Port of Klaipėda, there were only a few such cases. In the year 2002, a barge called "Modi-R" ran aground over the southern breakwater of Klaipėda. About 15 m^3 of oil products made its way into the marine environment. The tanker "Princess Pia", laden at the Klaipėda Oil Terminal with 50,000 tons of fuel oil, ran aground over a sunken shipwreck at the port gate (11 December, 2002). Contamination was successfully prevented at that time, and with part of the cargo having been unloaded, the tanker was tugged back to the port.

Other spills in the port were of a local type and not big, causing no significant harm to the environment.

In 2001, in the territorial sea within the Būtingė Oil Terminal's water area, two outflows of oil products into the marine environment were recorded. On the 6th of March, 0.3 tons of oil products spilled out. On the 23rd of November, while carrying out stevedoring works onboard the tanker "Catherine Knutsen," an underwater hose broke and about 60 tons of oil ran into the water.

On the 31st of January, 2008, there was an outflow of 2.25 tons of oil products from the tanker "Stena Antarctica" during the pumping of oil at the Būtingė Terminal. Oil drift modeling shows that the drift forecast for oil spilled at the Būtingė Terminal, given a southwest wind blowing at 18 m s^{-1}, reaches the coast after 5–6 h.

In Lithuania, the responsibility for works involving the clean-up of marine incidents lies with the Maritime Rescue Coordination Centre of the Naval Forces. When organizing, coordinating, and managing marine pollution elimination works, the Maritime Rescue Centre invokes all the forces and means of the navy, air force, border guard service, and seaport administration. Cases pertaining to pollution in the Curonian Lagoon are handled jointly with the border guard service. In the port territory, oil spills are eliminated using the forces of the port administration.

All works are organized in accordance with the plan of works concerned with the elimination of pollution incidents in the sea area.

2 Monitoring of Oil Pollution in Lithuania

2.1 Area Description

Nearly 83% of Lithuanian territory belongs to the catchment area of the Baltic Proper, including the river catchment areas of the Nemunas, the Bartuva, the Venta, and the Akmena-Dane. The population density of this territory is 57 inhabitants per km. The Lithuanian sub-basin catchment area is dominated by agricultural land (54%) and forests (31%), with 5% urban areas, 4% inland waters, 2% wetlands, and 4% devoted to various other land uses. The area's main river, the Nemunas, discharges into the semi-enclosed Curonian Lagoon [6]. Only about 90 km of the shore belongs to Lithuania, with its main part (51 km) being on the Curonian sand spit, which is declared the National Park and entered into the UNESCO list of protected areas [7]. The area includes the Lithuanian waters of the Baltic Sea, which are situated in the southeastern part of the Baltic Proper. Lithuanian waters are divided into four different types: transitional waters (central part, northern part, and the plume of the Curonian Lagoon waters), heavily modified waterbody (Klaipėda Strait), coastal waters (northern stony coast and southern sandy coast), and open sea waters (Fig. 2).

The offshore waters show the typical stratification pattern for the Baltic Proper with the upper layer (mean salinity 7–8 PSU) separated by a permanent halocline at 70–80 m depth from the more saline subhalocline water layer, which is oxygen

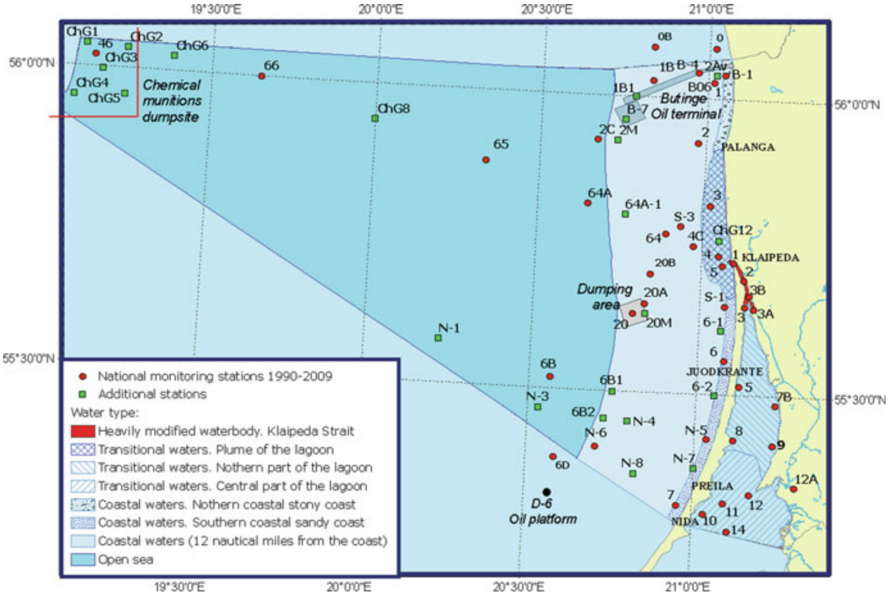

Fig. 2 Lithuanian monitoring and other stations in the Baltic Sea and Curonian Lagoon

deficient. The composition of the sediment is quite diverse: from coarse clastic material, to sands of various grade, to silt. There are three main lithological facies: boulders with shingle and gravel, coarse and medium sand, and fine sand [8, 9].

In the area north of Klaipėda, major hydrological features are determined by the interaction between the southeastern Baltic offshore waters and the runoff of the mostly freshwater Curonian Lagoon. Due to prevailing northern direction of currents this area is much more influenced by the freshwater outflow than the rest part of the coastal areas. The mainland submarine coastal slope, extending from the shore down to 25–30 m, is characterized by diverse bottom types. Its uppermost part, at 0–6 m, is covered by mobile quartz sand, while at greater depths the sand alternates with pebble-gravel deposits and large boulders. Benthic communities on the hard bottom are dominated by the blue mussel *Mytilus edulis* and invasive barnacle *Balanus improvisus* [9, 10].

Southward of the Klaipėda Strait, there are typical Baltic Proper waters. Along the Curonian Spit the bottom sediments are much more homogenous, with sand prevailing throughout the area. In general, the character of sediments changes from the mixture of sand and gravel in the wave-affected coastal area to aleurites and pelitic muds in deeper areas. Sandy bottoms at the depths of 20 m and downward are dominated by the bivalve *Macoma balthica* [9, 10].

The narrow (width 400–600 m) Klaipėda Strait area connects the Curonian Lagoon and the southeastern part of the Baltic Sea. This area is artificially deepened and its maximum depth is about 14 m. It is oligohaline with irregular salinity fluctuations from 0.5 to 8 PSU [10, 11].

The Curonian Lagoon is the largest coastal lagoon in the Baltic Sea. It is an enclosed shallow lagoon (mean depth 3.7 m). The southern and central parts of the lagoon are freshwater due to discharge from Nemunas (98% of total) and other rivers, while the northern part is oligohaline with irregular salinity fluctuations from 0 to 8 PSU. The Lagoon is a highly eutrophied water body and blue-green algae blooms are a regular annual phenomenon. The main water current in the Curonian Lagoon is the outflow of the Nemunas river, which empties into the Baltic Sea near the port of Klaipėda. Almost the whole bottom of the Curonian Lagoon is covered by recent sediments. The relict glacigenic sediments occur only locally and are exposed as small fields of boulders with pebbles and gravel accumulations overgrown by mollusk *Dreissena polymorpha* colonies [9, 12].

2.2 National Monitoring Cruises

During the period of 1990–2009, water and sediment samples were collected during the national monitoring cruises with research vessel “Vėjas” (in the Baltic Sea) or expedition boat “Gintaras” (in the Curonian Lagoon) (Fig. 3). Locations of sampling stations are presented in Fig. 2. There were four seasonal cruises (February, May, August, October–November) to the Baltic Sea and 12 sampling events (every month) to the Curonian Lagoon.

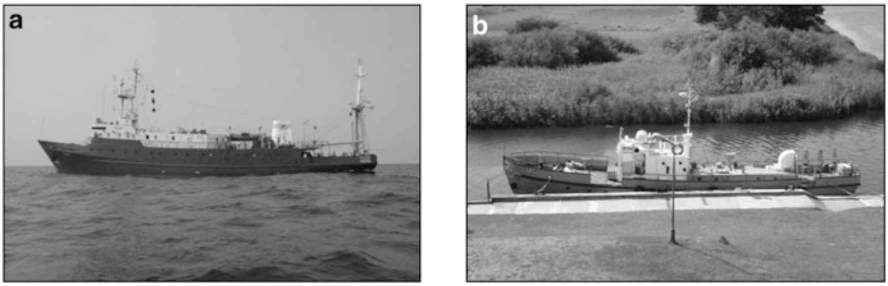

Fig. 3 Research vessels of the Center of Marine Research: (**a**) research vessel “Vėjas” for the national monitoring of the Baltic Sea (1980–2010; length: 55.6 m; width: 9.3 m; drought: 4.3 m; 7 laboratories; 12 crew members; 20 members of scientific group); (**b**) expedition boat “Gintaras” for the national monitoring of the Curonian Lagoon (1983–2010; length: 21 m; width: 4 m; drought: 1.6 m; 1 laboratory; 2 crew members; 5 members of scientific group)

Water samples for the analysis of total oil and polycyclic aromatic hydrocarbons (PAHs) were taken by plastic 5 l water sampler (PWS) into the clean glass bottles (1,000 ml). Bacterioplankton samples were taken by modified *ZoBelo* water sampler.

Sediment samples were collected using a large Van Veen grab sampler (75 kg, with a sampling area of 0.1 m^2). Sediment from the top ~1–3 cm was subsampled to glass containers. Samples were frozen immediately onboard. After transportation to the laboratory, samples were stored in a deep freezer at a temperature of $\leq -20°C$ until analysis.

2.3 Total Oil Hydrocarbons

Oil contamination is usually caused by an accidental or chronic release of one of three main types of oil: crude oil, heavy fuel, and diesel fuel oil [13]. Crude oils, consisting of a complex mixture of hydrocarbon and nonhydrocarbon compounds, vary widely in chemical composition and physical properties. While hydrocarbons comprise more than 75% by weight of most crude oils, nonhydrocarbons (compounds containing oxygen, nitrogen, sulfur, and metals such as copper, iron, nickel, and vanadium) can predominate in heavy crude oils [14, 15].

Oil spills contaminate the water by creating an oily layer. The oil spreads quickly over the sea surface, often covering extensive areas as slicks varying from micrometers to a centimeter or more in thickness. As the oil spreads and the oil thickness reduces, its appearance changes from the black or dark brown color of thick oil patches to iridescent and silver sheen at the edges of the slick. A common feature of spills of crude oil and some heavy fuel oils is the rapid formation of water-in-oil emulsions, which are often characterized by a brown/orange color and a cohesive appearance. Oil slicks travel downwind at 3–4% of the wind speed, spreading at a rate dependent on water temperature and composition of the oil. Light oils spread faster than heavy oils [14, 16, 17].

Several physical–chemical processes change the composition of oil in seawater. The main processes are evaporation, photochemical oxidation, emulsification, and dissolution. Low molecular weight volatile fractions evaporate, hydrocarbons undergo photooxidation, water soluble constituents dissolve in seawater, and immiscible components become emulsified. Evaporative loss of volatile hydrocarbons removes the toxic lower molecular weight components during the first 24–48 h of an oil spill. The loss of these volatile components substantially lowers the overall toxicity of the oil to water organisms [14, 16]. As the density of oil approaches that of seawater, it tends to sink. Sedimentation of oil is facilitated by the sorption of hydrocarbons to particulate matter suspended in the water column [14].

Oil pollution is recognized as one of the greatest hazards for the marine environment despite whether it happens in the form of large accidents or long-term small-scale spills and leakage. In regard to oil accidents the effects are at first acute, causing visible damage on biota and the environment, but at a later stage chronic harmful effects might take place [13]. The most visible effects of oil spills are caused by the oil on the surface: birds and seals are smothered, and their chances of survival are hampered by problems with their mobility or the insulating properties of their feathers or skin [18]. Other aquatic organisms are also highly impacted by the spilled oil, and massive mortality of marine life including fish, worms, crustaceans, and mollusks occur in a few days [19, 20]. Long-term chronic contamination by lower levels of oil-derived substances is more harmful to the environment than acute large spills because they deteriorate the overall conditions in the environment and lead to a permanent stress to organisms within the local ecosystem. It should also be pointed out, that chronic contamination can provoke genetic effects in different organisms and initiate damage in the genetic structure of populations [13, 21]. Oil is a serious threat to the Baltic Sea ecosystem. About 10% of all oil hydrocarbons in the Baltic Sea originate from deliberate, illegal discharges from machinery spaces or cargo tanks of vessels sailing in the Baltic [18].

Monitoring of THC in the Lithuanian part of the Baltic Sea is compulsory as oil is in the list of controlled substances in Lithuania (Wastewater Treatment Regulation, Official gazette, 2010, No.59-2938).

During the cruises to the Baltic Sea, the extraction of water samples for THC was done on board with carbon tetrachloride. Samples from the Curonian Lagoon were transported to the laboratory of the Center of Marine Research (from 2010 – Environmental Protection Agency Marine Research Department) for analysis. In the laboratory, after the purification with Al-oxide column, samples were analyzed by infrared spectrometry. As a calibration standard, a mixture of benzene, hexadecane, and iso-octane in carbon tetrachloride was used. A mixture of diesel fuel and lubricating oil was used for quality control. For total oil hydrocarbon determination, sediment samples were extracted with carbon tetrachloride and cleaned through aluminum oxide column. Concentrations of THC were determined by infrared spectrometry.

Long-term monitoring data are available for THC in water for the period of 1990–2007. Starting from 2008, a different method – gas chromatography – has been started to use. Two methods can't be directly compared as the sensitivity of methods is different – the limit of determination of the infrared spectrometry method was 0.03 mg l^{-1} and for gas chromatography method – 0.1 mg l^{-1}. Oil hydrocarbons data obtained by the infrared sprectrometry method is treated separately. The data of THC was grouped for different types of waters. Sampling stations and a number of measurements for each type of waters are shown in the Table 1.

Until 2010, in Lithuanian legislation the maximum permissible limit (MPL) for THC in water was 0.05 mg l^{-1}. From 2010, MPL for total oil in water was changed to 0.2 mg l^{-1}, the limit of quantification of gas chromatography method (0.1 mg l^{-1}) was taken into account. Nevertheless, 1990–2007 oil data was compared to more strict 0.05 mg l^{-1} MPL. For the period of 1990–2007, 14% of values were above the MPL in the open sea, 13% – in the transitional waters. Klaipėda Strait and coastal waters had 9% of exceeding the 0.05 mg l^{-1} limit values. Figure 4 shows, how the percent of values above the MPL has changed during a 18-year period. During the period from 1998 till 2004, the percent of values above the MPL didn't exceed 15%, although starting from 2005 the number of high THC concentrations increased. During the last 3 years (2005–2007), the percent of high values have increased in every type of waters up to 25% in Klaipėda Strait and 28% in the open sea (Table 1 and Fig. 4).

Table 1 Sampling stations, number of measurements and percentage of values above the maximum permissible limit (MPL) (0.05 mg l^{-1}) for 1990–2007 and 2005–2007 periods

Type of waters	Stations	Number of measurements	Values above the MPL 1990–2007 (%)	Values above the MPL 2005–2007 (%)
Transitional waters	Central part of the lagoon: 10, 12, 12A, 14 Northern part of the lagoon: 5, 7B, 8 Plume of the lagoon: 3, 4, 5	1,676	13	22
Heavily modified water body	Klaipeda Straight: 1, 2, 3, 3A, 3B	1,490	9	25
Coastal waters	Northern stony coast: 1, 1B, B-1, B-4, 2, S-3, 64 Southern sandy coast: 20, 20A, S-1, 6, N-5, N-6, 7	1,788	9	12
Open sea	2 C, 6B, 65, 66, 46	553	14	28

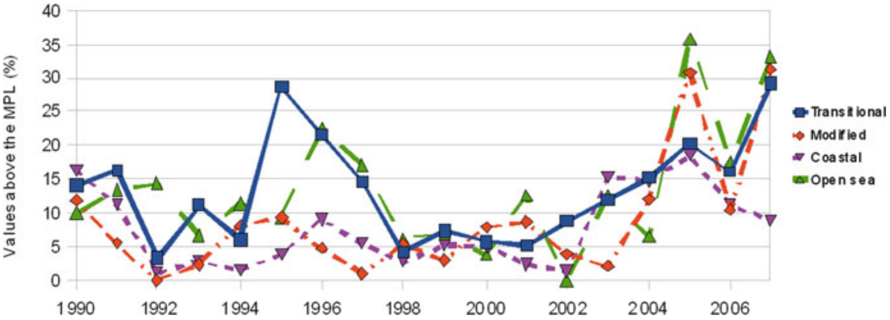

Fig. 4 The percentage of values of total hydrocarbon concentration in water above the maximum permissible limit (MPL) (0.05 mg l^{-1})

The dataset of THC in water for the period of 1990–2007 has been analyzed for significant trends. The data from all the stations and water horizons has been sorted according to areas of interest: open sea, northern coastal water, southern coastal waters, plume of the lagoon, Klaipėda Strait and Curonian Lagoon (Fig. 5).

The analysis of long-term (1990–2007) total oil concentrations in water showed that there were statistically significant increasing trends in northern coastal waters and plume of the lagoon (Fig. 5). The statistically significant increasing trend was also detected in the southern coastal waters for the period of 1992–2007. Statistically significant increasing trends were not detected in other areas of the Lithuanian Baltic Sea.

Spatial distribution of THC in sediments (Fig. 6) shows that there was elevated concentration of total oil at the station B-4 (26 mg kg^{-1} d. w.), which is located near the Būtingė oil terminal. Higher concentrations were also found at the dredged sediments dumping site stations 20, 20A, and 20 M and at some stations along the Curonian spit (S-1, 6–1, 6–2). Although according to the Lithuanian legislation document on “Sediment dredging in sea and sea-port areas and dredged sediment treatment rules” (Official gazette, 2008, No. 139–5521) almost all values (except station B-4) fall within the cleanest *I* category ($<$ 20 mg kg^{-1} d. w. of THC).

2.4 Polycyclic Aromatic Hydrocarbons

PAHs are of concern due to their persistence and potential to accumulate in aquatic organisms, particularly invertebrates. The compounds range from naphthalene ($C_{10}H_8$, two rings) to coronene ($C_{24}H_{12}$, seven rings). Common PAH compounds include two-ring compounds (naphthalene); three-ring compounds (fluorene, phenanthrene, anthracene); four-ring compounds (fluoranthene, pyrene, benzo(a)anthracene); and five-ring compounds (benzo(a)pyrene, benzo(b)fluoranthene, perylene). The low molecular weight PAH compounds, containing two or three rings, are acutely toxic to a broad spectrum of marine organisms. Examples of low molecular

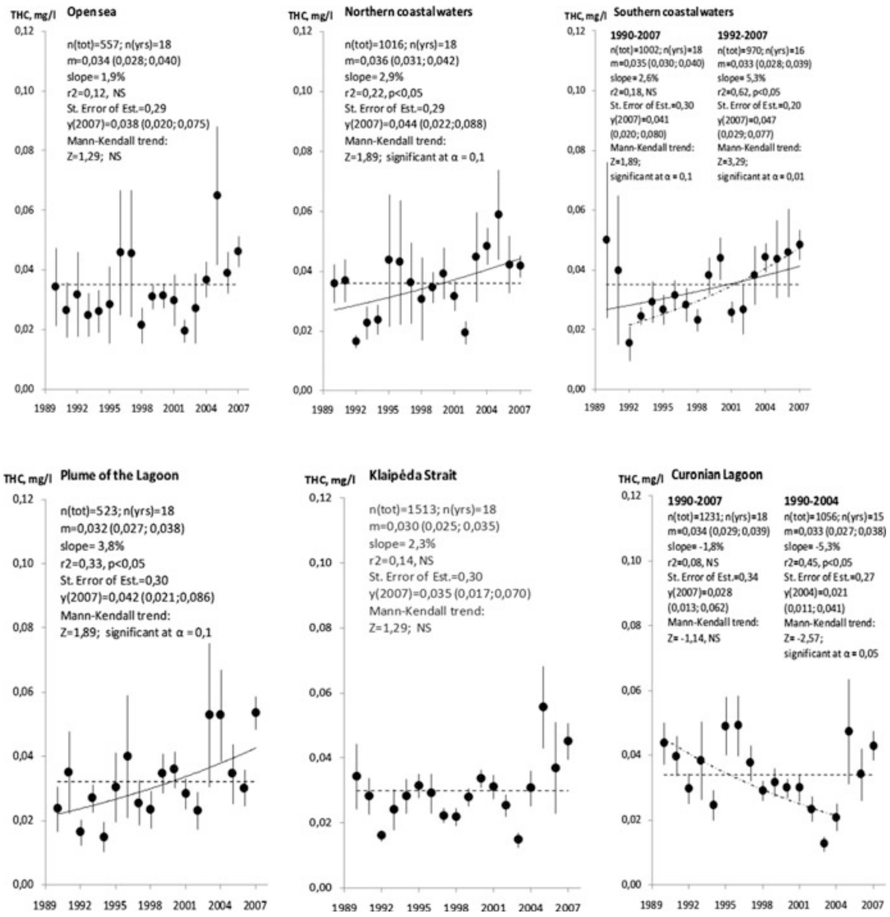

Fig. 5 Concentration of total hydrocarbons (THC) in different types of waters of the south-eastern Baltic Sea. *n(tot)* – total number of analyzes included together with the number of years *(n(yrs))*; *m* – the overall geometric mean value together with its 95% confidence interval; slope – the slope, expressed as the yearly change in percent; *r2* – the coefficient of determination together with a *p*-value; *y(2007)* – the concentration estimated from the regression line for the last year together with a 95% confidence interval; non-parametric Mann-Kendal trend test and the corresponding *Z*-value

weight PAHs that tend to be toxic are anthracene, fluorene, naphthalene, and phenanthrene. The high molecular weight PAH compounds, containing four, five, and six rings, are less toxic but have greater carcinogenic potential. High molecular weight PAH compounds that are carcinogenic include banzo(a)pyrene, benzo(c) phenanthrene, dibenzo(a,i)pyrene [14, 22].

Elevated levels of PAHs are commonly found in estuarine and coastal marine waters near heavily populated areas. Oil-related activities, ballast water discharges, dredging activities and disposal, oil and petroleum products spillage, effluent

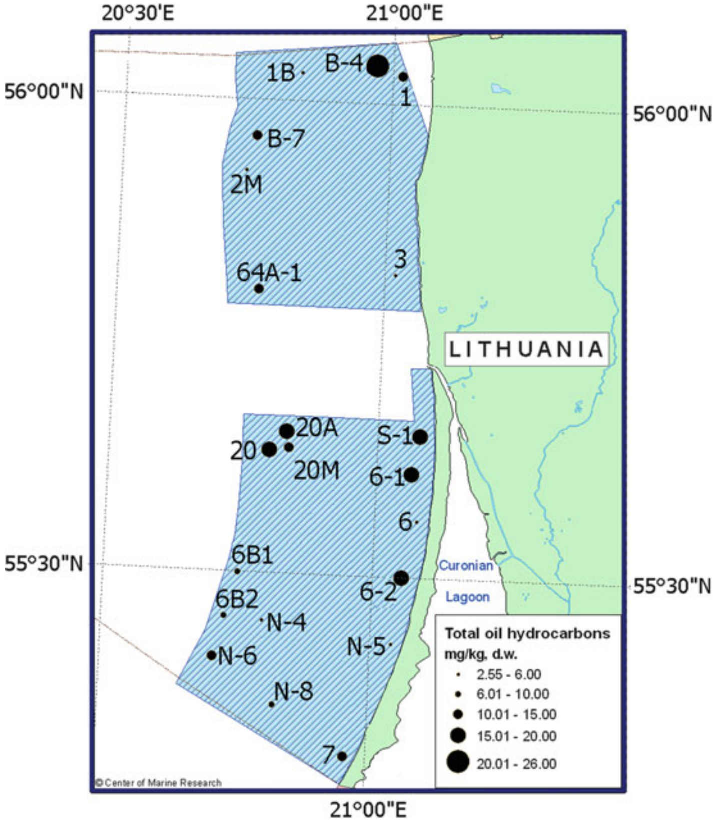

Fig. 6 Spatial distribution of total oil hydrocarbons in sediments in 2006

discharges, urban run-off, and atmospheric transport are all potential sources of PAHs [14, 22].

Anthracene, benzo(a)pyrene, benzo(b)fluoranthene, benzo(g,h,i)perylene, benzo (k)fluoranthene, and indeno(1,2,3-cd)pyrene are identified as priority hazardous substances; fluoranthene and naphthalene as priority substances by European Commission (Directive 2008/105/EC) and also by Lithuanian Wastewater Treatment Regulation (Order of Minister of Environment No. D1-236 of 17 May 2006; most recent amendments on 18 May 2010).

Concentrations of PAHs in sediment samples taken during the monitoring cruises were determined in the laboratory of Environmental Research Department (Lithuanian EPA) by high-performance liquid chromatography with fluorescence detection.

Concentrations of PAHs in 2006–2008 in sediments of the Baltic Sea and Curonian Lagoon are shown in Fig. 7. Almost in all samples the highest amount of fluoranthene was detected (from 22 to 72%), at the stations 12A- and 20-dominated benzo(b)fluoranthene (69 and 24%). Higher concentrations of summed

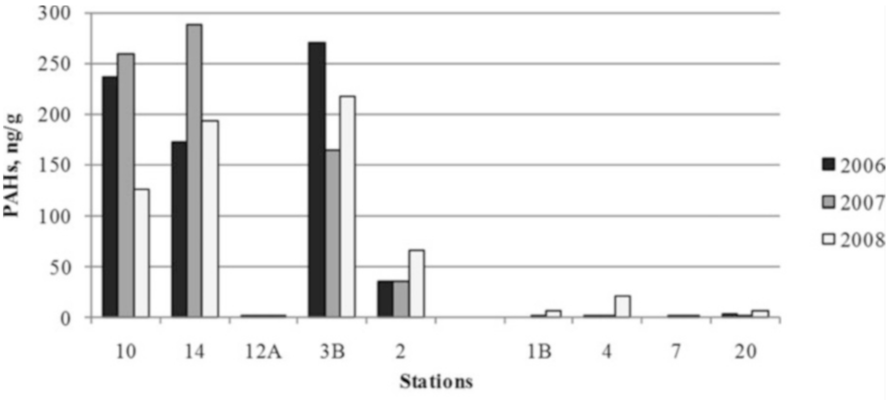

Fig. 7 Concentrations of summed PAHs in sediments in 2006–2008

PAHs were found in the sediments of Curonian Lagoon (stations 10 and 14), in the Klaipėda harbor (station 3B) and in the Klaipėda Strait (station 2).

The investigation of concentrations of PAHs in sediments was also done in 2006 (during the LIFE project). The highest concentrations of summed PAHs were found at the station N-4, 20 M (near the dredged sediments dumping site) and 1B (near the Būtingė oil terminal) (Fig. 8).

PAHs sources can be broadly divided into two main categories: petrogenic (fossil fuels, contamination is coming from either vessels or oil installations) and pyrolytic (from the incomplete combustion of organic material during urban and industrial activities). PAHs are mainly produced by pyrolysis, but are also present in crude oils, coal, coal tar, and various refinery products. Some PAHs have both natural and anthropogenic origins because they are the product of both wood and fossil fuel combustion. However, the anthropogenic contribution frequently outweighs PAH input from nearly all other sources [22, 23]. Molecular indexes, which are based on concentration ratios of selected compounds, can be used as source indicators when evaluating pyrolytic and petrogenic origins of PAH compounds [22–28].

Five indexes were calculated: phenanthrene/anthracene, fluoranthene/pyrene, chrysene/benz(a)anthracene, fluoranthene/(pyrene + fluoranthene), indeno(1,2, 3-cd)pyrene/(indeno(1,2,3-cd)pyrene + benzo(ghi)perylene) (Table 2).

A phenanthrene/anthracene ratio <10 and fluoranthene/pyrene ratio >1 indicate a pyrolytic origin, whereas a phenanthrene/anthracene ratio >15 and fluoranthene/pyrene ratio of <1 indicate a petrogenic origin. Concentration ratio of chrysene/benz(a)anthracene below 1 indicate pyrolytic origin and values above 1 – petrogenic origin [26]. Samples from the Lithuanian part of the Baltic are both of pyrolytic and petrogenic origins. All three indices indicated that the source of PAHs at the 6, 7, N-5, B-7, N-6, and 6B2 stations is petrogenic (coming from either vessels or oil installations).

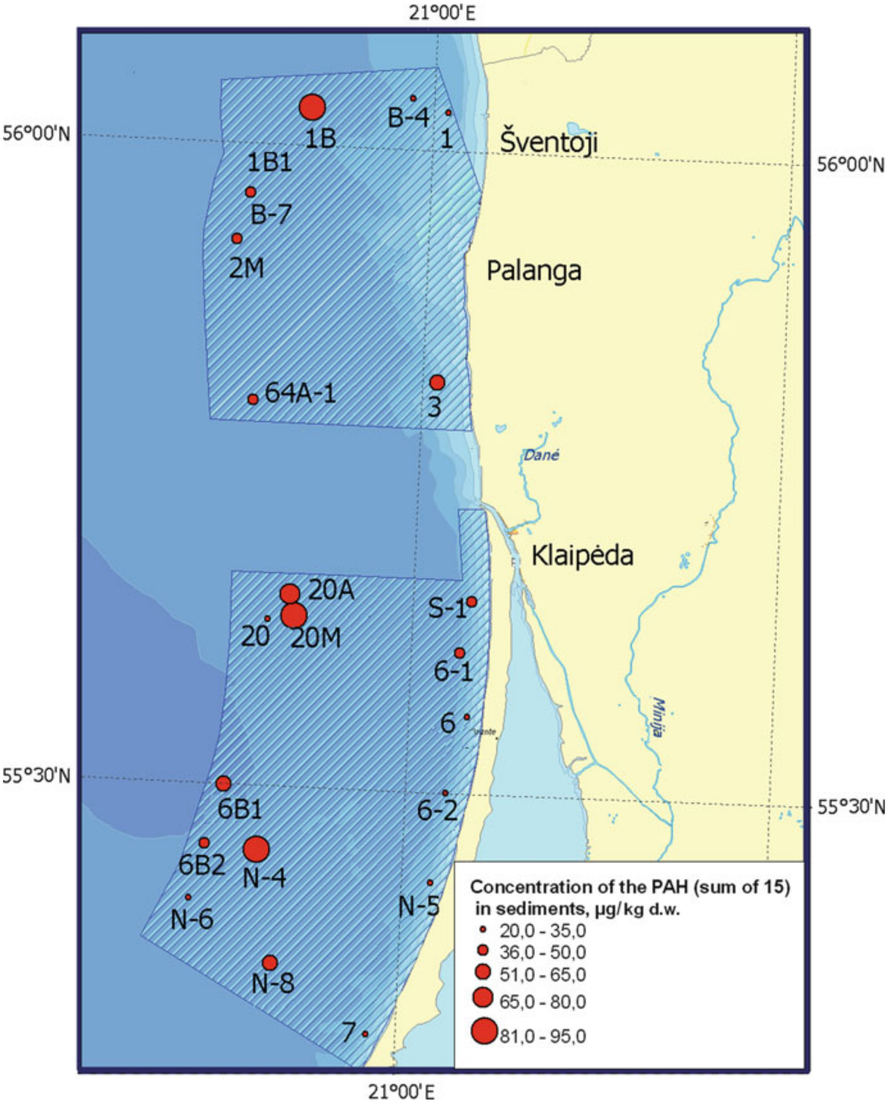

Fig. 8 Average concentrations of summed polycyclic aromatic hydrocarbons in sediments in 2006

Two concentration ratios are considered to be indicative of diesel engines: fluoranthene divided by the sum of pyrene and fluoranthene with a range of 0.60–0.70 and indeno(1,2,3-cd)pyrene divided by the sum of indeno(1,2,3-cd) pyrene and benzo(ghi)perylene with the range of 0.35–0.70 [26]. In this study, a diesel engine source was indicated at the 1B, N-4, 3, 20 M, 64A-1 stations which had comparatively high concentrations of summed PAHs compared to other stations.

Table 2 Molecular Indexes of selected PAHs (indexes marked in *bold* indicate petrogenic origin of PAHs; in ***bold and italic*** – indicate a contribution from diesel engines; PAHs under the detection limit marked as *gray cells*)

Station	Sampling date	Phen/ Ant	Fluoranth/ Pyr	Chr/ BaA	Fluor/ (Pyr + Fluor)	Ind/ (Ind + BghiP)
1B	2006–05	**17,8**	1,2	**2,0**	0,55	
	2006–08	**21,8**	1,2	**1,7**	0,55	
	2006–10	9,6	1,7	0,4	***0,63***	0,76
2 M	2006–05	14,6	1,4	0,9	0,59	0,83
N-8	2006–05	**21,1**	1,0	**1,1**	0,51	0,75
6	2006–05	13,7	1,4	0,7	0,58	
	2006–10	**22,8**	**0,8**	**2,0**	0,45	
7	2006–05	**21,3**	**0,9**	**1,7**	0,47	
	2006–10	**25,1**		**2,2**		
N-4	2006–08	14,5	1,9	**1,2**	***0,66***	
N-5	2006–08	**20,9**	1,2	**2,4**	0,54	
	2006–10	**20,1**	**0,7**	**2,0**	0,42	
1	2006–10	**22,1**	**0,9**		0,48	
3	2006–10	12,7	1,5	0,7	***0,60***	0,72
20	2006–10	13,7	1,3	0,7	0,57	
20A	2006–10	14,0	1,1	0,9	0,52	0,73
20 M	2006–10	6,8	1,8	0,2	***0,64***	0,73
S-1	2006–10	**27,3**	1,4	**1,1**	0,58	
B-4	2006–10	13,4	1,0	**2,3**	0,50	
B-7	2006–10	**24,2**	**0,7**	**2,4**	0,39	
N-6	2006–10	**22,6**	**0,8**	**2,9**	0,44	
64A-1	2006–10	14,4	1,3	0,6	0,57	***0,63***
6-1	2006–10	**17,5**	1,1	**1,6**	0,52	
6-2	2006–10	**19,4**	1,2	**1,5**	0,55	
6B1	2006–10	14,0	1,1	0,8	0,53	0,79
6B2	2006–10	**18,9**	**0,9**	**1,3**	0,49	0,78

2.5 Oil-Oxidizing Bacteria

Microbes play a pivotal role in the degradation of crude oil, often being the dominant factor controlling the fate of toxic hydrocarbons in aquatic environments. All together they can degrade as much as 40–80% of a crude oil spill. Several factors influence the biodegradation rates: oil composition, water temperature, nutrient availability, oxygen levels, and salinity [14].

Microorganisms react fast to changes of environment conditions. Therefore microorganisms are sensitive indicators of the state of ecosystems. The input of pollutants to the Baltic Sea induces significant changes in the composition of microbiocenosis. Oil-oxidizing bacteria use dissolved oil hydrocarbons in their cells' metabolic processes. Many hydrocarbon-oxidizing bacteria have constructive enzymatic systems that appear in the association of microorganisms with petroleum hydrocarbons. The capability of oil-oxidizing bacteria to utilize oil hydrocarbons as substrates could be used as a bioindicator of water ecosystem self-purification from oil pollution [29, 30].

Bacterioplankton data of the Baltic Sea and Curonian Lagoon was obtained during the period of 2000–2007 at 14 stations during every season. The abundance of oil-oxidizing bacteria in regions of investigation varied between 6 cells/ml and 60,000 cells/ml during the 8-year-period. In winter, the abundance of oil-oxidizing bacteria was about 10 cells/ml in the open sea, in the coastal waters the abundance of that group of bacteria reached 10–100 cells/ml. Sometimes oil-oxidizing bacteria were not found in the open sea in winter. The highest number of oil-oxidizing bacteria (about 1,000 cells/ml) was found in the Klaipėda Strait, near Nida (station 10) in the Curonian Lagoon and in the area influenced by Curonian Lagoon waters near Klaipėda (station 4). During the vegetation period (May, August, October–November), the abundance of oil-oxidizing bacteria was higher than in winter. Comparing the quantitative distribution of oil-oxidizing bacteria during the vegetation period in different types of waters, it was found that oil-oxidizing bacteria mostly appear in upper water layer than near the bottom. However, sometimes concentrations of oil-oxidizing bacteria in the bottom layer were much higher than in the surface, for example, station 20 in 2007 (Fig. 9). Figure 9 shows the typical distribution of the abundance of oil-oxidizing bacteria in the southeastern part of the Baltic Sea [31].

Evaluating the water quality according to oil-oxidizing bacteria, it was found that in the open sea and coastal waters during winter seasons the water was clean except the area of Būtingė oil terminal where water quality is characterized as average. During spring and summer, water quality in these areas was moderately polluted. Higher concentrations of oil-oxidizing bacteria were found in transitional waters comparing to open sea or coastal waters. The water quality of this area can be defined as moderately polluted and polluted in spring season. In the Klaipėda Strait, the water quality can be defined as moderately polluted with polluted areas near wastewater discharge of Klaipėda city. Analyzing oil-oxidizing bacteria in different areas, the highest concentrations were found in transitional waters and Klaipėda Strait [31].

3 Evaluation of the Environmental State of the Sea Area in the Lithuanian Territorial Waters and Economic Zone Adjacent to the Russian Oil Platform D-6

According to the research plan of the project, the sampling cruise has been organized in November 2005 to evaluate the environmental state of the Baltic sea area adjacent to the Russian oil platform D-6. Experts from Finnish Institute of Marine Research (FIMR, Finland) have participated in the project to make this evaluation independent.

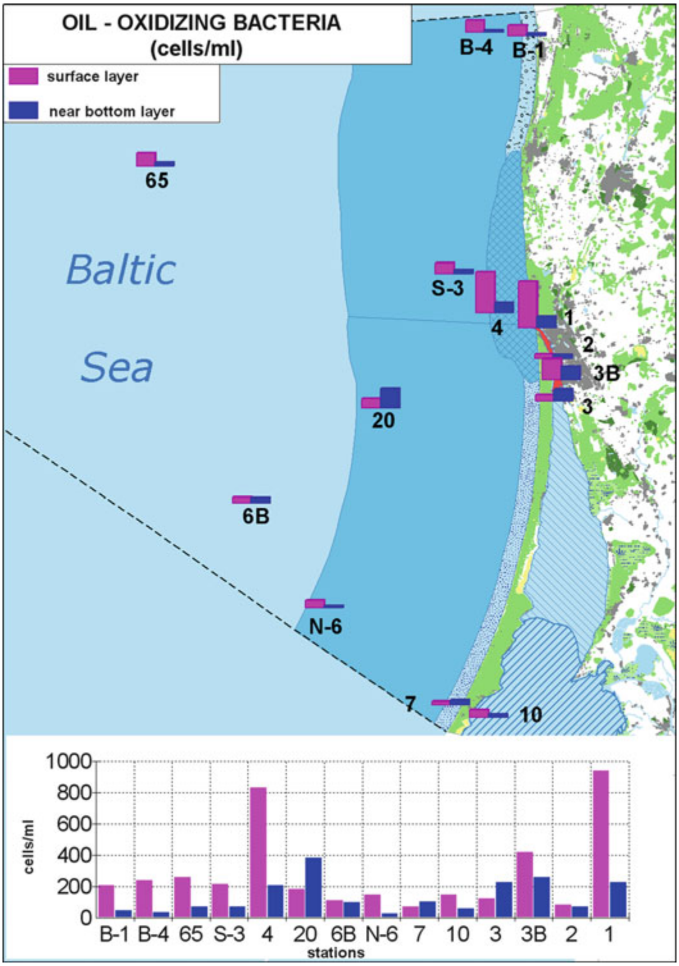

Fig. 9 Distribution of numbers of oil-oxidizing bacteria at different stations of the Baltic Sea and the Curonian Lagoon (average concentration from spring to autumn periods) in 2007

The results of the project showed that environmental conditions in 1995–2005 in the area reflect the conditions and trends observed in the Baltic Sea in general. However, the transitional zone forms an exception due to the influence of water outflow from the Curonian Lagoon. The highest levels of THC in the surface water were measured in the open-sea area in the mid-1990s and again in November 2005. In the coastal zone, the THC levels were systematically lower. 5–17% of the THC values exceed the maximum permissible limit (MPL) established by the Lithuanian legislation. Intensive shipping activity (e.g., Klaipėda harbor), illegal discharges, and oil spills from ships are potential causes for the peak-type appearance of THC in the surface water between 1995 and 2005. Presence of oil-oxidizing bacteria also indicated the occurrence of oil hydrocarbons in water [13].

In studies carried out in 2005, low levels of PAH were observed in sediments and bivalves. However, PAH levels observed at the only true soft-bottom station N-1 signified some degree of hydrocarbon pollution. Grain size of sediment particles at N-1 was small offering large adsorption surface for various chemical compounds. Molecular ratios of indicator PAH compounds imply that hydrocarbon pollution in the study area is mostly of pyrolytic, not petrogenic, origin and apparently from diesel engines. Heavy metal concentrations in sediments and biota (soft-bottom clam *Macoma balthica*) in the study area were within normal ranges. Concentrations of other hazardous compounds measured in the study area were below detection limit (alkylated phenols) or low (organotins); the latter, however, showing relatively high levels at station N-1 [13].

Biomarker responses in *Macoma balthica* showed significant differences between the populations. However, some of the enzymatic biomarkers may be affected by temperature differences between the study stations. Cytogenetic damage, measured as frequency of micronuclei (MN), was significantly higher in *M. balthica* from the offshore stations compared to the near shore. The clam population at the offshore station N-2 was in the most stressed condition according to the integrated stress response index (IBR) calculated using all eight biomarkers measured [13].

Modeling studies showed that, in case of an oil spill at the D-6 platform, the most dangerous winds in regard to oil contamination of the beaches of the Curonian Spit would be from western, southwestern and southern directions. The probability of oil reaching the shore of the Curonian Spit depends on seasonal variability in prevailing wind directions, the risk being the highest in summer and winter due to the prevailing western air mass movement. As an example of modeling scenarios, in stormy conditions (eastward current, speed 50 cm s^{-1}) the oil spill would reach the Curonian Spit (town of Nida) in 14 h [13].

Main recommendations of the project were the increase of monitoring activities in the area adjacent to the Russian oil platform D-6 and better co-operation between national institutes dealing with the marine environment in order to assure the best use of the available infrastructure, equipment, and facilities for cost-efficient monitoring.

4 Environmental Genotoxicity and Cytotoxicity Studies After the Būtingė Oil Spill

In 31 January 2008, the accidental spill of more than 2 tons of oil products from the tanker “Stena Antarctica” occurred during the pumping of oil from the Būtingė oil terminal. The spill has been distributed on the Lithuanian coast near Šventoji. On 11–12 of February 2008, blue mussels (*Mytilus edulis*) were sampled from the area closely located to “Stena Antarctica” oil spill site in the Būtingė oil terminal (Fig. 10). Mussels were also sampled in May and in August 2008. The main objective of this study was to evaluate the level of environmental genotoxicity and cytotoxicity in different sites of the Lithuanian economic zone of the Baltic Sea, which were affected by the oil spill from the tanker "Stena Antarctica."

MN are small chromatin-containing bodies found in cells. Their formation frequency is used for the indication of gentoxic agent action. The investigations of fish and mussels from the Baltic Sea showed the relevance of the approach in assessment of genotoxic effects, with clear correlations with contaminant gradients. MN is a cost-effective, simple, and rapid method which is convenient to employ in field samplings following standard procedures and protocols. The output is well defined and is easily recognizable. It allows the evaluation of the influence of genotoxic compounds at low concentrations and the assessment of dose–response relationships of genotoxins [21].

In the Lithuanian coast, MN frequency in mussels ranged from 1.08 ‰ (MN/1,000 cells) in Palanga location in June 2007 to 6.06 ‰ in the same location in August 2008. The reference level (1.2 ‰) in Palanga site was found also in June 2001, but after the accidental oil spill in Būtingė oil terminal (in November 2001), Palanga location was contaminated by oil and the genotoxicity level in 2002–2003 have increased up to 3.0 MN/1,000 cells [21, 32]; and remained significantly elevated until 2005. Full recovery of mussels was found only in June 2007. However, in January 2008, the oil spill accident has recurred and very similar scenarios of spilled oil distribution and genotoxicity elevation appeared again. As a result, the frequency of MN in mussels from the Palanga site increased up to 6.06 ‰, and reached the highest level registered in 2001–2008 at different study locations on the Lithuanian coastal and offshore zones [32].

It is noteworthy to stress that twofold to fourfold elevation of other nuclear abnormalities like nuclear buds, the other endpoint of the environmental genotoxicity, was found after the oil spill in 2008 compared to the level before the spill. The induction of binucleated cells in gills of mussels was elevated up to two times; induction of fragmented-apoptotic cells was increased up to nine times. The phenomenon in mussels appears evidently as a result of action of genotoxic and cytotoxic agents constituting the spilled oil [32]. Therefore, in assessment of oil spill damage, a usefulness of other than MN nuclear abnormalities has been confirmed [33–39].

The results of the study pointed to comparatively quick formation of genotoxicity and cytotoxicity caused by oil spill in winter at low temperature and revealed the need to highlight harmful effects after the oil spillage in marine environment [32].

5 Conclusions

Total oil hydrocarbons, polycyclic aromatic hydrocarbons, and oil-oxidizing bacteria indicate considerable pollution in some areas of the Lithuanian part of the Baltic Sea. Būtingė oil terminal, Klaipėda harbor, and Russian D-6 oil platform are potential oil pollution sources.

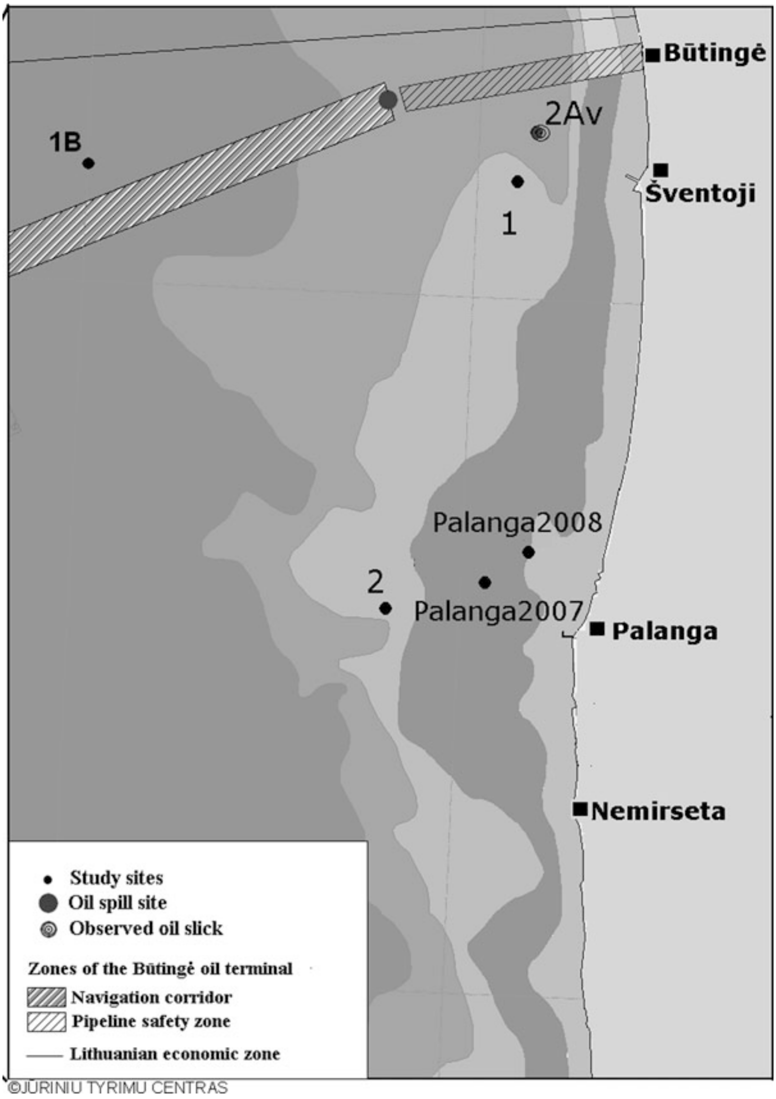

Fig. 10 Sampling stations for the monitor of environmental geno-cytotoxicity after the oil spill in 2008 (from [32])

Investigations show that THC concentrations in water frequently exceed the maximum permissible level (0.05 mg l^{-1}). Long-term studies (1990–2007) show that there are increasing trends of THC concentrations in some areas of the Lithuanian part of the Baltic Sea.

Calculated molecular indices of PAHs at tankers anchoring area and adjacent to the D-6 oil platform showed that the source of PAHs in the sediments was petrogenic, related to shipping or oil platforms. A diesel engine source of PAHs was indicated at the station near Būtingė oil terminal.

Significant increase of MN and other nuclear abnormalities was observed in mussels after the oil spill in the Būtingė oil terminal (January 2008). Elevated environmental genotoxicity and cytotoxicity responses were observed in mussels from the Palanga location 6 months after the oil spill event.

Lithuanian data on oil spills obtained under satellite and aerial monitoring is fragmented. No illegal oil spills were detected in Lithuanian waters in 2010 [40].

Complex investigations and monitoring of marine environment allow permanent control of the contamination and quality of the Baltic Sea and the Curonian Lagoon environment.

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Satellite Monitoring of Oil Pollution in the Southeastern Baltic Sea

Andrey G. Kostianoy, Olga Yu. Lavrova, Marina I. Mityagina, Dmytro M. Solovyov, and Sergey A. Lebedev

Abstract The chapter shows the examples and results of satellite monitoring of oil pollution in the Southeastern Baltic Sea obtained in 2004–2012. The beginning of this work was initiated by "LUKOIL-Kaliningradmorneft" in relation to installation of the D-6 offshore platform and production of oil in spring 2004. The results clearly show that the Southeastern Baltic Sea is highly polluted by oil products, and that this is related to intense shipping activities in the region. No pollution in the vicinity of the D-6 oil platform was detected during these years. Interannual variability of the number and surface of oil spills, as well as their seasonal and diurnal variability is discussed. The problem of transboundary oil pollution transport between EEZs of Poland, Russia, and Lithuania is highlighted.

Keywords Lukoil D-6 oil platform, Marine environment, Oil pollution, Operational satellite monitoring, The Southeastern Baltic Sea

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Contents

1 Introduction

Russia has two gates to the Baltic Sea. The first one is located in the easternmost part of the Gulf of Finland and the second one in the southeastern part of the Baltic Sea. Here, Kaliningrad Oblast (Region) is the most western part and an exclave of Russia, which is surrounded by Poland, Lithuania, and the Baltic Sea (Fig. 1). The administrative center and the largest port is Kaliningrad city, which is connected with the Baltic Sea by Kaliningrad Sea Canal 43 km long. The western part of Kaliningrad Oblast is located on the Sambian Peninsula, surrounded by the sea, and Vistula and Curonian lagoons, separated from the Baltic Sea by long sand-dune spits (Fig. 1). The biggest river is the Pregolya, which drains via Kaliningrad into Vistula Lagoon, then the Baltic Sea. Vistula Lagoon is shared between Russia and Poland. Curonian Lagoon and Curonian Spit, which is a UNESCO World Heritage Site, are shared between Russia and Lithuania (Fig. 1). The length of the Russian coastline in the Southeastern Baltic Sea is about 140 km.

Major industries in Kaliningrad Oblast include car production, maritime transport, shipbuilding, food, fishery, oil industry, amber production, etc. The area has several small oil fields onshore and offshore, including the largest oil field in the Baltic Sea "Kravtsovskoye" (D-6) located on the Baltic Sea shelf with geological reserves of about 21.5 million tons, and recoverable reserves about 9.1 million tons. The license for the right to develop the deposit belongs to the "LUKOIL-Kaliningradmorneft" (Kaliningrad) – a subsidiary of Lukoil Company (Russia). In spring 2004, Lukoil started oil production at the offshore ice-resistant stationary oil platform D-6, located in the Baltic Sea, 22.5 km from the national reserve, the Curonian Spit, a World Heritage Site, and in several kilometers from the marine border with Lithuania (Figs. 1 and 2). Due to the importance of tourism and fishing for the regional economy of Russia and Lithuania, pollution of the sea and coastlines may have disastrous effects for the area in case of oil leakage from the platform. Lukoil is following the principle of "zero discharge," which means a total ban on the discharge into the marine environment of all types of waste generated as a result of oil production. All waste is collected in sealed containers, which are then transported to shore for disposal and recycling. Nevertheless, the construction of the Lukoil D-6 oil platform in 2003 and beginning of oil production in 2004 raised big concerns

Fig. 1 Geographic map of Kaliningrad Oblast and the Southeastern Baltic Sea (based on the Google Earth map). An *asterisk* shows location of the Lukoil D-6 oil platform and the *dashed line* an underwater oil pipeline

Fig. 2 Lukoil D-6 oil platform at sea

about possible oil pollution and even protests of Lithuania, Poland, EU, and environmentalists against Lukoil's plans to exploit the oilfield.

Oil is pumped from the D-6 platform on land via underwater pipeline 47 km long, which is made of seamless steel pipes of 273 mm in diameter and a wall thickness of 18.3 mm. A mixture of oil and associated gas is transported to the gathering station "Romanovo," where it is processed into marketable oil, which is pumped via underground pipeline 31.6 km long to the complex oil terminal "LUKOIL I" near Izhevskoe settlement at the coast of Vistula Lagoon (Kaliningrad Bay). Water depth at this oil terminal allows to receive tankers of up to 20,000 tons and deliver yearly six million tons of oil and oil products. The underwater oil pipeline and oil terminal represent an additional threat to the marine environment in case of accidents.

Port of Kaliningrad is a Russian port on the southeastern coast of the Baltic Sea, the only ice-free Russian port on the Baltic. It consists of a commercial sea port, sea fishing port, and river port. Kaliningrad Sea Canal is a part of the port infrastructure. The port has an advantageous position in the Baltic Sea, because the distance to the biggest foreign ports on the sea varies from 400 to 700 km. Kaliningrad port is connected to ports of the Netherlands, UK, Germany, Poland, and Lithuania with container lines. In 2009 the turnover of the port amounted 12.4 million tons. Several busy shipping routes come to the entrance to Kaliningrad Sea Canal near Baltiysk town, where ships are waiting for permission to pass through the canal. Thus, the risk of oil pollution in the Baltic Sea waters of Russia is also related to tankers and ships visiting the port of Kaliningrad and Lukoil oil terminal.

2 Satellite Monitoring of the Southeastern Baltic Sea in 2004–2005

2.1 Goals, Objectives, and Methodology

In June 2003, "LUKOIL-Kaliningradmorneft" initiated a pilot project aimed to organize comprehensive environmental monitoring in the Southeastern Baltic Sea in relation to the forthcoming in March 2004 start of oil production at the "Kravtsovskoye" (D-6) oil field. Oil production is carried out on the sea ice-resistant stationary platform D-6 (Fig. 2) at a distance of 22.5 km from the Curonian Spit and 8 km away from the marine border with Lithuania (local depth is about 30 m). Since 1993 Russia hasn't carried out aerial surveillance of oil pollution in the Gulf of Finland and in Russian waters of Kaliningrad Oblast. In 2003, when the Lukoil D-6 oil platform was under construction, nobody performed satellite monitoring of oil pollution in this region. Thus, "LUKOIL-Kaliningradmorneft" decided to include in the standard marine ecological monitoring program satellite remote sensing of oil pollution around the platform and in the large area of the Southeastern Baltic Sea of about 60,000 km^2, which is almost one-sixth of the Baltic Sea total surface.

In June 2004, at the request of "LUKOIL-Kaliningradmorneft" we have developed and organized comprehensive operational satellite monitoring of the Southeastern Baltic Sea as an important component of environmental monitoring performed by the company [1–8]. It was based on daily operational receiving, processing, and analysis of various satellite data (ASAR ENVISAT, SAR RADARSAT, AVHRR NOAA, MODIS-Terra and -Aqua, TOPEX/Poseidon, Jason-1) on oil pollution of the sea surface, sea surface temperature (SST), sea level, concentration of chlorophyll and suspended matter, algal bloom, ice cover, mesoscale water dynamics, wind and waves on the vast area of the Southeastern Baltic Sea. In addition, the interactive operational numerical model Seatrack Web of Swedish Meteorological and Hydrological Institute (SMHI) was used for the prediction of the oil spill drift.

This extensive work required creation of a satellite monitoring group headed by Prof. A.G. Kostianoy (P.P. Shirshov Institute of Oceanology, Moscow), which included experts in various fields of remote sensing of the ocean from space, oceanography, meteorology, marine biology, and numerical modeling from the following scientific organizations: P.P. Shirshov Institute of Oceanology (Moscow), Russian Space Research Institute (Moscow), Geophysical Center of Russian Academy of Sciences (Moscow), Russian Research Institute for Space Instrument-Making (Moscow), Atlantic Research Institute for Fishery and Oceanography (Kaliningrad), and Marine Hydrophysical Institute of National Academy of Sciences of the Ukraine (Sevastopol). Each specialist performed clearly defined functions and had an hourly schedule agreed on time with other team members. The most important functions of the integrated monitoring system were duplicated, as well as means of communication and data transfer. It should be noted that the work performed by the team drastically differed from the "standard" scientific work in an academic institution, because it was executed 24 h a day in an operational regime, and the degree of responsibility for the credibility of the results was at the international level with all the consequences for the company "LUKOIL-Kaliningradmorneft" and the Russian Federation.

By that time, in the Russian Federation, such a complex system of satellite monitoring of oil pollution of the marine environment did not exist in the Baltic Sea, as well as in other Russian seas. Our monitoring system was a pioneering one in Russia, moreover it was successfully implemented in "LUKOIL-Kaliningradmorneft" in 2004–2005. As monitoring was carried out 24 h a day, 7 days a week all year round, we can assert that we organized an operational service for satellite monitoring of the Baltic Sea environment. In this way it lasted during 18 months till the end of 2005 [1–8]. Full analogs of such a system in the world at that time also did not exist, because existing permanent monitoring systems did not have the broad interdisciplinary, multisensor, and multiplatform approach and therefore had a number of well-known shortcomings. Full analogs and even superior monitoring systems occur only in case of major oil spills, for example, in case of the tanker *Prestige* in November 2002, or an accident on *Deepwater Horizon* oil platform in the Gulf of Mexico in April 2010, when the observing systems, organized after a catastrophe, include dozens of teams from national and international organizations, space agencies, meteo services, research institutes, coast guard, as well as satellites, aircrafts, helicopters, and ships. In the absence of accidents, normally, permanent, operational, interdisciplinary, multisensor, and multiplatform satellite monitoring of oil pollution is not performed anywhere.

The aim of this project was to organize and conduct comprehensive permanent satellite monitoring of the southeastern part of the Baltic Sea to detect contamination of marine waters by oil products, to identify areas of contamination, potential sources of pollution, direction and speed of oil pollution transport. The main objectives of the monitoring were as follows:

1. Detection of oil spills near the platform D-6, Russian coast and in the waters of the southeastern part of the Baltic Sea between 54°20′–58°N and 18–22°E
2. Identification of possible sources of contamination
3. Forecast the direction and speed of drift of the detected oil slicks and of potential pollution from the D-6 platform
4. Systematization and archiving of comprehensive information about the ecological state of the Baltic Sea and meteorological conditions

The real-time monitoring of oil pollution was based on the processing and analysis of the ASAR (Advanced Synthetic Aperture Radar) images acquired from all passes of ENVISAT satellite over the southeastern part of the Baltic Sea (the periodicity of passes was 12–72 h, the image size – 400 × 400 km, spatial resolution – 75 m per pixel) (Fig. 3) and SAR RADARSAT (selectively, when an interval between the ASAR ENVISAT images was 72 h, 300 × 300 km, 25 m per pixel) (Fig. 4). In accordance with the signed contract, Kongsberg Satellite Services (KSAT, Tromso, Norway) in real time (1–2 h after a satellite pass) sent to us raw digital images (data files), which we immediately processed and analyzed with the help of all sets of auxiliary satellite and metocean information and forecasts collected in previous days. Thus, we identified oil slicks occurred in Russian waters, those which were advected as a result of transboundary transport by wind and currents, as well as those which were identified on the extensive area of about 60,000 km^2 in the Southeastern Baltic Sea (including waters of Poland, Lithuania, Latvia, and Sweden).

Interpretation of radar images in order to correct identification of oil spills on the sea surface is a highly difficult task due to the presence of the so-called look-alikes of oil slicks on radar images, which can result from a number of natural processes in the ocean (sea) or atmosphere. Experience from previous satellite monitoring systems and scientific research based only on an analysis of radar imagery showed that there is a high probability of the so-called false alarms, when slicks on the sea surface have been erroneously interpreted as oil slicks. This is a characteristic feature of the final product of the suppliers of the processed satellite data. Due to this reason, and having at that time 15 years experience in the analysis of airborne and satellite radar imagery, we processed and analyzed radar data ourselves, and organized comprehensive monitoring, which included daily receiving and analysis of extensive auxiliary satellite, oceanographic and meteorological information. To avoid mistakes in the oil spill identification, in "simple" cases (evident oil spills) the analysis of ASAR/SAR images was

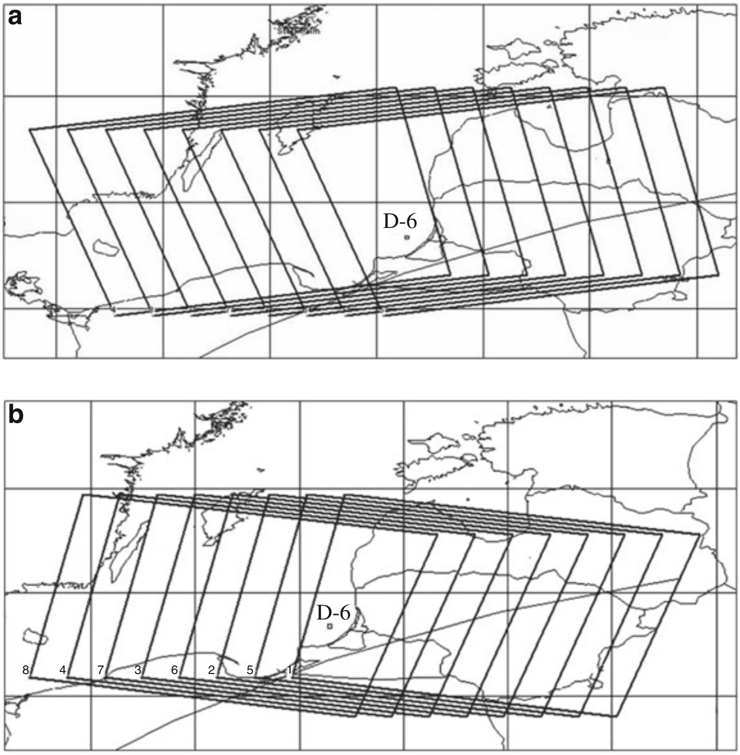


Fig. 3 Coverage of the Southeastern Baltic Sea (including D-6 oil platform) by the ASAR ENVISAT images in 35-day repeated cycle: (**a**) on the ascending passes, (**b**) on the descending passes

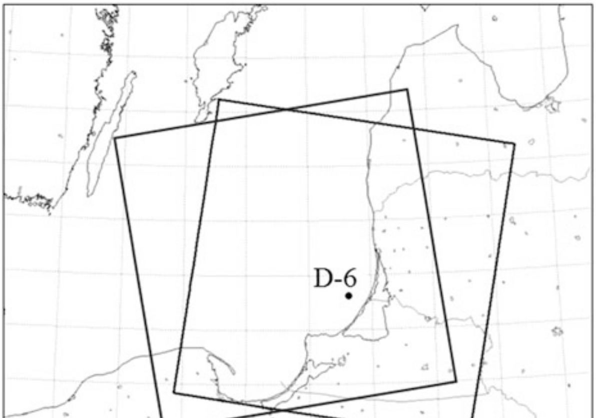


Fig. 4 Coverage of the Southeastern Baltic Sea (including D-6 oil platform) by the SAR RADARSAT images on the ascending and descending passes

made by at least two experts, in “difficult” cases (uncertain oil spills) the analysis was made by four experts with a “concilium” in the most difficult cases. Our experience shows that automatic oil spill detection cannot replace the expert analysis, especially in “difficult” cases.

For correct interpretation of satellite radar images and discrimination between oil slicks and various natural phenomena, as well as for a forecast of the speed and direction of oil spill drift, we daily collected and analyzed extensive hydrometeorological information and meteo forecasts from various sources (meteo centers, meteo stations, institutes, universities, airports, land meteo radars) in Sweden, Germany, Poland, Finland, Estonia, Latvia, Lithuania, and Russia. This information included: synoptic weather maps, cloudiness, air pressure, air temperature, humidity, rainfall, wind field (wind speed and direction, forecast), the field of surface waves (speed and direction, forecast), and current oceanographic information: the field of surface currents (speed and direction, forecast), distribution of chlorophyll in the surface layer, reports of hydrological and hydrochemical works at sea, information on algal bloom, ice cover, etc. In addition, we used data from the scatterometer SeaWind of QuikSCAT satellite and altimeter from Jason-1 satellite for information on the wind speed and wave height directly in the Baltic Sea. We also used fields of waves generated by the WW3 model of the Fleet Numerical Meteorology and Oceanography Center (FNMOC, USA) for the Baltic Sea.

For interpretation of radar images and oil slick drift forecast, we organized a reception, processing, and analysis of all informative (cloudless) infrared (IR) and optical images from all passes of NOAA (AVHRR), and Terra and Aqua (MODIS) satellites. The spatial resolution of these data is 250 m to 1 km. The satellite receiving station at Marine Hydrophysical Institute in Sevastopol was used for operational data acquisition from AVHRR NOAA 24 h a day, 7 days a week. These data were processed in order to construct maps of sea surface temperature (SST), optical characteristics of the sea surface, and surface currents. Maps of SST, total suspended matter, chlorophyll concentration, and bloom events (high concentration of blue-green algae in the surface layer in summer) can reveal specific features of meso- and small-scale structure and dynamics of the Baltic Sea waters, such as currents, eddies, dipoles and multipoles, jets, filaments, river plumes and outflows from the Vistula and Curonian lagoons. Consecutive daily infrared and optical images of AVHRR and MODIS allow the reconstruction of the real field of surface currents (direction and speed) with a resolution of 0.25–1 km, which is extremely important for the precise prediction of the direction and speed of oil spills drift. Such fine spatial resolution, even today, is not achieved in hydrodynamic models of the Baltic Sea. The combination of ASAR ENVISAT (SAR RADARSAT) radar images and MODIS images allows to understand why detected oil spots have sometimes a specific form and to predict their transport by mesoscale currents. We found that a superposition of both types of images (radar-optical) is a very effective procedure for analysis and prediction of an oil spill shape and drift.

Auxiliary satellite and metocean information helped very much in discrimination between oil slicks and look-alikes of oil slicks. Working in the Southeastern

Baltic Sea we encountered the following list of look-alikes: wind shadow areas, areas with weak local wind, organic films, bloom events, some types of ice cover, hydrological fronts, small-scale vortices, zones of upwelling, local runoff of different nature (e.g., sanitation), manifestations on the sea surface of oceanic internal gravity waves, atmospheric fronts, internal waves in the atmosphere, intensive small-scale atmospheric vortices, rain cells, and snow falls [6]. All these processes and phenomena may lead to a change in the spectrum of surface waves, weakening the resonance ripples, and appear on radar images as regions of low scattering (slicks), which can be misinterpreted as oil spills [6, 9].

The interactive operational numerical model Seatrack Web of Swedish Meteorological and Hydrological Institute (SMHI) [10] was used for prediction of drift of: (1) all large oil spills detected on radar images, (2) oil spills detected in the vicinity of the D-6 oil platform, (3) oil spills detected in the vicinity of Russian coasts, and (4) virtual (modeled) oil spills released from the platform D-6. The last task was our first experience in the application of the model for environmental risk assessment in the Baltic Sea [11]. Seatrack Web model is a unique European model which allows to calculate drift and transformation of spills of various petroleum products for 5 days ahead, as well as backward calculation for 30 days, with a spatial resolution of one nautical mile, basing on the renewing forecasts of the wind field (and other meteorological parameters) and currents every 3 h. Currently, this model is much improved in performance and has additional features like the incorporated AIS system. In addition, it is recommended by HELCOM to all the Baltic Sea countries for operational use in the case of oil spill observation [10].

Thus, the forecast of speed and direction of the likely transfer of detected oil spills was made basing on the comprehensive analysis of: (1) daily sequence of satellite radar imagery; (2) state of the sea surface from satellite radar data; (3) daily satellite images of the sea surface in the infrared and optical spectral bands; (4) satellite data on wind speed; (5) meteo information; (6) results of numerical simulations on the basis of the Seatrack Web model.

A complete methodology of our monitoring system is described in detail in [6], where we show a general monitoring scheme and step by step explain all the stages from planning of the requests for satellite imagery to a delivery of analytical reports to "LUKOIL-Kaliningradmorneft" during 3 h after a satellite pass in case of emergency and during 24 h in all other cases. Weekly we prepared and passed to "LUKOIL-Kaliningradmorneft" a progress analytical report called "The Sea Bulletin," which was an illustrated overview of the state of the southeastern part of the Baltic Sea, based on the results of complex satellite monitoring over the past week. By the end of the first year of monitoring in 2004, we prepared (in Russian and English) and proposed for publication the Annual Report of "LUKOIL-Kaliningradmorneft" on satellite monitoring of the Southeastern Baltic Sea [2], which is still available on the web site of "LUKOIL-Kaliningradmorneft" (http://www.lukoil-kmn.com/ecology/space-monitoring2004), as well as on the web site of the LUKOIL Company (http://www.lukoil.ru/materials/doc/ecology/eco_kosmos.pdf). Later, such kind of the booklet with the results of ecological monitoring became a yearly tradition for the company.

2.2 Examples of Oil Pollution

The majority of anthropogenic pollution of the sea surface, identified during satellite monitoring of the Southeastern Baltic Sea, were leaks and discharges of oil and oil-containing liquids from ships. Catastrophic oil spills especially during accidents of tankers are rare, and usually do not remain without attention of the press and the public. Much often we observe chronic pollution of the sea surface during routine operations on ships. The main sources of pollution releasing from ships are washing, ballast, and bilge waters. Namely these illegal discharges are so common that together cause much more damage to the ecosystem of the Baltic Sea than single catastrophic oil spills [12–15].

Successful detection of oil contamination by satellite synthetic aperture radars to some extent depends on weather conditions. This explains the fact that, based on radar data, the highest number of oil slicks is observed from May to September, when wind and waves are predominantly weak or moderate. From October to April, wind speeds over 12 m/s and storms are often. Under these conditions oil pollution films on the sea surface are rapidly destroyed and sink, and noticeable smoothing of the sea surface is not observed. Strong seasonal variability in number of detected oil spills has smaller relation with seasonal variability of ship traffic in the Baltic Sea, related with yearly freezing of the Bothnian Sea and the Gulf of Finland.

One of the main characteristic features that help to detect an oil slick on radar images is its geometric shape. From this point of view, discharges from ships can be divided into two classes – discharges from moving ships and discharges from motionless vessels. In both cases, oil slicks look like "foreign bodies" in the background of the overall structure of a radar image. When 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. Most often, it is a narrow straight strip or a strip with a break. If release occurs during radar imaging, or occurred just before it, the strip is narrowing toward the ship, and, as a rule, it is possible to identify the ship, 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.

In Fig. 5 there is an example showing "ideal" fresh discharge from moving ships. The radar image was acquired in conditions of moderate wind and small waves. The oil slick (black strip) is narrowing to the north, which means that a ship, dumping the oil, is moving northward. The bright white dot at the northern end of the strip shows the current position of the ship. The length of the detected oil slick was 31 km. In this and next figures, the rectangular fragments of the radar images are inserted into the geographic map, and zooms on the encircled oil spills are exported from the radar image for better visibility.

Often vessels make multiple discharges of polluted water in motion. In Figs. 6 and 7 there are three of such examples. In Fig. 6, at the latitude of Klaipeda (Lithuania) there is a clear intermittent oil slick 34 km long. It ends by the bright dot marking the position of a ship moving to the port of Klaipeda. Another intermittent oil slick

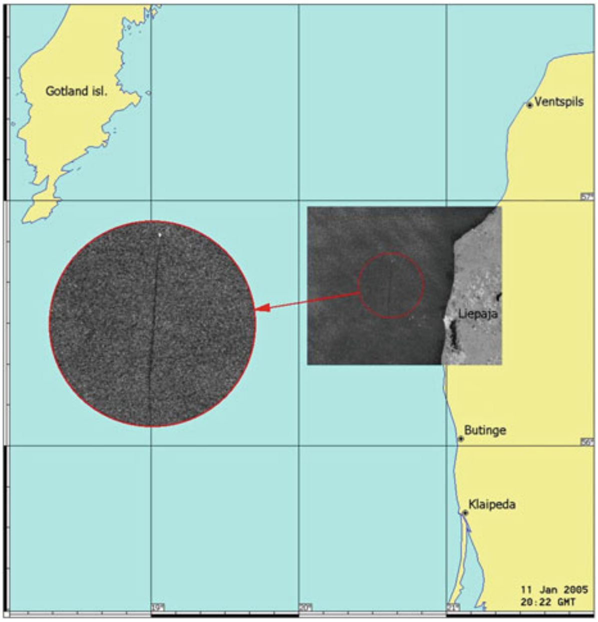


Fig. 5 Release of oil products from a moving ship in front of Liepaja (Latvia) on 11 January 2005 (©ESA, 2005)

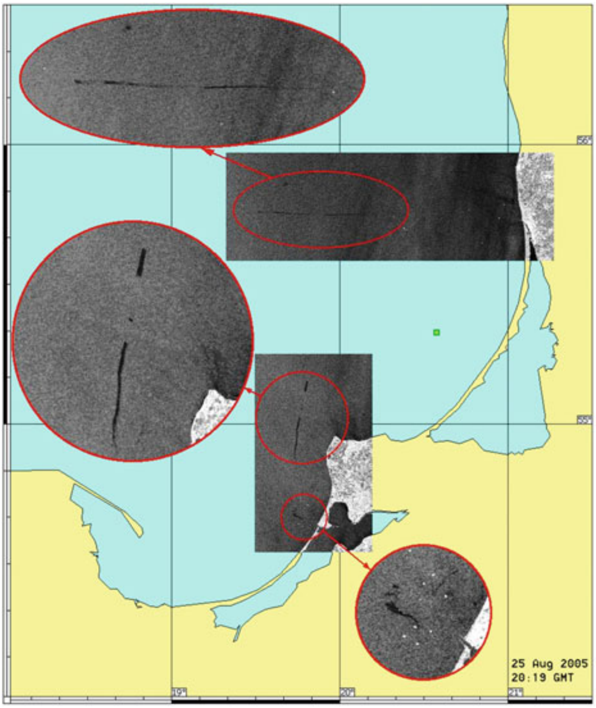


Fig. 6 Multiple releases of oil products from the moving ships in front of Klaipeda (Lithuania), northwestward of Sambian Peninsula (Russia), and from the stationary ship in front of the gate to Kaliningrad Canal (Russia) on 25 August 2005 (©ESA, 2005)

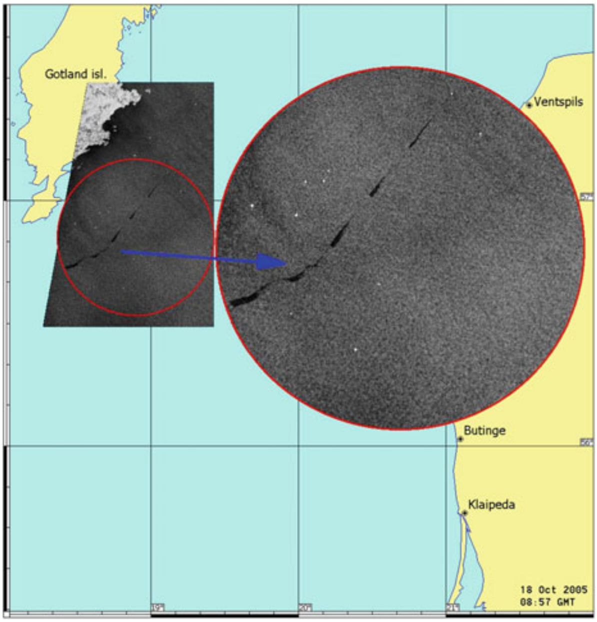


Fig. 7 Multiple releases of oil products from one moving ship near Gotland Island (Sweden) on 18 October 2005 (©ESA, 2005)

22 km long was observed on the same radar image to the northwest of Cape Taran (Sambian Peninsula, Russia). This spill occurred a few hours before the satellite pass, and it is impossible to identify the ship-polluter, because it is already far away. In Fig. 7, at the southeastward of Gotland Island (Sweden) there is a large dashed oil slick almost 80 km long, which stretches from the southwest to northeast along the main ship route in the Baltic Sea. The vessel (bright dot), moving to the northeast, is clearly visible at the radar image. Obviously, the discharge of oil products was carried out in several stages. The total area of oil contamination at the time of radar image acquisition was approximately 67.5 km^2. Other ships (white dots) can be identified at the same ship route along Gotland Island.

The more complex the meteorological conditions (stronger wind and higher waves), the more difficult it is to distinguish oil slicks on radar imagery. Several examples are shown in [6]. In these cases the contrast between the oil slick and surrounding waters is weak, it is difficult to define the direction of narrowing of the slick, and ships are difficult to detect. An unstable stratification of the air–sea boundary layer is an additional complicating factor, because it is displayed on the radar image as the cellular background, which partially hides the oil slick.

When release of oil is done from a motionless vessel in the absence of wind and waves, spreading of oil is more or less equal in all directions, and so the spot takes a rounded shape. However, the presence of wind, waves, and currents can have a significant impact on the structure of the slick. In some cases, the spot can stretch out in a line, as if there was release of oil from a moving ship. The same is valid for the cases of oil spills released from stationary oil platforms.

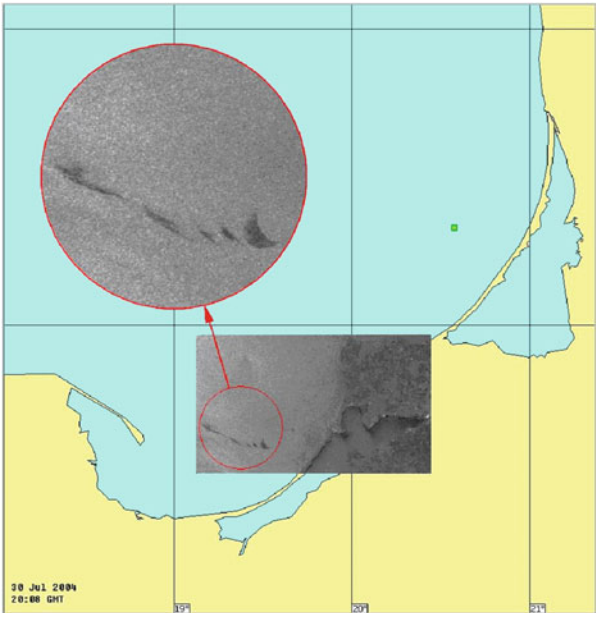


Fig. 8 The chain of oil spills in the Gdansk Bay on the ASAR ENVISAT image acquired on 30 July 2004 (20:08 GMT) (©ESA, 2004)

Analysis of the actual evolution of oil slicks, in the cases where the data allow doing it, is very important for improvement of the models used to calculate the drift and transformation of oil spills. A good illustration is the case of a large oil spill identified in the Gulf of Gdansk on 30 July 2004 (20:08 GMT) (Fig. 8). On the radar image we clearly find a large oil spill in the form of a chain of five spots of the total area of 26 km^2. The specific form of the oil spill allows to assume that, initially, the massive elongated oil pollution was localized to the east, and then, under the influence of currents and wind, drifted to the west and broke up into separate parts. This initial stage of the oil slick degradation was recorded on the radar image. Comparison of the radar and optical MODIS-Terra image, received in the morning (09:40 GMT) of the same day (Fig. 9, in which oil slicks were incorporated from the radar image), found that the chain of oil slicks is extended to the northwest on the periphery of the anticyclonic part of a dipole, which is a combination of a narrow jet with a pair of vortices of an opposite sign at the end. This dipole is located in the center of Gdansk Bay. Presumably, the advection of these oil slicks on 30 July could be affected by the intensity of the vortex motion in the dipole, the movement of the dipole itself, which in the period from 28 to 30 July turned clockwise to south on 90°, as well as by speed and direction of wind.

According to the forecast of the Seatrack Web model, the chain of oil spills had to move to the south under the influence of wind and currents, and in 2 days reach the Vistula Spit. This did not happen, because this numerical model does not always take into account the presence of the meso- and small-scale dynamic features such as vortices, dipoles, jets, filaments, and meanders. In Fig. 9 the oil

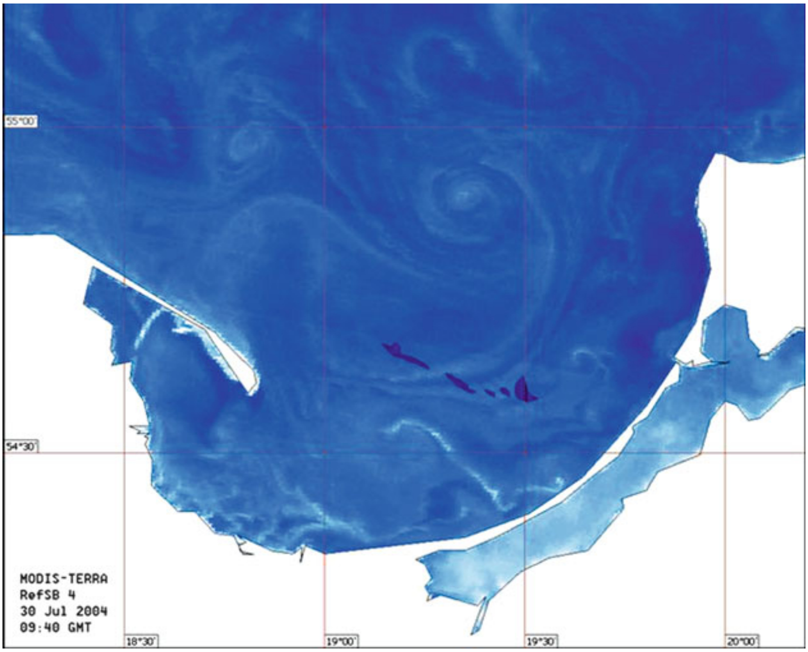


Fig. 9 The chain of oil spills (black patches) in the Gdansk Bay superposed on the optical MODIS-Terra image acquired on 30 July 2004 (09:40 GMT). *Dark blue color* shows clear waters, and *light blue color* shows turbid waters

slicks move almost along the streamlines of the current related to the anticyclonic vortex. A small discrepancy (a shift) in the chain position is due to a difference of 10 h between the time of the MODIS-Terra (morning) and ASAR ENVISAT (evening) images acquisition. It should be noted that in cloudy conditions, which are common in the Baltic Sea, the Seatrack Web model is the only source of information about the drift and evolution of oil spills, as well as on the field of surface currents.

Unauthorized discharge of water containing oil from vessels is not the only source of pollution of the sea surface in the southeastern part of the Baltic Sea. Over the period of the satellite monitoring, we repeatedly observed outflows of contaminated water from the Curonian and Vistula lagoons through the canals. Very often, this situation occurred in spring, when a lot of organic matter comes to the lagoons with numerous rivers and streams during spring floods. In addition, the ports of Baltiysk and Klaipeda, situated in the canals, contribute to the pollution of water. The higher is the concentration of oil, the longer the spill spreads, retains its shape and remains localized at the exit of the lagoon. Figure 10 shows two fragments of the same radar image acquired on 19 August 2005 at 20:08:19 GMT with contaminated outflows from Vistula and Curonian lagoons, respectively.

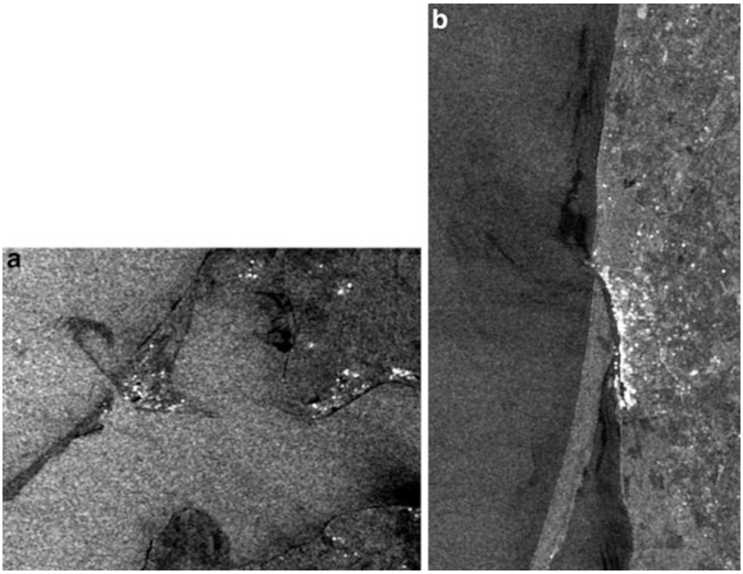


Fig. 10 Outflow of organic matter of mixed nature (dark patches directed northward) from Vistula Lagoon (**a**) and Curonian Lagoon (**b**) on 19 August 2005 (©ESA, 2005)

2.3 General Results of Satellite Monitoring

From 1 July 2004 to 30 November 2005, we received, processed, and analyzed 230 radar images from ENVISAT and 17 satellite images from RADARSAT. In total we identified 274 individual oil slicks on the surface of the southeastern part of the Baltic Sea [4–8]. A summary map of all oil spills detected in the Southeastern Baltic Sea is shown in Fig. 11. Real shapes and sizes of oil spills are shown. The dotted lines mark areas with traces of old weathered oil slicks. The location of the Lukoil D-6 oil platform is shown by a green square. Over the entire period of observation no oil slicks coming from the D-6 oil platform were found, which confirms the effectiveness of the environmental and production safety on the platform. As might be expected, the concentration of oil slicks on the map clearly draws the main shipping routes in the southeastern part of the Baltic Sea, directed to the ports of Ventspils, Liepaja, Klaipeda, Kaliningrad, as well as the line along Gotland Island. Looking in Fig. 11, it seems that one of the dirtiest places in the Baltic Sea is the aquatoria in front of the gate to Kaliningrad Canal, which is explained by a permanent concentration of ships waiting for permission to pass the Canal connecting to the port of Kaliningrad. Therefore, the main sources of oil pollution in the Southeastern Baltic Sea are ships. Surprisingly, but having more or less the same number of radar images, we did not detect “lines” of oil pollution leading to the ports of Gdynia and Gdansk in Poland. So, the southwestern part of the Gdansk Bay was quite clean. Also, no oil spills were detected in the Curonian Lagoon, as well as offshore of the Curonian Spit from Sambian Peninsula to Klaipeda.

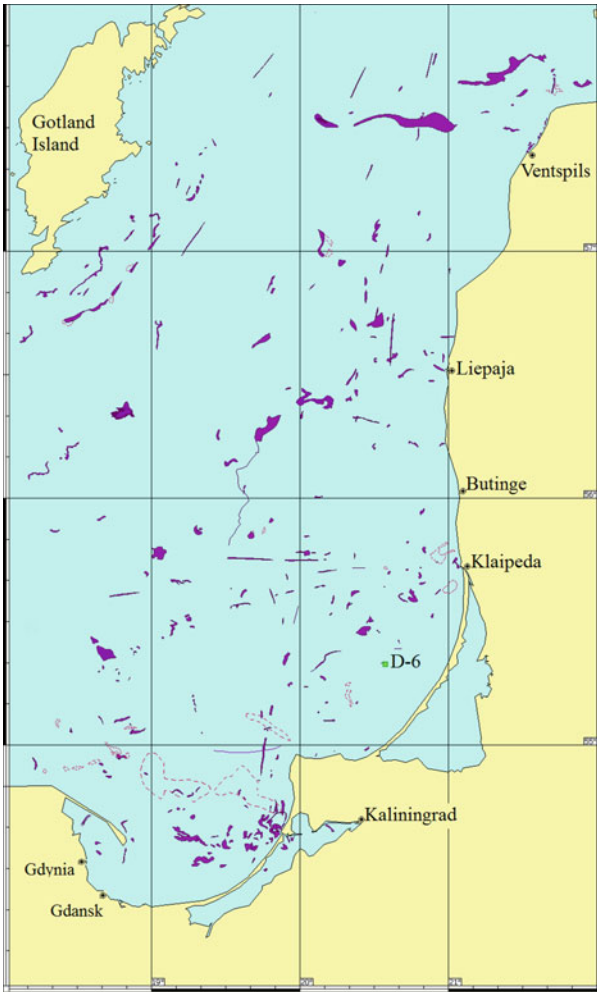


Fig. 11 Map of all oil spills detected by the analysis of the ASAR ENVISAT and SAR RADARSAT imagery from July 2004 to November 2005 [4–8]

We found significant seasonal variability in oil spill observations. In spring and summer of 2005 the number of oil spills was about three times larger than in winter and autumn. Another important observation is related with the “lifetime” of an oil spill at the sea surface in the radar image, which in most cases is less than 12 h. This fact was discovered by the analysis of pairs of subsequent radar images acquired with a time step of 12 h. In most cases, after 12 h we could not detect the same oil spill again. Only very large oil spills could be followed on radar images during a couple of days. This is explained by strong evaporation of oil from the sea surface, when during the first 12 h the spill may lose up to 50% of its volume, destruction of an oil spill by wind and waves, and by spatial resolution of radar imagery – 25–75 m/pixel. It means that the oil spill may be present in the sea, but be disintegrated in small separate patches, undetectable on the radar image. Thus, the set of all possible radar images could not provide valuable information on real lifetime of oil spills.

We received, processed, and analyzed about 1,600 satellite images in the infrared and optical bands from satellites NOAA (AVHRR), Terra and Aqua (MODIS) as auxiliary information necessary for the analysis of radar images and forecasts of oil spill drifts. About 240 maps of the near sea surface wind field were constructed basing on the SeaWind scatterometer data of QuikSCAT satellite and 73 maps of wave heights according to the Jason-1 altimeter data. A huge amount of daily metocean data was collected and analyzed too [4–8]. Interactive numerical model Seatrack Web of Swedish Meteorological and Hydrological Institute was used to predict the drift of all large oil spills detected in radar images. In addition, the model was used for daily forecast of drift and transformation of an oil spill for 48 h ahead with a 3 h step for the case of accidental release of 10 m^3 of oil from the D-6 platform. This daily forecast made it possible to plan and adjust actions to eliminate oil contamination from a potentially possible accident at the D-6 platform and the underwater oil pipeline. More details about these procedure and results can be found in [11]. A total of about 550 forecasts were made from July 2004 to November 2005 [2–8].

3 Satellite Monitoring of the Southeastern Baltic Sea in 2006–2012

Since January 2006 till today LUKOIL-Kaliningradmorneft continues satellite monitoring of the Southeastern Baltic Sea, but this is done by a private company “Slick Ltd.” (Kaliningrad) with participation of specialists from the Atlantic Branch of P.P. Shirshov Institute of Oceanology (Kaliningrad) [16, 17]. The monitoring area was reduced from 60,000 km^2 to 24,000 km^2 (an area closer to the Russian coast, limited by a blue line in Fig. 12), and, unfortunately, the monitoring scheme and methodology were transformed, as a result satellite monitoring lost its main peculiarity – a complex approach to oil spills detection and forecast of their drift. The processing, analysis, and detection of oil spills on radar images are done by Konsberg Satellite Services (Norway). ASAR and SAR imagery acquired from ENVISAT (European Space Agency), RADARSAT-1 (Canadian Space Agency), and RADARSAT-2 (CSA and MacDonald, Dettwiler and Associates Ltd. (MDA)) satellites are used for oil spill monitoring. ENVISAT was used till its failure in April 2012.

The reduced monitoring area comprises EEZ of Russia and Lithuania, and a part of Polish EEZ till 18°E (Fig. 12). This area is characterized by intense shipping related with a location of several largest ports and oil terminals. Figure 12 shows an accumulated map of all oil spills detected in this area from July 2004 till

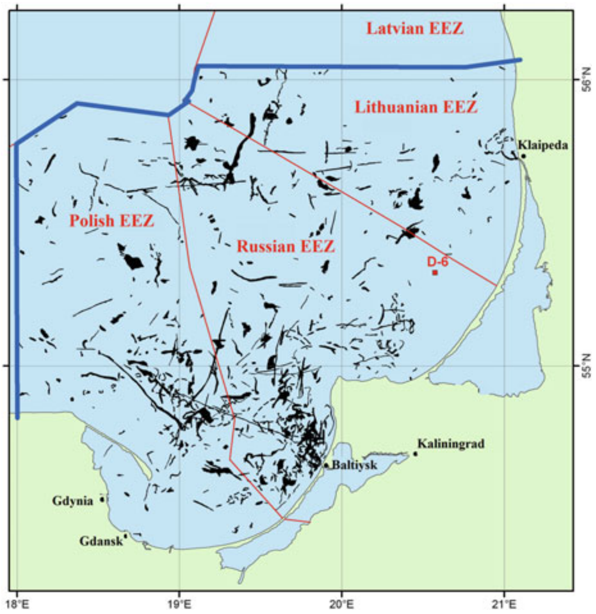


Fig. 12 Map of all oil spills detected by the analysis of the ASAR ENVISAT and SAR RADARSAT imagery from July 2004 to December 2012 in the reduced monitoring area, shown by the *blue line* [16, 17]. EEZ of Poland, Russia, and Lithuania are delimited by the *red line*. "D-6" dot shows the location of the Lukoil platform

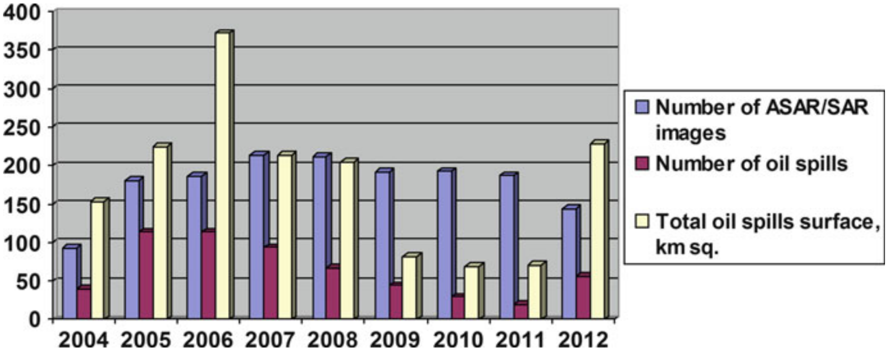


Fig. 13 Variability of the total number of analyzed ASAR/SAR images, the total number of detected oil spills, and the total oil spills surface in square kilometers in 2004–2012. Note that in 2004 the satellite monitoring was performed during 6 months only from July to December 2004

December 2012 (again the real shape and size of the spills are shown) [16, 17]. In 2006 the total number of detected oil spills (on the 2.5 times reduced area) and the total area of oil pollution amounted to 114 spills (371.7 km^2), in 2007 – 94 (213.7 km^2), in 2008 – 67 (198.7 km^2), in 2009 – 44 (81.7 km^2), in 2010 – 30 (69 km^2), in 2011 – 20 (71.3 km^2), and in 2012 – 56 (228.3 km^2) (Fig. 13) [17].

We recalculated the same characteristics for the same new area from the monitoring we performed in 2004 and 2005, and found the following values: during 6 months of 2004 we detected 40 oil spills on 93 radar images, and the total oil spill surface was equal to 153 km^2, in 2005 – 114 oil spills on 181 images, and 225 km^2. At the same time the yearly number of radar images during these years was stable and varied in the range between 181 in 2005 and 214 in 2007. A sharp decrease to 144 images in 2012 is related to the failure of the ENVISAT satellite (Fig. 13). To compare all these values for both monitoring periods – 2004–2005 and 2006–2012 – we constructed a graph showing year-to-year variability of the total number of analyzed ASAR/SAR images, the total number of detected oil spills, and the total oil spills surface in square kilometers (Fig. 13).

Analysis of the accumulative map of the detected oil spills locations shows that (Fig. 12):

1. The southeastern part of the Baltic Sea is a highly polluted area. This is related to intense shipping routes directed to the ports of Klaipeda and Kaliningrad (Baltiysk). Combined analysis of the location and shape of the detected spills with location of the ships, thanks to AIS (Automatic Identification System for ships), clearly indicates that the major source of sea pollution is shipping.
2. Looking at the map, it’s possible to reveal four to five spills lines (separate shipping routes) directed to Klaipeda in the sector from west to southwest. It’s interesting that ships start to discharge water containing oil products in the sea at a distance of 150–160 km from Klaipeda, i.e., beginning from the Polish and Russian EEZs.
3. The most polluted area is located in the Gdansk Bay, in Russian and Polish EEZs, which is related to the shipping routes coming to the gate to Kaliningrad Canal at Baltiysk town. Also, it’s possible to reveal several shipping routes directed to the north, northwest, and west from the gate. Ships start to discharge water containing oil products in the sea at a distance of 100 km from Baltiysk.
4. In the Gdansk Bay the Polish coastal zone is much cleaner than the Russian coastal zone. There are no visible oil spill lines leading to the ports of Gdansk and Gdynia.
5. The map reveals a big problem of transboundary oil spill transport, because oil pollution lines or polluted areas intersect borders between Polish and Russian EEZs, and Russian and Lithuanian EEZs. There are two reasons for this: (1) ships release oil when crossing these borders; (2) drift of oil spills due to currents and wind. This is not the case between Lithuanian and Latvian EEZs, which can be explained by low ship traffic crossing this border, and slow advection of oil spills to the north from the northernmost shipping route Klaipeda – West.
6. There is no pollution in the vicinity of the D-6 oil platform. This is explained by no leakages from the platform registered during 2004–2012, as well as by the location of the platform outside of the shipping route connecting Kaliningrad (Baltiysk) and Klaipeda.
7. There is no pollution offshore the Curonian Spit because of the same reasons.

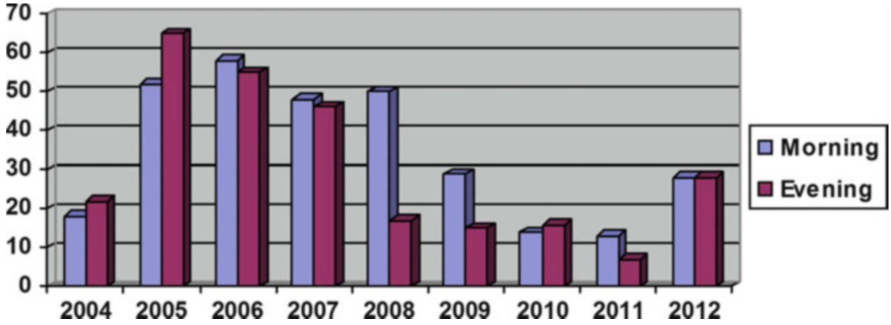


Fig. 14 The total number of oil spills detected in 2004–2012 in the morning and in the evening. Note that in 2004 the satellite monitoring was performed during 6 months only from July to December 2004

Analysis of the statistics on oil spills (Fig. 13) shows that in the Southeastern Baltic Sea, since 2006, we also observe a decreasing trend in the oil spill number and their total surface, which corresponds to the same trends announced by HELCOM, basing on the analysis of the confirmed oil spills [15, 18, 19]. During this time the number of oil spills has dropped from 114 in 2005–2006 to 20 in 2011. The total oil spill surface decreased from 372 km^2 in 2006 to about 70 km^2 in 2010–2011. In 2012 we observed an unexpected sharp rise of the number of oil spills to 56 and oil pollution surface to 228 km^2 [17].

Significant seasonal variability in oil spill detection is observed. During autumn and winter, oil spills were detected three to four times less than in spring and summer [16, 17]. Maximum of oil spills falls in the middle of the period between March and October. The same seasonal variability is valid for the oil spill surface too [16, 17]. This huge difference is explained by limitations of the SAR method to detect oil spills when the wind is stronger than 10 m/s, which is very often during the cold season in the Baltic Sea. In addition, strong wind–wave mixing contributes to more rapid formation of emulsions (“water in oil” and “oil in water”), thus preventing formation of oil slicks on the sea surface. This difference cannot be related to the seasonal variability of the ship traffic, because the Southeastern Baltic Sea does not freeze.

A comparison of the number of detected oil spills in the morning satellite images (acquired about 11:00 local time) and in the evening images (about 22:00 local time) showed that the probability of finding oil pollution in the morning was about 40% higher than that in the afternoon and evening in 2006–2009 [16] and 20% higher for the full 2004–2012 time period [17] (Fig. 14). The same difference is valid for the oil spill surface too [16, 17]. This fact indicates that illegal discharges of oil from vessels occur more often at night, when it is impossible for patrol aircrafts or ships to record this fact by photo and video camera. This once again confirms the advantages of satellite radar imagery for monitoring of oil pollution.

It is amazing to follow year-to-year changes of the ratio of the “morning” and “evening” oil spills in Fig. 14. In 2004–2005 the number of “evening” oil spills exceeded that of the “morning” ones. This means that ships, releasing oil during the day, did not pay attention to the possible control from patrol aircrafts and vessels, because they were aware about absence or weakness of this service in the southeastern part of the Baltic Sea, as well as they were unaware about satellite monitoring we started in 2004. Since 2006 the ratio changed in favor of the “morning” oil spills (night discharges), and their number in 2008–2009 was two to three times larger than that observed in the evening (Fig. 14). During this time period Lithuania did not increase the number of aerial surveillance flight hours (41–66), Russia did not perform aerial surveillance at all since 1993, and only Poland increased this number from 131 h in 2006, to 406 in 2008 and 561 in 2009 [18]. Partially this can explain a significant change in the ratio of the morning/evening oil spills, but we hope that satellite monitoring of the Southeastern Baltic Sea contributed to this change as well, because by 2006 it had become well known in the public. As concerns a small reverse occurred in 2010 when 14 morning versus 16 evening oil spills were detected, this can be explained by the low oil spill number (statistics) which is characterized by more uncertainties.

4 Alternative Satellite Monitoring of the Southeastern Baltic Sea in 2009–2011

Independent satellite monitoring of the Southeastern Baltic Sea was performed in the period between February 2009 and April 2012 by a team headed by Dr. Olga Lavrova (Russian Space Research Institute, Russian Academy of Sciences). It was done in the framework of a scientific research, which was supported by ESA (projects C1P.6342, C1P.5004, AOBE 2775, and C1P.1027) in the form of regular delivery of radar satellite imagery from ERS-2 and ENVISAT satellites [20, 21]. Over 3 years (2009–2011) of observation in the area, which exactly corresponds to that we used in 2004–2005, 122 cases of sea surface oil pollution as a result of ship discharges were detected and plotted in Fig. 15. Year-to-year numbers of detected oil spills are 37, 47, and 38, correspondingly. Total polluted areas are 150, 160, and 74 km^2. The individual oil spill area varied from 0.1 to 105 km^2. Again, a strong seasonal variability in oil spill observations was found. Normally, oil spills are observed from March to October with a maximum in June to August, and month-to-month distribution of detected oil spills looks like a typical Gaussian distribution [20, 21].

These values significantly differ from those shown in Part 3, which can be explained by different regions of monitoring, different number and type of radar imagery, and different methodology of oil spill detection and calculation of the oil spill surface. For example, in the larger area (Fig. 15) in 2009 we have 37 oil spills (oil surface 150 km^2) in comparison with 44 spills (81.7 km^2) in a smaller area

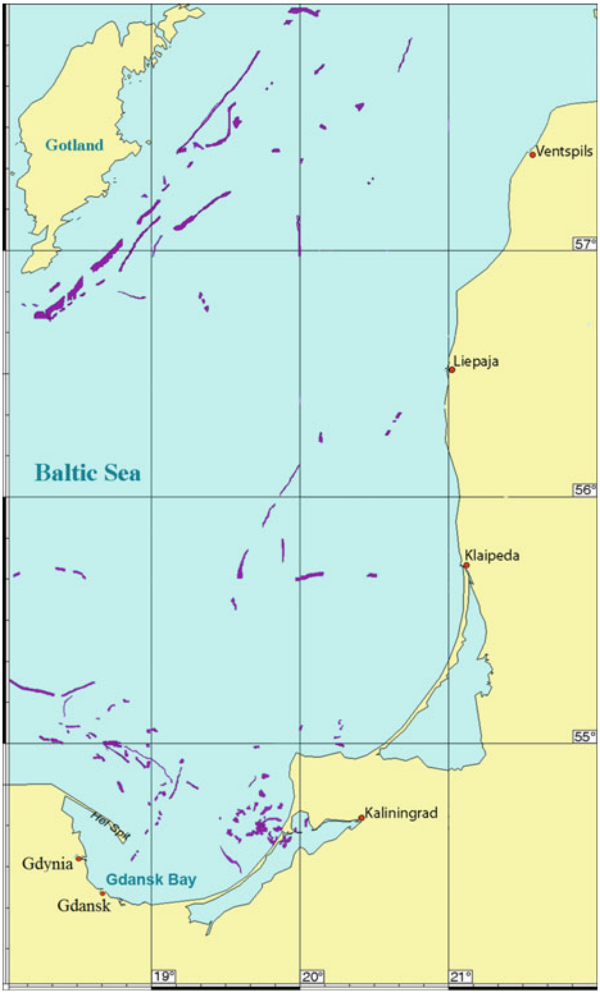


Fig. 15 Cumulative map of oil spills detected in the southeastern part of the Baltic Sea in 2009–2011

(Fig. 12), in 2010 – 47 (160 km^2) versus 30 (69 km^2), and in 2011 – 38 (74 km^2) versus 20 (71.3 km^2). Besides, the notable decreasing trend in the oil spill number was not confirmed by the results of satellite monitoring on the larger area. All these discrepancies show that there is significant difference between different monitoring systems, based more or less on the same set of radar imagery. This issue should be investigated in the framework of special comparative analysis.

Figure 15 shows the cumulative map of oil spills revealed from satellite radar data in the southeastern part of the Baltic Sea during the time period from January 2009 till December 2011 [20, 21]. It is possible to find out regions of most frequent discharges:

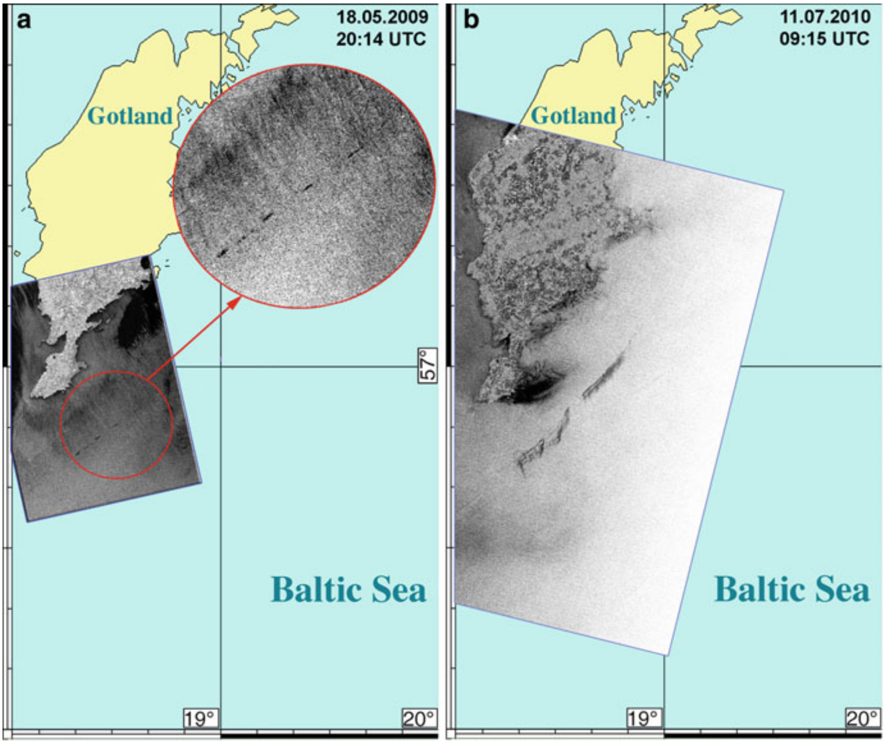


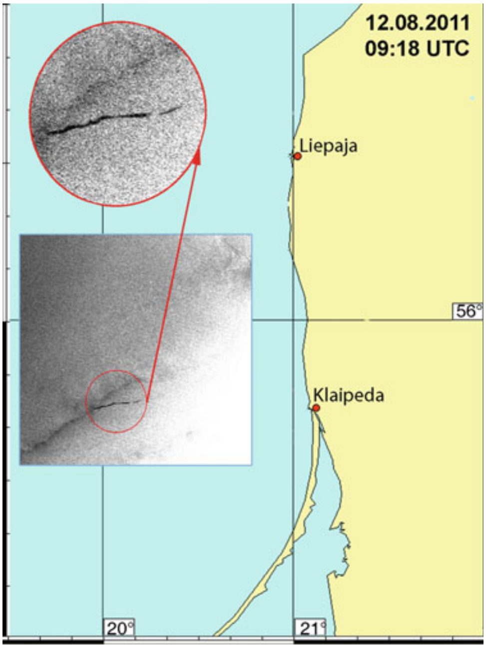
Fig. 16 Oil spills in the area eastward of Gotland Island as seen in satellite radar imagery: (**a**) ASAR Envisat, 18.05.2009, 20:14 UTC. Oil spills chain. Total length – 30 km, total surface – 5.1 km^2 (©ESA, 2009); (**b**) ASAR Envisat, 11.07.2010, 09:15 UTC. Weathered oil spills chain. Total length – 51 km, total surface –105 km^2 (©ESA, 2010)

1. The main shipping routes eastward of Gotland Island
2. Shipping routes to the ports of Kaliningrad, Klaipeda, and Liepaja
3. Area near the Hel Spit (Poland)
4. The part of the Gdansk Bay in the vicinity of the entrance to the gate of Kaliningrad Canal

Long-term satellite monitoring made it possible to reveal and analyze typical situations of sea surface pollution for each of these areas. We detected plenty of pollution events along the main shipping route eastward of Gotland Island. All these events are caused by spillages of oil-containing waters from moving ships. These spillages appear as straight dark (reduced signal) stripes in radar image following the ship route leading from southwest to northeast. Some ships continue dumping wastewaters for dozens of kilometers on their way. Quite often ships discharge wastewaters several times while they are moving.

Such examples are shown in Fig. 16. Figure 16a shows a well-defined dashed spill of nearly 30 km long which ends by a bright point indicating the position of a moving ship. The spillage was conducted shortly before the radar image acquisition and a film has just started to spread, the closer to the ship the narrower the spill,

Fig. 17 ASAR Envisat, 12.08.2011, 09:18 UTC. Oil spill from the moving vessel. Length – 12.5 km, surface – 6 km^2 (©ESA, 2011)



and one can observe a high radar contrast between the spill area and the clean sea surface. The example shown in Fig. 16b is characterized by wider film spreading under the influence of wind and waves and lower contrasts of the dashed spillage stretching for more than 50 km. The latter discharge took place several hours before a satellite pass over the sea and the responsible ship-polluter cannot be found. Apparently spillage was produced in several stages and the total polluted surface area had reached 105 km^2 by the moment of radar image acquisition [20, 21].

Wind has a great direct and indirect effect on the structure of a spill. Under the direct influence of the wind the film shifts over the sea surface, oil being accumulated on the leeward of the patch. Moreover, near-surface wind induces dynamic processes in the upper layer of the sea. The Langmuir circulation is the most common process which is caused by wind-driven spiral circulations of alternating directions with the axis almost parallel to the wind. Inside a vortex water moves in the plane perpendicular to the wind velocity vector. Thus on the sea surface alternating divergence and convergence zones appear, oil being concentrated in the latter. An oil spill transforms into streaks that are referred to as "comb-like structure." Such transformation of the spills left by a moving ship can be seen in Fig. 16b.

Film pollution events detected in the radar images acquired over the central part of the area of interest along the sipping routs leading to Klaipeda and Liepaja are characterized by lesser lengths and are less numerous. This may be due to the less intensive shipping traffic in this area. Many of the detected pollution events were weathered oil spills characterized by wider film spreading and lower radar backscattering contrasts. In Fig. 17 a weathered spill of 12.5 km long left

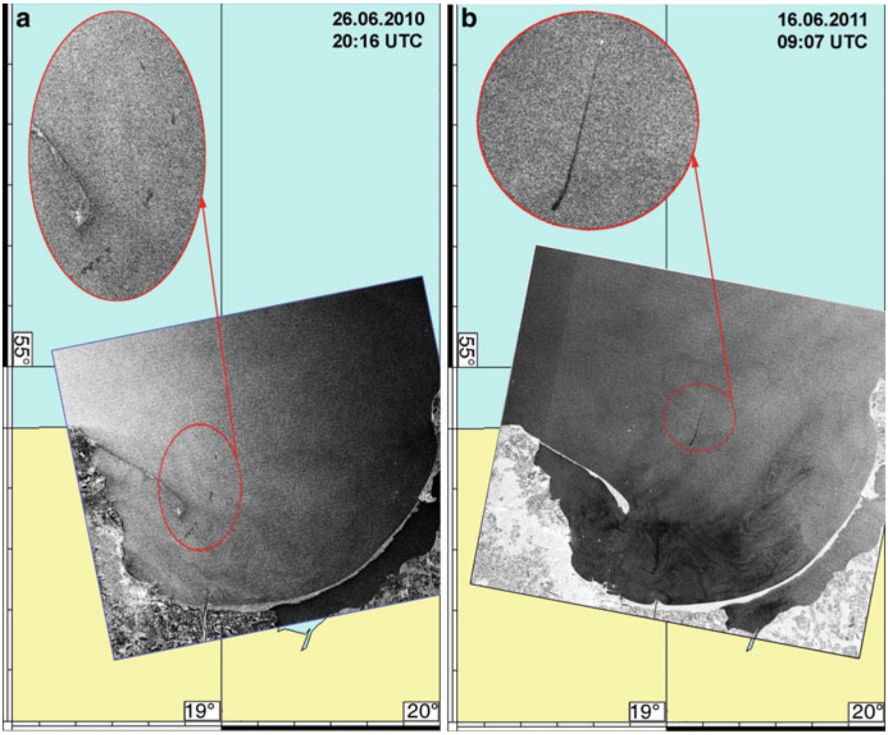


Fig. 18 Oil pollution in the Gdansk Bay: (**a**) ASAR Envisat, 26.06.2010, 20:16 UTC. Multiple spillages from a moving ship. Total length – 30 km, total surface – 6.8 km^2 (©ESA, 2010); (**b**) ASAR Envisat, 16.06.2011, 09:07 UTC. Fresh oil spill from a moving vessel. Length – 15.7 km (©ESA, 2011)

by a ship moving to or from the port of Klaipeda can be easily seen. The spill shape is distorted due to local currents and near-surface winds, and the narrowing of its most fresh part is not obvious. It is impossible also to explicitly identify a ship responsible for the spill.

Numerous spillages were detected northeastward of Hel Spit, Poland [20, 21]. Several of them have a form of enveloping curve duplicating the main sipping route leading from the port of Gdansk to western ports of the Baltic Sea and going round Hel Spit. An example of this kind of spillages is shown in Fig 18a. It depicts a multiple spillage spread under the influence of winds and waves. Other spillages in this area are stretched in the northeast direction along the route leading to the ports of the Eastern Baltic. An “ideal” example of how fresh a track of discharged wastes is depicted in a satellite image is given in Fig.18b. The ASAR Envisat image was acquired in the area of the Gdansk Bay under light wind and light sea surface disturbance. The dark stripe depicting the spillage becomes narrower to the northeast, which indicates that the ship-polluter moves in this direction. The bright white point in the northeastern end of the stripe shows the present location of the ship. The wastewater stripe extends for 15.7 km.

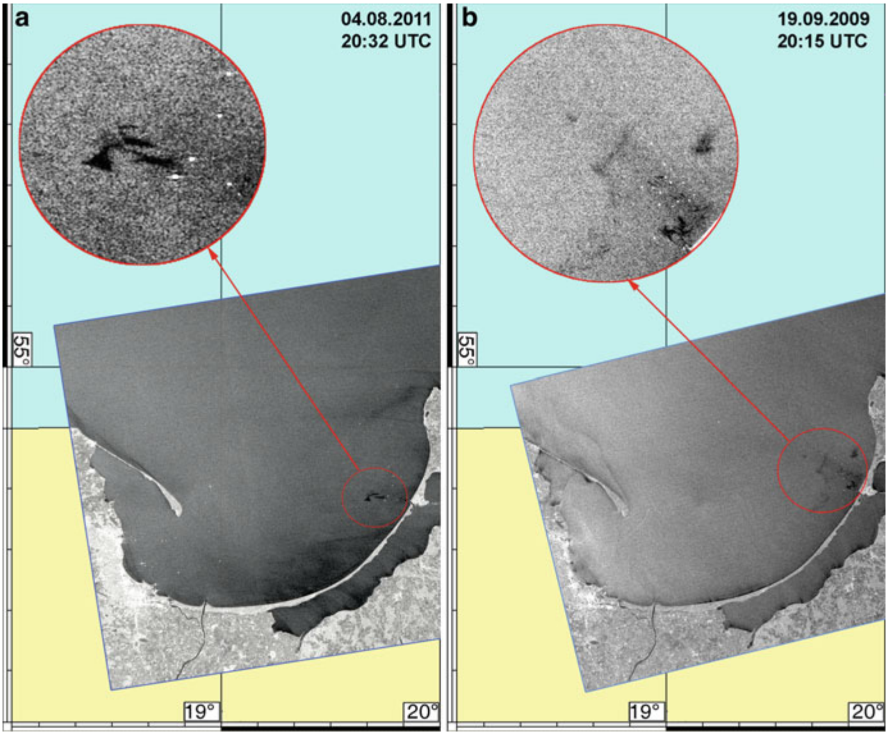


Fig. 19 Wastewaters discharged by ships in the anchorage site: (**a**) ASAR Envisat, 04.08.2011, 20:32 UTC. Total surface – 4.64 km^2 (©ESA, 2011); (**b**) ASAR Envisat, 19.09.2009, 20:15 UTC. Total surface – 31.4 km^2 (©ESA, 2009)

Pollution events detected in the Gdansk Bay near the entrance to the gate of Kaliningrad Canal are different from those described before. Water contamination in this area is mainly caused by wastewaters containing oil dumped from motionless ships in the anchorage site. The large number of spills having relatively small areas is detected in this area regularly, and an example of a typical situation in this area is shown in Fig. 19a. But sometimes oily films spread over the large area under the influence of near-surface winds, surface waves, and currents. This situation is shown in Fig. 19b, where the total polluted surface area is of 31.4 km^2 [20, 21]. Accumulative maps of oil spills for 2004–2005 (Fig. 11), 2004–2012 (Fig. 12), and 2009–2011 (Fig. 15) show that in any time period this area seems to be one of the most polluted in the Southeastern Baltic Sea.

5 Conclusions

Since 1993, regular aerial surveillance of oil spills in the Russian sector of the Southeastern Baltic Sea and in the Gulf of Finland has stopped. In June 2004, we organized daily operational service for monitoring of oil pollution in the Southeastern

Baltic Sea based on the operational receiving, processing, and analysis of ASAR ENVISAT and SAR RADARSAT-1 data as well as of other satellite IR, optical, scatterometer and altimetry data, meteorological and oceanographic information, and numerical modeling of currents required for identification of the slick nature in the sea and forecast of oil spill drift [1–8]. This work was initiated and financed by LUKOIL-Kaliningradmorneft in connection with the start of oil production from the continental shelf of Russia on the D-6 offshore platform in March 2004. Principal differences from the existing projects and satellite services were: (1) an operational monitoring regime of 24 h/day, 7 days/week for 18 months; and (2) a complex approach to oil spills detection and forecast of their drift.

In the absence of aerial and ship patrol surveillance, a satellite-based remote sensing system is capable of ensuring a relatively low-cost, high-standard observational system for oil pollution monitoring. SAR is the best instrument for detection of oil slicks on the sea surface from space because slicks modify seawater viscosity and damp short waves measured by SAR. Informative SAR images can be acquired regardless of the cloud cover and light conditions. Wide swath ($400 \times 400\ \text{km}^2$ for ASAR ENVISAT and $300 \times 300\ \text{km}^2$ for SAR RADARSAT) for simultaneous coverage is another main advantage of the satellite in comparison with aerial surveillance. However, oil spill detection by SAR has a problem of distinguishing oil slicks from look-alikes, such as sea areas covered by organic films, algal bloom, sea ice, wind shadows, rain cells, snow falls, and upwelling zones. Therefore, reliable automatic detection of oil spills on the basis of SAR data is not yet achieved and there is a risk of false alarms. This problem can be significantly reduced by a new approach, which consists in the combined use of all available quasi-concurrent satellite, oceanographic, and meteorological information, along with numerical modeling of oil spill transport.

Such an operational system was specially elaborated in the beginning of 2004 for monitoring oil pollution in the vicinity of the Lukoil D-6 oil platform in the Southeastern Baltic. Since 2006, the monitoring methodology was changed, but anyway satellite monitoring continues till present. Satellite monitoring of the oil field “Kravtsovskoye” (D-6) is currently the only operational tool to control oil pollution of the sea surface in the Russian EEZ, because in the framework of state environmental monitoring of the Baltic Sea satellite observations are not conducted. Over the entire period of satellite observations from 2004 to 2012 oil contamination of sea water resulted from the D-6 oil platform was not recorded. Areas of the most frequent detection of oil pollution are the major shipping routes in the Southeastern Baltic Sea directed to ports of Ventspils, Liepaja, Klaipeda, Kaliningrad, along Gotland Island, and anchoring points near the ports. Thus, the main sources of oil pollution in the sea are vessels of various types.

In the Southeastern Baltic Sea (including Russian EEZ), an area which is partially missing in the HELCOM statistics, we also observe a decreasing trend in the oil spills’ number and their total surface. On the fixed area of about 24,000 km^2, the yearly number of oil spills decreased from 114 in 2005–2006 to 20 in 2011 (with an unexpected rise in 2012 till 56). At the same time the total oil spill surface decreased from 225–372 km^2 in 2005–2006 till about 70 km^2 in 2010–2011 (with an unexpected rise in 2012 till 228 km^2).

A comparison of the number of detected oil spills in the morning and in the evening satellite images showed that the probability of finding oil pollution in the morning was about 40% higher than that in the afternoon and evening in 2006–2009 and 20% higher for the full 2004–2012 time period. In 2008 and 2009 this difference was as large as two to three times. This fact indicates that since 2006, illegal discharges of oil from vessels occur more often at night, when it is impossible for patrol aircrafts or ships to record the discharge by photo and video camera. This once again confirms the advantages of satellite radar imagery for monitoring of oil pollution.

Based on the number of oil spills detected in 2004–2005 (about 180 spills yearly on the area of about 60,000 km^2) and in 2006–2009 (about 80 spills yearly on 24,000 km^2), we can estimate the total number of oil spills for the Baltic Sea (377,000 km^2) as 1,100–1,300 yearly (we suppose that the spatial density of oil spills in the Baltic Sea is more or less the same as in its southeastern part) [8]. The minimum 20 oil spills that were observed in 2011 will give about 300 oil spills for the Baltic Sea. All these values may easily double and even triple if we take into account the following: (1) SAR satellites pass over a specific area in the Baltic Sea every 2 days in average; (2) significant reduction (three to four times) of oil spill observation in autumn and winter; (3) “lifetime” of an oil spill at the sea surface in the radar image in most cases is less than 12 h; and (4) spatial resolution of SAR/ASAR imagery is of 25–75 m/pixel [8].

Since 2004, we have elaborated several operational satellite monitoring systems for oil and gas companies in Russia and performed complex satellite monitoring of the ecological state of coastal waters in the Baltic, Black, Caspian, and Mediterranean Seas [6, 22]. The accident on the BP oil platform “Deepwater Horizon” on 20 April 2010 in the Gulf of Mexico showed that the absence of such a permanent complex satellite monitoring system makes all efforts related to cleaning operations at sea and on the shore during the first weeks after the accident less effective [6, 23]. Our experience in operational oil pollution monitoring in the Baltic Sea could be easily applied to the Caspian, Black, and Mediterranean Seas, other seas and regions of the world ocean.

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Seatrack Web: The HELCOM Tool for Oil Spill Prediction and Identification of Illegal Polluters

Cecilia Ambjörn, Olof Liungman, Johan Mattsson, and Bertil Håkansson

Abstract Seatrack Web is an online forecasting and hindcasting system for calculating the fate of oil spills at sea developed jointly by SMHI and DaMSA. The system uses forecasted wind and current fields to simulate the drift of particles representing oil or other substances in three dimensions. Seatrack Web has been implemented for several areas, one of which encompasses the HELCOM area (the Baltic Sea) and parts of the North Sea. HELCOM Seatrack Web is fully operational and available 24/7 for authorities and organizations that have been granted login access. The system is accessed via a Java client/server application with a GIS-based user-friendly graphical interface. A number of different oils are handled by the system, from gasoline to asphalt. The drift model includes state-of-the-art oil weathering algorithms for calculating evaporation and emulsification of these oils. The results of a drift simulation include particle tracks, changes in the oil properties and the overall fate of a spill.

Keywords Baltic Sea, Drift, Forecast, Java, Model, Oil spill, Online, Weathering

Contents

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1 Introduction

1.1 What Is Seatrack Web?

This chapter deals with Seatrack Web, an online forecasting system developed for predicting the movements of primarily oil spills at sea, but which can also be used for objects lost overboard from ships, algal blooms, dissolved substances, and various other substances or objects. It is an online tool that can not only be used in real-time forecasts during emergencies but also for investigations after the fact; so-called hindcasts. End users are typically authorities and organizations responsible for oil spill and pollution combating, marine forecasting, and marine environmental monitoring.

The system was originally developed in collaboration between the Swedish Meteorological and Hydrological Institute (SMHI) and the Danish Maritime Safety Administration (DaMSA) for use in the Baltic Sea and the eastern part of the North Sea, as the result of a HELCOM recommendation (see below). However, Seatrack Web has now been set up for several different locations on different scales, ranging from a small fjord on the Swedish west coast to the Black Sea. As a result, the continued development of the system and the underlying code is now carried out not only at SMHI and DaMSA but also at the Federal Maritime and Hydrographic Agency in Germany (BSH) and at the Marine Hydrophysical Institute in Ukraine (MHI), the latter on behalf of the Black Sea Commission within the framework of the MONINFO Project. In addition, the program code has also been supplemented with weathering algorithms developed and supplied by the Norwegian independent research organization SINTEF. However, as the focus of this book is the Baltic Sea, this chapter will describe the original Seatrack Web system implemented for the Baltic Sea and the eastern part of the North Sea – also referred to as HELCOM Seatrack Web – although the other operational systems are very similar.

The remaining parts of this section will deal with the history of Seatrack Web and the reasons for its existence. In Sect. 2, an overview of the three major parts of the Seatrack Web system is presented. Each part is then described in more detail in Sects. 3–5. This technical part of the chapter is followed by a section on the usage of and the results produced by Seatrack Web (Sect. 6). In Sect. 7, future developments and possibilities are discussed and the chapter ends with some general conclusions in Sect. 8.

1.2 Seatrack Web and HELCOM

Following the designation of the Baltic Sea area as a "special area" under the Annex I of the International Convention for the Prevention of Pollution from Ships (MARPOL 73/78), any discharge into the Baltic Sea of oil, or diluted mixtures containing oil in any form including crude oil, fuel oil, oil sludge, or refined products, is prohibited. This applies to oily water from the machinery compartments of any ship, as well as from ballast or cargo tanks in oil tankers. Despite the strict legal regime, almost 600 illegal discharges were observed in the Baltic Sea in the interval 2003–2004. The real number of discharges is considered to be even higher. Most of the observed illegal discharges are smaller than 1 m^3 but around 8% are larger, sometimes exceeding 100 m^3.

The illegally discharged oil has a number of negative effects including the killing of seabirds and the pollution of shores and beaches.

In a vast majority of cases of detected illegal discharges into the Baltic Sea, the polluters remain unknown. In 2006, out of the total number of 236 confirmed illegal discharges, the polluters were identified in only 18 cases. Therefore, strong enforcement of anti-pollution regulations within the HELCOM area is necessary and Seatrack Web can be an important tool in this respect.

Seatrack Web was developed following HELCOM Recommendation 12/6 of February 20, 1991, and is regarded as the common HELCOM modeling and drift forecasting system for oils and chemicals. At the HELCOM Response meeting of October 2002, it was recognized that the system at this time needed upgrading to meet the requirements of a new HELCOM recommendation (Recommendation 24/7) addressing further development and use of drift forecasting for oils and other harmful substances in the Baltic. In addition, various users of Seatrack Web had particular requests, such as to include more oils relevant for the Baltic Sea area, to add predictions of viscosity changes for use in clean-up operations, to model the interaction between oil and ice, extended GIS functionality, etc.

Together with further input given during meetings and workshops, as well as from the expert group developing the system, an extensive specification for a new version of Seatrack Web was established. An extensive upgrading of the system commenced in 2004 and resulted in a new version, Seatrack Web 2.0. Since then the system has been under continuous development and improvement, and this work is ongoing.

2 System Overview

The Seatrack Web system consists of three main parts:

1. Input data and forcing
2. The drift model
3. The client/server web application

The input data and forcing consists of two types of data: forecasts of meteorological and hydrodynamic conditions produced by forecast models, and other input data, such as maps, ship tracks from Automatic Identification System (AIS), satellite data, etc. The forecasts are necessary, whereas the other input data are not but greatly increase the usefulness of Seatrack Web. The forecasts are produced regularly as part of a separate operational forecasting process and made available to the drift model, i.e., they are already present when required and need not be produced on demand. The other input data are similarly delivered regularly and available at all times, or part of the system setup.

The drift model is the part of the system that computes the actual movement and fate of an oil spill, an object or another substance. It is executed on demand, i.e., when requested by a user for a specific case. It takes input from the user via the client/server web application, runs a simulation based on the meteorological and hydrodynamic forecasts for the period in question, and outputs results which are read and presented to the user by the client/server web application.

The client/server web application consists of the user interface (the client) and a server that handles requests from users, starts simulations using the drift model and makes the results available to the users. The client is in the form of a Java program that runs on the user's computer and which uses a GIS-based interface. The client and the server communicate via the internet.

The three parts of the system and the data flow is sketched in Fig. 1.

HELCOM Seatrack Web is currently in operational use both at DaMSA and SMHI, with separate but almost identical setups of the drift model and client/server web application.

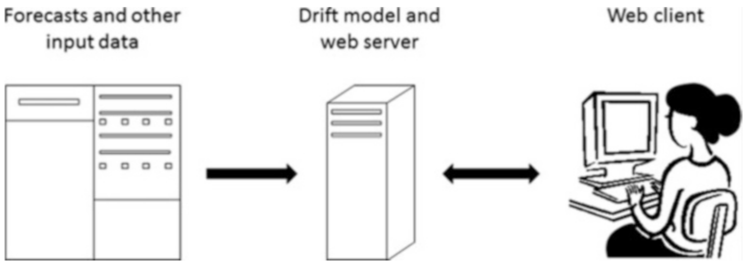


Fig. 1 An outline of the Seatrack Web system, showing the three main parts and the data flow

3 Input Data and Forcing

3.1 Meteorological and Hydrodynamic Forcing

The minimum forcing data required to perform a drift forecast is the three-dimensional current field for the forecast period. In HELCOM Seatrack Web, this is provided by the operational ocean forecast model HIROMB (High Resolution Operational Model for the Baltic Sea). This model covers the Baltic and North Seas, and comes in two versions: one with horizontal resolution three nautical miles covering both the Baltic and the North Seas, and one with horizontal resolution one nautical mile covering the Baltic Sea and its entrance areas (see Fig. 2). The model presently has 50 layers in the vertical with a maximum resolution of 4 m. HIROMB also includes an ice model and is run four times a day at SMHI, producing forecasts of current velocities, turbulence, sea levels, salinities, temperatures, and ice conditions.

The hydrodynamic model HIROMB is in turn forced by meteorological forecasts. Currently, two versions of HIROMB are run: one using meteorological forcing from the HIRLAM model (High Resolution Limited Area Model) run at SMHI and producing 48 h forecasts, and one using five day forecasts from ECMWF

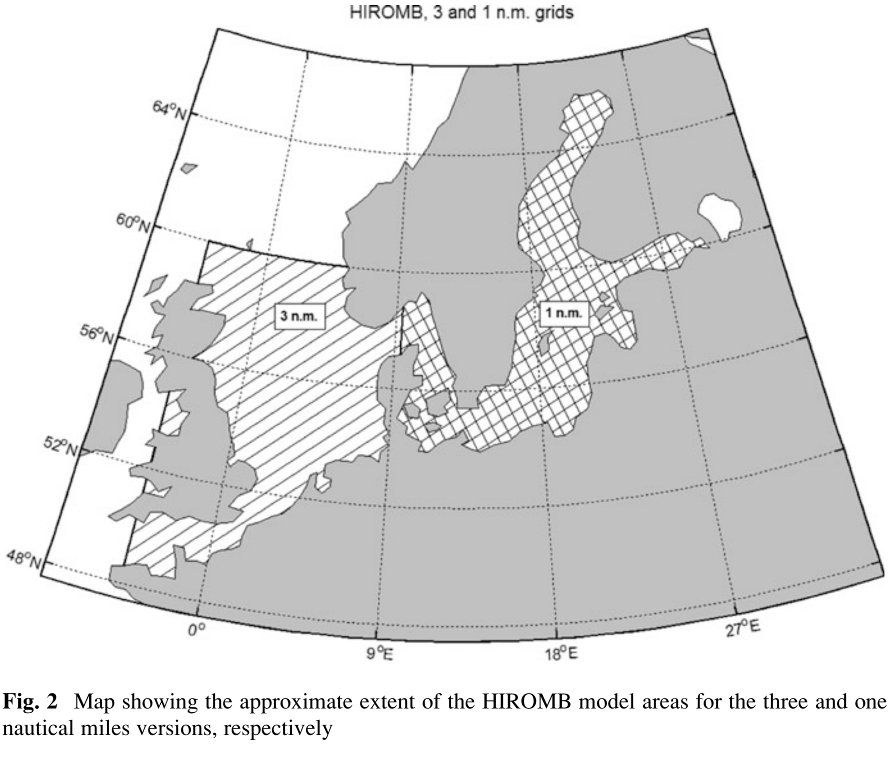


Fig. 2 Map showing the approximate extent of the HIROMB model areas for the three and one nautical miles versions, respectively

(European Centre for Medium-Range Weather Forecasts). Hence, HIROMB produces forecasts for both the coming 48 h and the coming five days. The short term forecast is available for both one and three nautical miles resolution, whereas the five day forecast is only available for three nautical miles resolution.

HELCOM Seatrack Web also uses the meteorological forecasts for the wind directly. The wind is used to calculate the near-surface profile of current velocities, which will be further described below. In addition, for objects that extend above the surface it is possible to add a wind drag by specifying what percentage of the wind velocity should be added to the drift velocity of the object.

The forcing input is automatically preprocessed as soon as a new forecast is available, producing binary files in the internal format of the Seatrack Web drift model for fast access. These files are stored for a limited time, such that forcing data is available as far back as approximately one month before the current date (this varies slightly depending on the version of the HIROMB model). Hence, calculations can be made within a time window stretching from about a month before the current date to at most five days into the future. Forcing input from earlier dates can be made available upon request.

The preprocessing also produces input files that are used by the client/server web application for presenting the surface current velocities, the wind velocities, and the ice concentration in the graphical user interface, as well as metadata regarding the availability of forcing data.

3.2 Other Input Data

There is obviously a great deal of other input data used in the Seatrack Web system. Necessary data are the bottom topography (HELCOM Seatrack Web currently uses the bathymetry of the HIROMB model) and a detailed coastline, but many other types of geo-referenced data, such as sensitive areas, potential polluters, reference points, etc., can easily be added to the user interface as it is based on a GIS-platform.

Here we will focus on two types of additional input data that show how the usefulness of the Seatrack Web system has been extended. They are ship tracks based on AIS data and detected oil spills extracted from satellite images.

3.2.1 AIS Data

Since Seatrack Web can be run backward in time, it is possible to backtrack and determine the origin of a detected oil spill. By integrating information from AIS, the results from a backtracking simulation can be superimposed on ship tracks, hence aiding in identifying the polluter.

The AIS data are continuously imported into Seatrack Web and can be displayed as ship tracks. Thus, the information on the whereabouts of vessels is available in real time. The AIS data are stored for one month, i.e., ship tracks can be viewed as far back as one month before the current date.

Incorporating AIS data into Seatrack Web has proved to be a very effective tool, substantially increasing the possibilities to identify ships suspected of illegally discharging oil into the sea. This feature is available to the relevant competent authorities in all HELCOM countries. Training on its use has been performed in Denmark, Estonia, Finland, Lithuania, Poland, Russia, and Sweden.

3.2.2 Satellite Data

Satellite data are currently not used directly in Seatrack Web but as part of a system for monitoring of algal blooms. From satellite images, algal blooms can be detected. Their extent is exported to a text file containing positions which can be loaded into Seatrack Web and plotted on the map. A forecast for the drift of the bloom can then be simulated using the imported positions as the initial positions of particles in Seatrack Web. Alternatively, the user can draw an area around the displayed positions and use this as the initial algal bloom location.

Functionality is being developed for directly importing information on oil spills detected using satellite imagery (see Sect. 7).

4 Drift Model

The Seatrack Web drift model is built around a Lagrangian particle tracking code called PADM (Particle Advection and Dispersion Model). This means that the substance whose drift and fate is being forecasted is represented as a cloud of particles. Hence, in the case of an oil spill, each particle will represent a part of the total mass and volume of the oil. Every particle is tracked individually in three dimensions. The processes affecting the fate of the particles can be divided into two categories:

1. Spreading, i.e., how the particles are moved by the surrounding flow field.
2. Weathering, i.e., changes in the particle properties due to substance-specific processes.

Spreading is not only the passive advection due to the currents but also includes random turbulent motions, vertical dispersion of oil caused by breaking waves, the initial gravity-induced radial spreading of oil slicks and vertical motion due to differences in buoyancy. Thus, the spreading processes are, in the case of oil, influenced by the weathering processes when these alter properties such as the density or viscosity of the oil.

Currently only oil weathering is included but in principle many other biochemical processes, such as the decay of a chemical, could be included.

4.1 Spreading

PADM assumes that the flow field is defined in a structured grid, i.e., a three-dimensional mesh of boxlike cells, each with six faces and eight vertices. The flow vectors are defined on the faces of the cells, whereas scalar properties such as salinity and temperature are defined in the cell centers. Assuming that the x-component of the velocity only varies in the *x*-direction, the *y*-component only in the *y*-direction, etc., it can be shown that the particle will follow a well-defined streamline, as long as the flow field does not change with time and the particle remains in the box [1,2]. This so-called passive advection can be modified by the following spreading processes:

1. Turbulent mixing
2. Stokes' drift
3. Horizontal gravity-induced surface spreading
4. Vertical dispersion by breaking waves
5. Buoyancy-induced vertical movements
6. Ice drift, wind drag, and boundary interaction

4.1.1 Turbulent Mixing

The turbulent mixing is calculated by adding a random turbulent velocity whose magnitude is determined by the turbulent intensity at the point where the particle is located. The turbulent intensity is defined by the turbulent kinetic energy and its dissipation rate, both of which are calculated by the HIROMB model as part of its turbulent closure scheme. The turbulent particle velocity is calculated from the turbulent intensity using a Markov chain model [1,3]. This means that the turbulent velocity is not completely random but depends on the value from previous times, i.e., the turbulent velocity has a "memory" in proportion to the time scale of the turbulent eddies in the flow field. For long time intervals, the correlation with previous values goes to zero. The model also takes into account gradients in the turbulent intensity.

Note that the turbulent mixing is only relevant for particles that are suspended or dissolved in the water column. It does not account for the more large-scale horizontal spreading of a cohesive oil slick at the surface. Horizontal surface spreading of an oil spill is initially after a discharge caused by gravity-induced spreading (see Sect. 4.1.3) but is later on dominated by small scale variations such as horizontal eddies, Langmuir circulation, wind gusts, etc. One process that is included in PADM is the combined effect of vertical dispersion (see Sect. 4.1.4) and a vertical current shear (see Sect. 4.1.2). The result is that buoyant oil droplets that are dispersed to different depths will experience different current velocities and thus resurface in different positions, producing a horizontal spreading.

4.1.2 Stokes' Drift

The Stokes' drift is an important mechanism contributing to the surface wind drift, i.e., the near-surface drift due to the wind. Depending on the wind speed and the wave spectrum, a straightforward calculation of the Stokes' drift yields a drift speed of somewhere between 1 and 2% of the 10 m wind speed. This should be compared to the popular rule-of-thumb which gives the total surface drift as 3% of the wind speed.

Stokes' drift is the net drift produced by the fact that the orbital motions caused by deep-water wind waves are not exactly closed, a result of the decrease of the orbital velocities with depth. This process is rarely modeled explicitly in hydrodynamic models, although it may be implicitly included in the bulk formulation of the surface boundary conditions. Furthermore, in large-scale hydrodynamic models it is not possible to resolve all the details near the surface, and thus some kind of parameterization of the near-surface velocity profile is necessary. At a solid boundary, the classic logarithmic law of the wall may be employed, but at the free surface this is unlikely to be appropriate [4]. Hence, in drift modeling it is common to simply use the rule-of-thumb mentioned above as an estimate of the surface drift velocities, sometimes with a modification of the direction to account for the difference between the wind direction and the surface current direction.

In PADM, however, the actual Stokes' drift is calculated as a function of depth from a two-dimensional wave energy spectrum, which is then added to the mean velocity in the surface layer predicted by the hydrodynamic model [1]. Ideally, the wave energy spectrum should be forecasted using a spectral wave model, but currently a parameterized Donelan–Banner spectrum is used [5]. This spectrum is calculated from the wind and the fetch in each point in the model. Finally the Stokes' drift is modified by the presence of ice, such that the drift velocity is set to zero for ice concentrations exceeding 70% and reduced linearly for lower ice concentrations.

4.1.3 Horizontal Gravity-Induced Surface Spreading

Horizontal gravity-induced surface spreading is only relevant for oil. It is basically the radial spreading that you would see if you poured oil on a table top. The oil will spread radially, fast at first and then slower and slower, until it reaches a terminal thickness determined by the oil's viscosity. Fay's classic formula [6] describes how the area of an oil slick increases with time. This formula has been rewritten in terms of the change in oil thickness [1]. To apply it to a cloud of particles, each particle is modeled as a disc whose thickness varies according to the rewritten version of Fay's formula. Factoring in changes in volume due to weathering or discharge of oil, the resulting radii of all discs can be calculated. The gravity-induced spreading of the particle cloud is then determined by ensuring that the discs do not overlap as they grow in size and become thinner.

4.1.4 Vertical Dispersion by Breaking Waves

Vertical dispersion is defined as the process of spreading substances from the surface into the water column. For dissolved or suspended substances, this is simply modeled using the small-scale turbulent mixing (see Sect. 4.1.1). Cohesive buoyant oil slicks, however, are unlikely to disperse this way. An oil slick needs to be broken up into droplets which then, if they are buoyant, must be forced down into the water column.

A suggested mechanism for this is the breaking of waves over an oil slick. Hence, in PADM we use the empirical expressions derived by Delvigne and Sweeney [7], which yield the mass of oil to be dispersed for a given time interval as a function of the droplet diameter, the breaking wave energy, the fraction of the surface covered by breaking waves, the oil slick area, and the time interval. The breaking wave energy and the fraction of the surface covered by breaking waves are estimated from the significant wave height and the wind speed, respectively. The significant wave height is in turn calculated from the wave spectrum. Once the total mass to disperse has been determined, particles are selected randomly and dispersed until the total mass to disperse has been reached. Each particle is assigned a droplet diameter from a predetermined range of size classes and then injected to a depth selected randomly from the range zero to the intrusion depth, a parameter proportional to the breaking wave height.

The mass to disperse is modified by a factor related to the ice concentration, such that for high ice concentrations no dispersion occurs since it is assumed that high ice concentrations will strongly dampen the wave field. Once an oil particle has dispersed, it is assumed to represent a cloud of droplets of equal diameter, which then will be advected, mixed, and rise (or sink).

4.1.5 Buoyancy-Induced Vertical Velocities

Particles that are lighter or heavier than the surrounding sea water may rise or sink. This buoyancy-induced vertical velocity can be calculated from the classical Stokes' formula, but this is only valid for small spherical droplets. For larger diameters, this formula will severely overestimate the vertical velocity. Hence, a two-regime formula developed primarily for oil is used [8] but with the coefficients modified according to a more complex three-regime model [1,9].

4.1.6 Ice Drift, Wind Drag, and Boundary Interaction

In the case of high ice concentrations (>0.7), the hydrodynamic flow field is modified in such a way that the surface current is replaced by the ice drift velocity. Thus, it is assumed that the oil will move with the ice.

For objects that extend above the surface, i.e., are not fully submerged, it is possible to add a drag due to the wind, by specifying a percentage of the wind velocity that will be added componentwise to the horizontal flow velocities.

Boundaries in PADM can be of different categories: the sea surface, the coastline, the bottom, and so-called open boundaries through which exchange with water bodies exterior to the model may occur. For each boundary category, a boundary action can be set. This determines what action should be taken when a particle's trajectory intersects a boundary. Three types of boundary actions are currently available in PADM: slip, halt, and deactivation.

- *Slip* means that a particle cannot pass through a boundary but may move tangentially along it.
- *Halt* means that the particle is held at the location where it hit the boundary and its position is no longer updated, unless it is released again. However, other processes such as weathering may continue to act on the particle.
- *Deactivate* means that the particle is deleted and no longer takes part in the calculations.

In the current implementation of HELCOM Seatrack Web, different boundary actions have been set depending on the type of substance represented by the particles. For oils, the slip action is used for the sea surface but for all other boundaries deactivation occurs. This means that oil that intercepts the coastline or the bottom is assumed to stick in place and not undergo any more weathering. For other substances, e.g., floating objects, algae, etc., the slip action is used for all boundaries except open boundaries, where instead deactivation occurs.

4.2 Weathering Model

When Seatrack Web is used to forecast oil drift each particle represents a quantity of oil with a common set of properties:

- Mass of oil
- Mass of water-in-oil
- Total mass and volume of oil and water-in-oil
- Density of oil
- Bulk viscosity

These properties are variables that change due to two different processes: evaporation and emulsification. Evaporation is only calculated for oil on the surface. If the total mass of a particle reaches zero, all the oil is assumed to have evaporated and the particle is deactivated. It is further assumed that dispersed oil droplets do not form a water-in-oil emulsion. Thus, if oil that has formed an emulsion is dispersed, all the water is immediately removed.

Different types of petroleum products can be simulated. These are broadly categorized as: oil classes, specific oils, and oil lumps.

Oil classes are used when the specific type of oil is not known. The three classes available today are light oils (viscosities less than 100 cSt), medium oils (viscosities in the range 100–1,000 cSt) and heavy oils (viscosity greater than 1,000 cSt). This is useful when simulating a spill where the exact oil product is unknown, but where observations may give some indication of the oil's viscosity. In practice, the class light oils is represented by light diesel fuel, the class medium oils by what is termed intermediate oil and the class heavy oils by Bunker C.

The specific oils available in HELCOM Seatrack Web are listed in Table 1. Depending on the oil being simulated different weathering models are used, as different empirical constants have been determined for different sets of petroleum products. In HELCOM Seatrack Web, there are two alternative weathering models: one based on a proprietary code supplied by SINTEF [10] and the original Seatrack Web model based on simple empirical formulae [11,12]. Which model is used for which oil is also shown in Table 1.

4.2.1 SINTEF Model

This model is based on tables of empirical data for relevant oil properties which show how these properties change in time. Interpolation into these tables gives the values at a given point in time, and these values are then used to determine the evaporation, emulsification, density, and viscosity.

To calculate the evaporation, empirical data on the evaporated fraction in percent f_e at different evaporation exposure times is used. The mass of oil M after a given time of exposure is then simply given by

$$M = \left(1 - \frac{f_\mathrm{e}}{100}\right) M_0. \tag{1}$$

Here, M_0 is the initial mass of fresh oil. The evaporation exposure time t_evap is, however, not only a function of time, but of several other factors as well. The increase in the exposure time is given by

$$\Delta t_\mathrm{evap} = \Delta t (1 - C_\mathrm{ice}) \frac{W}{W_\mathrm{ref}} \frac{h_\mathrm{ref}}{h} T_\mathrm{corr}. \tag{2}$$

W_ref and h_ref are reference values for the wind speed and oil thickness, respectively, for which the property tables have been generated. The temperature-dependent correction factor is given by

$$T_\mathrm{corr} = 2^{\frac{T - T_\mathrm{ref}}{8}}. \tag{3}$$

Table 1 Oils available in HELCOM Seatrack Web, including the weathering model used

Oil name	Weathering model
Gasoline	Original Seatrack Web
Jet fuel and kerosene	Original Seatrack Web
Light diesel fuel	Original Seatrack Web
Fuel oil No. 2	Original Seatrack Web
Light-medium crude	Original Seatrack Web
Lubricating oil	Original Seatrack Web
Intermediate oil	Original Seatrack Web
Bunker B	Original Seatrack Web
Heavy crude	Original Seatrack Web
Bunker C	Original Seatrack Web
Asphalt	Original Seatrack Web
Orimulsion	Original Seatrack Web (test)
High viscosity fuel oil	Original Seatrack Web (test)
Balder (IKU-96)	SINTEF
Ekofisk Blend 2000	SINTEF
Grane (SINTEF)	SINTEF
Gullfaks A-B	SINTEF
Gullfaks Soer (IKU)	SINTEF
Kristin_Corr	SINTEF
Norne (IKU)	SINTEF
Oseberg A (IKU)	SINTEF
Sleipner (IKU)	SINTEF
Statfjord A	SINTEF
Ula (IKU)	SINTEF
Valhall 2000	SINTEF
Aasgard 2002	SINTEF
Duc (IKU)	SINTEF
Siri	SINTEF
South Arne 5C	SINTEF
South Arne 13C	SINTEF
Fuel oil No. 6LS (IKU)	SINTEF
IF 180-LS Esso (SINTEF)	SINTEF
IF 180-NS Esso (SINTEF)	SINTEF
IF-180 Shell	SINTEF
IF-380 Heavy fuel oil	SINTEF
IF-30 Bunker (IKU)	SINTEF
Marine diesel (IKU)	SINTEF
IFO 380 Fu Shan Hai	SINTEF

Here, T is the sea surface temperature and T_{ref} a reference temperature for which the property tables have been generated. The maximum exposure time, i.e., when no more evaporation occurs and the oil is completely weathered, is set to 140 days.

To calculate the emulsification empirical data on the mass fraction in percent of water in a water-in-oil emulsion m_{w} for different emulsification exposure times is used. The mass of water in a water-in-oil emulsion M_{w} is then calculated as

$$M_{\mathrm{w}} = M \frac{m_{\mathrm{w}}}{100 - m_{\mathrm{w}}}. \tag{4}$$

The emulsification exposure time t_{emul} is again not only a function of the time but is also calculated using the following expression for the increase in exposure time:

$$\Delta t_{\mathrm{emul}} = \Delta t \frac{((1 - C_{\mathrm{ice}})W + 1)^2}{(W_{\mathrm{ref}} + 1)^2}. \tag{5}$$

The density of the oil ρ_{oil} is determined from tabulated empirical data for different evaporation exposure times (2). The particle density including water-in-oil emulsion ρ_{P} is calculated according to

$$\rho_{\mathrm{P}} = \frac{1}{\frac{(1 - m_{\mathrm{w}})}{\rho_{\mathrm{oil}}} + \frac{m_{\mathrm{w}}}{\rho}}, \tag{6}$$

where ρ is the density of seawater.

The oil viscosity in cP μ_{oil} is also determined from tabulated empirical data for different evaporation exposure times (2). The empirical data also contain values for the viscosity of a stable water-in-oil emulsion μ_{emul} in cP at different emulsification exposure times (5). First, the viscosity considering only evaporation is determined by interpolation into the table of empirical data on μ_{oil} and then adjusted for the actual sea water temperature T according to

$$\mu_{\mathrm{oil}}(T) = 10^{10^{\lambda}} \tag{7}$$

where

$$\lambda = -0.0045(T - T_{\mathrm{ref}}) + \log(\log(\mu_{\mathrm{oil}})). \tag{8}$$

Here, T_{ref} is the reference temperature for which the property tables have been generated. The particle viscosity including the effect of emulsification μ_{P} is then determined according to

$$\mu_{\mathrm{P}} = F_{\mathrm{emul}} \mu_{\mathrm{oil}}(T). \tag{9}$$

The ratio between the viscosities of water-in-oil emulsion and oil F_{emul} is determined by interpolating at the current emulsification exposure time into a new table, generated by dividing the empirical data on μ_{emul} by the data on μ_{oil}. The particle viscosity can be converted to kinematic particle viscosity (unit cSt) using

$$v_{\mathrm{P}} = \frac{\mu_{\mathrm{P}}}{0.001 \rho_{\mathrm{P}}}. \tag{10}$$

4.2.2 Original Seatrack Web Model

All oils are represented using a two-component model, i.e., they consist of a volatile and a nonvolatile component. The oil properties are defined in a database file and comprise the following set of parameters:

- Densities of the volatile and nonvolatile components
- Viscosity
- The maximum water fraction of emulsified oil
- The level of evaporation required for emulsification to begin
- An emulsification rate coefficient
- The fraction of the oil which is nonvolatile
- Two rate coefficients for evaporation
- Three coefficients for calculating the viscosity

The densities and the viscosity are approximate standard values for fresh oils at typical sea water temperatures. At the beginning of a simulation, oils are considered either fresh or completely weathered. In Table 2, the properties of the oils for which the original Seatrack Web weathering model is used are presented.

Evaporation is calculated based on simple expressions for the evaporation of the form [11,12]

$$f_e = (C_1 + C_2T)\ln\left(\frac{t}{60} + 1\right). \tag{11}$$

Here, f_e is the percentage fraction of the particle mass that has evaporated and C_1 and C_2 are coefficients. Values for the coefficient for different oils are presented in [12]. The last term is simply to avoid a singularity at $t = 0$.

Equation (11) is a solution to the ordinary differential equation

$$\frac{df_e}{dt} = \frac{(C_1 + C_2T)}{60}e^{\frac{-f_e}{(C_1+C_2T)}}. \tag{12}$$

Here, we will model the fractional evaporation rate $E = f_e/100$ as

$$\frac{dE}{dt} = C_e e^{-\frac{K}{C_e}E}. \tag{13}$$

The coefficients C_e and K have dimension $1/t$. The solution to (13) is

$$E = \frac{C_e}{K}\ln\left(e^{\frac{K}{C_e}E_0} + K(t - t_0)\right). \tag{14}$$

Here, $E_0 = E(t_0)$. We can identify the coefficients by equating (12) and (13), yielding

$$K = \frac{1}{60}$$

Table 2 Table showing the properties of the oils employing the original Seatrack Web weathering model. For definition of the symbols see the text. A hyphen (-) implies that the parameter is dimensionless

	ρ_n	ρ_v	ν_{ref}	$m_{w,\ max}$	E_{emul}	C_R	E_{max}	C_1	C_2	a	b	c
	(kg m^{-3})		(cSt)	-	-	(s m^{-2})	-	-	°C^{-1}	-	-	-
Gasoline	700	700	0.5	0	0	2×10^{-6}	1	13	0.045	0.3	2.5	0.65
Jet fuel and kerosene	850	790	2.5	0	0	2×10^{-6}	0.8	7	0.045	0.3	2.5	0.65
Light diesel fuel	900	805	2.4	0	0	2×10^{-6}	0.5	4	0.045	4.7	2.5	0.65
Fuel oil No. 2	900	805	10	0	0	2×10^{-6}	0.5	4	0.045	1	2.5	0.65
Light-medium crude	950	735	6.5	0.9	0.2	2×10^{-6}	0.4	3	0.045	16.2	2.5	0.65
Lubricating oil	900	830	150	0	0	2×10^{-6}	0.4	3	0.045	0.9	2.5	0.65
Intermediate oil	950	835	140	0	0	2×10^{-6}	0.4	3	0.045	8.6	2.5	0.65
Bunker B	950	650	555	0	0	2×10^{-6}	0.12	0.2	0.045	14.6	2.5	0.65
Heavy crude	1,000	950	5,050	0.4	0.1	2×10^{-6}	0.2	1	0.045	9.2	2.5	0.65
Bunker C	1,000	855	4,740	0.26	0.03	2×10^{-6}	0.12	0.2	0.045	16.4	2.5	0.65
Asphalt	1,000	1,000	3,280	0	0	2×10^{-6}	0.1	0.05	0.045	23.8	2.5	0.65
Orimulsion (test)	1,020	1,020	25,000	0	0	0	0	0	0	0	0	0
High viscosity fuel oil (test)	1,015	1,015	13,500	0	0	0	0	0	0	0	0	0

and

$$C_e = \frac{K}{100}(C_1 + C_2 T).$$

We can thus calculate E at time t as a function of temperature and the value at time t_0. To account for the presence of ice, the right hand side of (13) is multiplied by a correction factor, r_{ice}. This yields

$$E = \frac{C_e}{K} \ln\left(e^{\frac{K}{C_e}E_0} + K r_{\text{ice}}(t - t_0)\right). \tag{15}$$

The remaining oil mass is then calculated according to

$$M = M_0(E_{\max} - E) + M_n. \tag{16}$$

Here, $E_{\max}$ is the maximum fraction that can evaporate, i.e., the volatile fraction in fresh oil, and M_n is the constant mass of the nonvolatile component. The ice correction factor is given by

$$r_{\text{ice}} = \begin{cases} 0 & C_{\text{ice}} \geq 0.8 \\ \dfrac{0.8 - C_{\text{ice}}}{0.5} & 0.3 \leq C_{\text{ice}} < 0.8 \\ 1 & C_{\text{ice}} < 0.3 \end{cases}. \tag{17}$$

The mass fraction of water in a water-in-oil emulsion, m_w, is defined by

$$m_w = \min\left(m_{w,\max}, \frac{M_w}{M_w + M}\right). \tag{18}$$

Here, $m_{w,\max}$ is an oil-specific maximum water fraction for water-in-oil emulsion and M_w is the mass of water in the water-in-oil emulsion. The rate of change of m_w is [6]

$$\frac{\mathrm{d}m_w}{\mathrm{d}t} = R\left(m_{w,\max} - m_w\right). \tag{19}$$

The rate at which the oil forms an emulsion, R, is related to the wind speed W, as the process requires agitation of oil and water. However, emulsion only takes place if a sufficient fraction, E_{emul}, of the volatile components has evaporated. Thus, the emulsion rate R is modeled by

$$R = \begin{cases} 0 & E < E_{\text{emul}} \\ r_{\text{ice}} C_R W^2 & E \geq E_{\text{emul}} \end{cases}. \tag{20}$$

Here, r_{ice} is the same reduction factor as for evaporation (17) to account for the presence of ice and C_R is an oil-specific constant coefficient. Integrating (19) yields the following expression for the water fraction:

$$m_{\mathrm{w}}(t+\Delta t) = m_{\mathrm{w,max}} - e^{-R\Delta t}\big(m_{\mathrm{w,max}} - m_{\mathrm{w}}(t)\big). \tag{21}$$

For a two-component model, the oil density is simply

$$\rho_{\mathrm{oil}} = \frac{1}{m_{\mathrm{n}}/\rho_{\mathrm{n}} + m_{\mathrm{v}}/\rho_{\mathrm{v}}}. \tag{22}$$

Here, m_{n} and m_{v} are the mass fractions and ρ_{n} and ρ_{v} are the densities of the nonvolatile and volatile oil components. The particle density ρ_{P} including the effect of emulsification is calculated using (6).

The particle viscosity in cSt, including the effect of emulsification, is determined from the amount of the volatile fraction that has evaporated (E) and the degree of emulsification (fraction of water-in-oil) according to

$$v_{\mathrm{P}} = v_{\mathrm{ref}} e^{aE} e^{\frac{bm_{\mathrm{w}}}{1-cm_{\mathrm{w}}}}. \tag{23}$$

Here, v_{ref} is the reference oil viscosity (cSt) given in the oil properties database file whereas a, b and c are constant coefficients specific for each oil [6].

5 Client/Server Java Application

Seatrack Web is an online system accessible via the Internet using a client/server Java application. This allows users, after logging in to the system via a web page, to start an oil drift simulation and present the results on their own computers, even though the actual simulations are executed on a remote server. The technical architecture consists of three main components: (1) a database containing users, usage statistics, configuration data, and news for the Seatrack Web start page, (2) a server consisting of a Java Servlet that communicates with the drift model and the database, and (3) the Java client that runs the graphical user interface (GUI) on the user's computer.

When the user starts a calculation in Seatrack Web, the client establishes a connection to the server, which starts the drift model. After a drift calculation is completed, the model results are transferred back to the client where they can be visualized in various ways in the GUI.

5.1 Java Client and Graphical User Interface

The GUI employs the Java Web Start technology. The Java client application including background maps is automatically downloaded and installed on the user's hard drive. When the user clicks the start link on the Seatrack Web home page, the version of the Java client is checked against the server version and an update is downloaded if necessary. Otherwise, the cached version of the client is executed. This design saves download time and administration of the client installations.

To create the GIS-based GUI which can display maps and other relevant geographic information, an open source Java library for map applications called OpenMap™ (BBN Technologies) is used. The resulting GUI is thus very similar to other GIS software, with a map and standard functionalities such as zooming, panning, etc. In addition, specific tools and menus have been implemented to allow the user to define an oil spill, set up the simulation parameters, and display the results in various ways (see Sect. 6.2).

An important advantage of this so-called rich client technology is that demanding visualizations such as animations are performed noticeably faster than if the GUI would have been implemented in a web browser. Since the GUI runs on the user's computer, every input and every change in the visualizations need not be transmitted over the internet but are handled locally once the result files have been downloaded. Of course, the transfer time is dependent on the speed of the user's internet connection.

5.2 Java Servlet

At the server end, Java Servlet technology is used. The server handles authentication of the user, communication with the client application, and execution of the drift model. When the user requests a simulation, the server performs a number of tasks:

- Receiving the simulation settings from the client application
- Preparing the settings file for the drift model
- Setting up the execution environment for the drift model
- Executing the drift model
- Responding to client requests for status updates
- Transmitting the results to the client
- Handling and transmitting additional data upon request. This includes AIS and possibly satellite data as well as forcing data (surface currents, wind, and ice concentration) and the availability of forcing data which have been prepared during the preprocessing stage (see Sect. 3.1).

The system naturally must be available 24/7 with minimal downtime. Hence, the Java Servlet as well as the preprocessing scripts and software have been operationalized as a critical system, including automatic monitoring, rapid intervention upon a critical failure, and a separate backup system.

The present technology is not very scalable, running on a single multicore machine. However, some tens of concurrent users can still be accommodated. The primary issue is the number of simulations being executed simultaneously. However, the scalability will be improved in the near future (see Sect. 7).

6 Usage and Results

In this section, we will briefly present the output of the drift modeling as well as a user's view of the system, including important features and functionalities in the GUI. We will also present a validation using data in the form of airborne SLAR images of an actual oil spill.

6.1 Model Output

The fundamental outputs of a simulation are the tracks of the individual particles. The three-dimensional position of each particle is currently stored every 15 min. In addition, the trajectory of the center position of the particle cloud, calculated as the mean position of all the active particles, is output as well. These results are visualized in the map.

In the result table (see Fig. 6), some overall properties of the particle cloud are presented as functions of time. These include the center position, the speed (in knots) and direction of the current at the center position, and the speed (in m/s) and direction of the wind at the center position.

In the case of oil, a number of overall properties for the entire spill are also calculated and presented in the result table. These are based on the physical and chemical properties of each particle computed by drift model and include the following parameters:

- The total volume of the spill (m^3)
- The mean viscosity (cSt; weighted by mass)
- The mean density (kg/m^3; weighted by mass)
- The fraction of the initial mass of oil (%) that has evaporated
- The fraction of the initial mass of oil (%) and the volume (m^3) that is on the surface
- The fraction of the initial mass of oil (%) and the volume (m^3) that is dispersed into the water column
- The fraction of the initial mass of oil (%) and the volume (m^3) that is on the sea bed

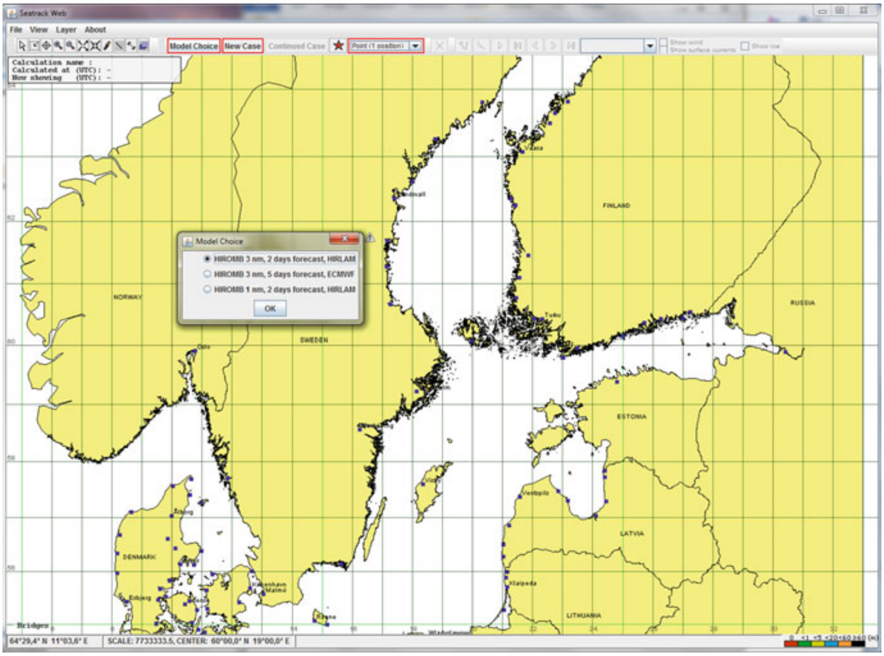
- The fraction of the initial mass of oil (%) and the volume (m^3) that is on the shoreline
- The overall relative water content (%)

The sum of the different fractions of the initial mass of oil is 100%.

6.2 *Using Seatrack Web*

When a user logs into Seatrack Web, the first thing that happens is that the GUI is adapted for that particular user, meaning that certain features may be activated or deactivated depending on the needs and rights of the privileges of the user in question. An example of this is the AIS ship tracks feature described earlier (see Sect. 3.2).

The first thing to be done is to define the location of the oil spill, either as a point, a line, or a three- or four-sided polygon. This is done by simply clicking in the map, but can also be input manually as positions. Next, a choice can be made between which hydrodynamic forecast should be used: a two-day forecast based on meteorological forcing from the HIRLAM model using either the one or three nautical miles HIROMB models, or a five-day forecast based on meteorological



Calculation name :
Calculated at (UTC): -
Now showing (UTC): -

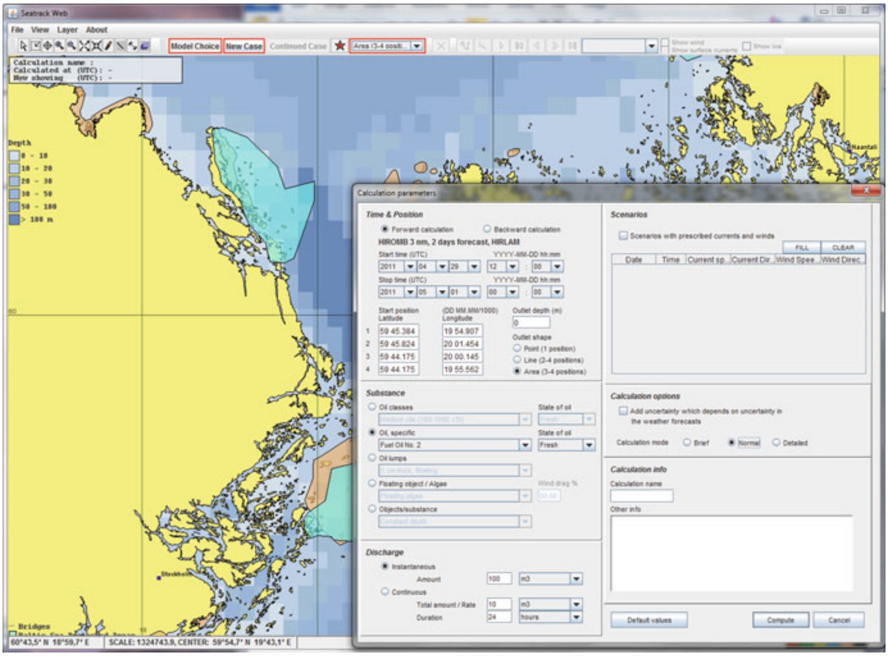
Model Choice

● HIROMB 3 nm, 2 days forecast, HIRLAM
○ HIROMB 3 nm, 5 days forecast, ECMWF
○ HIROMB 1 nm, 2 days forecast, HIRLAM

OK

64°29,4' N 11°03,6' E
SCALE: 7733333.5, CENTER: 60°00,0' N 19°00,0' E

Fig. 3 The GUI of HELCOM Seatrack Web showing the Model Choice dialogue box and the full extent of the model area



Calculation parameters

Time & Position

● Forward calculation ○ Backward calculation

HIROMB 3 nm, 2 days forecast, HIRLAM

Start time (UTC) YYYY-MM-DD hh:mm: 2011 04 29 12 : 00

Stop time (UTC) YYYY-MM-DD hh:mm: 2011 05 01 00 : 00

	Start position Latitude	(DD MM.MM/1000) Longitude
1	59 45.384	19 54.907
2	59 45.824	20 01.454
3	59 44.175	20 00.145
4	59 44.175	19 55.562

Outlet depth (m): 0

Outlet shape: ○ Point (1 position) ○ Line (2-4 positions) ● Area (3-4 positions)

Substance

○ Oil classes

● Oil, specific: Fuel Oil No. 2; State of oil: Fresh

○ Oil lumps

○ Floating object / Algae

○ Objects/substance

Discharge

● Instantaneous: Amount 100 m3

○ Continuous: Total amount / Rate 10 m3; Duration 24 hours

Scenarios

☐ Scenarios with prescribed currents and winds

Date	Time	Current sp.	Current Dir.	Wind Spee...	Wind Direc.

Calculation options

☐ Add uncertainty which depends on uncertainty in the weather forecasts

Calculation mode ○ Brief ● Normal ○ Detailed

Calculation info

Calculation name

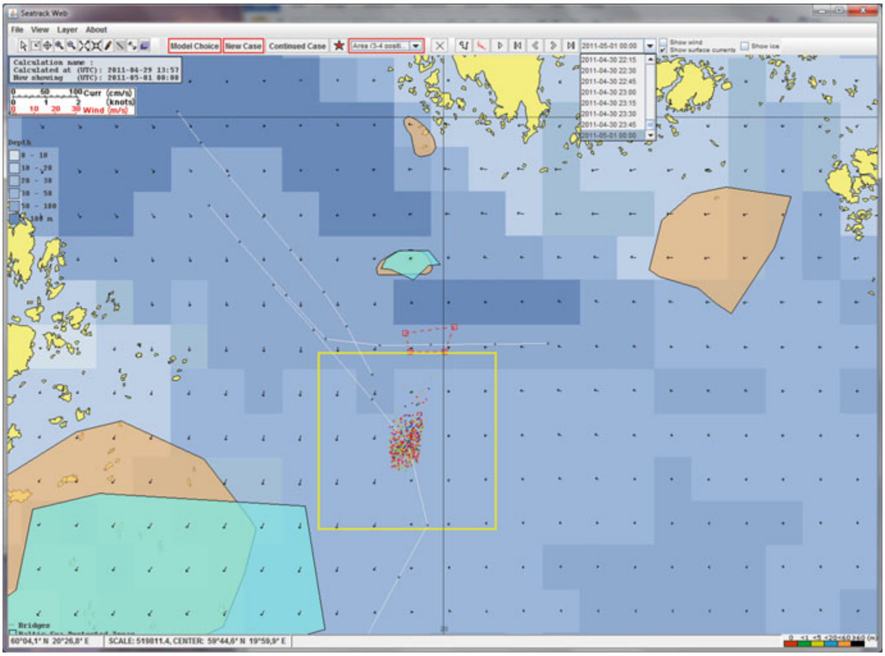
Other info

Fig. 4 The GUI of HELCOM Seatrack Web showing the Calculation Parameters input window. In the map layers showing the bathymetry of the 3 nautical miles model, Baltic Sea protected areas and important bird areas have been activated

forcing from ECMWF and the three nautical miles HIROMB model. This is shown in Fig. 3. After completing this stage, a new case is defined by reviewing the default simulation input parameters and modifying them where appropriate. The user can select a forward or a backward calculation, modify the time period and the discharge position, select a substance, and define the type of discharge and the amount discharged. In addition, it is possible to create simple user-defined scenarios where the wind and current are not read from the meteorological and hydrodynamic forecasts but prescribed in advance. Finally, the user may choose the *Calculation Mode* (in effect, the number of particles to be used), add an uncertainty factor, and enter information describing the simulation (see Fig. 4).

Once the user has pressed *Compute*, the model simulation starts on a remote server and the progress is shown on the screen. As soon as the simulation has been completed, the results are downloaded and the final particle positions displayed in the map. It is now possible to visualize the model results in several different ways. These include animating the particle drift, plotting the trajectory of the center of the particle cloud, as well as plotting the trace of the particles, i.e., the particle positions at all times (equivalent to the impacted area). The color of each particle indicates its depth (see Fig. 5).

Many other types of information can be added to the map. Firstly, the wind and surface current vectors can be plotted and animated, as well as the ice cover.



Calculation name :
Calculated at (UTC): 2011-04-29 13:57
Now showing (UTC): 2011-05-01 00:00

2011-05-01 00:00
2011-04-30 22:15
2011-04-30 22:30
2011-04-30 22:45
2011-04-30 23:00
2011-04-30 23:15
2011-04-30 23:30
2011-04-30 23:45
2011-05-01 00:00

60°04,1' N 20°26,8' E
SCALE: 519811.4, CENTER: 59°44,6' N 19°59,9' E

Fig. 5 The GUI of HELCOM Seatrack Web showing the results of a simulation. The *colored points* represent the oil (*color* indicating depth of each particle) and the *red quadrilateral* is the initial spill area. In the map are also shown surface current vectors and a few ship tracks from AIS data. The drop-down menu at the top can be used to select the time step to view

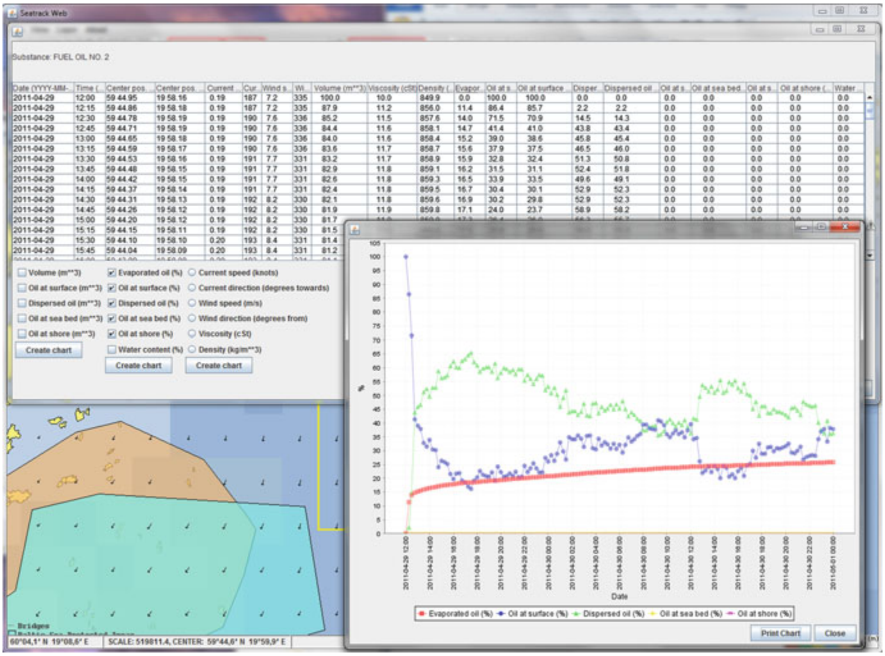
A number of predefined GIS layers can be turned on and off, including the depths in the hydrodynamic model, the coastline of the hydrodynamic model, protected areas, important bird areas, major ship routes, borders, etc. Of course AIS data may be shown and text can be added to the map and edited.

The results of the drift simulation can also be viewed as a table, by selecting *Results table* under the *View* menu. This shows the properties of the particle cloud as a function of time and also allows for the generation of xy-plots of the different properties (see Fig. 6).

Finally, the user may save the simulated case locally to be opened again later and may choose to perform a so-called *Continued Case*, meaning that the current results are used as the start conditions for a new simulation. In this case, it is also possible to shift the entire particle cloud by modifying the center position of the cloud.

6.3 Examples of Results

Around noon on Saturday 31 May 2003, MV Fu Shan Hai, fully laden with a cargo of 66,000 metric ton of fertilizer loaded in Ventspils, Latvia was struck by a



Substance: FUEL OIL NO. 2

Date (YYYY-MM-...	Time (...	Center pos. ...	Center pos. ...	Current ...	Cur...	Wind s...	Wi...	Volume (m**3)	Viscosity (cSt)	Density (...	Evapor...	Oil at s...	Oil at surface ...	Disper...	Dispersed oil ...	Oil at s...	Oil at sea bed ...	Oil at s...	Oil at shore (...	Water ...
2011-04-29	12:00	59 44.95	19 58.16	0.19	187	7.2	335	100.0	10.0	849.9	0.0	100.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2011-04-29	12:15	59 44.86	19 58.18	0.19	187	7.2	335	87.9	11.2	856.0	11.4	86.4	85.7	2.2	2.2	0.0	0.0	0.0	0.0	0.0
2011-04-29	12:30	59 44.78	19 58.19	0.19	190	7.6	336	85.2	11.5	857.6	14.0	71.5	70.9	14.5	14.3	0.0	0.0	0.0	0.0	0.0
2011-04-29	12:45	59 44.71	19 58.19	0.19	190	7.6	336	84.4	11.6	858.1	14.7	41.4	41.0	43.8	43.4	0.0	0.0	0.0	0.0	0.0
2011-04-29	13:00	59 44.65	19 58.18	0.19	190	7.6	336	84.0	11.6	858.4	15.2	39.0	38.6	45.8	45.4	0.0	0.0	0.0	0.0	0.0
2011-04-29	13:15	59 44.59	19 58.17	0.19	190	7.6	336	83.6	11.7	858.7	15.6	37.9	37.5	46.5	46.0	0.0	0.0	0.0	0.0	0.0
2011-04-29	13:30	59 44.53	19 58.16	0.19	191	7.7	331	83.2	11.7	858.9	15.9	32.8	32.4	51.3	50.8	0.0	0.0	0.0	0.0	0.0
2011-04-29	13:45	59 44.48	19 58.15	0.19	191	7.7	331	82.9	11.8	859.1	16.2	31.5	31.1	52.4	51.8	0.0	0.0	0.0	0.0	0.0
2011-04-29	14:00	59 44.42	19 58.15	0.19	191	7.7	331	82.6	11.8	859.3	16.5	33.9	33.5	49.6	49.1	0.0	0.0	0.0	0.0	0.0
2011-04-29	14:15	59 44.37	19 58.14	0.19	191	7.7	331	82.4	11.8	859.5	16.7	30.4	30.1	52.9	52.3	0.0	0.0	0.0	0.0	0.0
2011-04-29	14:30	59 44.31	19 58.13	0.19	192	8.2	330	82.1	11.8	859.6	16.9	30.2	29.8	52.9	52.3	0.0	0.0	0.0	0.0	0.0
2011-04-29	14:45	59 44.26	19 58.12	0.19	192	8.2	330	81.9	11.9	859.8	17.1	24.0	23.7	58.9	58.2	0.0	0.0	0.0	0.0	0.0
2011-04-29	15:00	59 44.20	19 58.12	0.19	192	8.2	330	81.7												
2011-04-29	15:15	59 44.15	19 58.11	0.19	192	8.2	330	81.5												
2011-04-29	15:30	59 44.10	19 58.10	0.20	193	8.4	331	81.4												
2011-04-29	15:45	59 44.04	19 58.09	0.20	193	8.4	331	81.2												

Fig. 6 The GUI of HELCOM Seatrack Web showing the Results Table window and a plot chart

container ship, MV Gdynia, at a location north of Bornholm. Fu Shan Hai soon began to sink and the crew was evacuated within two hours. At 18:50 UTC, Fu Shan Hai sank at 55° 20.7′ N, 14° 45.7′ E to a depth of approximately 65 meters. Fu Shan Hai carried approximately 1,700 m^3 of fuel oil, which began to leak into the sea during the night and continued to leak for several days afterward.

The HELCOM Seatrack Web system was used to forecast the drift of the oil spill from Fu Shan Hai. After the spill event, a few SLAR images taken from aircraft during the spill were made available. These have been interpreted, plotted in a map, and compared to the results of the Seatrack Web forecasts. Please note that this was an earlier version of HELCOM Seatrack Web with only a three nautical mile resolution.

In Fig. 7, the observed oil spill and the forecast are shown at around 04:00 UTC on 3 June. The agreement is clearly quite satisfactory. The modeled spill has reached approximately the same distance from the shoreline as the observed spill, the overall trajectories agree and the model also replicates the wider east front of the observed spill.

A comparison between the observed and forecasted oil spill on 3 June at around 12:00 UTC are presented in Fig. 8. Again, the agreement is quite satisfactory, both regarding timing and the shape of the spill. Hence, Seatrack Web managed to forecast fairly accurately when and where the oil spill reached the shoreline.

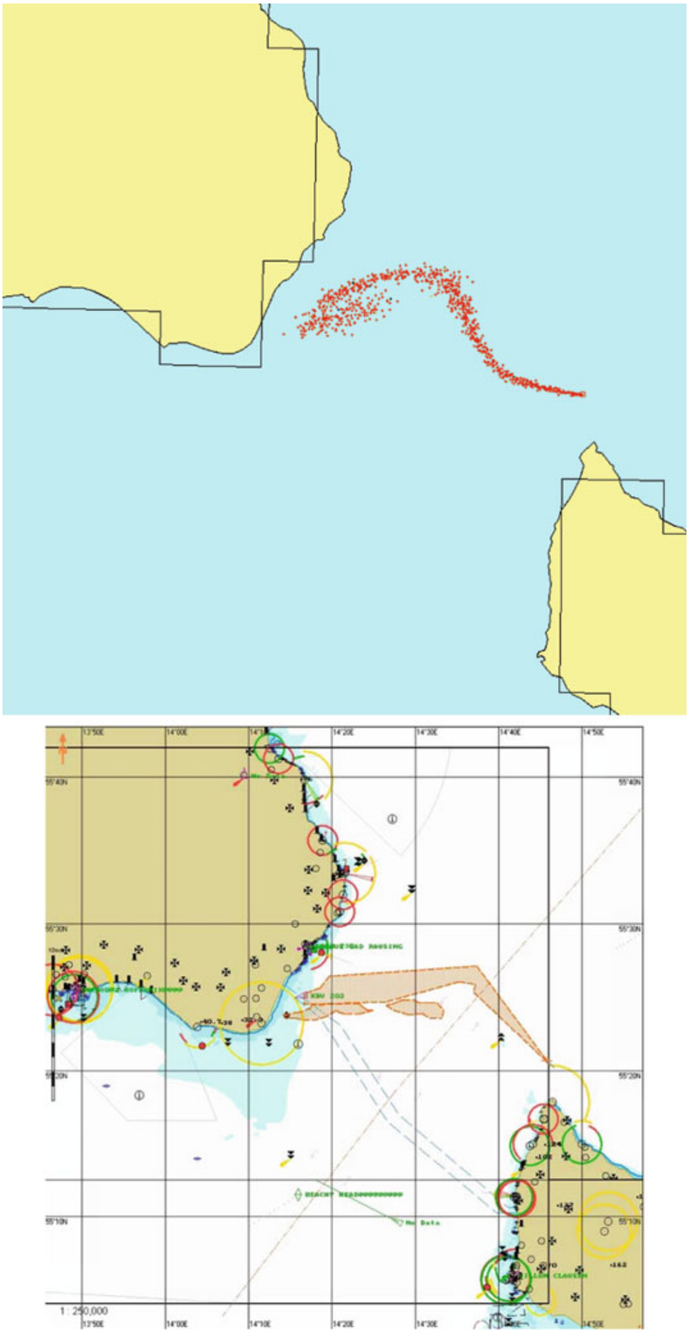


Fig. 7 The Fu Shan Hai spill as forecasted by Seatrack Web (*upper panel*) and observed via airborne SLAR images (*lower panel*) on 3 June 2003 at around 04:00 UTC

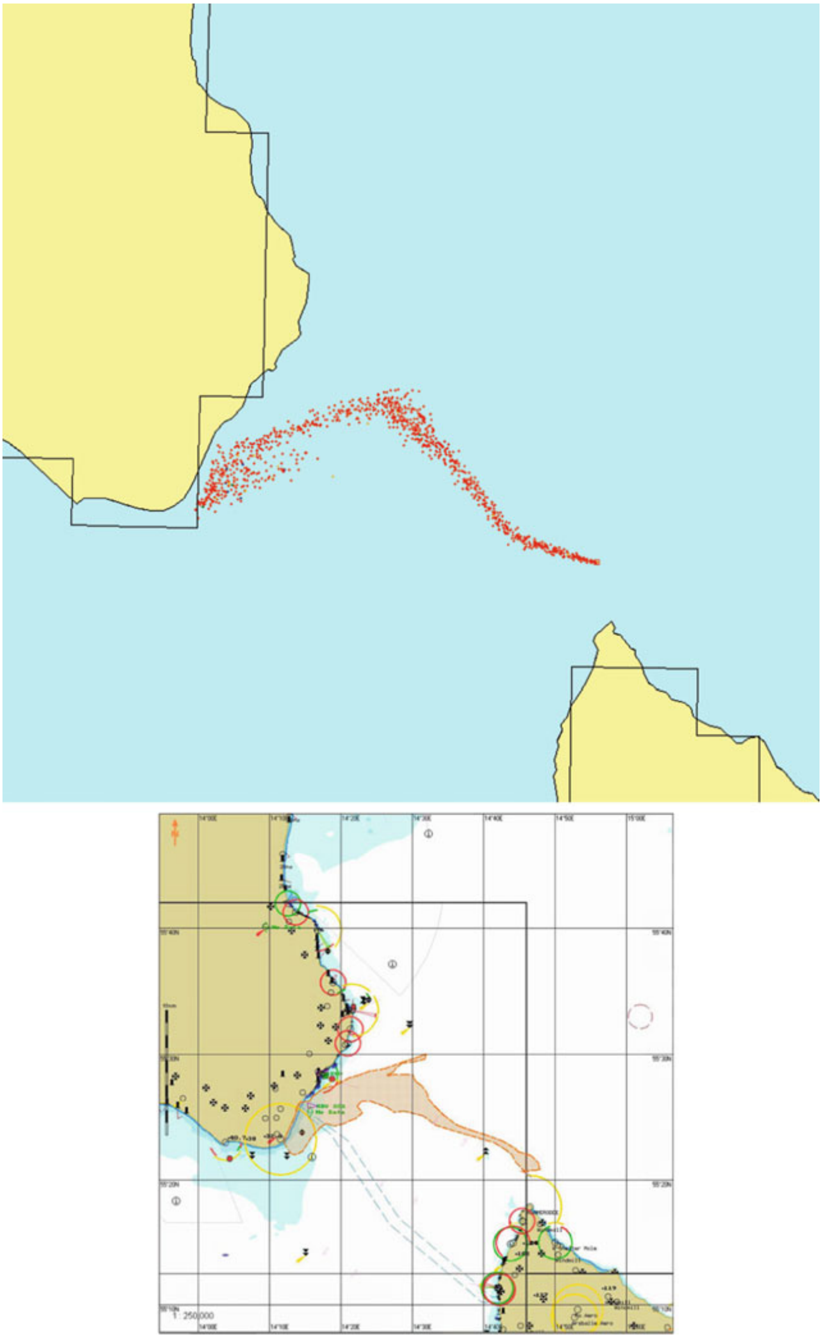


Fig. 8 The Fu Shan Hai spill as forecasted by Seatrack Web (*upper panel*) and observed via airborne SLAR images (*lower panel*) on 3 June 2003 at around 12:00 UTC

7 Future Developments

Perhaps the most important factor determining the quality of the forecasts produced by the Seatrack Web system is the quality of the hydrodynamic and meteorological forecasts that force the drift model. This can be improved in various ways, such as increased resolution, data assimilation, improved understanding of key processes, calibration against observations, etc. However, this is a separate issue that will not be dealt with further here.

Focusing on Seatrack Web, there are basically three areas where developments are in progress:

1. Improving the drift model by improving the description of the processes important to oil spill modeling (e.g., the near-surface advection or the weathering algorithms). This also includes enhancing code clarity to reduce the risk of coding errors and to facilitate cooperative development efforts. Improving the performance can also benefit the quality by permitting more computationally costly algorithms and solutions.
2. Increasing the usability by adding features that are important to responsible authorities, incident commanders, and other decision makers, such as incorporating additional local information, simplifying the simulation set up process, integrating other decision support systems into Seatrack Web or vice versa, tailor the output presentation, etc.
3. Improving the security, reliability, and scalability of the client/server application.

Currently three development efforts are under way or being considered within the first category: (1) to use wave spectra from wave forecast models rather than a parameterized spectrum, (2) to improve the implementation of the turbulent mixing, and (3) determining a realistic model of the horizontal dispersion of surface oil. A future wish list would include more sophisticated weathering algorithms and a mechanistic description of the vertical dispersion of surface oil.

Development in progress within the second category includes: (1) refining the current method for defining the initial spill by allowing the user to define a polygon of arbitrary shape and any number of vertices, (2) implementing a system for importing preprocessed satellite images of spills, and (3) improving the access to AIS data throughout Europe. The European Maritime Safety Agency (EMSA) is currently testing functionality for exporting satellite-based Synthetic Aperture Radar (SAR) images of detected spills at sea. Once this has been completed, these geo-referenced images can be imported into Seatrack Web and displayed in the user interface. The user can then define an initial spill area for a forecast based on an image of the actual spill. More sophisticated methods for defining the spill area – e.g., by automatically creating a polygon in Seatrack Web based on a satellite detection of an oil spill – will also be developed and Seatrack Web will then provide automated forecasts and backtracking simulations to EMSA whenever an oil spill is detected.

The third category entails implementing the server software in a load balancing environment, using Web Service technology for handling the execution of the drift model. This will allow for multiple redundant hardware and Seatrack Web Java Servlets. It would also make it easier for other applications to interact with Seatrack Web. A REST-based Web Service software has been developed and is currently being tested. In the future, the Seatrack Web GUI may be moved into the web browser and the whole system may also be used together with Web Map Services (WMS) for displaying Seatrack Web simulation results in a standardized way for possible third parties.

8 Conclusions

Just as weather forecasting has become an integral and vital part of human society, the ability to forecast accidental oil spills is becoming standard practice all over the world. The need for such tools has been clearly highlighted by the recent Montara and Deep Horizon oil spills. With the projected increase in shipping within the Baltic Sea, it is safe to say that the development and operation of HELCOM Seatrack Web should be considered a necessity and the forethought of HELCOM is to be commended.

It is in the nature of forecasting that it will never be an exact science. However, the model description and results presented here hopefully will bolster confidence in the usefulness of HELCOM Seatrack Web. It is therefore important to spread knowledge about this tool and to continuously integrate its use in oil spill response through training, multilateral agreements, and exercises.

Of course, much can still be done to improve systems such as Seatrack Web. Considering the stakes and potential extra costs of an oil spill response based on inferior data, further development should not be neglected. It is also important to realize that oil spill modeling covers many disciplines, from physical oceanography and hydrodynamics to oil chemistry and ecotoxicological issues, requiring the input from many avenues and research and fruitful collaboration.

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Seatrack Web: A Numerical Tool for Environmental Risk Assessment in the Baltic Sea

Andrey G. Kostianoy, Cecilia Ambjörn, and Dmytro M. Solovyov

Abstract In the framework of several projects related to organization of the complex satellite monitoring of the Lukoil D-6 oil platform in the southeastern Baltic Sea and a construction of the Nord Stream gas pipeline in the whole Baltic Sea we elaborated a new, very effective technology for the quantitative environmental risk assessment, based on the Seatrack Web model. For every kilometer of the coastline, the Baltic Sea Protected Area, Important Bird Area, as well as for any part of the sea surface it allows to calculate in percent a probability to be polluted by oil, resulted from operations in ports, oil terminals, oil platforms, oil pipelines, and shipping activities (main ship routes) in the Baltic Sea. Three case studies are discussed in the chapter. This methodology can be used in the Baltic Sea countries and in the international organizations for the environmental risk assessment.

Keywords Baltic Sea, Coastal zone, Environmental risk assessment, Important bird area, Marine environment, Marine protected area, Oil pollution, Seatrack Web model

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Contents

1 Introduction

Shipping activities in the Baltic Sea, including oil transport and oil handled in harbors, have a number of negative impacts on the marine environment, marine protected areas (MPAs), important bird areas (IBAs), and coastal zone. Oil discharges from ships cause the contamination of seawater, shores, and beaches, which may persist for a long time (up to several years) and represent a threat to marine ecosystems and resources, MPAs, and IBAs. One of the main tasks in the ecological monitoring of the European seas is an operational satellite and aerial detection of oil spillages, determination of their characteristics, establishment of the pollution sources, and forecast of probable trajectories of the oil spill transport. Satellite imagery can help greatly identifying probable spills over very large areas and then guiding aerial surveys for precise observation of specific locations. The Synthetic Aperture Radar (SAR) instrument on board ENVISAT, ERS-2, TerraSAR-X, TanDEM-X, and RADARSAT-1 and -2 satellites, which can collect data independently of weather and light conditions, is an excellent tool to monitor and detect oil on water surfaces. Visible and infrared wavelength remote sensing from MODIS-Terra and -Aqua, MERIS Envisat, and AVHRR NOAA optical scanners and radiometers can help in monitoring of suspended matter distribution and transport, as well as bloom events in summertime.

In June 2004 to November 2005, a complex daily operational service, aimed to the ecological monitoring of the southeastern Baltic Sea in connection with a beginning of oil production at continental shelf of Russia on the Lukoil D-6 oil platform in April 2004, was organized on the base of daily satellite remote sensing (AVHRR NOAA, MODIS, TOPEX/Poseidon, Jason-1, ASAR ENVISAT, and SAR RADARSAT-1 imagery) of oil spills, SST, chlorophyll and suspended matter concentration, mesoscale water dynamics, wind, and waves [1–3]. Later this experience was used for satellite monitoring of the whole Baltic Sea, the Black and Caspian seas, and Sea of Azov [4].

One of the tasks for the Lukoil D-6 oil platform monitoring system was a drift forecast for the detected oil spills on the ASAR images. It was successfully done on the base of the interactive numerical model Seatrack Web, which is a powerful operational tool specially focused on this purpose. This numerical model on the Internet platform has been developed at the Swedish Meteorological and Hydrological Institute (SMHI) in close cooperation with Danish authorities and other partners from the Baltic Sea countries. The forecasting system is based on an operational weather model ECMWF and HIRLAM, and a hydrodynamic model HIROMB, which calculates the current field. The model allows to forecast the oil spill drift and transformation of its characteristics for 5 days ahead or to make a hind cast (backward calculation) for 30 days in the whole Baltic Sea with spatial resolution of one nautical mile and temporal resolution of 15 min [5–7].

Construction of the Lukoil D-6 oil platform at a distance of 22.5 km from the Curonian Spit (shared between Russia and Lithuania), a UNESCO heritage site, and in 8 km from the marine border with Lithuania had a big concern from the environmental point of view. Several experts on national and international levels argued that if an accident will happen at the platform, then with 100% probability the oil spill will reach the Curonian Spit coast due to main favorable direction of winds and currents. A discussion of this problem has required more realistic values due to a fact that winds and currents are very unstable in the southeastern Baltic Sea. This task was solved by Kostianoy et al. [1–3] who invented a new methodology for such a risk assessment basing on the statistical analysis of a large number of daily oil spill drift forecasts produced in the Seatrack Web runs. Later this technology was applied to a part of the main ship route in the Gulf of Finland, southward of Gotland Island and in the environmental risk assessment related to the construction of the Nord Stream gas pipeline [8–10]. Our experience in these three case studies is presented in the chapter. Our technology may be used in the environmental risk assessment for the MPAs, IBAs, land, and island coastal zones, as well as for other hot spots in the Baltic Sea, in relation to potential oil pollution resulted from the main ship routes, ports, oil terminals, and oil pipelines.

2 Environmental Risk Assessment

Environmental risk assessment (ERA) is a part of the risk management procedure [11–15]. ERA is carried out to examine the effects of an entity or agent on humans (Health Risk Assessment) and ecosystems (Ecological Risk Assessment) [14]. ERA covers a broad spectrum of risks (physical, chemical, biological, etc.), receptors (individuals or population; fauna, flora, or whole ecosystem; coastal zone, buildings, materials, etc.), and end-points (mortality and morbidity; business, property, and revenue loss; species extinction, total fish catch, etc.) [14]. Risk assessment is determined as qualitative or quantitative value of risk related to a concrete hazard or a situation.

Qualitative risk assessment normally uses expert opinion to estimate a probability or frequency of the risks and the appropriate impact through the linguistic expressions, such as likely, may occur, not likely, and very unlikely [14]. Very often, such a subjective approach may be sufficient to assess the risk of the system depending on the hazard type, nature of the risk, potential impact, and available resources. In most of the cases, a quantitative risk assessment is required, to which huge efforts in developing the adequate methods of risk analysis has been addressed. According to [14] “quantitative risk analysis (QRA) is the determination of the probability and consequences of potential losses in numerical terms. The assignment of probability values to the various events in the risk model provides for a quantitative assessment of risk." QRA requires calculation of two components of the risk – the probability of the potential loss and its magnitude.

Methods for assessment of risk may differ between economy sectors and whether it pertains to general financial decisions or environmental, ecological, or public health risk assessment. Despite of the diversity of approaches to ERA, several general steps can be identified in different literature sources: (1) problem formulation (what needs to be assessed), (2) hazard identification (source of the risk), (3) release assessment (probability of the risk), (4) exposure assessment (ways to reach the receptor, frequency, intensity, probability to be exposed to a pollution), (5) consequence or effect assessment (effect on the receptors), (6) risk characterization and estimation (quantitative and qualitative measures of the risk), and (7) risk evaluation (how important is the risk) [11, 14].

In [15] we can find the following five stages in carrying out an ERA:

1. Hazard identification. This typically includes identification of the property or situation that could lead to harm. This step is sometimes also known as problem formulation.
2. Identification of consequences if the hazard was to occur. This step is sometimes also known as hazard identification.
3. Estimation of the magnitude of the consequences. This can include consideration of the spatial and temporal scale of the consequences and the time to onset of the consequences. When considering chemicals, this step can sometimes be termed release assessment.
4. Estimation of the probability of the consequences. There are three components to this, the presence of the hazard, the probability of the receptors being exposed to the hazard, and the probability of harm resulting from exposure to the hazard. This step can sometimes be called exposure assessment or consequence assessment.
5. Evaluating the significance of a risk (often termed risk characterization or risk estimation) is the product of the likelihood of the hazard being realized and the severity of the consequences.

"Green Leaves III," the latest edition of the UK Government's Guidelines for Environmental Risk Assessment and Management, provides generic guidelines for the assessment and management of environmental risks [13]. These guidelines replace earlier versions published in 1995 by the Department of the Environment and in 2000 by the UK Department of the Environment, Transport and the Regions and the Environment Agency. This last revision brings the guidelines in England and Wales in line with current state in the field of environmental risk management [13]. Four main components of risk assessment are identified: (1) formulating the problem, (2) carrying out an assessment of the risk, (3) identifying and appraising the management options available, and (4) addressing the risk with the chosen risk management strategy.

According to this document, essential components of environmental risk assessment and management can be summarized as follows [13]: "When a risk problem is highlighted, the source, pathways and receptors under potential threat should be recognised. An assessment plan is then needed to outline the data requirements for assessment and the methods needed for data collection and synthesis. Resources for the assessment can be allocated following initial risk screening and prioritisation. Identifying the hazard at the beginning of the assessment should clearly define the harm to the environment that is of concern. An estimation of the potential consequences of the hazard being realised and an evaluation of the probability of impact can then be carried out. This evidence collected is used to provide judgement as to the significance of the risk."

US Guidelines for Ecological Risk Assessment state that this assessment "evaluates the likelihood that adverse ecological effects may occur or are occurring as a result of exposure to one or more stressors" [12]. The Guidelines note that "It is a flexible process for organizing and analyzing data, information, assumptions, and uncertainties to evaluate the likelihood of adverse ecological effects. Ecological risk assessment provides a critical element for environmental decision making by giving risk managers an approach for considering available scientific information along with the other factors they need to consider (e.g., social, legal, political, or economic) in selecting a course of action." This process is divided in three primary phases: (1) problem formulation, (2) analysis, and (3) risk characterization [12]. In problem formulation, risk assessors evaluate goals and select assessment endpoints, prepare the conceptual model, and develop an analysis plan. During the analysis phase, assessors evaluate exposure to stressors and the relationship between stressor levels and ecological effects. In risk characterization, assessors estimate risk through integration of exposure and stressor–response profiles, describe risk by discussing lines of evidence and determining ecological adversity, and prepare a report [12].

An important aspect of risk assessment is the estimation of the associated uncertainty. A relatively common, simplistic, approach is based on a risk ranking matrix where, for example, "Probability of receptors being exposed" and "Consequences of hazard being realized" are expressed in terms like "very low, low, medium, high, and very high." In more complex cases, it may be appropriate to use (semi)qualitative risk assessment approaches. They may be completed through the use of statistical models such as probability analysis, Poisson distributions, or Bayesian theory [15]. Such approaches can define the pathway and consequences using modeling/estimation techniques that allow the level of exposure of a receptor, and the consequences to the receptor, to be better determined, as well as in some cases probabilistic models can be used to estimate the actual probability of risk occurring [13, 15]. These statistical models require the use of past and current data, as well as assumptions about future trends. These data may be accumulated from the observations or modeling.

In 2004, working on the contract with Lukoil Company for operational complex satellite ecological monitoring of the large area around the D-6 oil platform in the southeastern Baltic Sea, we elaborated a new technology for calculation of the probability of potential oil pollution of the surrounding waters and a coastal zone of Lithuania and Russia resulted from a potential accident at the oil platform, based on the daily runs of the operational numerical model Seatrack Web [1–3]. Below it will be shown that this new approach can be successfully used in a very important, central part of the environmental risk assessment procedure – quantitative estimation of the probability of the consequences of a hazard (oil pollution). The proposed methodology also shows one of the ways to solve the problem of the estimation of the associated uncertainty in the risk assessment.

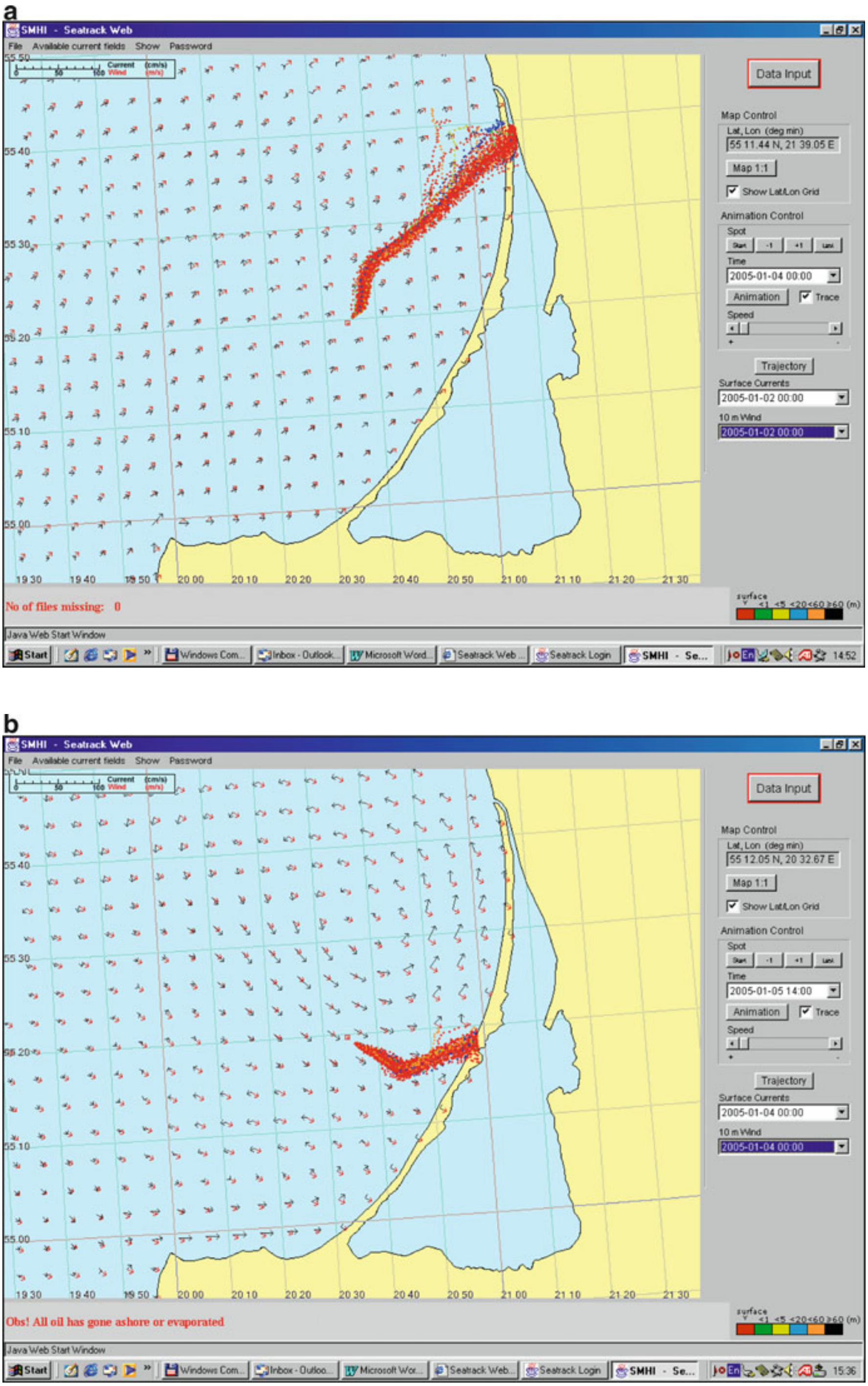
3 Case Study 1: Lukoil D-6 Oil Platform

In June 2004 in the framework of a contract with "LUKOIL-Kaliningradmorneft" (Kaliningrad, Russia), we elaborated and organized a complex satellite monitoring of the southeastern Baltic Sea as an important part of the control of ecological state of the marine environment around the D-6 oil platform [1–3]. The system was based on the receiving and analysis of ASAR/SAR, optical and infrared satellite data from a set of satellites – Envisat, Radarsat-1, NOAA, Terra and Aqua, TOPEX/Poseidon and was working in operational regime 24 h a day, 7 days a week, and 365 days a year. As a result, daily we had comprehensive information about oil pollution, sea surface temperature, chlorophyll and suspended matter concentration fields, currents, bloom events, ice cover, wind, and waves for the large area of the southeastern Baltic Sea. This information was completed by a broad set of meteorological information and forecasts from national and international agencies.

Interactive numerical model Seatrack Web (SMHI) [5–7] was used in this monitoring system for a 48-h forecast of an oil spill drift for: (1) all the major oil spills detected on the ASAR Envisat and SAR Radarsat-1 satellite images within a frame of 400 km × 400 km in the southeastern Baltic Sea and (2) virtual (modeled) oil spills of 10 m^3, released daily from the D-6 platform. Daily routine modeling of the D-6 virtual oil spill drift allowed to plan and correct actions to eliminate oil pollution resulting from a potential accident at the platform and quickly make assessments of environmental risks associated with oil pollution of the sea and coastal waters of the Curonian Spit (shared between Russia and Lithuania) and Sambia Peninsula (Russia). In total, about 550 drift forecasts have been made for real and virtual oil spills from June 2004 to November 2005 [1–3]. Below we will concentrate on the results of assessment of potential oil pollution from the D-6 oil platform.

We believe that the Seatrack Web model produces quasi-realistic forecasts because: (1) it is based on the European operational weather models ECMWF and HIRLAM, 3-D hydrodynamic model HIROMB; (2) it has a spatial resolution of 1 nm and temporal resolution of 15 min; (3) it is recommended by HELCOM for use by the Baltic Sea countries; and (4) it has more than 15 years long history of practical use in the Baltic Sea by different organizations and countries.

Figure 1 shows examples of numerical modeling of the virtual oil spills for 6 days in January 2005. Red plume shows a trajectory of an oil spill drift at the sea surface during 48 h after a release from the location of the D-6 platform. Width of the plume shows its lateral spreading. A strong day-to-day variability of the speed and direction of the oil spill drift is associated with large observed variability of the



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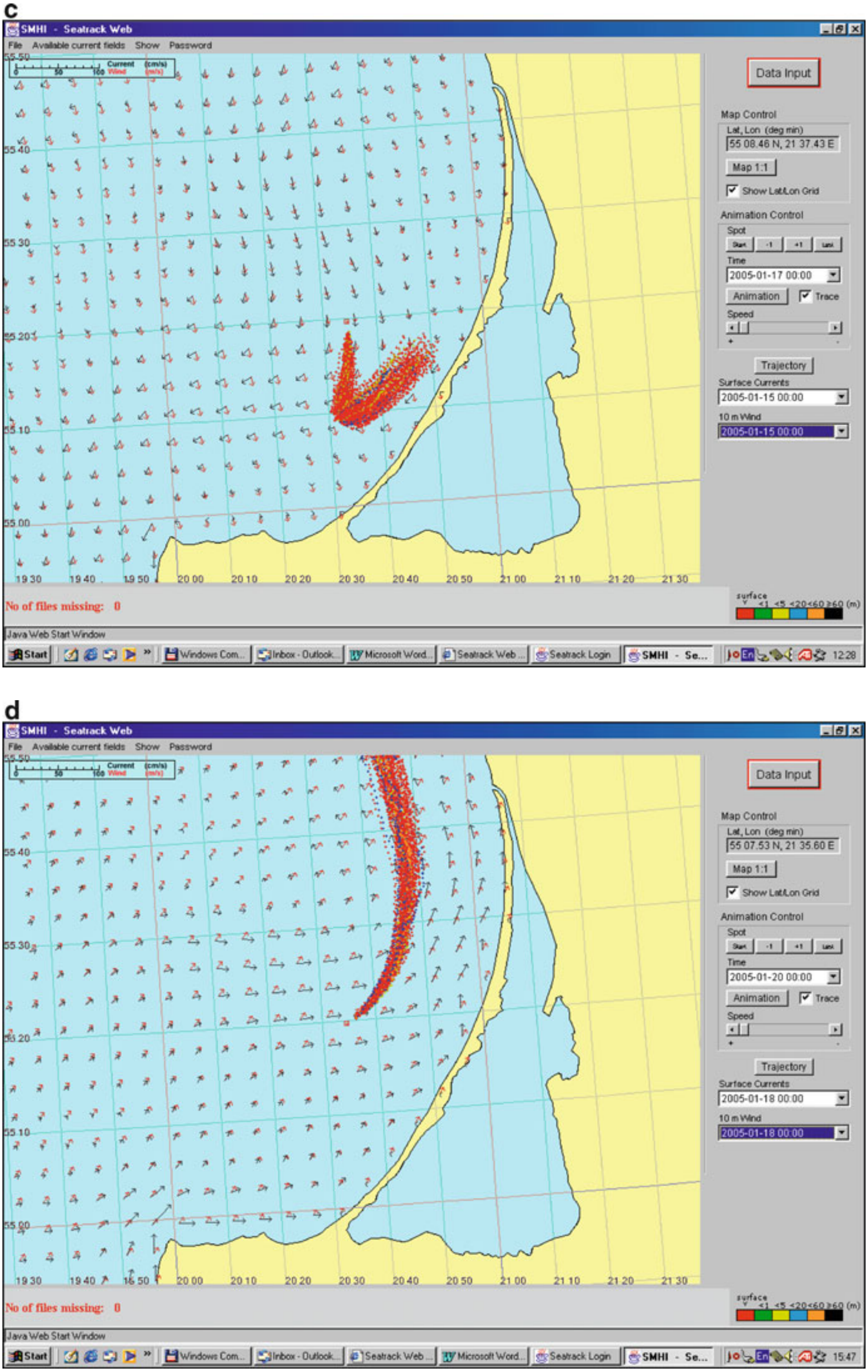
Obs! All oil has gone ashore or evaporated

Fig. 1 (continued)



c

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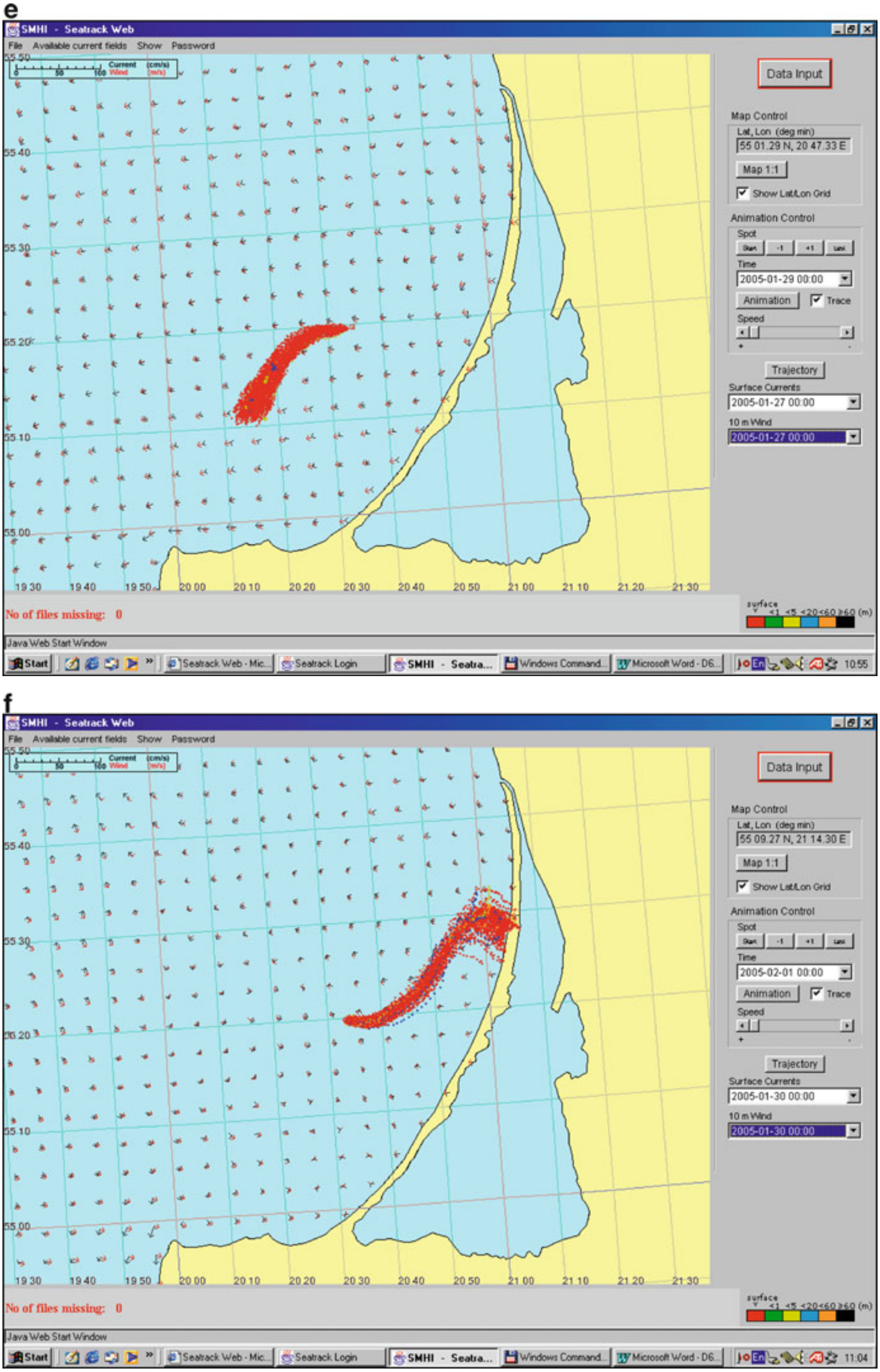

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Fig. 1 A drift forecast for a virtual oil spill released from the Lukoil D-6 oil platform on 2 (**a**), 4 (**b**), 15 (**c**), 18 (**d**), 27 (**e**), and 30 (**f**) January 2005

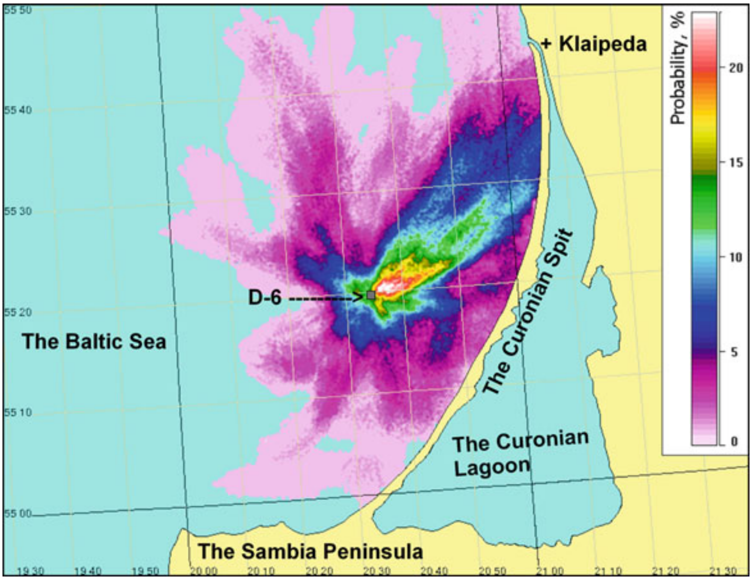

Fig. 2 Probability (%) of propagation of potential oil pollution from the Lukoil D-6 platform during 48 h after a release of 10 m^3 of oil

wind field and the resulting water circulation in this shallow sea area. Figure 1 demonstrates that the spill released from the platform, for example, on 2, 4, and 30 January 2005 in 48 h could reach the coastline of the Curonian Spit in different places. Other examples show that the spill may drift in different directions, including parallel to the Curonian Spit coastline (Fig. 1d), without landing the shore. This once again confirms the need for use of operational real metocean data in the numerical simulations instead of averaged climatological characteristics of the wind pattern and general water circulation scheme.

We accumulated daily forecasts for oil spill drift from the platform during 48 h for the time period from 1 July to 31 December 2004 (184 maps) and obtained a statistical map of the area of oil distribution and a probability in percent of an oil location in any point of the investigated marine area and a coastal zone (Fig. 2). It is clear that the better (the longer data set – of several years) statistics will guarantee the better results. Figure 2 shows that: (1) oil spill may drift in any direction but with different probability; (2) the most probable direction is to northeast; (3) the coast of Sambia Peninsula will not be affected by the pollution; (4) any point of the Curonian Spit may be polluted, but with different calculated probability; (5) any point within the 15 km long zone at the Curonian Spit coast has a maximum probability (10%) to be polluted; and (6) during 48 h oil spill may reach even the coast of Lithuania northward of Klaipeda, but with a probability less than 3%.

Figure 3 shows another representation of the obtained results, where we calculated a probability for an oil spill to drift in a certain direction from the platform. We divided the field as following: the main 150° sector was directed to the

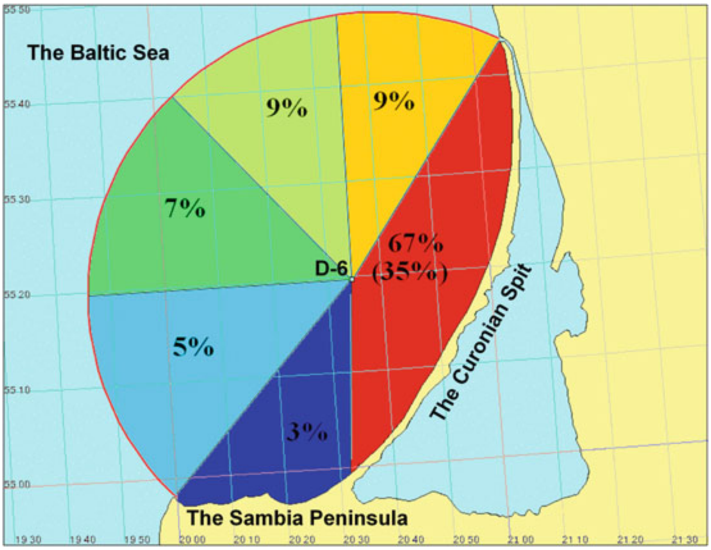

Fig. 3 Probability (%) of oil spill propagation in different sectors (directions) from the D-6 platform during 48 h after a release of 10 m^3 of oil

Curonian Spit (Russian and Lithuanian parts together) and the rest area was split in five almost equal sectors of about 45°. The result shows that: (1) in 67% of cases the oil spill will drift in the sector directed to the Curonian Spit; (2) only in a half of these events (35%) the spill reached the coastline of the spit (which is three times less than declared by the experts), due to a strong alongshore current, which entrain oil pollution along the Curonian Spit; (3) the probability for other sectors varies from 3% to 9%, accounting in total for one third of all possible drift directions; and (4) the least likely drift direction is focused on the coast of the Sambia Peninsula (Fig. 3).

A similar exercise could be conducted for modeling the possible leakage of oil from a bottom oil pipeline 45 km long, connecting the D-6 platform with coastal oil installations at the Sambia Peninsula.

4 Case Study 2: Main Ship Route in the Baltic Sea

An increase of maritime transportation during the past two decades in the Baltic Sea has increased the probability of illegal oil discharges [16]. In Fig. 4, we accumulated oil spills detected in the Baltic Sea in 1989–2002 (and taken from the official data of [16]) on a single geographical map, which has automatically drawn the main ship routes in the Baltic Sea and approaches to the main ports and oil terminals. This map clearly justifies that the main polluters in the Baltic Sea are ships, and the majority of the detected oil spills is located on the ship route between

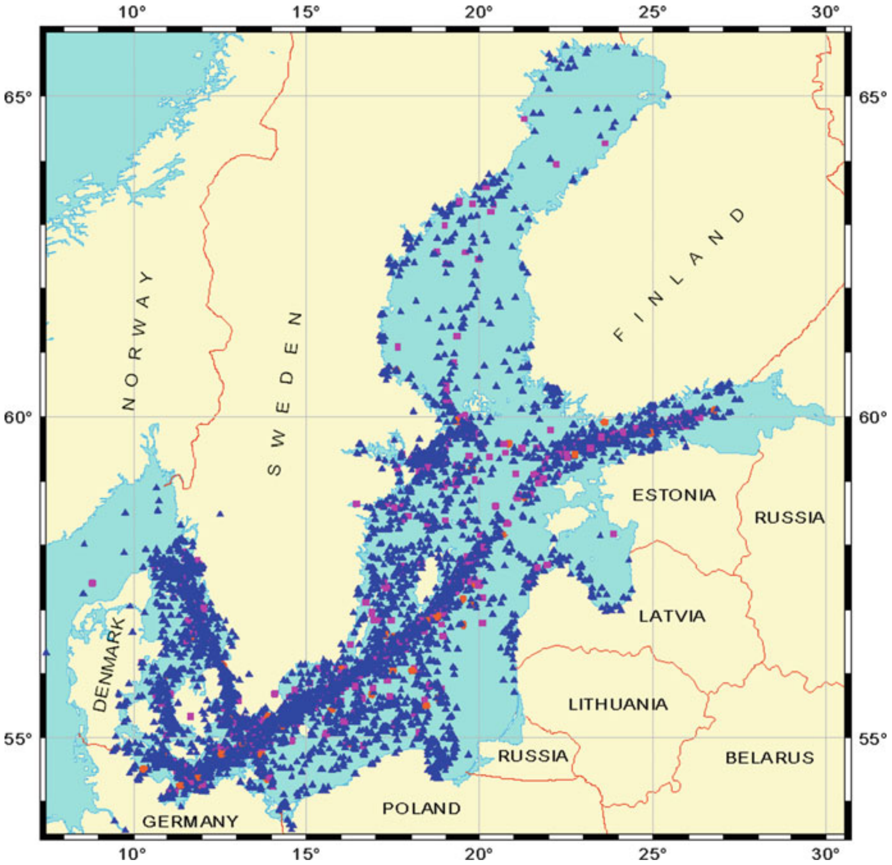

Fig. 4 Map of oil spills detected in the Baltic Sea in 1989–2002 [HELCOM Response]. Category 1 (▲) – <1 m^3, category 2 (■) – 1 m^3 < 10 m^3, category 3 (▲) – 10 m^3 < 100 m^3, category 4 (●) – >100 m^3

the Gulf of Finland and southwestern part of the Baltic Sea (Fig. 4). Our idea was to investigate the impact of this ship route, in terms of potential oil pollution, on the marine environment, the Baltic Sea Protected Areas (BSPAs), Important Bird Areas (IBAs), and a land or islands coastline. We used our methodology for two regions along this ship route: the entrance to the Gulf of Finland and an area southward of Gotland Island. Figures 5–7 show three examples of oil spill drift modeling and the resulting probability charts for potential oil pollution, made for July–August 2007.

Figure 5a shows a drift of a virtual oil spill of 10 m^3 during 48 h, which was released on 23 July 2007 at a specific point (red square) of the ship route passing through the Gulf of Finland. We put this point at the line, which delimits MARIS response zones between Finland and Estonia, at 23°E, which is approximately the entrance to the gulf. The same type of numerical experiment was done daily from 1 July to 31 August 2007. Thus, basing on the compilation of 62 maps of oil spill drifts, we could construct Fig. 5b and calculate a probability of oil spill drift.

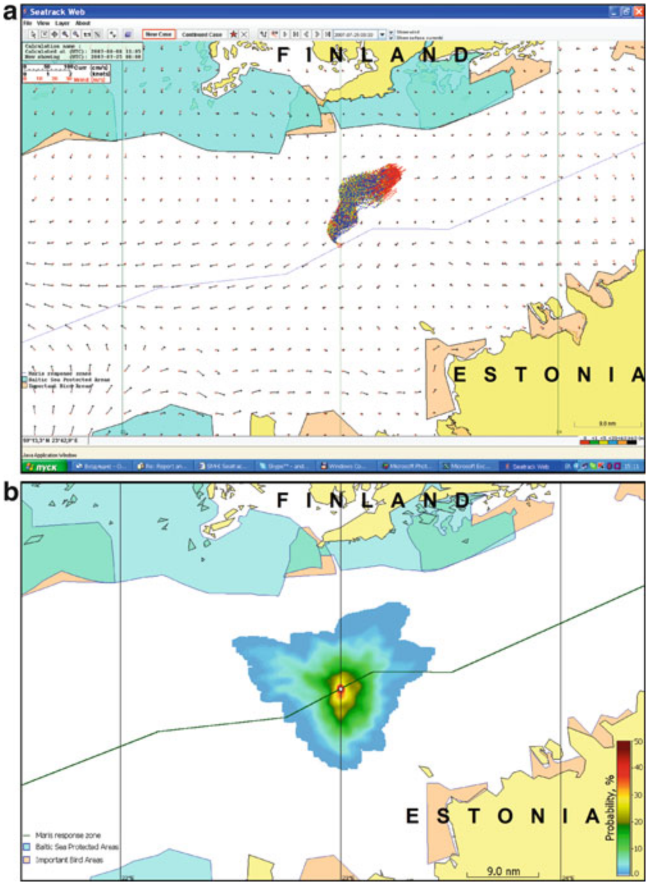

Fig. 5 Modeling of oil spill drift in the Gulf of Finland: (**a**) shows oil spill drift on 23 July 2007; (**b**) shows probability (%) of oil spill drift calculated on the base of daily modeling at this point for real wind and currents conditions in July–August 2007. BSPAs are shown in *blue*, Important Bird Areas – in *light-brown* colors, coastal zones of Finland and Estonia are colored by *yellow*, *blue line* shows delimitation of the MARIS response zones

Figure 5b shows that for this time period there is no impact of possible oil spills drift on the surrounding BSPAs along the coasts of Finland and Estonia, which are marked by blue and light-brown colors. This is explained by low wind speed and weak currents observed during July and August 2007. These weather conditions differ from those observed on 26 July–15 August 2006, when a virtual oil spill could drift 33.5 nm during 2 days with a velocity up to 50 cm/s in the same area (compare with Fig. 14). Thus, potential releases of oil spills from the ships at this specific point may represent a threat to seven protected areas located along the coasts of Finland and Estonia, as well as to the islands and coasts of these Baltic countries.

We repeated the same procedure for the same time period for a point located at 18°E, 28 km southward of Gotland Island. Figure 6a shows a drift of a virtual oil spill

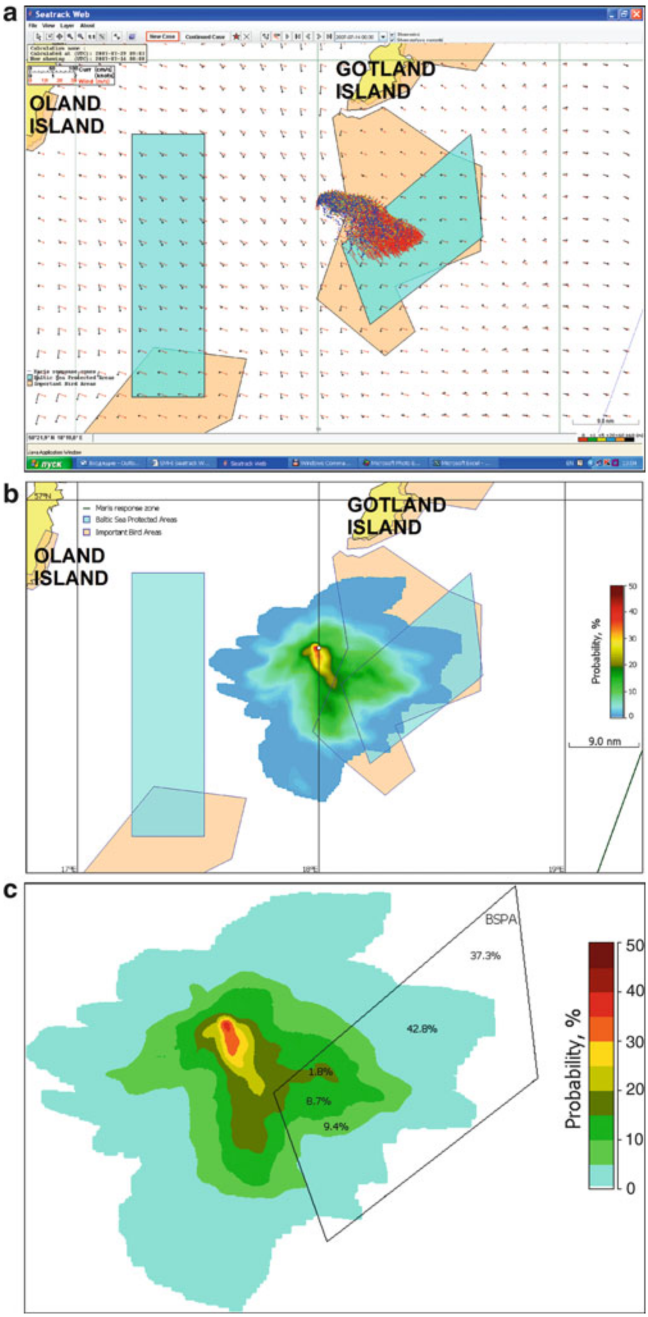

Fig. 6 Modeling of oil spill drift southward of Gotland: (**a**) shows oil spill drift on 12 July 2007; (**b**) shows probability (%) of oil spill drift calculated on the base of daily modeling at this point for real wind and currents conditions in July–August 2007; (**c**) shows the impact of this point in the ship route on the nearest BSPA

of 10 m^3 during 48 h, which was released on 12 July 2007 at a specific point (red square) of the ship route passing southward of Gotland Island. In the vicinity of this point, we observe the BSPA, which is shown in blue color, and the IBA, which is shown in light-brown color. Both protected areas intersect each other. The oil spill plume crosses both of them in Fig. 6a. Another coastal IBA surrounds the southernmost part of Gotland Island. Westward from the selected point, an elongated rectangular BSPA is located. This BSPA partially intersects another IBA on its south. Further westward we see the eastern coast of Oland Island and its coastal IBA.

Based on the compilation of 62 daily maps of oil spill drifts for 1 July–31 August 2007, we could calculate a probability of oil spill drift from this point (Fig. 6b). Figure 6b shows a significant impact of the selected point at the ship route southward of Gotland on the BSPA and IBA located eastward. In this case, the area of potential pollution is very large, but there are two prevailing directions of the pollution drift – to the south and southeast. Moreover, it is clear that different parts and surface of the BSPA and IBA are under the threat with a different probability, which is possible to calculate. We did it only for the BSPA. Figure 6c shows that only 37.3% of the BSPA surface will be free of pollution, as well as where these parts are exactly located. About 42.8% of the area (blue color) will be polluted with a probability of 0–5%, 9.4% – with a probability of 5–10%, 8.7% – with a probability of 10–15%, and 1.8% – with a probability of 15–20%. The same can be done for the IBA, which is covered by potential oil pollution also. We have to note again that under different weather conditions, even during the same time period, we may expect another shape of the probability diagram with other prevailing directions and probability values. For instance, we can compare this result with that obtained in 2006 (see Fig. 20). Thus, a 1-year long statistics, which covers all the seasons, is required for more credibility.

Seatrack Web model allows calculation of a forecast of oil pollution drift when it is released from a line also. Figure 4 shows that any point of the ship route in the vicinity of Gotland Island anytime may represent a potential source of oil pollution, thus it is possible to imagine that the ship route represents a line, from which oil is released simultaneously. Southward from Gotland Island we drew a 150-km long line, which is approximately a median line for all detected oil spills in this region in 1989–2002, based on HELCOM data [16]. And we repeated the same procedure for the same time period from 1 July to 31 August 2007 (Fig. 7).

Figure 7a shows a forecast for a 48-h oil pollution drift on 12 July 2007. Its general direction was to southeast, but with highest velocity in the central part of the line. The oil plume crosses both BSPA and IBA southward of Gotland Island and eastward of Oland Island. Again, basing on 62 individual daily forecasts, we calculated the probability map of oil pollution (Fig. 7b). It shows a significant impact of oil pollution produced by this virtual massive oil release. The marine area under the threat varies from 15 to 35 km both sides from the line with highest probability in the southeast direction. In this case, the statistics show that both BSPAs, both IBAs, and even the coastal IBA along Gotland Island, and the coast of Gotland are potentially threatened by oil pollution resulted from the ship route with clearly calculated probability. We did it for two BSPAs only and found that about

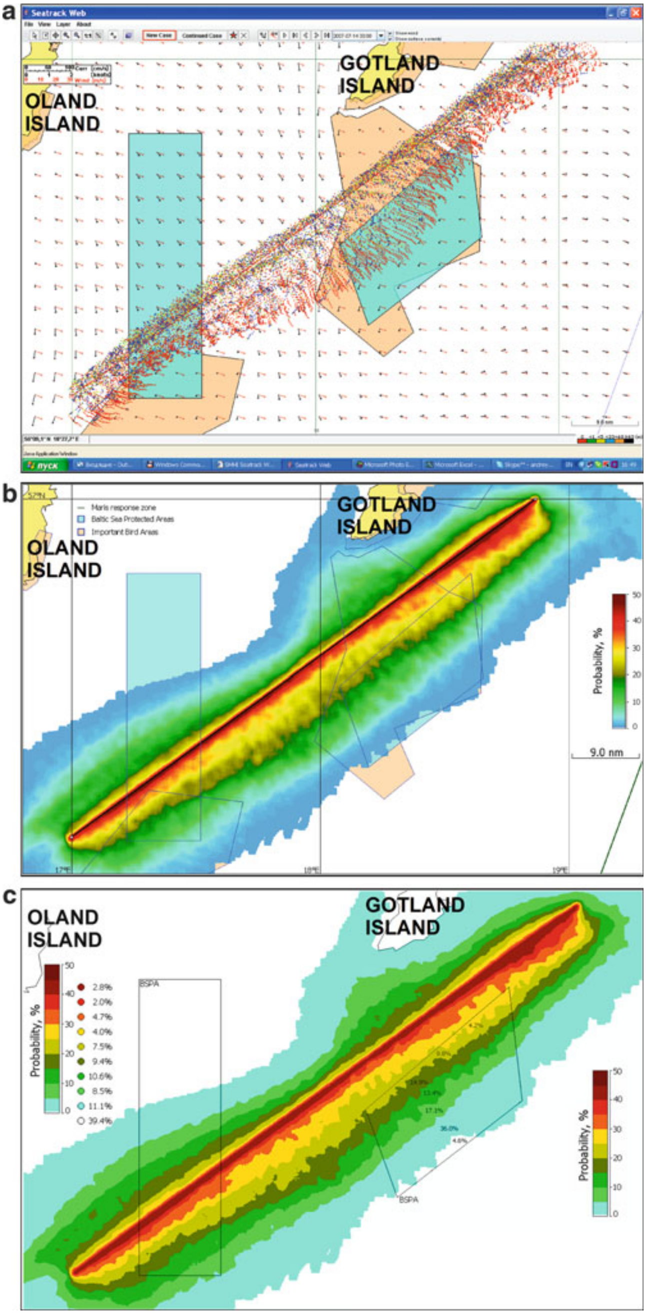

Fig. 7 Modeling of oil spill drift released from a long part of the ship route located southward of Gotland: (**a**) shows oil spill drift on 12 July 2007; (**b**) shows probability (%) of oil spill drift calculated on the base of daily modeling at this line for real wind and currents conditions in July–August 2007; (**c**) shows the impact of this part of the ship route on both BSPAs

60% of the first BSPA located eastward of Oland Island and 95% of the second one located southward of Gotland Island will be polluted with the indicated probability (Fig. 7c).

For instance, for the first BSPA: 39.4% of its surface (white area) will be free of potential oil pollution, 11.1% (blue color) will be polluted with a probability of 0–5%, 8.5% – with a probability of 5–10%, 10.6% – with a probability of 10–15%, 9.4% – with a probability of 15–20%, 7.5% – with a probability of 20–25%, 4.0% – with a probability of 25–30%, 4.7% – with a probability of 30–35%, 2.0% – with a probability of 35–40%, and 2.8% – with a probability of more than 40% (Fig. 7c). For the second BSPA: 4.6% of its surface (white area) will be free of potential oil pollution, 36.0% (blue color) will be polluted with a probability of 0–5%, 17.1% – with a probability of 5–10%, 13.4% – with a probability of 10–15%, 14.9% – with a probability of 15–20%, 9.8% – with a probability of 20–25%, and 4.2% – with a probability of 25–30% (Fig. 7c). As in the previous cases, longer statistics are required for more credibility.

5 Case Study 3: Nord Stream Gas Pipeline

In 2006, we used the same technology in the environmental risk assessment related to the future construction of the Nord Stream gas pipeline in the Baltic Sea (it was started in May 2010) [8–10, 17]. That time it has a bit different name – the North-European gas pipeline. During the construction works in the sea, we can expect water pollution by oil as a result of normal operation or accidental release from the pipelay vessel, dredging mechanisms, tugs, barges, and other floating supporting facilities. The following are examples of the results of numerical modeling of the drift of oil spills resulted from accidental releases of oil in the specific seven points along the whole route of the gas pipeline from Russia to Germany. For all seven points, we used a Light diesel fuel, as oil product in the model, which has a kinematic viscosity of 2.4 cSt and density of 849.9 kg/m^3. For a point N4, where a compressor station was planned to be constructed, we additionally used Fuel oil N2 (10.0 cSt, 849.9 kg/m^3), Light medium crude (6.5 cSt, 850.5 kg/m^3), and Lubricating oil (150.0 cSt, 870.6 kg/m^3) with quite different oil properties. As model initial conditions, we used one-time oil spill volume of 10 m^3 at the sea surface. This volume, actually as in all the above-mentioned cases, was chosen on the basis of statistical data on oil pollution by HELCOM and the Bonn Agreement, under which oil spills of up to 1 m^3 are encountered in 80% of cases, and from 1 to 10 m^3 – in 15% of the total number of spills [16, 18]. Thus, we have chosen a typical volume of an oil spill, which covers 95% of all possible cases.

Seatrack Web modeling was conducted from 26 July to 15 August 2006 [17]. The calculation of the oil drift was held for a period of 48 h from the time of discharge of oil products in the 00:00 UTC each day. The spatial resolution was of 1 nautical mile and step in time of 1 h. Each oil spill was described by 500 numerical dots. Due to a lack of space, in the chapter we have not shown examples of individual daily

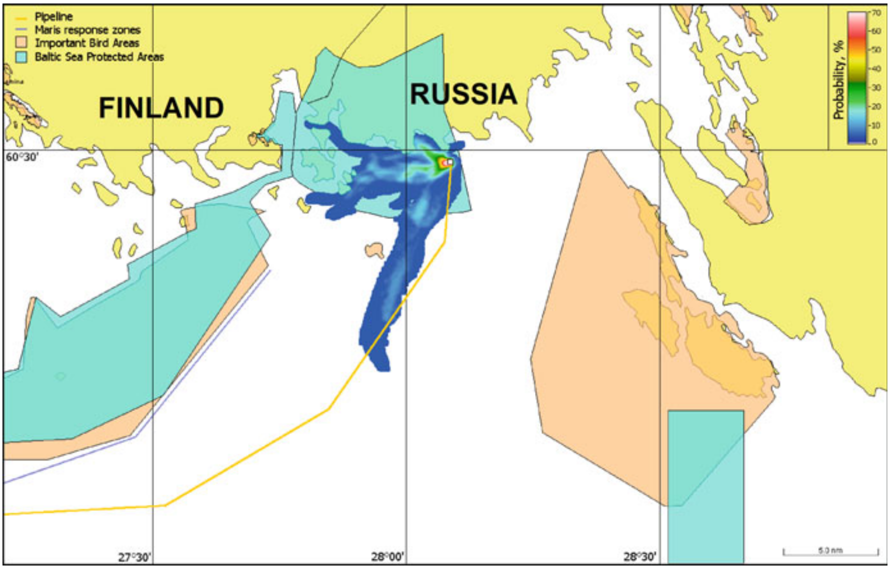

Fig. 8 Probability (%) of oil pollution calculated for a point N1 for 26 July–15 August 2006. Hereinafter the BSPAs are shown in *blue*, Important Bird Areas – in *light-brown* colors, coastal zones are colored by *yellow*, *blue line* shows delimitation of the MARIS response zones, *yellow line* is the Nord Stream gas pipeline route

forecasts but presented the resulting probability maps constructed on the base of 21 individual forecasts, as well as statistical data on the direction and velocity of a pollution drift. Every map has BSPAs (marked by blue color), IBAs (marked by light-brown color), the planned (in 2006) route of the Nord Stream gas pipeline (yellow line), and the delimitation of the MARIS (Maritime Accident Response Information System for the Baltic Sea) response zones (blue line).

Point N1. The point with coordinates 60°29.57′N and 28°05.25′E is located in the Gulf of Finland at the entrance of the gas pipeline to the Baltic Sea (Fig. 8). The point is located directly in the BSPA waters through which the gas pipeline passes. The model drift of oil pollution on 26–28 July 2006 shows that even in the summer calm weather period, the spill during 2 days can drift by a distance of 13 nm, and thus pose a threat not only to the long indented coastline of the Russian Federation, but for the vast IBA, located just 7.7 nm east and southeast from this point, as well as for the BSPA and IBA located in the waters of Finland at a distance of 9.2 nm [17]. The probabilistic analysis shows that in the analyzed period of time, the spills have been propagated mainly to the west between the islands and were deposited on their shores up to the border with Finland (Fig. 8). This is clearly seen in the histogram distribution of the hourly drift direction (Fig. 9). The oil spill drift velocity was within 0–16 cm/s with a maximum probability of 5 cm/s (Fig. 10). The average drift velocity was equal to 6.2 cm/s, which is explained by weak winds and slow currents during this time period [17].

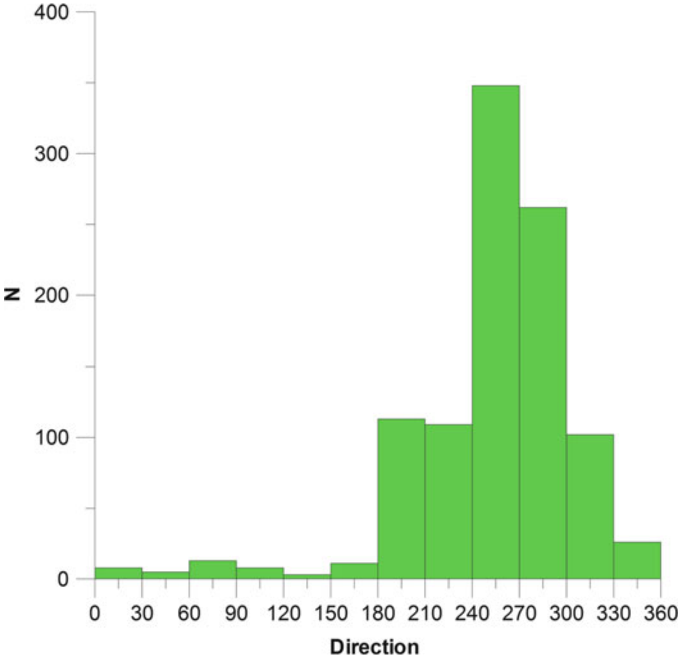

Fig. 9 The histogram of the hourly oil spill drift direction (degrees)

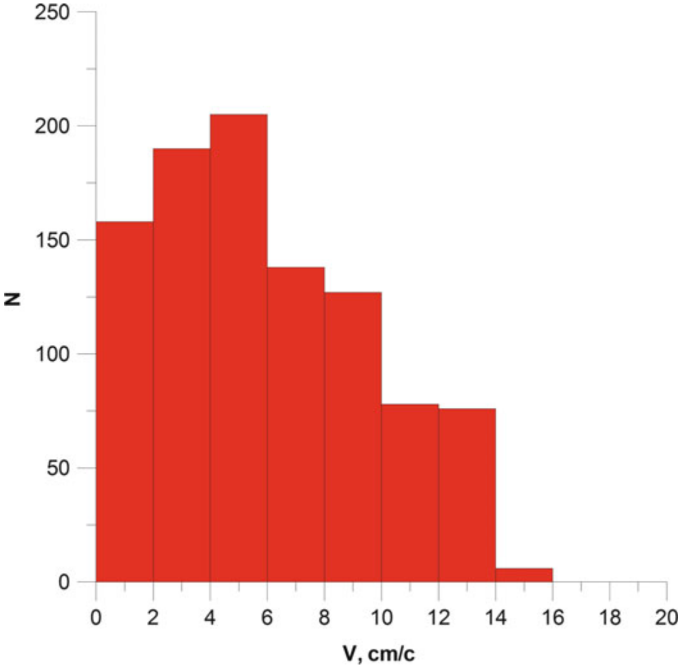

Fig. 10 The histogram of the hourly oil spill drift velocity (cm/s)

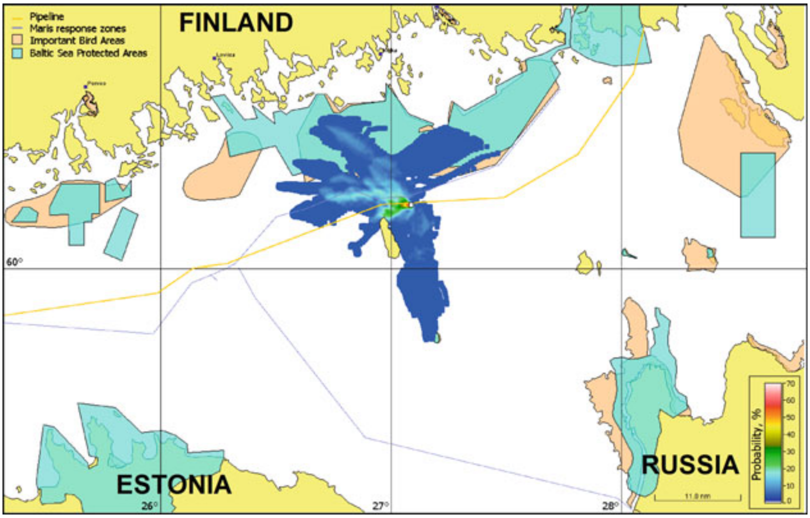

Fig. 11 Probability (%) of oil pollution calculated for a point N2 for 26 July–15 August 2006

Point N2. The point with coordinates 60°08.17′N and 27°05.17′E is located in the Gulf of Finland to the northeast of Gogland Island (Fig. 11). This point is in close proximity to the border with the Exclusive Economic Zone (EEZ) of Finland, in which there are large and almost coincided BSPA and IBA. The model oil spill drift on 14–16 August 2006 shows that even in summer conditions, the spill during 2 days can drift on the distance of 16 nm, and thus pose a threat not only to these protected areas but also to the islands and even the coast of Finland, located at a distance 14–20 nm from the gas pipeline route [17]. This is confirmed by a probabilistic analysis of the oil pollution drift, which shows that in the analyzed period of time, the spills have been mainly propagated to the west, northwest, northeast, and even to south, where they can reach another very small protected area with coordinates 59°51′N and 27°11′E (Fig. 11). Predominantly westward oil spill drift is confirmed by a histogram of the hourly oil spill drift direction (Fig. 12). The oil spill drift velocity was already two times higher than that at point N1 and was in the range of 0–31 cm/s with a maximum probability in the range of 5–10 cm/s (Fig. 13). The average drift velocity was 11.2 cm/s, which is also explained by the relatively weak winds and slow currents in the summer [17].

Point N3. The point with coordinates 59°35.13′N and 23°29.69′E is located at the outlet of the Gulf of Finland in the EEZ of Finland (Fig. 14). This point is at 3.5 nm from the EEZ of Estonia, 19 nm from three IBAs and the coasts of Estonia, 10 nm from the combined BSPA and IBA areas near the coasts of Finland, 17 nm from the coasts of Finland, and at 20 nm from the next pair of protected areas northwestward from this point (Fig. 14). The model oil spill drift on 13–15 August 2006 shows that even in summer conditions, the oil spill can drift during 2 days on a distance of 33.5 nm, and thus pose a threat not only to the seven protected areas but also for the islands and even coasts of Finland and Estonia [17]. This is confirmed by a probabilistic analysis of the pollution drift, which shows that in the analyzed

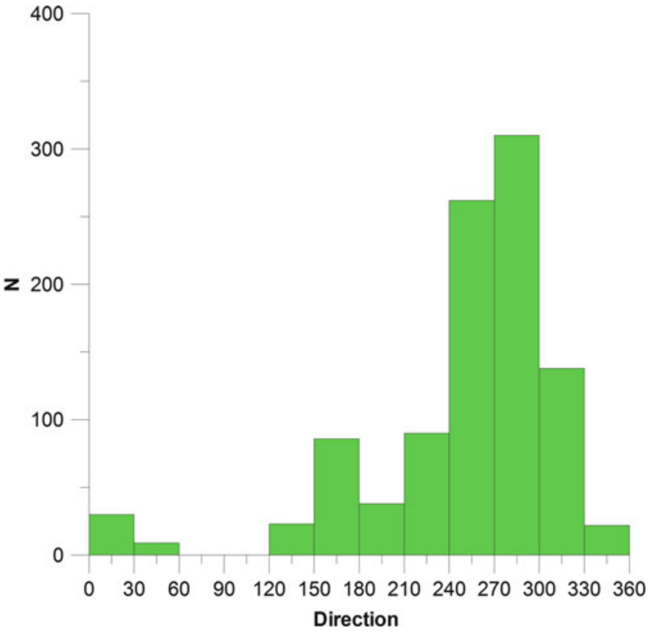

Fig. 12 The histogram of the hourly oil spill drift direction (degrees)

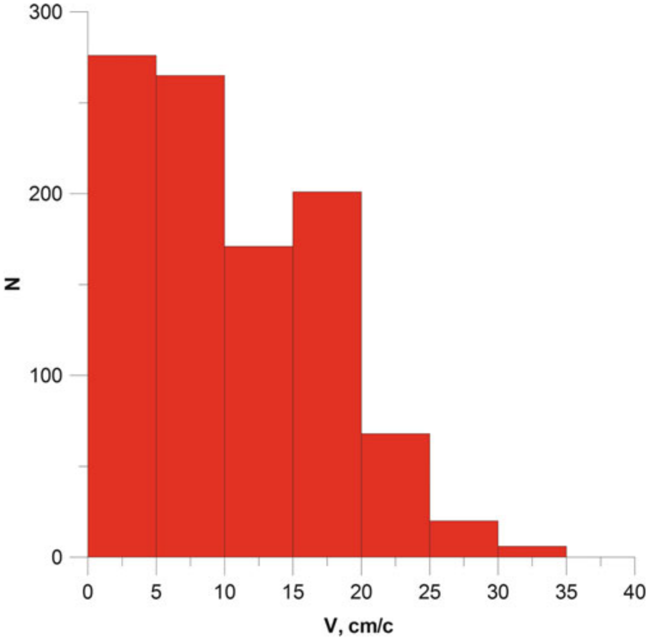

Fig. 13 The histogram of the hourly oil spill drift velocity (cm/s)

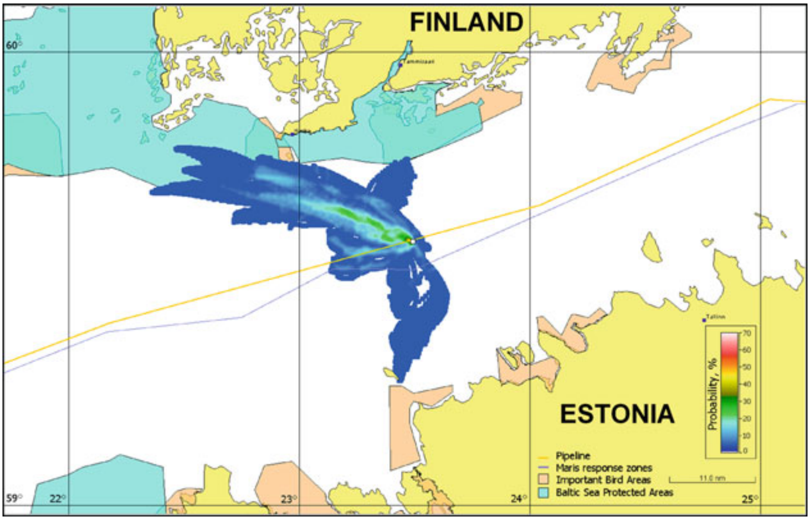

Fig. 14 Probability (%) of oil pollution calculated for a point N3 for 26 July–15 August 2006

period of time, the oil spills predominantly propagated to the northwest and partially covered the protected areas of Finland. A general northwestward oil pollution drift was confirmed by a histogram of the hourly oil spill drift direction (Fig. 15). The oil spill drift velocity was higher than at point N2 and was in the range 1–49 cm/s with a maximum probability in the range 10–15 cm/s (Fig. 16). The average drift velocity was equal to 16.7 cm/s [17].

Point N4. The point with coordinates 58°24.90′N and 20°05.73′E is located to the northeast of Gotland Island in the Swedish EEZ (Fig. 17). This point is at 10.4 nm from the EEZ of Estonia, 26.7 nm from EEZ of Latvia, 29.3 nm from EEZ of Finland, 21.5 nm from the BSPA around Gotska Sandön Island (24 nm), and at 29.2 nm from the IBA around Fårö Island (35.3 nm) (Fig. 17). The model oil spill drift on 5–7 August 2006 shows that even in summer conditions, the oil spill can drift during 2 days on a distance of 23 nm, and thus pose a threat not only to two protected areas and islands of Sweden but also to the EEZ of Sweden, Estonia, and Latvia [17]. This is confirmed by a probabilistic analysis of the pollution drift, which shows that in the analyzed period of time, the oil spills predominantly propagated to the northwest and partially covered the protected area around Gotska Sandön Island. A general west–northwestward oil pollution drift was confirmed by a histogram of the hourly oil spill drift direction (Fig. 18). The oil spill drift velocity corresponded to that at point N3 and was in the range 1–44 cm/s with a maximum probability in the range 10–15 cm/s (Fig. 19). The average drift velocity was equal to 16.6 cm/s [17].

Point N5. The point with coordinates 56°38.12′N and 18°52.49′E is located to the south of Gotland Island in the Swedish EEZ (Fig. 20). This point is at 18 nm from the EEZ of Latvia, 36–45 nm from EEZ of Lithuania, Russia, and Poland,

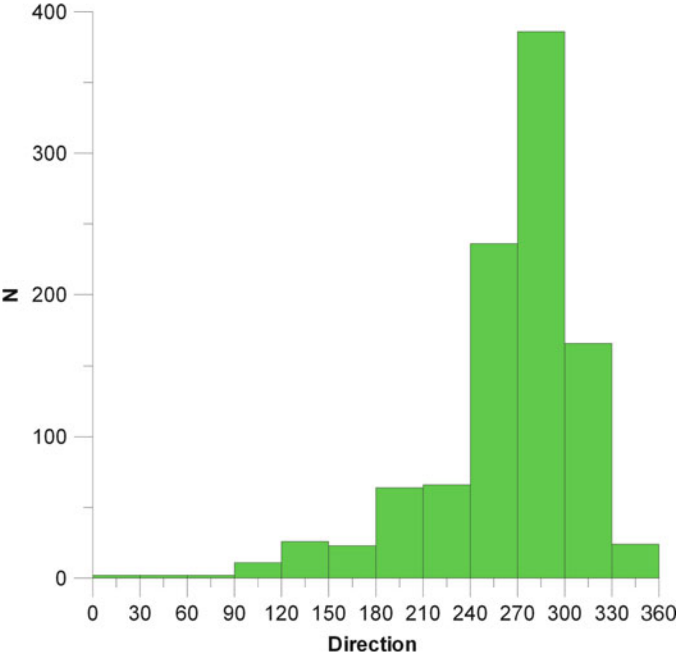

Fig. 15 The histogram of the hourly oil spill drift direction (degrees)

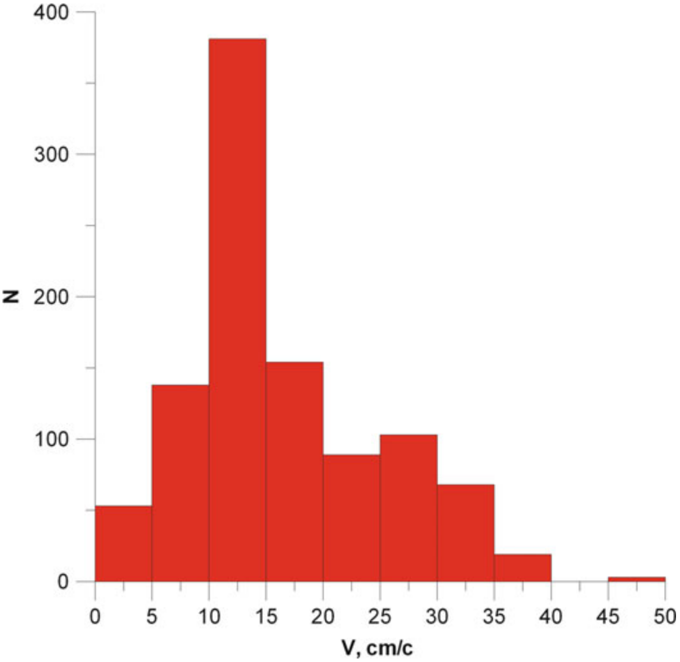

Fig. 16 The histogram of the hourly oil spill drift velocity (cm/s)

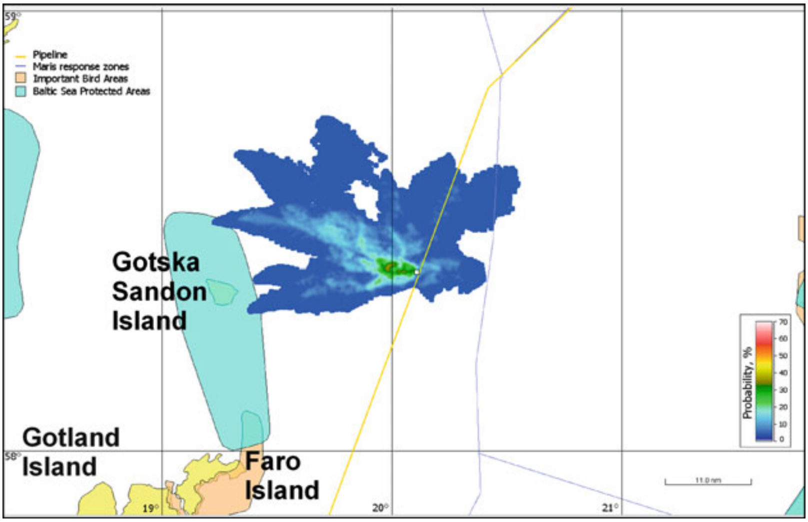

Fig. 17 Probability (%) of oil pollution calculated for a point N4 for 26 July–15 August 2006

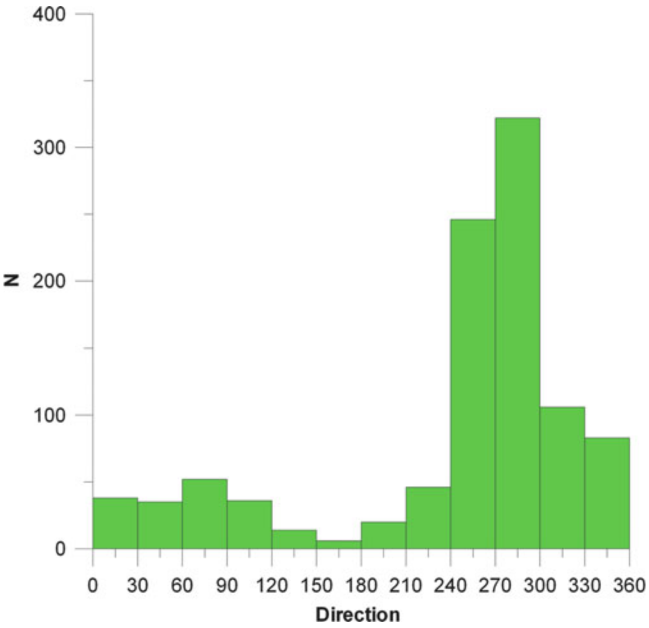

Fig. 18 The histogram of the hourly oil spill drift direction (degrees)

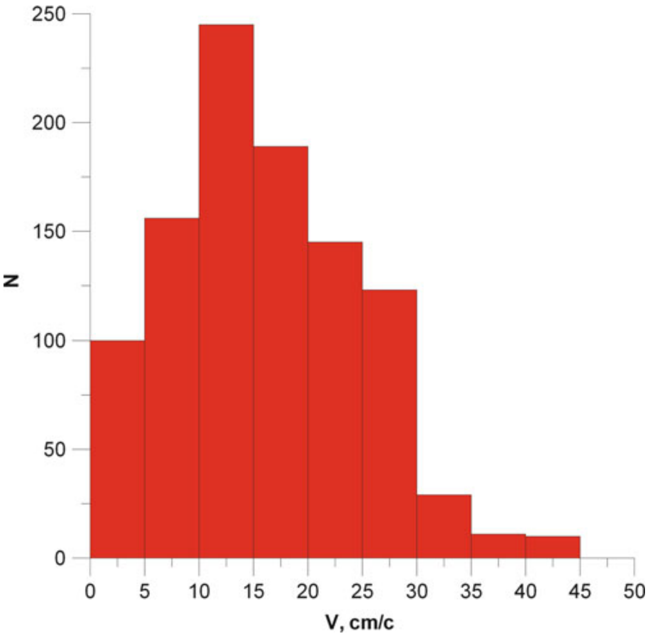

Fig. 19 The histogram of the hourly oil spill drift velocity (cm/s)

6.7 nm from the combined BSPA and IBA (to the west), 26.3 nm from Gotland Island and its coastal IBA, and at 44.5 nm from the BSPA located westward of 17.5°E (Fig. 20). The model oil spill drift on 5–7 August 2006 shows that even in summer conditions, the oil spill can drift during 2 days on a distance of 38.8 nm, and thus pose a threat not only to the above-mentioned protected areas and Gotland Island but also to the EEZ of Latvia, Lithuania, Russia, and Poland [17]. This is confirmed by a probabilistic analysis of the pollution drift, which shows that in the analyzed period of time, the oil spills predominantly propagated to the west, northwest, and northeast, and partially covered the protected areas southward of Gotland Island. A clear bimodal oil pollution drift (to the west–northwest and north–northeast) was confirmed by a histogram of the hourly oil spill drift direction (Fig. 21). The oil spill drift velocity was a bit lower than at point N4 and was in the range 0–44 cm/s with a maximum probability in the range 5–10 cm/s (Fig. 22). The average drift velocity was equal to 16.4 cm/s [17].

Point N6. The point with coordinates 54°49.10′N and 15°19.48′E is located to the southeast of Bornholm Island in the EEZ of Denmark (Fig. 23). This point is at 13 nm from the coast of Bornholm Island and its coastal BSPA, 30 nm from EEZ of Germany, and at 40 nm from the EEZ of Sweden and coast of Poland (Fig. 23). Besides, five BSPAs and three IBAs are located in the circle with a radius of 40 nm. The model oil spill drift on 5–7 August 2006 shows that even in summer conditions, the oil spill can drift during 2 days on a distance of 36.3 nm, and thus pose a threat not only to the above-mentioned protected areas, coasts of Bornholm Island and

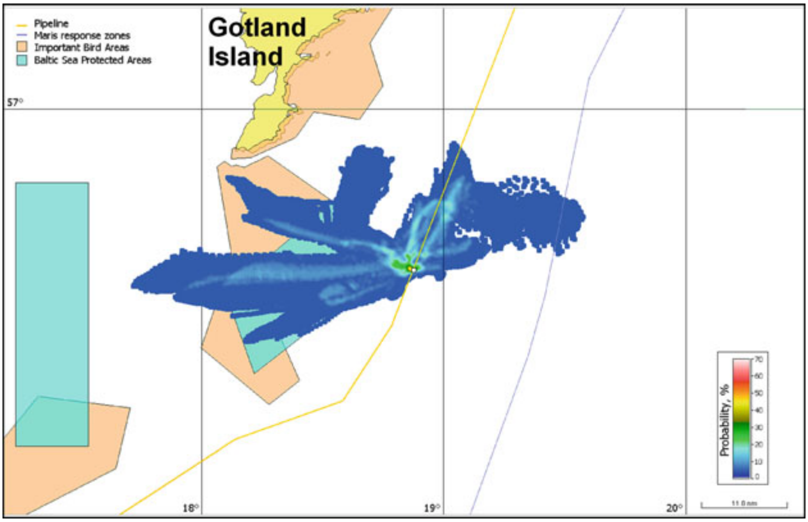

Fig. 20 Probability (%) of oil pollution calculated for a point N5 for 26 July–15 August 2006

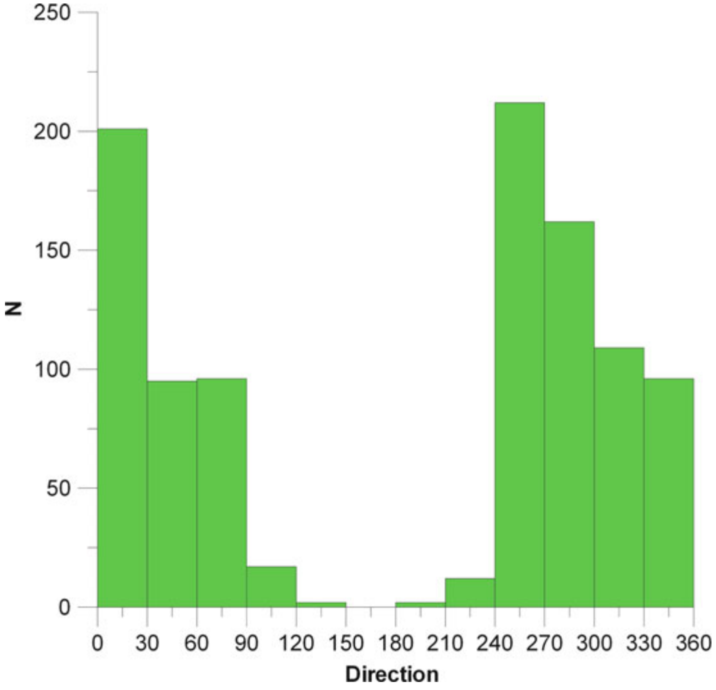

Fig. 21 The histogram of the hourly oil spill drift direction (degrees)

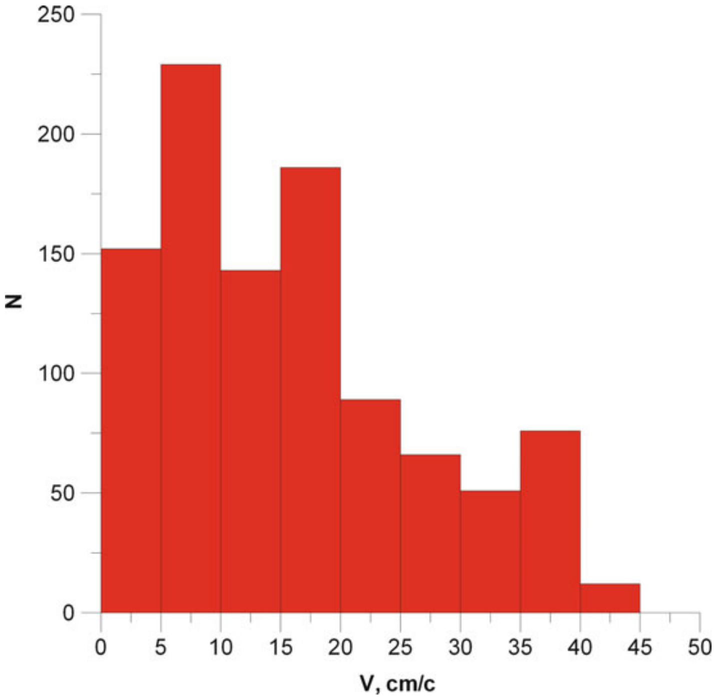

Fig. 22 The histogram of the hourly oil spill drift velocity (cm/s)

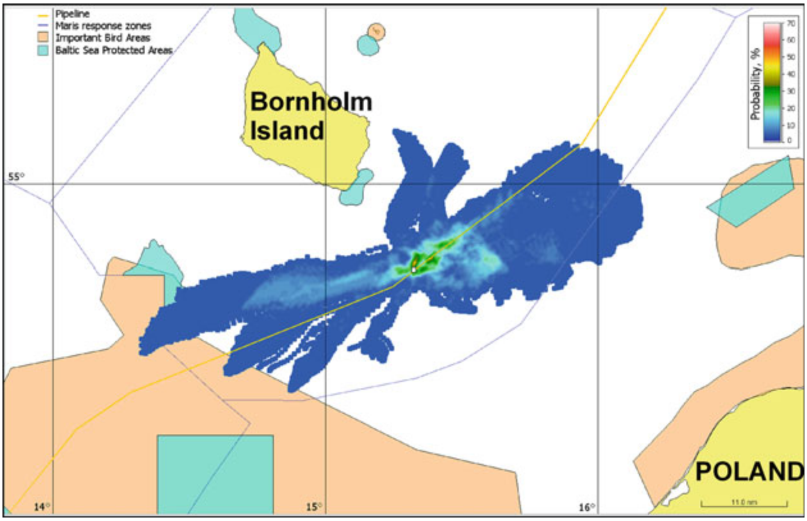

Fig. 23 Probability (%) of oil pollution calculated for a point N6 for 26 July–15 August 2006

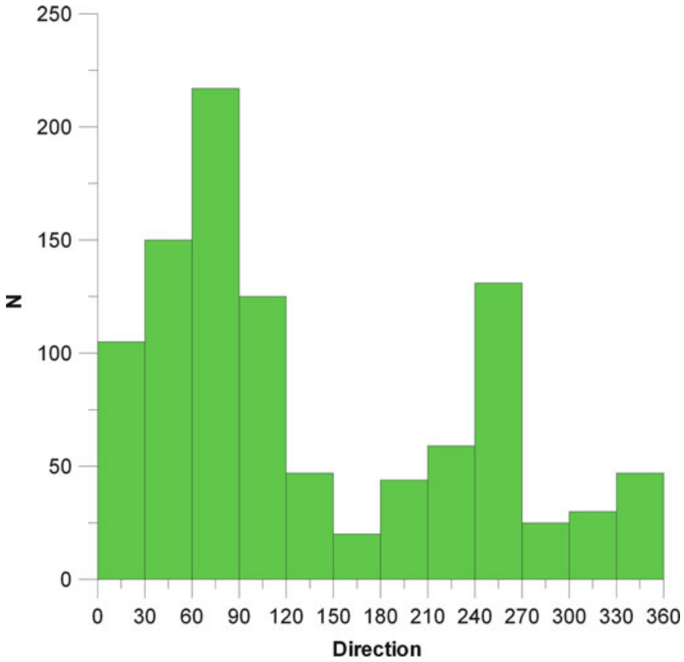

Fig. 24 The histogram of the hourly oil spill drift direction (degrees)

Poland, but also to the EEZ of Germany and Sweden [17]. This is confirmed by a probabilistic analysis of the pollution drift, which shows that in the analyzed period of time, the oil spills predominantly propagated to the southwest and northeast and partially covered two protected areas of Denmark and Germany. A clear bimodal oil pollution drift (to the southwest and northeast) was confirmed by a histogram of the hourly oil spill drift direction (Fig. 24). The oil spill drift velocity was in the range 1–54 cm/s with a maximum probability in the range 5–10 cm/s (Fig. 25). The average drift velocity was equal to 16.2 cm/s [17].

Point N7. The point with coordinates 54°15.77′N and 13°44.70′E is located at the exit from the Bay of Greifswald, in which the BSPA and IBA are located (Fig. 26). This point is at 15 and 22.2 nm from another two German BSPAs, 21 nm from the EEZ of Poland, 33 nm from EEZ of Denmark, and directly in the large IBA, stretching to the east (Fig. 26). The model oil spill drift on 14–16 August 2006 shows that even in summer conditions, the oil spill can drift during 2 days on a distance of 20 nm, and thus pose a threat not only to the above-mentioned protected areas, coasts of Germany and Poland, but also to the EEZ of Denmark [17]. This is confirmed by a probabilistic analysis of the pollution drift, which shows that in the analyzed period of time, the oil spills predominantly propagated to the southwest inside the bay and to the northeast being inside the BSPA and IBA of Germany. A general oil pollution drift to the northeast was confirmed by a histogram of the hourly oil spill drift direction (Fig. 27). The oil spill drift velocity was in the range 0–22 cm/s with a maximum probability in the range 0–2 cm/s (Fig. 28). The average

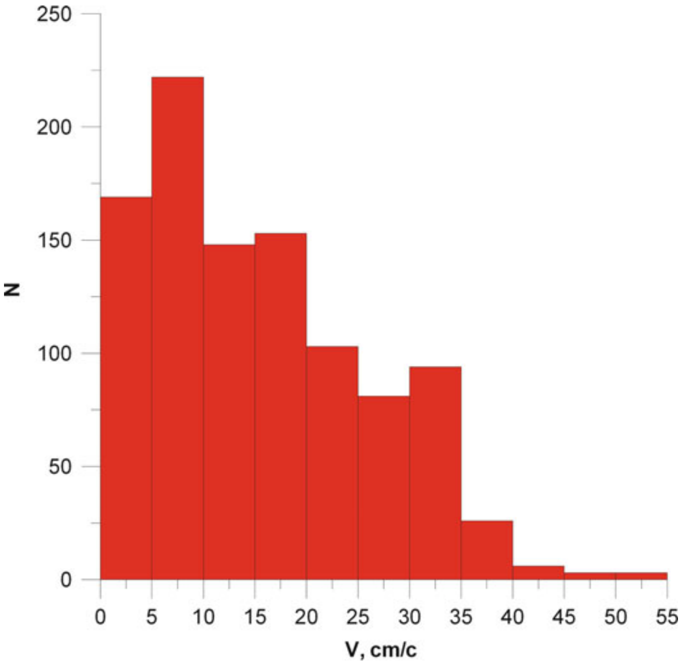

Fig. 25 The histogram of the hourly oil spill drift velocity (cm/s)

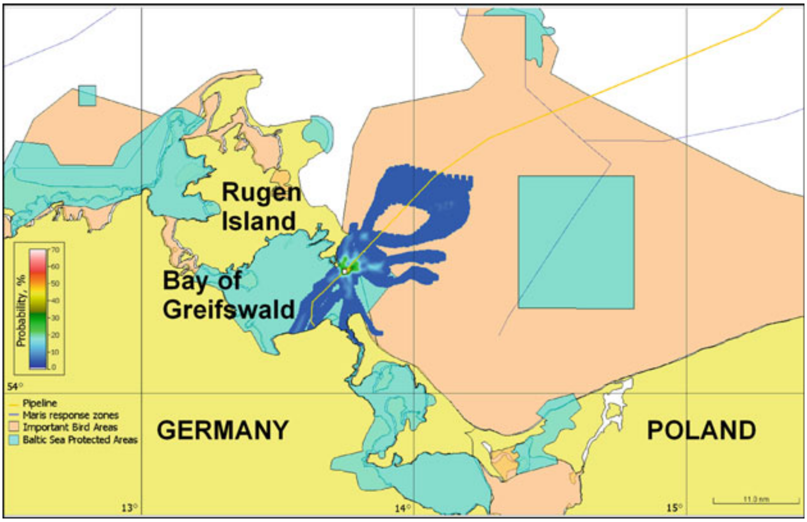

Fig. 26 Probability (%) of oil pollution calculated for a point N7 for 26 July–15 August 2006

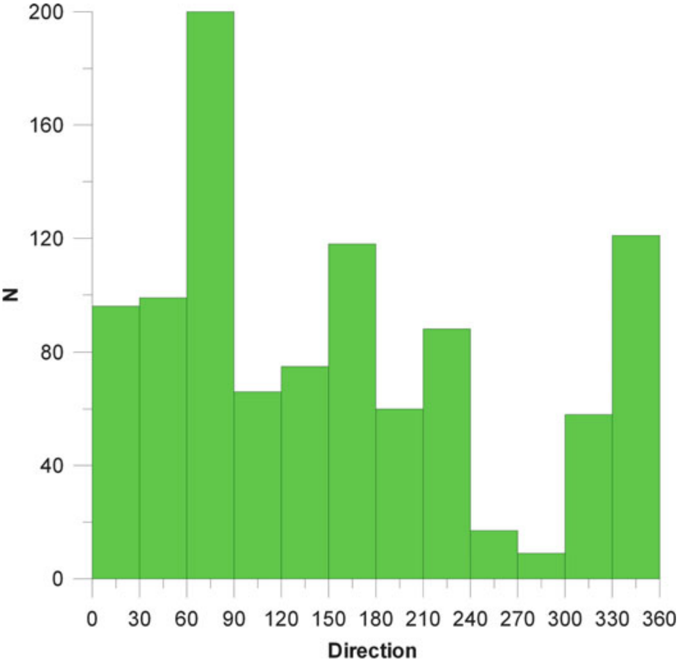

Fig. 27 The histogram of the hourly oil spill drift direction (degrees)

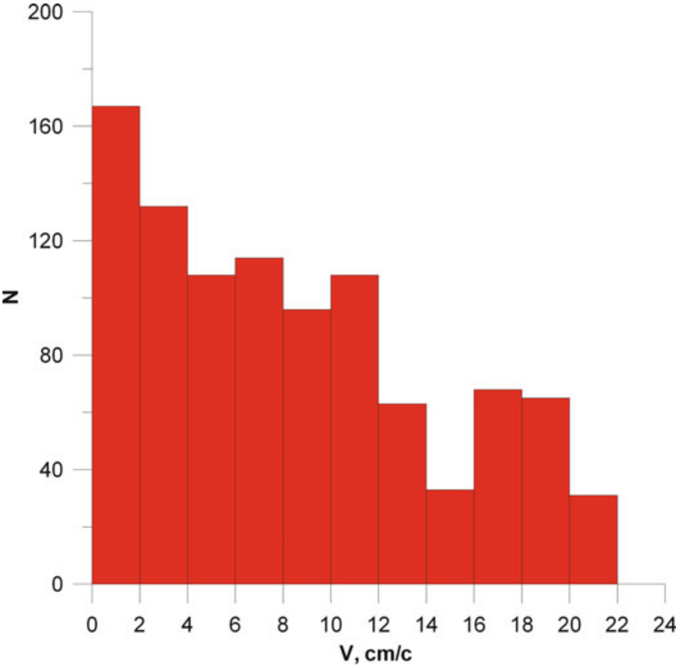

Fig. 28 The histogram of the hourly oil spill drift velocity (cm/s)

drift velocity was small – 8.7 cm/s, which is explained by slow currents in the semi-enclosed bay and weak winds in the summer time [17].

6 Marine Protected Areas in the Baltic Sea

Marine protected areas (MPAs) are zones of the world ocean, inland seas, and coasts where wildlife is protected from damage and disturbance. There are many definitions of MPA, but the most widely used is that, given by the International Union for Conservation of Nature (IUCN): “A clearly defined geographical space, recognised, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values.” There are many types of MPAs worldwide, which have a broad range of conservation objectives. MPAs enable us to protect and restore the ecosystems, including species and habitats, keep a biodiversity of marine life, provide natural areas for scientific study, and let public enjoy nature.

World Database on Marine Protected Areas has in its records information about more than 5,000 MPAs in the world, 90% of them have a national and 10% have an international status [19]. It is interesting to know that percentage of world oceans covered by MPAs is 0.65% only. In the Baltic Sea, there are several hundreds of national and international MPAs with the following distribution between countries (in alphabet order): Denmark – 167, Estonia – 9, Finland – 26, Germany – 40, Latvia – 4, Lithuania – 4, Poland – 5, Russia – 4, and Sweden – 489 [19]. In 1994, 62 Baltic Sea Protected Areas (BSPAs) were designated under HELCOM Recommendation 15/5. In 2008, their number raised to 90, and today the HELCOM BSPA Database has a list of 111 sites with the following distribution between countries (in alphabet order): Denmark – 47, Estonia – 7, Finland – 23, Germany – 26, Latvia – 5, Lithuania – 4, Poland – 10, Russia – 6, and Sweden – 31 [20]. Today, the BSPAs cover about 12% of the Baltic Sea area (Figs. 29 and 30). A need for an increase of the number and area of BSPAs is stipulated by the fact that ecosystems and fish stocks are in a vulnerable conditions in the Baltic Sea. The situation is aggravated by commercial fishing, eutrophication, chemical pollution, and regional climate change.

The above-described methodology may be applied to all the BSPAs, IBAs, and any part of the coastal zone and islands in the Baltic Sea in order to quantitatively assess the impact of the observed oil pollution resulted from the ship routes and potential oil pollution from ports and oil terminals, offshore oil platforms and pipelines on these areas [8, 9]. Thus, for every protected area and any part of the coastal zone or islands, we can calculate a degree of vulnerability in terms of a probability to be polluted by oil. Such a map for the whole Baltic Sea would be very useful for national and international environmental agencies, organizations, and research institutes. The hot spots on this map will help to detect, locate, and precise the shape of new BSPAs that must be organized in the nearest future to protect the Baltic Sea environment.

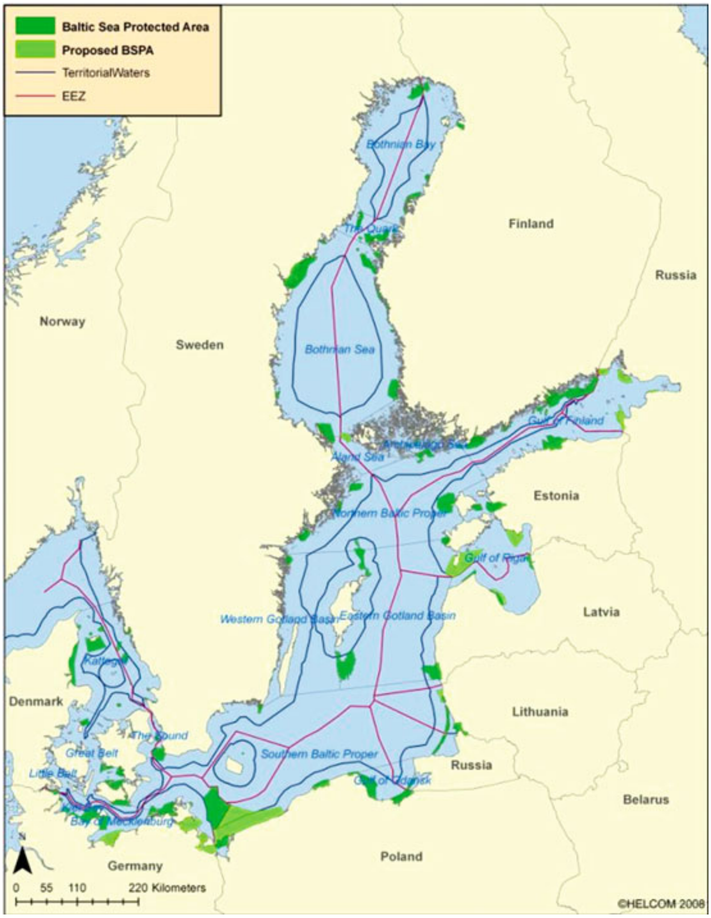

Fig. 29 The status of the Baltic Sea Protected Areas in 2008 [20]

International Maritime Organization (IMO) has designated the Baltic Sea as a Particularly Sensitive Sea Area (PSSA), which is a recognition that the sea is particularly sensitive and under threat related to shipping and maritime activities [21]. IMO defines a PSSA as "an area that needs special protection through action by IMO because of its significance for recognized ecological, socio-economic, or scientific attributes where such attributes may be vulnerable to damage by international shipping activities." The PSSA designation means that the countries of the region can agree on specific measures "Associated Protective Measures" (APM) to reduce the risk of environmental damage from international shipping [21]. A number of such APM has been introduced in other PSSAs around the world, which have improved the ecological situation significantly in many areas. By 2006, only one APM was associated with the Baltic PSSA: the maritime traffic separation scheme in central and southwestern Baltic, which improved the environmental security of the Baltic Sea [21]. It is clear that a number of additional APMs could

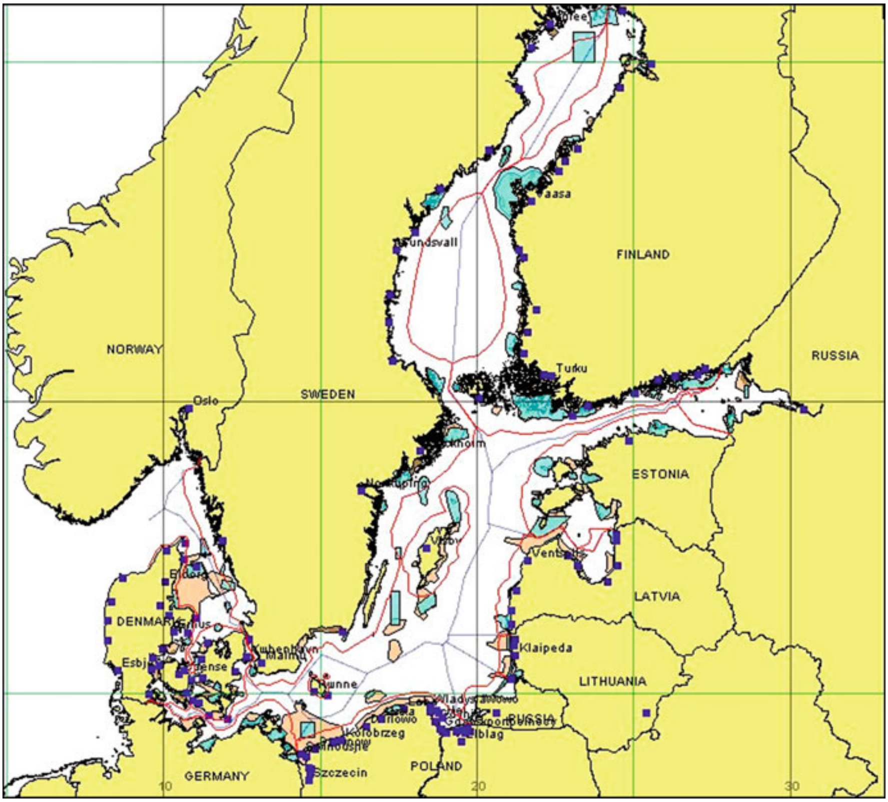

Fig. 30 The Baltic Sea Protected Areas (*blue* areas) and Important Bird Areas (*light-brown* areas) in 2012 according to the Seatrack Web model. *Red lines* shows limits for territorial waters, *blue lines* – delimitation of the MARIS response zones

make shipping in the Baltic much safer and thus the marine environment and coastal zone more secure. These measures could be based on the results of the statistical analysis of oil spill drifts in real weather and marine conditions provided by our methodology and Seatrack Web model (see the Gulf of Finland and Gotland Island case studies in Part 4). This new approach could be a promising component for implementation of the EU Baltic Sea Strategy.

Also, the proposed methodology could be very useful for more accurate costs assessment related with a major oil spill in the Baltic Sea. For example, three case studies in the southern Baltic Sea with a scenario when 10,000 t of oil spilled in the sea during an accident of a tanker showed that the total cost associated with an oil spill varies from 100 to 400 million Euro [22]. In this research, the costs related to oil spills are categorized in three groups: (1) direct costs refer to costs for cleaning the beaches; (2) market costs refer to losses of profits in different industries that are dependent on a clean coastal environment (e.g., tourism or fisheries); and (3) nonmarket costs refer to environmental costs and other costs that are not priced in a market [22]. The cost calculations strongly depend on the length of the coastline that will be polluted and if the protected and fishery areas, recreation and tourist zones were affected. The methodology described in this chapter allows to precise the exact parts of the coastline that are potentially under the threat of oil pollution resulted from accidents and routine shipping activities. Moreover, every kilometer of the land and island coastline can have a calculated probability to be polluted. This information will significantly improve the costs assessment procedure related to accidental and routine oil spill pollution.

7 Conclusions

We can summarize that in the framework of several projects related to organization of the complex satellite monitoring of the Lukoil D-6 oil platform in the southeastern Baltic Sea and a construction of the Nord Stream gas pipeline in the whole Baltic Sea we elaborated a new, very effective technology for the quantitative environmental risk assessment, based on the Seatrack Web model. For every kilometer of the coastline, the Baltic Sea Protected Area, Important Bird Area, as well as for any part of the sea surface, it allows to calculate in percent a probability to be polluted by oil, resulted from operations in ports, oil terminals, oil platforms, oil pipelines, and shipping activities (main ship routes) in the Baltic Sea. Moreover, the proposed methodology allows to calculate exactly what part (in % or km^2) of the protected area will possibly be affected by oil pollution with its own probability.

This technology was applied to different installations of oil and gas industry, as well as to shipping activities in the Baltic Sea. The obtained results have been shown in three case studies discussed in this chapter. It should be noted that the obtained maps with the probable oil spill drift and areas of potential impacts of oil pollution, as well as the statistical characteristics of velocity and direction of oil spill drift are more demonstrative than those that can be used to determine the real potential areas of exposure. This is explained by low statistics used for the construction of the probability maps: 184 daily forecasts for the case of D-6 oil platform, 62 – for the main ship route in summer conditions, and 21 – for the Nord Stream gas pipeline route in summer conditions. In autumn and winter, the drift velocity can be twice as large, and hence the zone of influence may be twice as wide. The directivity diagram of the general oil pollution drift and the form of the impact zone may also change significantly.

Probability of oil pollution, for example, from an oil platform is normally calculated basing on the climatic averaged data on water circulation and wind pattern, which do not represent real conditions for oil spill drift, as well as for unrealistic time periods up to several months. The advantage of the proposed methodology is that it is using a huge number of daily forecasts of oil spill drift based on real metocean data assimilated in the Seatrack Web model every 3 h from the whole Baltic Sea.

In the performed projects, we did not have a task to construct probability maps basing on the full-scale multiyears statistics. Our aim was to show that we elaborated a very useful numerical instrument for environmental risk assessment and that the impact of oil pollution from different sources is large enough to have coastal zones, islands, BSPAs, and IBAs in the Baltic Sea under a certain threat, which can be calculated. A special work is required and could be done to provide precise data on the impact zones in any season of the year and give the potential probability (in percent) of a threat for any protected area, part of the coastline or the EEZ of the Baltic States.

We hope that the methodology of calculation of the probability of potential oil pollution of the Baltic Sea marine protected areas and a coastal zone, based on the operational numerical model Seatrack Web, will be used in the Baltic Sea countries and in the international organizations for the environmental risk assessment. An application of this technology can be easily used to produce a general map of the hot spots in the whole Baltic Sea in terms of the marine or coastal areas, which are the most vulnerable to the existing threats/sources of oil pollution like the main ship routes, ports, oil terminals, and oil pipelines. It can be used also for a construction of new installations in the sea.

The interface among risk assessors, risk managers, and interested parties during planning at the beginning and communication of risk at the end of the risk assessment is critical to ensure that the results of the assessment can be used to support a management decision [12]. Environmental risk assessment must express results clearly, show major assumptions and uncertainties, identify reasonable alternative interpretations, and separate scientific conclusions from policy judgments. Risk managers use risk assessment results, along with other factors (e.g., economic or legal concerns), in making risk management decisions and as a basis for communicating risks to interested parties and the general public [12]. Then, they may consider whether follow-up activities are required. Because of the diverse expertise required, especially in complex environmental and ecological risk assessments for the Baltic Sea, risk assessors and risk managers must work in multidisciplinary international teams.

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Satellite Monitoring of the Nord Stream Gas Pipeline Construction in the Gulf of Finland

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Abstract This chapter explains the need for comprehensive satellite environmental monitoring of the Nord Stream gas pipeline construction in the Baltic Sea, including monitoring of oil pollution, the spread of suspended matter, algal bloom, and thermal effects at the sea surface. Examples of the different types of the observed contamination along the pipeline route long before the pipeline construction are shown. This chapter is focused on the results of oil pollution monitoring during the pipeline construction, and also shows the results concerning the satellite monitoring of ice cover, suspended matter, algal bloom, and thermal effects on the sea surface in the Gulf of Finland.

Keywords ASAR imagery, Baltic Sea, Coastal zone, Gulf of Finland, Marine environment, Nord Stream gas pipeline, Oil pollution, Satellite monitoring

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1 Introduction

The Nord Stream offshore gas pipeline is a transport system designed for natural gas export from Russia to Germany and then to the European Union via the Baltic Sea. It goes from the compressor station of Gazprom Company near Portovaya Bay in the Vyborg District of Leningrad Region to the receiving gas terminal at Lubmin near Greifswald on the northern coast of Germany (Fig. 1). The pipeline offshore route 1,220 km long transects the Exclusive Economic Zones (EEZ) of five states – Russia, Finland, Sweden, Denmark, and Germany, as well as waters of the territorial seas of Russia, Germany, and Denmark.

The Nord Stream gas pipeline (NSGP) has become a new gas supplier to Europe, which allowed to connect directly the largest Russian gas fields with Western Europe. Construction of the first line of the pipeline with a capacity of 27.5 billion m^3 of gas per year began in April 2010 and was completed in June 2011. Gas supplies to Europe through the first line of the pipeline began on 8 November 2011. Construction of the second line began in May 2011. On 18 April 2012 pipe number 99,953, the last pipe of the second line, was welded onto pipeline, which was lowered onto the seabed off the coast of Gotland Island by the *Castoro Sei* laybarge. According to the schedule, transportation of gas via the second line will begin in the last quarter of 2012. After the release of gas pipeline at full operational capacity, it will deliver 55 billion m^3 of gas per year for at least 50 years.

As the ecological conditions of the Baltic Sea (even regardless of the pipeline construction) for several reasons are of great concern to the Baltic States, a network of national marine laboratories and institutions perform a monitoring of various physical, chemical, and biological parameters of the Baltic Sea. Obviously, such an ambitious project as the NSGP construction attracts attention from national and international organizations responsible for protection of the Baltic Sea environment.

The pipeline has been planned with deep awareness of the environmental issues and specific conditions of the Baltic Sea, basing on the comprehensive Environmental Impact Assessment program that was conducted during several years before implementing the project [1]. The construction process of the pipeline may cause, in particular, the following impact on the marine environment: (1) oil pollution due to the operation of ships, pipelay vessel, dredge ships, and mechanisms in the sea; (2) increase of suspended matter concentration due to dumping of sand and gravel, and dredging operations; (3) provoking of local algal bloom events in summertime due to vertical mixing resulted from dumping and dredging works.

Fig. 1 The scheme of the Nord Stream gas pipeline route in the Baltic Sea

During the operation of NSGP, at the compressor station, before going to the sea, the gas will be pumped with a pressure of about 220 bar and must be heated much more than 40°C to avoid its condensation in the tube on its long way to Germany due to low temperature at the bottom of the sea. Despite a thickness of the tube of 27–41 mm, a corrosion protective layer of 3 mm and a thickness of concrete cover of 60–110 mm (which makes the tube heavier), the pipeline may represent an extended permanent heating element with a diameter of 1.4 m. A potential permanent thermal convection from the tube may cause local warming of water column over the tube with a sea surface temperature (SST) anomaly, the increase of eutrophication in the surface layer of the sea, the growth of biomass of blue–green algae, and even constitute a barrier to fish migration routes.

Thus, there are two very important and interrelated tasks in relation to the NSGP construction and exploitation: (1) to monitor in the operational regime the ecological state of the sea at the site of the pipeline construction and (2) to discriminate between natural effects and anthropogenic impacts, related to the construction itself. If a notable thermal convection from the tube is observed, a permanent satellite monitoring of the entire pipeline route will also be required at the stage of its operation.

An integral part of any modern environmental monitoring of land or sea is a satellite-based multiparametric monitoring, which has great additional features and advantages in comparison with ground-based methods. All four types of potential contaminants and impacts (oil pollution, suspended matter, algal bloom, and thermal effects) are well tracked from satellites [2], so the program of integrated environmental monitoring related to the NSGP construction must include a satellite component, which will be focused on these four parameters. It should be noted that in situ monitoring at the point of construction will be insufficient because the spatial characteristics of the observed pollution are unknown. Moreover, they may be caused by natural processes like mixing of coastal waters, yearly algal bloom, thermal anomalies in the form of eddies, meanders, and filaments, as well as oil pollution may be explained by "alien" oil spills resulted from the nearest ship route. In addition, satellite data cover very large areas of the Baltic Sea (including protected areas, EEZ of neighboring countries), which allows to establish the sources of pollution and compare quantitatively the impact of the NSGP construction with other natural or man-made factors.

A detailed motivation for organization of the NSGP satellite monitoring was prepared by A.G. Kostianoy in 2006 in a form of the Technical Report under the contract with PeterGaz LLC [3]. That time the pipeline had a bit different name – the North-European Gas Pipeline. The document included detailed recommendations for satellite monitoring of the pipeline construction, including analysis of metocean data and numerical modeling of the oil pollution transport, based on the Seatrack Web model. The recommendations were based on our experience in complex satellite monitoring of oil pollution around the Lukoil D-6 oil platform installed in 2004 in the southeastern Baltic Sea [2, 4–6]. The motivation was supported by the environmental risk analysis related to potential oil pollution resulted from the construction sites. The appropriate examples are shown in one of the chapters in this book [7]. The advisability of satellite monitoring of the NSGP construction was mentioned in several scientific publications [8–10]. We have to note that the elaborated satellite monitoring technologies for marine oil and gas industries are of great interest both in Russia and abroad [2, 11, 12].

In this chapter, we will focus on the motivation and the results of oil pollution monitoring during the NSGP construction, and also show the results concerning the satellite monitoring of ice cover, suspended matter, algal bloom, and thermal effects on the sea surface in the Gulf of Finland.

2 Motivation for Satellite Monitoring of the NSGP

2.1 Oil Pollution

According to the world statistics, maritime transportation is responsible for about 45–50% of oil pollution observed in the ocean. For comparison, oil production at the shelf gives only 2–3%. Very often, it is suggested that only oil tankers are responsible for pollution of the marine environment. Observations in the ocean show that ships of different types are potential polluters – oil tankers, cargo, container, fishing, military, ferry, and even cruise ships. The distribution of the ships in the world's fleet (about 35,000 commercial vessels, 1 billion tons in total) is as follows (by total tonnage): tankers – about 39%, bulk carriers – 26%,

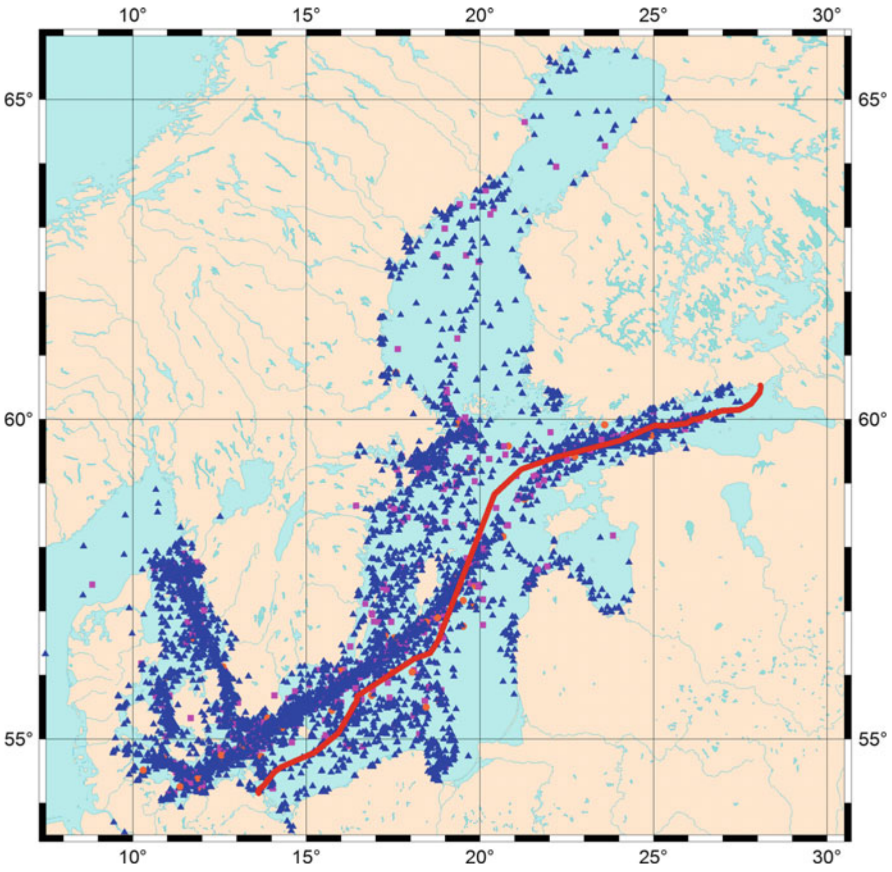

Fig. 2 Map of oil spills detected in the Baltic Sea in 1989–2002 basing on HELCOM data [HELCOM Response, 2009]. Category 1 (▲) - $<1\ \text{m}^3$, category 2 (■) - $1\ \text{m}^3 < 10\ \text{m}^3$, category 3 (▲) - $10\ \text{m}^3 < 100\ \text{m}^3$, category 4 (●) - $>100\ \text{m}^3$. *Red line* denotes the approximate route of the NSGP

containers – 17%, other types – 15%. Different estimates show that 0.5–8.4 million tons of petroleum (oils) come yearly to the sea from all known sources, thus about a half of this value belongs to the ships [13].

In the last two decades in the Baltic Sea a number of new oil terminals have been built. The last one was officially open on 23 March 2012 in Ust-Luga (Russia) in the Gulf of Finland. This resulted in a significant increase of oil transportation via the Baltic Sea, which was accompanied by a rise of transportation of other goods and a total increase of ship traffic. Every day in the Baltic Sea there are about 2,000 large ships, 14% of them being tankers. Figure 2 gives an idea on a degree and a spatial distribution of oil spills, detected in the Baltic Sea in 1989–2002 by aerial surveillance [14]. As expected, the accumulated spatial distribution of oil spills clearly outlines the major shipping routes in the sea aimed at the major ports and oil

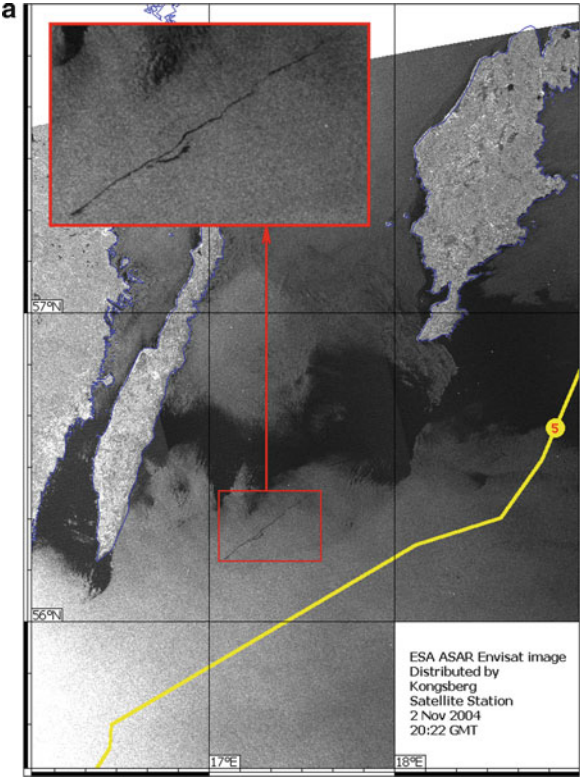

Fig. 3 (continued)

terminals. Therefore, the main sources of oil pollution are the ships that have repeatedly been observed in satellite radar images of the sea surface [2–6, 15–18].

We put over a red line, which indicates an approximate route of the NSGP (Fig. 2). In many parts of the sea it coincides exactly with the ship route, and a line with a highest concentration of oil spills in the Baltic Sea. Thus, along the pipeline route we have already been yearly observing the maximum of oil spills discharged from ships well before the Nord Stream construction (Figs. 2 and 3). For instance, Fig. 3b shows an example of a serial release of oil products to the sea, presumably from a tanker, which washed separate tanks one by one in the vicinity of the future Nord Stream line.

That is, pipeline construction will take place at a time when passing ships can discharge oil products, and produced oil spills can be attributed to the pipeline construction with possible subsequent sanctions. This fact leads to a supplementary task: oil spills must be distinguished between potential “own” pollution and “alien” pollution belonging to the transient ships, which will require a justification documentary. It is for this reason we suggested that operational satellite monitoring of oil pollution along the construction works on the pipeline must be a priority [3]. We proposed that ecological monitoring of the NSGP in the Baltic Sea has to

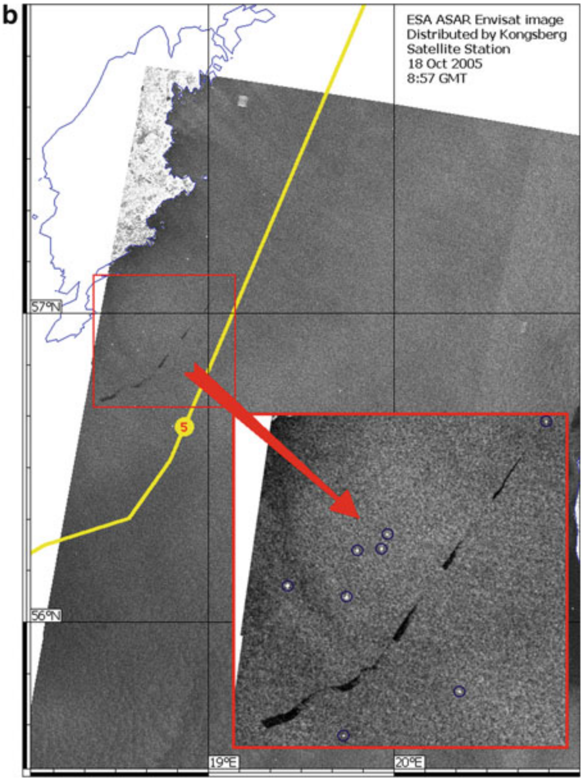

Fig. 3 Oil spills detected in the Baltic Sea in the vicinity of the planned route of the NSGP (*yellow line*) on 2 November 2004 (**a**) and 18 October 2005 (**b**) on ASAR Envisat imagery [4, 5]. Zooms on oil spills are shown in *red boxes*. *White dots* in (**b**) are ships around the spill with a tanker – polluter in the northeastern corner of the frame

include the operational satellite monitoring of all oil spillages detected in the vicinity of the site of the pipeline construction, and determination of their characteristics, establishment of the pollution sources, and forecast of probable trajectories of the oil spill transport. The interactive numerical model Seatrack Web SMHI was mentioned to be used for forecasting of the drift of the detected oil spills in the vicinity of the pipeline construction for assessment of ecological risks related to potential oil pollution of the neighboring coasts and marine protected areas in the Baltic Sea [7].

2.2 Suspended Matter

The construction process of the pipeline will cause the development of local plumes of sedimentary material resulted from dumping of sand and gravel on the seabed or induced by dredging activities at the bottom and in the coastal zone. From the other side, Figs. 4 and 5 show locations of very large areas with high concentration of

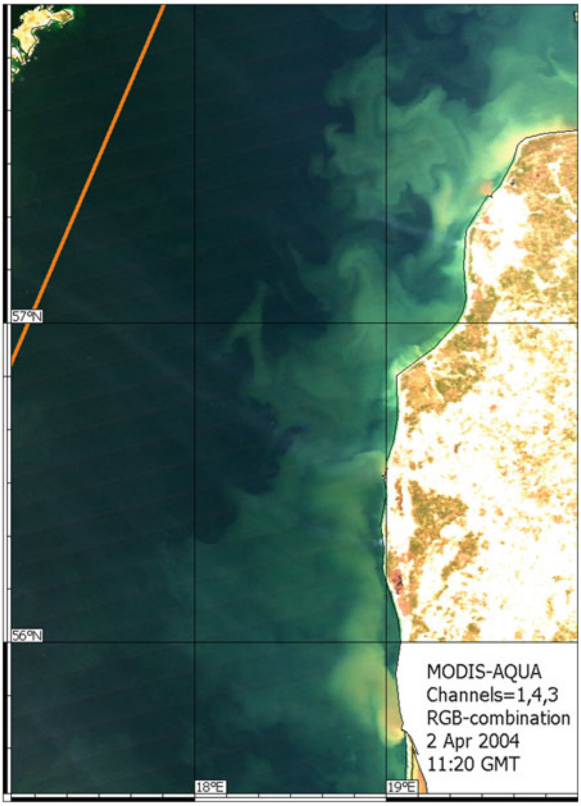

Fig. 4 Suspended matter distribution in the central eastern Baltic Sea derived from MODIS-Aqua on 2 April 2004 (spatial resolution 500 m). *Orange line* marks the planned route of the NSGP

suspended matter (light colors in Fig. 4) which is a natural phenomenon resulted from the mixing of coastal waters. Owing to the strong wind events, the material in the shallower areas is brought into suspension and advected by the currents. Usually, the transport of fine material starts in the shallow coastal regions when the wind speed exceeds a value of 10 m/s. Thus, the transport of fine material is weak during the summer and early autumn and is most intense in winter season.

The analysis of optical imagery acquired by MODIS-Aqua and MODIS-Terra in 2004–2005 showed that areas with high concentration of suspended matter up to 70 km wide are located along the coasts and have a nonuniform structure, which is explained by mesoscale dynamical processes (eddies, meanders, jets), which redistribute suspended matter over the Baltic Sea, including the central parts of the sea where the NSGP will pass (Fig. 4). Such kind of natural phenomena are observed yearly in different parts of the sea, especially along the coasts of Lithuania, Latvia, and around the Estonian islands. The other source of turbid waters are plumes from bays and rivers. Figure 4 shows such a turbid plume propagating from the exit of the Curonian Bay northward along a coast of Lithuania, which is clearly visible in the southern part of the frame. Figure 5 shows a transport of huge amount of suspended matter in the Gdansk Bay from the Vistula River mouth due to spring

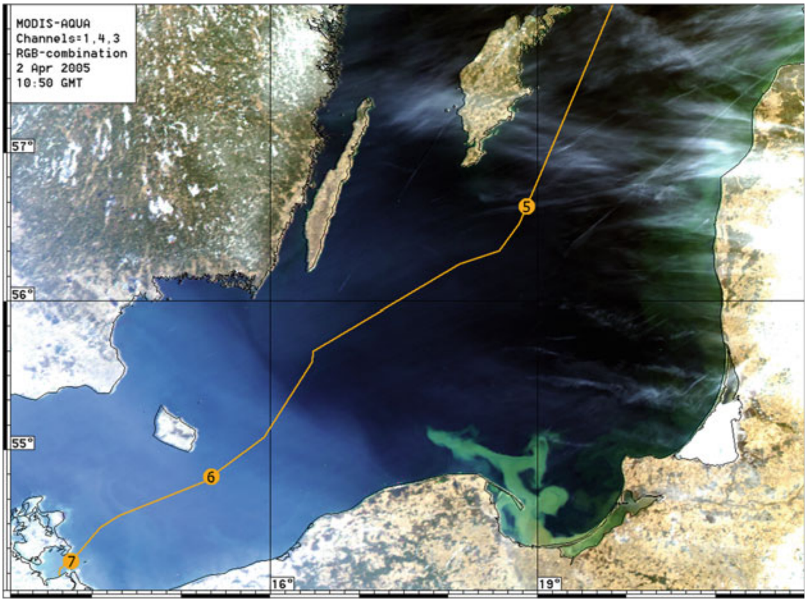

Fig. 5 Suspended matter distribution in the southern Baltic Sea derived from MODIS-Aqua on 2 April 2005 (spatial resolution 500 m). *Orange line* marks the planned route of the NSGP

flooding. It was observed that such a river plume may propagate up to 150 km from the mouth of the Vistula River thanks to coastal current, mesoscale eddies, and jets. We can also note that in this particular case the river plume moves northwestward, i.e., against the classical schemes of water circulation in this region and with very high velocity.

Discrimination between natural and anthropogenic effects in the generation of suspended matter fields was proposed for inclusion in the list of tasks for complex satellite monitoring of the NSGP construction [3].

2.3 Algal Bloom

The NSGP construction process may theoretically cause, in particular, local algal bloom events in summertime due to vertical mixing and transport of nutrients to the sea surface, resulted from dumping and dredging works. From the other side, occurrence of cyanobacteria is a natural phenomenon in the brackish Baltic Sea water and is known for about 7,000 years. But since the 1960s the blooms of cyanobacteria have increased in biomass, duration, and harmfulness [19]. Every year in summer different types of cyanobacteria form massive algal blooms in the Baltic Sea, which is very well detected by optical satellite remote sensing of the ocean color (Fig. 6). This is an effective technique to monitor the life cycle of an algal bloom.

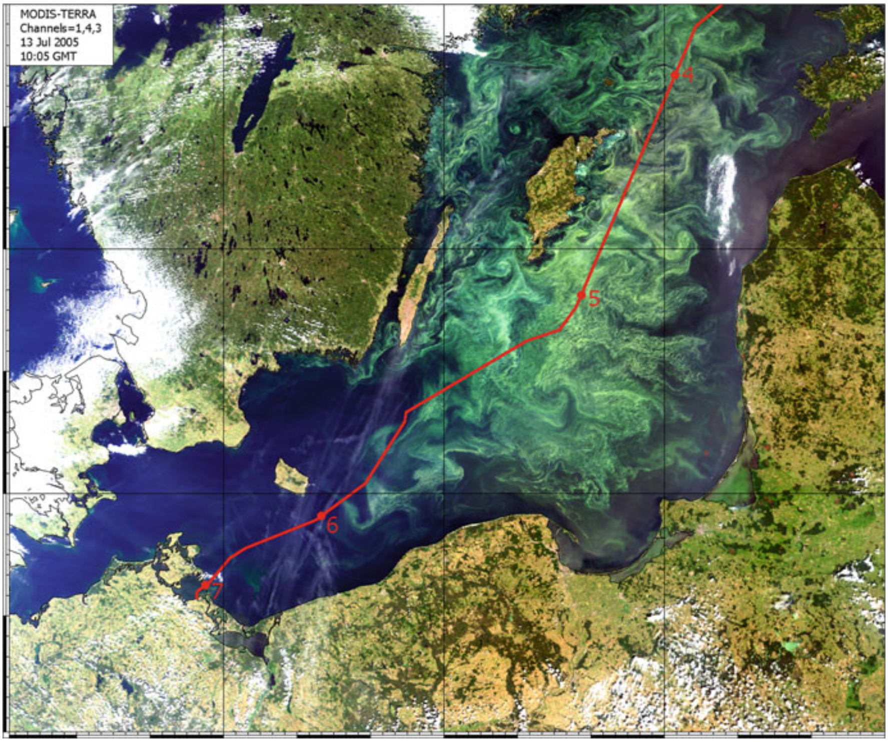

Fig. 6 Algal bloom in the Baltic Sea derived from MODIS-Aqua and -Terra on 13 July 2005. *Red line* marks the planned route of the NSGP

Intense blue–green algal growth is directly linked to high phosphorus concentrations in surface waters caused by excessive nutrient loads coming especially from agriculture and municipal wastewaters. Warm, calm, and sunny weather during July to August 2004–2006, in combination with the available phosphate, resulted in a widespread and very intense bloom (Fig. 6). It stretched from the Gulf of Finland to the German coast, and was one of the worst ever in the history of the Baltic Sea. Another reason for the high levels in the main basin of the Baltic Sea is the phosphorus, which is released from the bottom sediments of the sea when the oxygen situation is poor. Autumn and winter storms mix the water column and transport phosphorus into the surface layer, where it is in the reach of algae.

Similar processes may be provoked by the NSGP construction during dumping of sand and gravel and dredging at the bottom. This is why we have to discriminate between natural and anthropogenic effects, which can be done via permanent satellite monitoring of the construction sites [3]. It is clear that areas covered by natural bloom (up to 60,000 km^2) are much larger than the possible anthropogenic ones, but we suggested this algal bloom control also in order to show that the proposed monitoring systems takes into account all possible impacts resulted from the NSGP construction.

The analysis of algal bloom and suspended matter spatial distribution around the future NSGP route in satellite imagery (both represent a very good tracer at the sea surface) allowed to obtain a very important result: the zones of the impact of the pipeline construction (e.g., advection of oil pollution or suspended matter) may reach 80 km on both sides from the pipeline due to meso- and small-scale dynamical structures [3].

2.4 *Thermal Effects*

Gas supply to Europe via the first line of the NSGP started on 8 November 2011. Before going to the sea, at the compressor station the gas is pumped with a pressure of about 220 bar and is heated much more than 40°C to avoid its condensation in the tube on its long way to Germany due to low temperature at the bottom of the sea. Despite a thickness of the steel tube of 27–41 mm, a corrosion protective layer of 3 mm and a thickness of concrete cover of 60–110 mm (which makes the tube heavier), the pipeline may represent an extended permanent heating element with a diameter of 1.4 m. A potential permanent thermal convection from the tube may cause local warming of water column over the tube with a SST anomaly, the increase of eutrophication in the surface layer of the sea, the growth of biomass of blue–green algae, and even constitute a barrier to fish migration routes. Unfortunately we do not know the working values of gas pressure and temperature to make some estimates of a possible thermal convection over the pipeline. It is clear that the impact of this convection will depend also on the surrounding water temperature, vertical density stratification, local depth, season of the year, and mixing processes. It is also evident, that this effect will decrease with a distance from the compressor station at the coast of Portovaya Bay. Thus, if in the Russian sector of the NSGP such a thermal impact will be low or absent, there is no sense to check it along the other parts of the pipeline.

Satellite monitoring allows to detect the first order different effects from such a possible thermal convection, because if the convection will be strong, it will reach and be displayed at the sea surface. Spectroradiometers and radar installed at Aqua, Terra, NOAA, and Envisat satellites allow to detect anomalies in SST, ocean color, suspended matter, chlorophyll concentration, ice cover, and roughness of the sea at the scale of hundreds of meters. We started such a monitoring of these parameters since November 2011. If we will not observe any signatures of thermal convection at the sea surface at this scale, there is a sense to check it at a scale of first tenths of meters with a help of an unmanned aerial vehicle (UAV) [or UAS – unmanned aircraft system, which is the official United States Federal Aviation Administration (FAA) term for UAV] with an infrared camera or by a towing thermistor from a boat. If the result will be negative again, we recommend to use a towing CTD-probe or a remote-controlled underwater vehicle (ROV) in the bottom layer of the sea to make exact measurements of the convection from the pipeline.

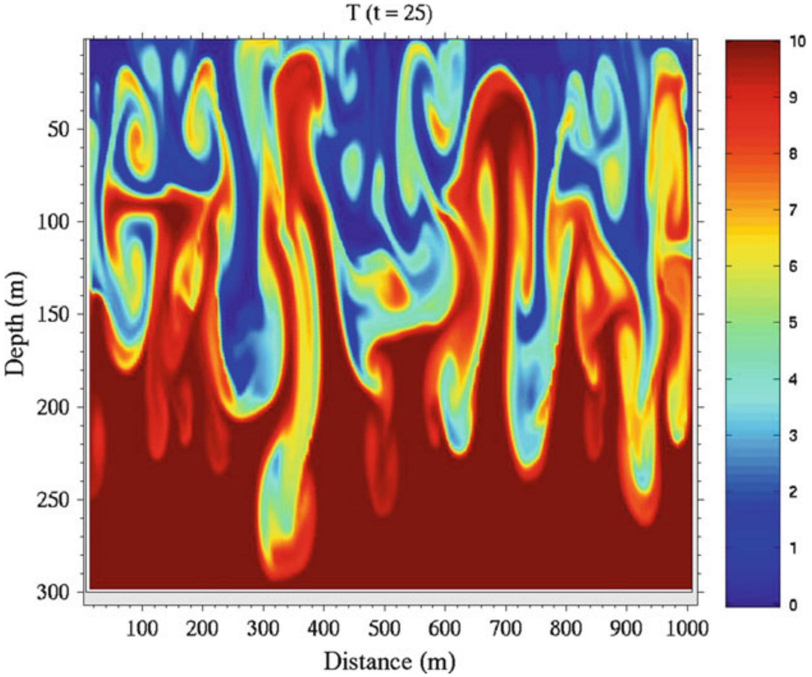

Fig. 7 Two-dimensional thermal convection from the ocean bottom simulated by numerical modeling [29]

Figure 7 shows an example of numerical modeling of a thermal convection from the bottom of the sea. Theoretically this picture may represent a side view on the possible convection from the pipeline. We have to note that along the Mid-Ocean Ridge system we can observe a significant thermal convection related to hydrothermal vents, which is a natural analog of a warm pipeline. As a result hydrothermal plumes are formed at intermediate depths of the ocean at the level of their density equilibrium. Close to the bottom they represent hot hydrothermal fluids with temperature as high as 60–460°C.

3 Observation of Oil Pollution Along the NSGP Route

Starting from January 2009 and till 8 April 2012 the satellite radar monitoring of the aquatic area of the Gulf of Finland was carried out by the Space Radar Laboratory of the Space Research Institute of the Russian Academy of Sciences, headed by Dr. O.Yu. Lavrova. The main attention was focused on the detection of oil pollution as well as biogenic and anthropogenic surfactant films. The basic data were medium resolution (75 m/pixel) radar images obtained by synthetic aperture radars onboard Envisat and ERS-2 satellites of the European Space Agency (ESA). More than 500

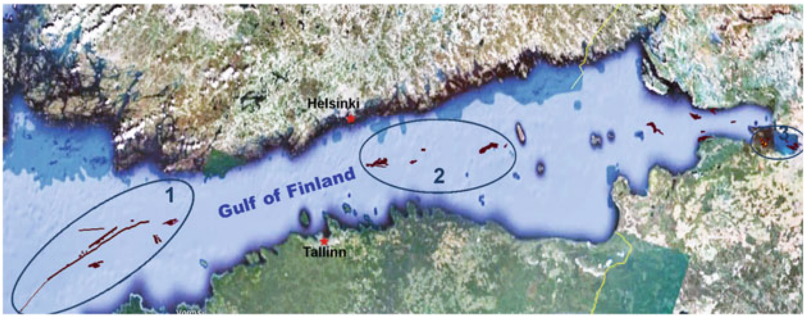

Fig. 8 Map of oil spills revealed from satellite radar imagery in the Gulf of Finland in January 2009 to 8 April 2012

ASAR Envisat and SAR ERS-2 radar images of the sea surface in the region of interest were obtained, processed, and analyzed. Unfortunately, on 8 April 2012 ESA announced that Envisat unexpectedly stopped sending data to Earth receiving stations. On 9 May 2012, after a month of efforts to regain contact with the satellite, the end of the Envisat satellite operations was declared by ESA. Independently, from 1 May 2010 till 8 April 2012 the satellite radar monitoring of the Russian sector of the NSGP was carried out by the satellite monitoring team from P.P. Shirshov Institute of Oceanology of the Russian Academy of Sciences, headed by Prof. A.G. Kostianoy, working under the contract with Nord Stream AG (Moscow Office) on the monitoring of the impact on the marine environment from the construction of the pipeline [20–22].

During the time period from January 2009 till 8 April 2012 on radar images we detected 45 cases of sea surface pollution of anthropogenic origin in the Gulf of Finland. Figure 8 represents the accumulated map of these oil spills (black patches and lines) with their real size and shape. According to this map, we can outline (encircled in Fig. 8) three regions of the most intense pollution: (1) entrance to the Gulf of Finland, (2) central part of the Gulf eastward of the shipping route Helsinki-Tallinn, and (3) the Neva Bay (see Fig. 9). Long-term satellite monitoring made it possible to reveal and analyze typical situations of sea surface pollution for each of these areas.

Regular SAR observations revealed a very high level of sea surface pollution at the entrance to the Gulf of Finland (Fig. 8). All the detected pollution events in this region are concentrated along the main shipping routes and are caused by spillages of oil-containing waters from moving ships. In the case of spillage from a moving ship there appears a narrow either straight or kinked dark (reduced signal) stripe in radar image following the ship route. If the discharge occurs in the moment of image acquisition or just before it, the stripe is narrower because the track is still fresh and not diffused. Usually in such situations, it is possible to identify the ship responsible for the spillage. Some ships continue dumping wastewaters for dozens of kilometers on their way. In Fig. 10a–c four examples of radar signatures of fresh spillages from moving ships are given.

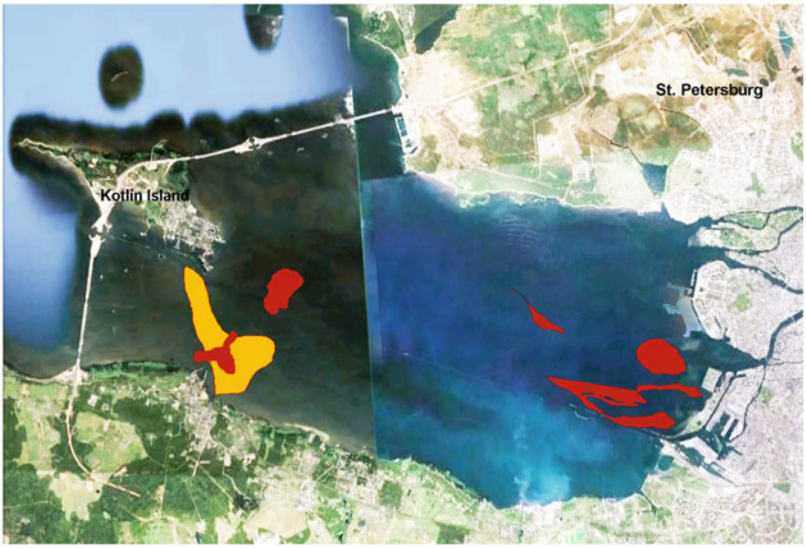

Fig. 9 Map of oil spills revealed from satellite radar imagery in the Neva Bay (the easternmost part of the Gulf of Finland) in January 2009 to 8 April 2012

Figure 10a shows a fragment of the ASAR Envisat image acquired on 6 June 2009 in the area northwestward of Saaremaa Island (Estonia) under weak wind and surface wave conditions. Spillages from two ships moving one after another out of the Gulf of Finland are well seen. This is proved by the pollution slick lines which become thinner to the southwestward ends, where a ship-polluter must be located. Unfortunately, the ship traffic in this area is so intense that there are several candidates for the role of polluter even at the beginning of the spill at the time of the satellite pass. Bright white dots indicate the ships location. The total spillage extends for 88.6 km.

More often illegal discharges were detected along the ship route northward of Hiiumaa Island (Estonia). Radar images shown in Fig. 10b and c were obtained on 17 June 2010 and 25 June 2011, respectively. In both cases the narrowing of the spills in the southwestern direction indicates the direction of the ships motion. Bright dots at the southwestern ends of the black stripes indicate the locations of ships at the moment the image was taken. The first spill extends for 3.5 km and the second one for 6.24 km. The situations of this type were often observed during the period of monitoring, but they cannot be related to the NSGP construction, because of a concentration of oil spills in one specific region, while the construction process goes slowly along the NSGP route, and because at any time the pipelay ship represents a quasi-stationary (motionless) vessel, but not a moving one. Thus, the spill from a quasi-stationary ship must look like a patch, but not a line.

Film pollutions detected in the radar images taken over the central part of the Gulf of Finland are characterized by lesser lengths but larger areas (Fig. 8). Their geometrical forms correspond to that either of spillages from motionless ships under windless condition and calm sea, when oil spreads in all directions with the

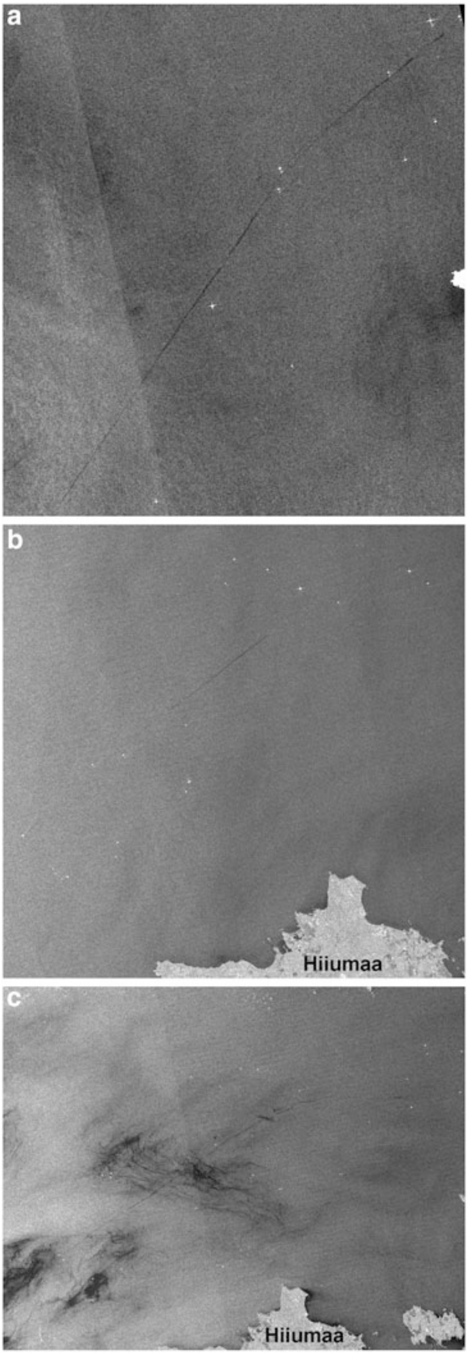

Fig. 10 Oil spills (*black straight lines*) as seen in the satellite radar images of the westernmost part of the Gulf of Finland (© ESA): (**a**) ASAR Envisat, 06 June 2009, 20:16 UTC. Two fresh oil spills from moving vessels. Total length – 88.6 km; (**b**) ASAR Envisat, 17 June 2010, 19:59 UTC. Fresh oil spill from the moving vessel. Length – 3.5 km; (**c**) SAR ERS-2, 25 June 2011, 19:58 UTC. Fresh oil spill from the moving vessel. Length – 6.24 km. Ships in the sea are visible as *bright white dots*

same velocity and oil patch on the sea surface has round shape, or to the "old" weathered spills distorted due to local currents and near-surface winds. It is also impossible to explicitly identify a ship responsible for the spill. Quite often, unstable stratification of the sea–atmosphere boundary layer is a hindering factor that results in cellular background of a radar image, which makes the detection of oil spills difficult.

The illustrative examples of spillages of this type are shown in Fig. 11. A spillage from a motionless ship is shown in Fig. 11a. The spill was spread under the influence of the moderate southern wind and northeastern along-coast current, its surface is of 6.27 km^2. The biggest spillage over the period of monitoring was detected in ASAR Envisat image taken over the central part of the Gulf of Finland (Fig. 11b, c). It was located 14 km southwestward of Gogland Island (Russia) and 7 km southward of the NSGP route. In 4 km westward of this oil spill we observe a smaller one of the size of 3 km × 1 km (Fig. 11c). The large one is a typical example of a weathered oil spill. Under the direct influence of the wind the film shifts over the sea surface, oil being accumulated on the leeward of the patch. Moreover, near-surface wind induces dynamic processes in the upper layer of the sea. The Langmuir circulation is the most common process which is caused by wind-driven spiral circulations of alternating directions with the axis almost parallel to the wind. Inside a vortex water moves in the plane perpendicular to the wind velocity vector. Thus on the sea surface there appear alternating divergence and convergence zones, oil being concentrated in the latter. An oil spill transforms into streaks that are referred to as "comb-like structure." The shape of the spill is distorted under the influence of local currents and south-southeastern wind with speed 4 m/s. The total polluted surface area had reached 28.5 km^2 by the moment of radar image acquisition. It is also impossible to explicitly identify a ship responsible for the spill. The pollution was revealed in the area of an intensive ship traffic and a lot of bright dots indicating locations of the ships at the moment the image was taken are seen near the spill, as well as one ship was observed directly inside the spill (Fig. 11c). On 3 August 2010 we detected an elongated comb-like spill 12.7 km long with a surface of 8.4 km^2 in 50 km northeastward of Tallinn (Fig. 11d). Again, several ships were located in the vicinity of this a bit weathered oil spill, thus, it was impossible to detect a polluter.

The Neva Bay is the easternmost part of the Gulf of Finland between the Neva River mouth and Kotlin Island (Figs. 8 and 9). The Saint Petersburg Dam, connecting Kotlin Island with both coasts, separates the bay from the Baltic Sea and prevents the city to be periodically flooded due to strong westerly winds (Fig. 9). The Neva Bay has an area of 330 km^2. Film pollutions of the sea surface in the Neva Bay are mostly caused by coastal outflows which are composed mainly of industrial and household wastewater, ground rainwash, and accidental runoffs from industrial plants and ports of Saint Petersburg. Particularly, widespread slick areas located in close proximity to the coastal line near the Lomonosov town were detected in several radar images (see Fig. 12a). A lot of slicks are often observed in direct proximity to the Neva River mouth (see Figs. 9 and 12b). Furthermore, some spillages are detected along the main shipping routes directed to the Neva Bay, westward of Kotlin Island (Fig. 8).

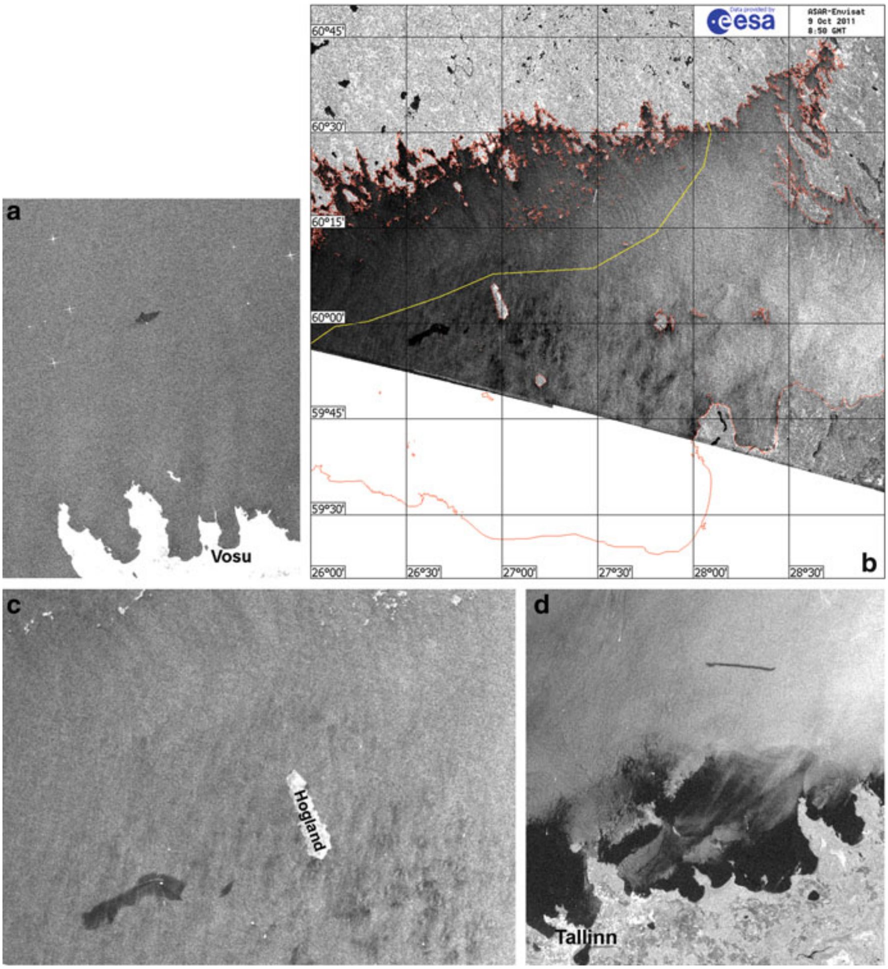

Fig. 11 Oil spills (*black patches*) as seen in the satellite radar images of the central part of the Gulf of Finland (© ESA): (**a**) ASAR Envisat, 22 July 2010, 20:06 UTC. The release of oil-containing waters from the motionless vessel. Surface – 6.27 km^2; (**b**) ASAR Envisat, 09 October 2011, 08:50 UTC. Weathered oil spill – "comb-like" structure. Surface – 28.5 km^2; (**c**) zoom on oil spill shown in (**b**); (**d**) ERS-2, 03 August 2010, 09:26 UTC. An elongated comb-like spill. Length – 12.7 km, surface – 8.4 km^2. *Yellow line* in (**b**) shows the NSGP route

Accumulation of the anthropogenic pollution of the Neva Bay represents serious threat to the marine environment and coasts because of a limited water exchange with open waters of the Gulf of Finland due to a dam. The situation is aggravated by the rising river shipping traffic across Saint Petersburg. For example, in 2010, 5,124 ships crossed the city, in which 1,168 with petroleum products. As a result 72 oil spillages have been observed and eliminated by ecological port services. Approximately the same numbers of oil spills have been detected in 2011. An additional potential threat represents the Saint Petersburg oil terminal with a turnover of 12.5 million tons.

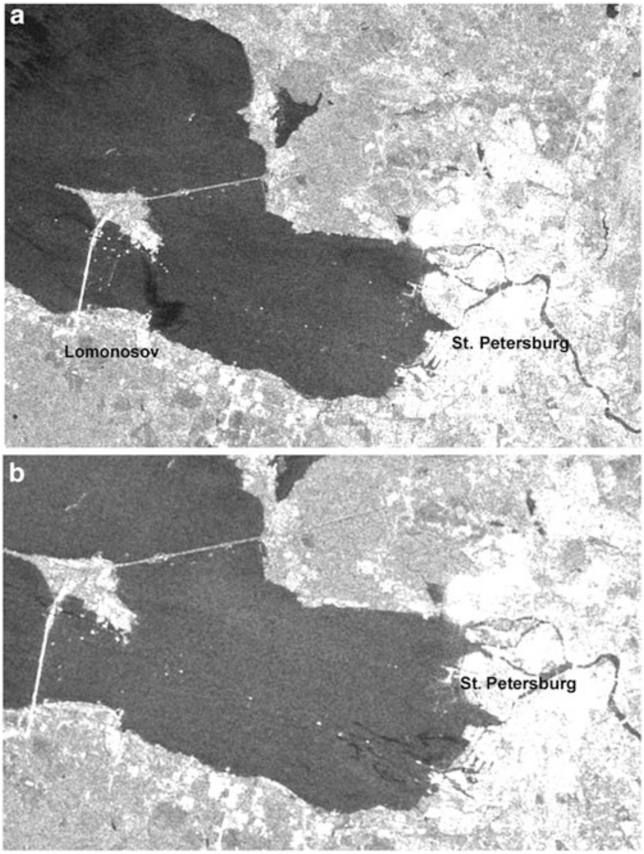

Fig. 12 Surface slicks (*black patches*) seen in the satellite radar images of the Neva Bay (the easternmost part of the Gulf of Finland) (© ESA): (**a**) ASAR Envisat, 03 November 2010, 08:33 UTC. Widespread slick area near the Lomonosov town. Surface – 13.1 km^2; (**b**) ASAR Envisat, 24 August 2011, 08:37 UTC. Anthropogenic slicks in direct proximity to the Neva River mouth. Surface – 3.5 km^2

Main parameters of the most notable pollution events detected in satellite radar images are summarized in Table 1. All year round satellite monitoring of the Gulf of Finland performed in January 2009 to April 2012, including the time of the NSGP construction from May 2010 till April 2012, made it possible to draw the following conclusions. Over the period of observation, 45 events of sea surface pollution of anthropogenic origin have been detected. The area of individual oil spills varied from 0.1 to 28 km^2, total polluted areas being of 28, 57 and 116 km^2 for years 2009, 2010, and 2011, correspondingly. It should be noted that all cases of surface pollution in the Gulf of Finland were detected in satellite radar images acquired from April to November periods. Strong near-surface winds persist over the area of interest in the periods from end of November to January. Imprints of atmospheric phenomena sometimes cover the major part of radar image taken in

Table 1 Main parameters of the largest oil spills and slicks detected in the Gulf of Finland from January 2009 to April 2012

Date	Time (UTC)	Latitude	Longitude	Length (km)	Area (km^2)	Comments
2009/05/11	09:03	58°40′44.87″N	21°30′22.85″E	36.3	20	An elongated spill at the entrance to the Gulf of Finland near the Saaremaa Island
2009/05/24	08:50	59°14′29.33″N	21°50′31.57″E		0.54	Entrance to the Gulf of Finland. Two rounded spills
		59°18′2.72″N	21°58′40.47″E		0.78	
2009/06/06	20:16	58°54′28.41″N	21°15′16.44″E	88.6	6.645	A narrow straight spill
2010/05/16	08:38	60° 6′44.71″N	29° 1′9.18″E		13.4	Large slick distorted due to near-surface winds
2010/06/17	19:59	59°23′58.47″N	22°11′32.51″E	23.7	3.5	Fresh multiple spillages from a moving vessel
2010/07/15	08:53	59°52′54.00″N	25°18′25.17″E		9.7	A weathered spill
2010/07/22	20:06	59°53′13.91″N	25°44′58.23″E		6.27	A fresh spillage from a motionless vessel
2010/08/03	09:26	59°52′30.41″N	25°18′15.71″E	12.7	8.4	An elongated comb-like spill
2010/10/03	08:36	60° 2′9.35″N	28°31′24.66″E		14.5	A weathered comb-like spill
2011/04/28	09:02	59°25′13.71″N	22°51′18.99″E	11	0.99	Two narrow kinked spills
2011/05/05	19:30	60°4′22.61″N	29°26′35.69″E		0.68	Two low-contrast slicks
		60°1′31.67″N	29°5′9.24″E		1	
		59°59′18.00″N	29°4′31.19″E		3.9	A slick caused by coastal outflows
2011/05/10	19:44	59°53′14.13″N	25°21′17.36″E	14.9	2.3	Narrow kinked spills
2011/05/24	19:43	59°57′52.24″N	29°51′23.18″E		1.8	The Neva Bay area A spillage from a motionless vessel
		59°56′6.86″N	29°47′33.93″E		0.7	The Neva Bay area A slick caused by coastal outflows near Lomonosov town
2011/06/19	08:56	59°15′1.42″N	22°9′2.40″E		15	A large slick
		59°30′56.69″N	23°0′19.85″E		20.6	A weathered comb-like spill
2011/06/22	08:45	60°8′40.60″N	29°13′9.59″E		4.9	A slick caused by coastal outflows

(continued)

Table 1 (continued)

Date	Time (UTC)	Latitude	Longitude	Length (km)	Area (km^2)	Comments
2011/06/25	19:58	59°8′47.18″N	21°36′11.72″E	78	6.24	A narrow straight spill
2011/07/09	19:48	59°57′54.29″N	25°51′58.55″E	2.76	0.2208	A rounded spill
2011/08/16	08:29	59°56′34.50″N	30°4′41.47″E		3.3	Two slicks near the Neva River mouth
		59°55′24.16″N	30°10′35.05″E		2.8	
2011/08/21	20:11	59°27′21.87″N	22°5′13.68″E	16.8	1.2	A low-contrast narrow dashed spill
2011/08/24	08:37	59°54′13.31″N	30°9′4.55″E		3.5	The Neva Bay area. Slicks near the coastline
2011/10/09	08:50	59°59′19.77″N	26°40′22.84″E		28.5	The biggest spillage over the period of monitoring
		59°58′51.37″N	26°48′35.44″E		1.1	A rounded spill
2011/11/03	08:33	59°55′33.50″N	29°48′22.25″E		13.1	The Neva Bay area. A slick caused by coastal outflows near Lomonosov town
2011/11/03	19:59	59°31′1.68″N	22°33′26.27″E	41.7	4.20	A narrow dashed spill

this region, and the variations of radar signal intensity they introduce are rather high. This makes it practically impossible to identify film pollutions of the sea surface at these locations in radar images. In the period from January to March almost all area of the Gulf of Finland is covered by ice.

As concerns the NSGP construction in 2010–2011 and oil pollution in the Gulf of Finland, we did not get signatures of such a relationship. The main reason for oil pollution in the Gulf of Finland before, during, and after the construction of NSGP are shipping activities, which are rising during the last two decades. We have to recognize that, fortunately, the Nord Stream Company did not have problems with national authorities of the Baltic Sea states concerning discrimination between “own” and “alien” oil spills. From one side, this is a result of a high quality work of the Nord Stream Company in the sea, from the other side, fortunately, large oil spill have not been released at the time and in the vicinity of the pipelaying sites.

4 Monitoring of Suspended Matter, Thermal Effects, and Algal Bloom

4.1 Suspended Matter

The results of the satellite monitoring of suspended matter, thermal effects, and algal bloom along the NSGP route in Gulf of Finland are outside of the main scope of this chapter and a book devoted to oil pollution, but we would like to mention here brief information about these issues also.

Extensive consultations on the environmental aspects of the Nord Stream Project at the international level in the framework of the Convention on Environmental Impact Assessment in a Transboundary Context of the United Nations Economic Commission for Europe [23, 24] and national level [25] initiated the proposals for a need of water turbidity monitoring during the pipeline construction. The main factors for increasing the concentration of suspended matter during the construction of offshore gas pipelines are preparation of the seabed for laying the pipeline by constructing pillars of gravel at the bottom grooves to avoid sagging of the tube (prelay rock dumping) and follow-up with gravel filling (postlay rock dumping) in order to achieve a stability of the pipe at the bottom during gas transport, as well as pipelaying of the tube itself. Dredging in Portovaya Bay for burial of the pipeline in the bottom and the intersection of the shoreline can also lead to an increase in water turbidity. It should be noted that the Baltic Sea is a relatively shallow sea, so a large amount of suspended matter is formed by vertical mixing (making turbid) under the rough sea at shallows. Turbidity of water is most intense in the autumn and winter, when wind speed is greatest.

Instrumental monitoring of turbidity distribution was carried out along the whole line of the NSGP [26], including the waters of the Russian Federation [27]. In addition, considering the wishes of the Russian environmental and scientific organizations, for example, the State Scientific Research Institute for Lake and River Fisheries of the Federal Agency for Fisheries, from the first day (12 May 2010) of the gas pipeline construction in Russian waters a daily satellite monitoring of suspended matter propagation was organized under a leadership of Prof. A.G. Kostianoy with a support of Moscow Office of Nord Stream AG [20–22].

The tasks of the satellite monitoring of the NSGP construction in the Russian waters of the Gulf of Finland included the following [20–22]: (1) identification of patches of turbid waters in the area of construction of the Russian section of the pipeline and in the surrounding waters of the eastern Gulf of Finland; (2) determination of distribution range of suspended matter; (3) delineation of the anthropogenic effects of the pipeline construction and the natural processes that lead to increased water turbidity; (4) monitoring of the transboundary transport of suspended matter. For the purposes of satellite monitoring we used all informative (cloud-free along the pipeline route) daily satellite images, received with the Moderate Resolution Imaging Spectroradiometer (MODIS) of 250–1,000 m spatial resolution installed on satellites Terra and Aqua (NASA, USA) and the MEdium Resolution Imaging Spectrometer (MERIS) of 260 m resolution on the ENVISAT satellite (ESA). In May to November 2010 we have received in quasi-operational regime, processed and analyzed 26 MODIS and 23 MERIS satellite images, in May to November 2011 – 65 MODIS and 47 MERIS satellite images.

The analysis of satellite monitoring of suspended matter fields in conjunction with the analysis of meteorological information allowed to distinguish and quantify the effects of anthropogenic impact and natural processes of resuspension of sediments in the eastern part of the Gulf of Finland [20–22, 28]. The results obtained in 2010–2011 allow concluding that the spatial extent of areas of high water turbidity due to natural processes may be from tens to a thousand times greater than that caused by the construction of the NSGP. Most clearly the formation of suspended matter fields related to the construction of the Russian section of the NSGP was seen in Portovaya Bay during the construction of dams and dredging. The surface of turbid waters in about 20 registered cases was 0.1–8 km^2, but their concentrations did not exceed 6 g/m^3.

Daily satellite imagery showed that from 12 May to 30 September 2010 plumes of turbid waters occasionally appeared along the coasts of Finland, Estonia, southern coast of Russia, and in the Gulf of Vyborg (Fig. 13). They were produced, apparently, by a wind–wave mixing of coastal waters and a runoff of small rivers after the rains. The area of water with high concentration of suspended matter (8–10 g/m^3), due to natural causes, in some places was hundreds of kilometer square, and in July 2010, June and July 2011 it reached 1,000 km^2 (Fig. 13) [20–22]. These values were supported by independent composite satellite maps of turbid waters in the Gulf of Finland regularly produced by Finnish Environment Institute.

Transboundary transport of suspended matter was found to be an important factor in increasing the turbidity of water in some areas of the Gulf of Finland [20–22]. In July 2010, June and July 2011 within 2 weeks the transport of turbid waters (up to 4 g/m^3 of TSM) was observed from the area of Finland into the waters

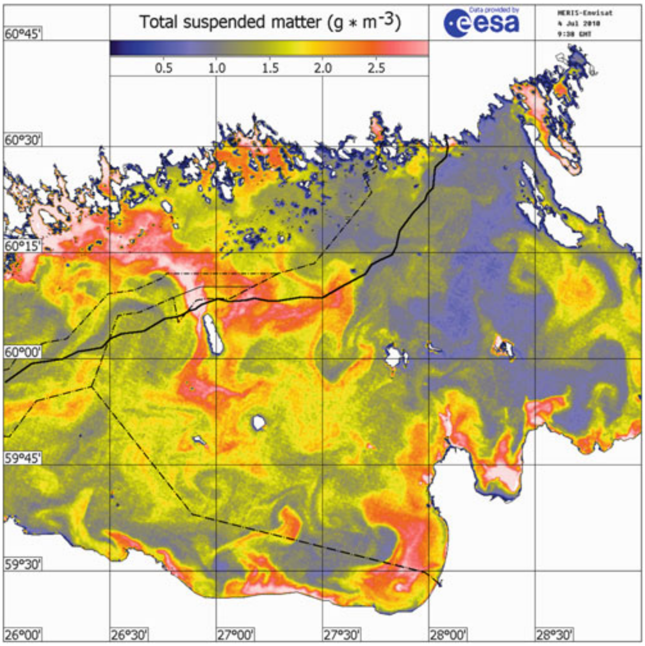

Fig. 13 Spatial distribution of the total suspended matter in the surface layer of the eastern part of the Gulf of Finland on 4 July 2010 (09:38 GMT) basing on the MERIS Envisat data (©2010, ESA). *Black line* is the NSGP route, *dashed lines* are marine borders between countries, and *white areas* are coasts and islands

of the Russian Federation, including the route of the NSGP. Historical satellite imagery of MODIS and MERIS for 2006–2009 showed that this is a normal natural phenomenon in this area that was yearly observed long before the NSGP construction. This information is confirmed by the turbidity maps of Finnish Environment Institute for 2006–2009 as well.

We may also conclude that the use of satellite monitoring of the suspended matter distribution resulted from the anthropogenic impact of construction of offshore pipelines, ports, and terminals is a very effective tool for assessment of the transboundary impact on the environment in the framework of the UNECE Espoo Convention [23].

4.2 Thermal Effects

Gas supply to Europe via the first line of the NSGP started on 8 November 2011. The main task for a satellite monitoring in 2012 was investigation of thermal effects on the sea surface in the Russian sector of NSGP, such as detection of local anomalies of SST and anomalies in the structure of ice fields, which could be

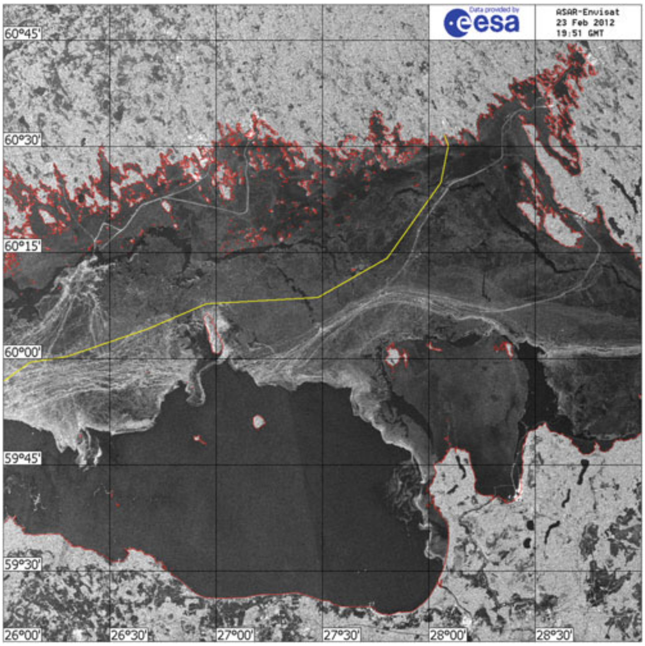

Fig. 14 Satellite ASAR Envisat image of the eastern part of the Gulf of Finland on 23 February 2012 (©2012, ESA). Spatial resolution – 75 m. The NSGP is shown by *yellow line*. Ice-free sea surface is visible in the southern part of the frame as a *uniform gray area*. The other part of the gulf is covered by ice. *Multiple white lines* in the ice are main routes of icebreakers and ships directed to the ports and oil terminals

similar to the straight lines of the pipeline. Since 1 January 2012 we organized a satellite monitoring of ice cover in the eastern part of the Gulf of Finland with a help of ASAR Envisat imagery of 75 m spatial resolution. From 1 January to 8 April 2012 we have received and analyzed 33 satellite radar images of ice cover. This year ice covering in the eastern part of the Gulf of Finland has started very late – on 24 January along the coast and islands of Russia. By 28 February ice covered all the eastern part of the gulf and from 10 March it started to melt in the southeastern part of the gulf. By 7 April, when the last image was received from Envisat, which stopped to operate on 8 April, separated large ice fields were still present in the easternmost part of the Gulf of Finland.

All radar images have been analyzed in order to detect strips in ice or polynyas located exactly over the NSGP route (Fig. 14). These signatures have neither been detected in the Russian sector of the NSGP nor in the vicinity of Portovaya Bay, where potential thermal effect could be expected maximal (Fig. 15). We did not find also any changes in the roughness of the sea in the ice-free areas in radar imagery. All this proves that, at least, there is no significant thermal impact on the sea surface from the pipeline. In the next months of the year 2012 the satellite monitoring will be oriented on the detection of local SST anomalies along the NSGP.

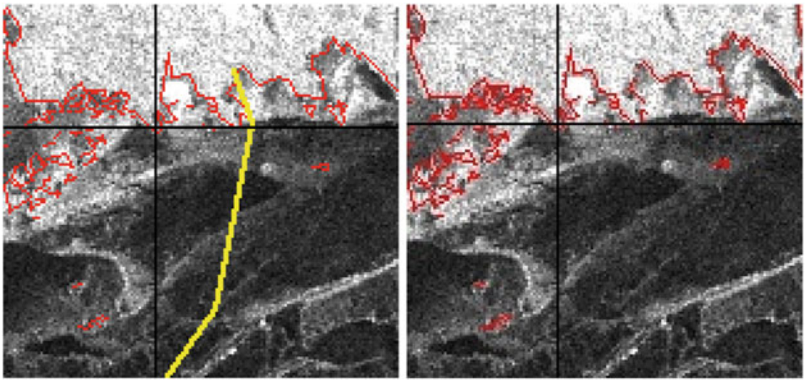

Fig. 15 Satellite ASAR Envisat image of Portovaya Bay and surrounding area on 28 February 2012 (©2012, ESA). Spatial resolution – 75 m. The NSGP is shown by *yellow line* on the *left panel*. *Right panel* shows that below the line there are no strips in the ice which coincide with the NSGP route

4.3 Algal Bloom

In 2010–2011 during the NSGP construction in Russian waters of the Gulf of Finland we did not observe any local anomalies in the suspended matter distribution along the pipeline route, except of Portovaya Bay. We did not find anomalies in chlorophyll concentration as well.

In the summertime potential thermal convection from the pipeline can increase a supply of nutrients to the sea surface and, thus, provoke artificial bloom events at the sea surface, which can be detected from space by measurements of chlorophyll concentration. We can also expect a change in the ocean color of the sea surface and a concentration of suspended matter due to an upwelling of water with different optical characteristics, which can be measured only by MODIS, because MERIS was installed at Envisat satellite. This will be checked during the ongoing complex satellite monitoring of NSGP in 2012. With a launch of a second line of NSGP in operation in the end of summer 2012, the power of a thermal convection may double. In this connection, there is a sense to repeat satellite monitoring of ice cover in winter 2012/2013, and SST and optical characteristics in 2013.

5 Conclusions

The NSGP has been planned and constructed with deep awareness of the environmental issues and specific conditions of the Baltic Sea, basing on the comprehensive Environmental Impact Assessment program that was conducted during several years before implementing the project. It was shown that the construction process of the pipeline may cause, in particular, the following impact on the marine environment: (1) oil pollution due to the operation of ships, pipelay vessel, dredge ships, and mechanisms in the sea; (2) increase of suspended matter concentration due to dumping of sand and gravel, and dredging operations; (3) provoking of local algal bloom events in summertime due to vertical mixing resulted from dumping and dredging works. A potential permanent thermal convection from the tube with heated gas may cause local warming of water column over the tube with a SST anomaly, the increase of eutrophication in the surface layer of the sea, the growth of biomass of blue–green algae, and even constitute a barrier to fish migration routes in a worst-case scenario.

Thus, there are two very important and interrelated tasks in relation to the NSGP construction and exploitation: (1) to monitor the ecological state of the sea at the site of the pipeline construction and (2) to discriminate between natural effects and anthropogenic impacts, related to the construction itself. Such a complex satellite monitoring was performed in Russian sector of NSGP in the Gulf of Finland by initiative and with a support of Moscow Office of Nord Stream AG since the beginning of construction in May 2010. The results obtained in 2010–2012 show that the observed oil pollution in the Gulf of Finland is not related to the NSGP construction. An expected anthropogenic increase of turbidity in marine waters was found only in Portovaya Bay of the size less than 10 km^2, while natural fields with high concentration of suspended matter were as large as 1,000–5,000 km^2. We did not find any signatures of thermal convection on the sea surface in the ice cover, SST anomalies, or sea surface roughness. Chlorophyll concentration fields had natural origin without any peculiarities related to the NSGP location.

Our 2 years long experience in complex satellite monitoring of the NSGP construction proved its efficiency in monitoring of the suspended matter distribution and oil pollution resulted from the anthropogenic impact of construction of offshore pipelines, ports, and terminals. Satellite monitoring is a very effective tool for assessment of the transboundary impact on the environment in the framework of the UNECE Espoo Convention.

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Conclusions

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Abstract We discuss the HELCOM yearly statistics for 1988–2011 on the confirmed oil spills and flight hours of aerial surveillance in the Baltic Sea, as well as the results of the CleanSeaNet satellite service provided by the European Maritime Safety Agency. We note that the observed very low level of oil pollution in the Baltic Sea and very low number of the identified polluters, along with a huge number of very expensive flight hours and satellite radar images may have a negative feedback on the sustainable development of the future monitoring system for the Baltic Sea. The results of investigation of oil pollution in waters of Finland, Russia, Latvia, Lithuania, and Germany are discussed. We briefly refer to a recent research on the state of the oil spill preparedness in the Baltic Sea countries. Some of the recommendations for improvement of the integrated oil pollution monitoring system for the Baltic Sea are given.

Keywords Marine environment, Oil pollution, Satellite monitoring, The Baltic Sea

Degradation of the Baltic Sea environment is caused by a wide range of human activities in the catchment area where 85 million people live. In the Baltic Sea shipping is an important branch of the European and World economy, which drives and supports increased trade and economic prosperity of different countries. Industrial

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and municipal waste, agricultural runoff, atmospheric deposition, and oil pollution due to shipping activities are among the main causes of the Baltic Sea environment degradation [1].

The Baltic Sea is particularly sensitive to oil spills, because of low temperatures, sea ice, absence of tides, specific ecosystems, small size of the sea, large number of islands, wetlands, marshes, lagoons, slow water exchange, and ventilation. It has been estimated that more than 100,000 seabirds are affected by oil spills every year in the Baltic Sea. Even a relatively small spill in a sensitive area may have serious consequences and even threaten the global survival of certain species [1].

In 2005, the Baltic Sea was designated as a particularly sensitive sea area (PSSA) by the International Maritime Organization (IMO). The PSSA designation is recognition by the IMO that the area is particularly sensitive and under threat from human activities related to shipping and maritime activities. This is also a recognition on the international level of the local interests in protecting the marine environment from stress caused by ships and other maritime activities. The PSSA designation means that the countries of the region can agree on specific measures "Associated Protective Measures" (APM) to reduce the risk of environmental damage from international shipping [1].

The Baltic Sea is one of the world's busiest waterways. It has about 40 ports and oil terminals. Nine percent of the world's trade and 11% of the world's oil transportation (250 million tons per year) pass through Baltic Sea waters. It is estimated that this will increase by 64% between 2003 and 2020 [2]. In 2009, vessels entered or left the Baltic Sea via Skaw 62,743 times; approximately 21% of those ships were tankers, 46% were other cargo ships, and 4.5% were passenger ships [3]. Forecasts of the Finnish Centre for Maritime Studies for the year 2015 according to three basic scenarios of economic development in Russia, Finland, and Estonia give a value of 322.4–507.2 million tons of cargo to be transported in the Gulf of Finland, which is 23–93% more than in 2007, and under any scenario, growth in turnover will occur mainly due to Russia. The share of oil and petroleum products among other goods will rise and can reach 158–262 million tons. For the transportation of petroleum products from 6,655 to 7,779 tankers will be used [4].

In the Baltic Sea, about 2,000 large ships and tankers are at sea every day. Illegal discharges of oil and petroleum products from ships, ship accidents, collisions, and groundings represent a significant threat to the Baltic Sea. There is little oil production at sea; therefore, ships are primarily responsible for oil pollution in the Baltic Sea, which is proved by cumulative maps of geographical distribution of the observed oil spills, showing that oil spills are concentrated along the main ship routes in the Baltic Sea. Thus, shipping, including oil transport, has a major negative impact on the marine environment and coastal zone.

Every ship entering the Baltic Sea must comply with the antipollution regulations of the Helsinki Convention and Marine Pollution (MARPOL) Convention. Even though strict controls over ships' discharges have been established by the Baltic Sea countries, illegal spills and discharges continue to happen [3, 5]. Fortunately, the number of illegal oil spills detected by aerial surveillance has been reduced significantly over the last 20 years, from 763 spills in 1989 to 122 spills in

2011 (Table 1). This is 56 less than in 2009 and 27 less than in 2010. Also, the volume of individual oil spills has been decreasing, in 2011, 6% of oil spills had volume of 1–10 m^3, 16% – 1–0.1 m^3, and 76% – less than 0.1 m^3. The total estimated volume of oil spills observed in 2011 amounted to 24 m^3, which is 50% less than in 2010 (49 m^3) [5].

A decreasing trend in the number of observed illegal oil discharges despite rapidly growing density of shipping, increased frequency of surveillance flights, and usage of satellite imagery, provided by the CleanSeaNet satellite service of the European Maritime Safety Agency (EMSA) since 2007 illustrates the positive results of the complex set of measures known as the Baltic Strategy, implemented by the Contracting Parties to the Helsinki Convention [5]. We can add here the efforts of other international organizations, the Baltic Sea national authorities, research institutes, private companies, shipping companies, and NGOs.

The analysis of Table 1 and the yearly number of flight hours per country for 1988–2011 [5] shows that:

1. HELCOM data seem to be underestimated in figures in comparison with other estimates of the number of oil spills and total oil pollution in the Baltic Sea, which are 100–1,000 fold greater (see Discussion and References in the chapter “Introduction”).
2. Since 1993 Russia does not carry out aerial surveillance in the Southeastern Baltic Sea and in the Gulf of Finland. Only in 2010 there were performed 10 flight hours with no spill detected.
3. Since 1994 Lithuania seems to have no regular and effective aerial surveillance, because no oil spills have been detected. Moreover, since 2001 there is a steady decrease of flight hours from 300 to 18 in 2011.
4. Since 2005 Latvia seems to have no effective aerial surveillance (having 384–298 flight hours in 2005–2008), because 0 and 5 oil spills yearly are not realistic figures. The number of flight hours has dropped from 298 in 2008 to 3 in 2011.
5. Accumulative traces of oil spills in Fig. 2 of the Introduction show the main ship routes in the Baltic Sea, as well as the approaches to major sea ports and oil terminals. This proves that the main responsibility for oil pollution in the Baltic Sea lies on ships.

The Baltic Sea States’ aerial surveillance fleet today consists of more than 20 airplanes and helicopters, most of which are equipped with up-to-date remote sensing equipment – side-looking airborne radar (SLAR), synthetic aperture radar (SAR), IR and UV scanner, microwave radiometer (MWR), laser fluorosensor (lidar) (LFS), FLIR high resolution IR-camera. The Baltic Sea States have to conduct aerial surveillance for detecting oil pollution and suspected ships as a minimum twice per week over regular traffic zones including approaches to major sea ports as well as in regions with regular offshore activities. Other regions with sporadic traffic and fishing activities should be covered once per week [6]. Also the coordinated extended pollution control flights (CEPCO), which constitutes continuous surveillance of specific areas in the Baltic Sea for 24 or more hours, should be carried out twice a year [6].

Table 1 Country-wise data on the number of confirmed oil spills observed in national waters in the Baltic Sea in 1988–2011 [5]

	Denmark	Estonia	Finland	Germany	Lithuania	Latvia	Poland	Russia	Sweden	Total
1988	129			90			40	82	168	509
1989	159			139			69	184	212	763
1990	34			45		73	88		184	424
1991	46			85	8	20	14	3	197	373
1992	18	18		76	34	15	92	13	278	544
1993	17	7		43	28	6	110		250	461
1994	30	4		75			104		375	588
1995	48	3	26	55			72		445	649
1996	36		42	44			50		241	413
1997	38	3	104	34			25		234	438
1998	53	10	53	23		33	33		249	454
1999	87	33	63	72		18	18		197	488
2000	68	38	89	51		17	51		158	472
2001	93	11	107	51	0	6	24		98	390
2002	54	8	75	44		21	25		117	344
2003	37	4	40	60		14	39		84	278
2004	30	19	36	42	0	13	10		143	293
2005	28	24	32	34	0	5	5	2	94	224
2006	41	31	29	22	0	0	3		110	236
2007	43	58	29	30		2	15		61	238
2008	41	46	28	24		5	22		44	210
2009	34	20	16	15		1	27		65	178
2010	33	25	15	22	0	1	14	0	39	149
2011	18	14	16	13	0	0	5	0	56	122

In 2011, 5,541 flight hours were carried out by eight Baltic Sea countries (except of Russia), which is an increase of 30% compared to the previous year. In 2011, six countries continued to carry out flights at night (when deliberate oil discharges are more likely to occur), which constituted 15% of all flight hours (12% in 2010). In 2011 the total number of flight hours increased and the number of observed spill decreased which gave to the lowest recorded PF Index (pollution per flight hour) (0.022) so far for the whole Baltic Sea [5]. Obviously, this is a positive result, which indicates a steady decrease of oil pollution in the Baltic Sea, but from the other side the fact that during 100 flight hours it is possible to find now only two confirmed oil spills, whose volume in a majority (3/4) of cases is less than 100 L, means a significant increase of the cost of aerial operations required for oil spill detection. For example, according to HELCOM data [5], in 2011 Sweden performed 3,225 flight hours (almost 9 h a day) to detect only 3.28 m^3 of oil in 56 small patches in own waters. For example, in Germany the cost of one flight hour of aerial observations on specially equipped patrol aircrafts may cost 3,500 Euro (http://www.havariekommando.de/en/cis/inventory/Aircraft/57_01/index.html). Thus, aerial surveillance starts to be very expensive in terms of efficiency of oil detection, and this may be a new future problem concerning funding of aerial monitoring operations, which has to be taken into account today.

Since 2007 the aerial surveillance in the Baltic Sea was supported by the satellite remote sensing technique for oil spill detection. CleanSeaNet is a near-real-time satellite-based oil spill and vessel monitoring service. It entered into operation on 16 April 2007 [6]. The service is continually being expanded and improved and provides a range of different products to the Commission and to EU Member States. The legal basis for the CleanSeaNet service is the Directive 2005/35/EC on ship-source pollution and on the introduction of penalties, including criminal penalties, for pollution offenses (as amended by Directive 2009/123/EC). EMSA has been tasked to "work with the Member States in developing technical solutions and providing technical assistance in relation to the implementation of this Directive, in actions such as tracing discharges by satellite monitoring and surveillance" [6].

The CleanSeaNet is now considered the most comprehensive oil spill monitoring and vessel detection service in Europe, supplying over 2000 services a year to its 26 participating states. The Baltic Sea Member States represented in CleanSeaNet are the following: Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Poland, and Sweden. In addition to the regular monitoring service, the Agency provides assistance to Member States during emergency situations. This is usually requested by Member States through the Monitoring and Information Centre of the European Commission in Brussels, which coordinates the assistance during emergencies. In relation to CleanSeaNet, it usually takes the form of additional services over an area where an incident or accident has occurred, in order to monitor the extent of a spill and changes over time [7].

In 2011, EMSA provided 528 satellite scenes for the users of CleanSeaNet in the Baltic Sea (647 in 2010), indicating 182 possible detections (186 in 2010). In the HELCOM area, 40% (72) of the spill indications were checked and out of these 11% (8) were confirmed to be mineral oil (15% in 2010) [5]. Basing on the statistics of oil spills for February 2011–June 2012, EMSA reported that in 37% of verified cases, there was confirmed presence of a polluting substance in the water, although this was not always mineral oil [7]. This means that there are evident problems in the methodology of correct identification of oil spills in the satellite radar images, because oil was confirmed only in 11% of cases, which is a very low value, and in 89% of cases it was a false alarm. It seems that the same question (as for aerial surveillance) may arise regarding the efficiency of the satellite monitoring system from the financial point of view, taking into account that, depending on available satellites, the cost of 500 radar images (without labor cost for processing and analysis of satellite imagery) may vary from 0.25 to 1 million Euro. Failure of the *Envisat* satellite in April 2012 makes monitoring more expensive.

Comparison of the number of oil spills detected in the Southeastern Baltic Sea in the morning (about 11 hours local time) and in the evening (about 22 hours local time) satellite images showed that the probability of finding oil pollution in the morning imagery is about 40% higher than in the afternoon and evening [8, 9]. This fact indicates that the illegal discharge of oil from vessels occurs more often at night, when the record of this fact by photo and video camera from the patrol aircrafts or ships is impossible. Moreover, night flights constituted only 15% of all flight hours in 2011. This once again confirms the advantages of satellite radar imagery for monitoring of oil pollution.

In the majority of cases of detected illegal discharges polluters remain unknown. In 2011, the polluters were identified only in 11 cases (9%) from 122 confirmed illegal discharges [5]. The identification of ships suspected in illegally discharging of oil is facilitated by the operational Seatrack Web oil drift forecasting model, which is combined with the ships' automatic identification system (AIS) and satellite information. This low number of the identified polluters is incomparable with all the efforts taken by HELCOM, EMSA, and national aerial surveillances.

Paradoxically, but such low values of oil pollution in the Baltic Sea in terms of the number of oil spills and their total volume from one side, and a very low number of the identified polluters and a huge number of flight hours and satellite radar images, which cost a lot of money, from the other side, may have a negative feedback on the sustainable development of the future monitoring system for the Baltic Sea.

To rise the efficiency of the aerial surveillance authorities have to improve the tactics of aerial observations, which has to take into account the real traffic along the main ship routes, operational information from the AIS and port authorities, to increase the number of night flights, and probably to use unmanned aerial vehicles (UAV), which have now a wide range of research and civilian applications, as well as more than 12 h endurance and range more than 200 km. To rise the efficiency of the satellite surveillance in the Baltic Sea EMSA has to significantly improve the methodology of oil spill detection which has to take into account daily operational metocean and AIS data and different kind of other infra-red, visible, and radar satellite information – all, what we call multisensor, multiplatform, and multidisciplinary approach, which we elaborated 10 years ago during the monitoring of the Lukoil D-6 oil platform in the Southeastern Baltic Sea [10–14]. We hope that all these measures will also help to increase the number of the identified polluters.

The book contains five “national” chapters, written by specialists in oil pollution from Finland, Russia, Latvia, Lithuania, and Germany. Reader will find a lot of interesting information concerning oil pollution issues in these Baltic Sea countries.

In Finland, the Ministry of the Environment has the supreme responsibility for the management and supervision of the oil pollution response. The Finnish Environment Institute (SYKE), operating under the Ministry, is the competent governmental oil and chemical pollution response authority. SYKE is in charge of measures against pollution incidents at open sea and in the coastal waters (in case of large accident). SYKE acts also as the nationally appointed competent authority empowered to request and give international assistance in combating marine pollution caused by oil or other harmful substances. On a regional level, the Rescue Services Regions are responsible for combating of oil spills in their coastal and land areas. There are ten Rescue Service Regions that have the Baltic Sea coastline. The Finnish National Oil Pollution Compensation Fund plays a key role when it comes to funding oil response activities. The Fund finances the purchases of Rescue Service Regions’ response equipment and it can be used as a buffer to finance oil spill response costs [15].

Since 1995, Finland has had two surveillance aircrafts *Dornier 228-212* that are equipped with special equipment to detect oil spills. They are owned and operated by the Finnish Border Guard. According to the cooperation agreement between SYKE and the Finnish Border Guard, the surveillance aircraft crew monitors the environment for oil spills when they patrol over the Baltic Sea. The most important surveillance equipment for oil pollution monitoring is side looking airborne radar (SLAR), which can detect oil as far as 20 nautical miles distance from the aircraft route. This means that the narrow Gulf of Finland can be covered from Finnish to Estonian coast within one flight. The thickness of the slick can be measured by IR/UV (Infrared/Ultraviolet) scanner providing estimates of its volume. The forward looking infra red (FLIR) camera and onboard AIS receiver enable vessel identification, whose location together with the oil slick position is displayed on the operators graphical user interface. Finnish Border Guard helicopters monitor marine environment and are used for verifying oil spill indications made from satellite images. They play a key role in taking oil samples from the sea. In order to ensure the best use of resources, Finland, Estonia, and Sweden cooperate in marine pollution surveillance. These neighboring countries exchange their flight plans and carry out surveillance activities also in the neighboring countries’ waters [15].

Satellite images are considered as an important supplementary tool for aerial surveillance activities in Finland. Since April 2007, Finland has been a user of the EMSA CleanSeaNet system and now receives annually 250–300 satellite scenes free of charge. All the satellite-based detections of oil have to be checked by an aircraft, helicopter or a vessel. About 50% of the possible oil spills detected by the satellite service are identified as oil by the verification flight. All these efforts have led to a significant decrease of the number of oil spills in the Finnish EEZ from 107 in 2001 to 16 in 2011. The average volume of oil spills became smaller. Most of them are located in the Gulf of Finland waters along the main shipping line. There is little pollution in the Bothnian Sea [15].

Russia has two separate coasts in the Baltic Sea – in the easternmost part of the Gulf of Finland and in the Southeastern Baltic Sea. As it was mentioned before, since 1993 Russia does not carry out aerial surveillance of oil pollution in both regions. This is partially compensated by irregular satellite monitoring of the Gulf of Finland and regular monitoring (since 2004) of the Southeastern Baltic Sea by academic institutions (e.g., P.P. Shirshov Institute of Oceanology and Space Research Institute of Russian Academy of Sciences) and private companies (e.g., Lukoil) [10–14, 16]. Some of the results of the satellite monitoring in the Gulf of Finland performed in 2009–2012 are shown in this book, in the chapter devoted to the Nord Stream gas pipeline construction.

In the Southeastern Baltic Sea (including Russian EEZ), an area which is partially missing in the HELCOM statistics, we also observe a decreasing trend in the oil spills' number and their total surface. From June 2004 to November 2005, during 18 months of daily operational monitoring of the Lukoil D-6 oil platform and surrounding area of 60,000 km^2 in total 274 oil spills were detected in 230 ASAR *ENVISAT* images and 17 SAR *RADARSAT-1* images [10–14, 16]. In 2006 the total number of oil spills (on a 2.5 times reduced area) and area of oil pollution amounted to 114 spills (371.7 km^2), in 2007 – 94 (213.7 km^2), in 2008 – 67 (198.7 km^2), in 2009 – 44 (81.7 km^2), in 2010 – 30 (69 km^2), in 2011 – 20 (71.3 km^2), and in 2012 – 56 (228.3 km^2) [8, 17]. Yearly oil spills clearly reveal the main ship routes in the Baltic Sea directed to ports of Ventspils, Liepaja, Klaipeda (routes from different directions), Kaliningrad, and along Gotland Island. No oil spills originated from the D-6 oil platform were revealed in 2004–2012.

In Latvia, till 2007 the Marine and Inland Waters Administration (MIWA) of the State Environmental Service was responsible for organization of oil pollution control in the sea by conducting one to two flights per week depending on available funding and weather conditions permitting visual observations. Since 2007 the Latvian Coast Guard, National Armed Forces, and MIWA have access to the EMSA CleanSeaNet services and satellite radar imagery. In 2007–2010 Latvia received 878 satellite images, in 249 of them there were indications of possible oil spills, 33 of them were located in the Latvian EEZ. The observed decrease of detected oil spills can mostly be attributed to very successful implementation of no-special-fee system, which means that ships have to pay a certain fee covering the costs of reception, handling and disposal of ship-generated waste irrespective of whether or not ship-generated wastes are actually delivered [18].

In Latvia annually 10–19 oil pollution events, ranging from less than 1 kg and up to more than 5 tons, are reported in port areas. In 2000–2008 127 oil pollution events were registered in Latvian port areas: in 84 cases oil spills were originated from ships (discharges of bilge waters, fuel, fuel oil and lubricants during small accidents), 36 cases were related to the port infrastructure, seven oil spills were of unknown or historical origin. Most of oil spills were less than 0.1 m^3; however, a substantial number of oil spills of 0.1–1 m^3 have been observed as well. Oil spills bigger than 1 m^3 were registered several times only: e.g., discharge of bilge waters in 2000 or a ship fire in 2007 [18]. Outside of the port areas, oil spills are concentrated along the most intensively used ship routes, including those coming to the ports of Liepaja, Ventspils, and Riga. Latvian aerial surveillance has occasionally recorded oil spills which are likely of transboundary origin. It was noted that the most likely transboundary pollution can be expected from the very busy port of Klaipeda (Lithuania), where 8,348 ships have serviced in 2008, and Butinge oil terminal, which has been in function since 1999, and is located between Klaipeda and the Latvian border [18]. We can note here that the dominant coastal current is directed northward from Lithuanian to Latvian waters.

The risk of oil pollution in waters of Lithuania is related to tankers and ships visiting the port of Klaipeda and Butinge oil terminal, ships passing through or along Lithuanian waters, as well as from the Lukoil D-6 oil platform, located in Russian waters close to the Russian–Lithuanian marine border. The Lithuanian coast has suffered the consequences of oil spills several times, the most severe event was the accident of a tanker *Globe Asimi* near Klaipėda in November 1981. In Lithuania, the responsibility for clean-up related to marine incidents lies on the Maritime Rescue Coordination Centre of the Naval Forces. When organizing, coordinating, and managing marine-pollution elimination works, the Maritime Rescue Centre involves all the forces and means of the national Navy, Air force, Border Guard, and seaport administration [19].

HELCOM statistics says that since 1994 there are no oil spills in Lithuanian waters. From the other side sea water sampling in different parts of the Lithuanian aquatoria shows that since 2000 there has been a significant rise of the number of samples which exceeds the maximum permissible limit of the total hydrocarbon concentration in sea water (0.05 mg/L) from 5% to about 30% from all samples in 2007. The statistically significant increasing trend in oil pollution was detected in all coastal waters of Lithuania, as well as in the plume coming from the Curonian Lagoon [19]. There should be a reason for this.

In Germany operational oil pollution surveillance has been performed for almost 30 years. This is an important part of the duties and responsibilities of the German Central Command for Maritime Emergencies. Sophisticated state-of-the-art sensors (SAR, SLAR, IR, UV, microwave radiometer, laser fluorescence) are used for frequent airborne surveillance, while satellite SAR data have been used since the early 1980s as an additional information input on a routine basis. Since 2007 the EMSA CleanSeaNet has acted as a support service for the EU Member States for their marine pollution control. Today, the use of satellite services and multi-sensor aircrafts is enhanced by a numerical oil spill drift model to form a combined operational monitoring system. The operational oil spill drift model is provided by the German Federal Maritime and Hydrographic Agency (Bundesamt für Seeschifffahrt und Hydrographie, BSH). The basic circulation model BSHcmod is a 48 h forecast model, which covers the Baltic Sea and the southern part of the North Sea. Meteorological forcing is provided twice a day through the meteorological forecast model of the German Weather Service (Deutscher Wetterdienst, DWD) and wave forcing through DWD’s wave model [20].

According to HELCOM data, the intensity of aerial surveillance in Germany is raising. In the beginning of 1990s there were about 150–200 flight hours, and by 2011 this number reached 648 flight hours, from which 182 flight hours (28%) were performed in darkness. The number of confirmed oil spills is also decreasing: in the beginning of 1990s it was in the range of 43–139 per year, but in 2005–2011 it became 13–34 [5].

In this book HELCOM reports that maritime traffic inflicts multiple pressures on the Baltic Sea biodiversity including noise, release of nutrients, coastal erosion, disturbance of seabed, oil spills, and spreading of alien species [21]. Impacts on the marine ecosystem are wide, affecting not only species but also quality of habitats and the marine environment in general. From the *Exxon Valdez* (1989), *Prestige* (2002) and other large accidents it is known that oil spills cause significant short-term reduction in phyto- and zooplankton biomass, reduced abundance and species richness of littoral invertebrates, reduced fish reproduction, death of thousands of birds, stranding of marine mammals and turtles, and long-term chronic effects lasting from several months to several years, and even a decade. Some of these impacts have already been observed in the Baltic Sea after the accidents of *Tsesis* (1977), *Antonio Gramsci* (1979), and *Globe Asimi* (1981). Annually, 100,000–500,000 ducks, guillemots, and other bird species are estimated to die due to small oil spills in the Baltic Sea without large-scale tanker catastrophes [21].

Fortunately, the Baltic Sea has its own reserves to fight against oil pollution. Microbes play a significant role in the degradation of crude oil, often being the dominant factor controlling the fate of toxic hydrocarbons in aquatic environments. All together they can degrade as much as 40–80% of a crude oil spill. Several factors influence biodegradation rates: oil composition, water temperature, nutrient availability, oxygen levels, and salinity [19]. Total amount of hydrocarbons, which the bacterioneuston can oxidize during the vegetation period in the Baltic Sea, is estimated as of 1,200–5,000 tons [22]. This estimate shows a capability of the sea to a complete self-cleaning from anthropogenic oil pollution by natural processes. This fact may explain why we do not observe in general accumulation of oil pollution in the sea, because the above-mentioned values are equal or exceed the estimates of the oil volume yearly coming to the Baltic Sea, discussed in the Introduction. For example, the most recent observations in Latvian coastal waters indicate that the current level of oil pollution does not cause visible impact on the marine ecosystem, although in the past oil pollution represented a serious threat due to frequent small scale oil spills and occasional big accidents with tankers like *Antonio Gramsci* near Ventspils in 1979 and *Globe Asimi* in Klaipeda port in 1981 [18]. From the other side, monitoring of Lithuanian waters showed a significant increase of micronuclei and other nuclear abnormalities in mussels after the oil spill in Butinge oil terminal in January 2008. Elevated environmental genotoxicity and cytotoxicity responses were observed in mussels at the Palanga location 6 months after the oil spill event. A previous oil spill case at Butinge oil terminal in November 2001 showed that full recovery of mussels from the same toxicology problems was found only in June 2007 [19]. These examples show that the impact of oil pollution on the marine environment is different, but it may be significant and can last up to 6 years.

The main challenge is that the real degree of oil pollution in the Baltic Sea is unknown, because the number of observed oil spills and estimates of the total volume of oil pollution from different sources differ significantly. Partially this is explained by known differences in aerial surveillance, satellite monitoring, and in-situ measurements. All these methods have their own advantages and limitations and should complement each other. Anyway, it is clear that statistics on oil spills is not complete and not comparable in different parts of the sea due to different efforts and methods applied for oil pollution monitoring (different number of oil patrol ships, aircrafts and helicopters per country and per unit of the sea area, the number of flight hours per country and unit of the sea area, the number of night flight hours, availability of different sensors at aircrafts, usage of satellites, a number of ASAR/SAR images acquired and analyzed yearly, application of complex satellite monitoring based on the multisensor and multiplatform approach along with the analysis of metocean data, local peculiarities of the water area, and numerical modeling).

Although the number of observations of illegal oil discharges shows a decreasing trend over 20 years, it should be noted that for some areas and countries aerial surveillance is not evenly and regularly carried out and therefore there are no reliable figures for these areas [6]. We have to add to the uncertainties in the oil pollution statistics considerable seasonal variability in observations of oil spills on the sea surface and predominance of the "night" discharge of oil spills from the ships that used to avoid any direct visible evidence of pollution, and responsibility for this fact.

For example, since 1993 Russia does not carry out aerial surveillance in the Gulf of Finland and in the Southeastern Baltic Sea. The existing satellite monitoring is performed on a regular basis since 2004 only in the Southeastern Baltic Sea and by a private company Lukoil-Kaliningradmorneft. According to HELCOM data, since 1994 Lithuania and since 2005 Latvia seem to have had no regular aerial surveillance of oil pollution. Regular aerial well-equipped surveillance is very expensive and it is clear that countries in economic recession reduce their aerial and in-situ monitoring. Daily satellite monitoring may partially solve this problem, because satellites cover simultaneously very large areas of the Baltic Sea.

Organization of the Baltic International Satellite Monitoring Center in HELCOM could solve many problems in the operational monitoring of oil pollution in the Baltic Sea [9]. It will:

1. Ensure full and uniform coverage of the Baltic Sea area by remote sensing control.
2. Reinforce aerial surveillance and improve oil pollution monitoring.
3. Establish daily satellite monitoring for the countries where it was not yet applied.
4. Remove duplication of satellite monitoring for the same area performed by neighboring countries.
5. Reduce the total cost of operational satellite monitoring for all countries.
6. Provide data to all the Baltic Sea States in the same format.
7. Solve the problem regarding different technologies, methods, and algorithms used for the analysis of satellite data in different countries and in the EMSA CleanSeaNet.

8. Solve the problem of the “night” oil spill pollution which is getting more and more acute.
9. Stimulate exchange of data and cooperation between countries.
10. Solve the problem of transboundary oil pollution and contribute to early warning in this case.
11. Improve the ecological state of the Baltic Sea, coastal zones, and shores of the Baltic Sea States.
12. Stimulate organization of analogous operational monitoring centers for the seas with a high density of shipping and/or oil/gas exploration/production industry, i.e. the North Sea, the Mediterranean Sea, the Black Sea, the Caspian Sea, the Gulf of Mexico, coastal zone of Nigeria, the Barents Sea, etc.

Wide usage of the SMHI Seatrack Web model for oil spill drift forecast is required. The system was originally developed in collaboration between the Swedish Meteorological and Hydrological Institute (SMHI) and the Danish Maritime Safety Administration (DaMSA) for use in the Baltic Sea and the eastern part of the North Sea, as the result of a HELCOM recommendation. The first version of Seatrack Web was introduced in 1995, and since then, Seatrack Web has been used successfully for oil spill drift forecast. It was developed to be a friendly tool for authorities responsible for oil spill response in the Baltic Sea region. Seatrack Web’s main purpose is to calculate the drift and transformation of oil spills in the Baltic and North seas. The program can also be used for substances other than oil, such as chemicals, algae, and floating objects. In addition to an oil drift forecast for 5 days ahead, it is possible to make a backward calculation for 30 days [23].

The AIS data is continuously imported into Seatrack Web and can be displayed as ship tracks. Thus, the information on the whereabouts of vessels is available in real time. The AIS data is stored for one month, i.e. ship tracks can be viewed as far back as one month before the current date. Incorporating AIS data into Seatrack Web has proved to be a very effective tool, substantially increasing possibilities to identify ships suspected of illegally discharging oil into the sea. This feature is available to the relevant competent authorities in all HELCOM countries. Training on its use has been performed in Denmark, Estonia, Finland, Lithuania, Poland, Russia, and Sweden [23].

Originally, the Seatrack Web model was not devoted to the ecological risk assessment but we found it very useful for this purpose as well [24]. The ecological risk assessment for all ports, oil terminals and platforms, subsurface oil pipelines, ship routes, the Baltic Sea Protected Areas, and any part of the 8,000 km long coastline of the Baltic Sea can be done on the base of methodology we elaborated in 2004 and successfully used for Lukoil D-6 oil platform and in 2006 for the Nord Stream gas pipeline construction [9, 10, 12, 24]. This will allow revealing quantitatively and precisely hot spots in the marine area, islands, and coastline of the Baltic Sea vulnerable to the impact of the shipping oil pollution. Such a general map of the Baltic Sea with calculated probability for any point of the sea and the coastline to be polluted may serve as a guideline for the Baltic Sea States to improve their monitoring systems.

Oil spill preparedness in the Baltic Sea countries was recently investigated in the framework of the Baltic Master II Project [2]. One of the important conclusions from the Baltic Master II is that the preparedness to deal effectively with oil spills at the local and regional level in most of the Baltic Sea countries is poorly developed. Different countries have worked with contingency planning to a varying degree. For example, Poland had no larger spills along the coasts but has invested much time and money into response preparedness. Sweden had several smaller to medium size oil spills, but there is large variation among municipalities concerning the preparedness level. Different countries have set different goals for their oil spill response as well, for example, Finland is prepared for a maximum oil spill of 30,000 tons, Germany for 15,000 tons, Sweden 10,000 tons, and the Russian Federation for 5,000 tons. Important aspects are related to the need for updated and well-rehearsed contingency plans. The need to test these plans in real exercises, including international cooperation, with regular intervals was emphasized in particular [2].

So far, as the Baltic Sea ecosystem undergoes increasing human-induced impacts, especially associated with intensifying shipping and oil transport, further research of the links between physical, chemical, and biological parameters of the ecosystem, complex monitoring of the Baltic Sea state, and especially, oil spills monitoring are of great importance. Oil spill behavior, modeling, prevention, effects, control, and cleanup techniques require supplementary information about a large number of complex physical, chemical, and biological processes and phenomena.

The large number of discharges of hydrocarbons that annually take place in European waters, the vast quantity of waste generated by the sea traffic in Europe, lack of adequate port installations for waste management and the toxicity of compounds thrown into the sea make chronic hydrocarbon pollution a priority for improving the environmental quality of European seas [25, 26]. The growing availability of airborne, satellite, and sea observation data should encourage interest, involvement and investment into complex operational monitoring systems from the side of the state authorities responsible for the environment, pollution control, hydrology and meteorology, coastal protection, transport, fisheries and hazard management, as well as from the side of private companies operating in the sea and coastal zone.

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