Chapter 9
Remote Sensing of Oil Films in the Context of Global Changes

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Abstract Since the middle of the 20th century, during the global industrialization, crude oil has become a major source of energy, and the problem of oil spills in the sea has become a public concern. Spilled oil interacts with marine environments, causing damage to marine ecosystems and influencing the ocean-atmosphere interaction. The impact of accidental spills is catastrophic for coastal zones, and has far-reaching consequences, not realized or anticipated previously. Sea surface oil films play a significant role in important climate processes such as the exchange of momentum, heat and gas between the ocean and the atmosphere. However, nowadays there is no estimating method for determining how fully and how frequently the ocean is covered by oil films, even when slicks are imaged from space. Remote sensing is believed to offer an effective mean for accounting of the global impact of oil films, which could lead to an improvement of representing air-sea interactions in climate models. Among remote sensing techniques, spaceborne Synthetic Aperture Radar (SAR) is the primary remote sensor used for oil spill surveillance. Oil films floating on the sea surface are detectable by SARs, because they damp the short surface waves that are responsible for the radar backscattering. The European and Asian seas have been chosen as test basins to work out an oil spill mapping technology using SAR images, and these studies demonstrated the high potential of SAR-equipped satellites. An approach for oil spill mapping has been also developed. It is based on studies conducted within the analysis framework of a geographic information system (GIS). GIS-made oil spill maps can be a valuable source of information about oil spill distribution, statistics and sources. They allow scientists to identify the most polluted waters – an important step in development of monitoring scenario. Finally, a basis for the determination of volumes and extent of floating oil based on satellite remote sensing is provided. This paper reviews and discusses this problem in the context of global changes.

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1 Introduction

In the last several decades, significant advances have been made in studying air-sea fluxes over the ocean (Toba, 2003; Garbe et al., 2007). The study of the boundary between the atmosphere and the ocean is very important. This air-sea interface, supporting marine life, is one of the most physically, chemically and biologically active interfaces, and plays a major role in the exchange processes of gases, materials, and energy (Kraus, 1972). Many scientists consider it a "mirror" of climate changes. A considerable amount of new research over the last decade has led to wider understanding of the vital importance of the interface between the ocean and the atmosphere, and how it may interact with the processes involved in global changes (Liss and Duce, 1997; Toba, 2003; Garbe et al., 2007). However, predictions of future climate changes based on existing knowledge vary greatly, and detailed forecasts are still subject to debate (Toba, 2003). One key uncertainty is caused by the lack of accurate knowledge of transport processes in the air-water interface, especially in the presence of oil films, both natural and man-made, which pose the main resistance to transfer processes between the ocean and the atmosphere. Modeling and predictions of global climate can only be improved by gaining a more complete understanding of the transporting mechanisms across the air-sea boundary. However, these mechanisms and the interactions involved are very complex and still not fully understood.

Oil in the sea, or "oil spills", are the releases of liquid petroleum hydrocarbons into the marine environment due to human activity, and are a form of oil pollution. In the ocean, oil is frequently released into coastal waters. The oil and petroleum products consist of different mixtures of liquid materials, including crude oil and/or refined petroleum products. Oil is also released into the marine environment from natural geological sources, known as oil seeps (or seepage) on the seafloor.

In the sea, crude oil and most oil products are subjected to weathering processes (Fig. 9.1), which include spreading, drifting, dispersion, evaporation of lighter fractions, chemical transformation, emulsification, photo- and bio-oxidation, etc. Because oil floats on the sea surface, it affects the marine life and limits the life-cycle of plankton organisms. This affects the food chains in the marine ecosystems and eventually the fauna population (Oil in the sea, 2003).

Oil films covering the ocean surface from time to time can now be detected and resolved at sufficient temporal and spatial resolution, because they smooth the sea surface roughness (Fig. 9.2). Satellite-derived oil spill products have the appropriate resolution and can be used instead of conjecture and hypothesized "products" that often do not appropriately resolve oil films variability.

In the last several decades, synthetic aperture radar (SAR) images were extensively used to obtain statistical and quantitative information about oil pollution
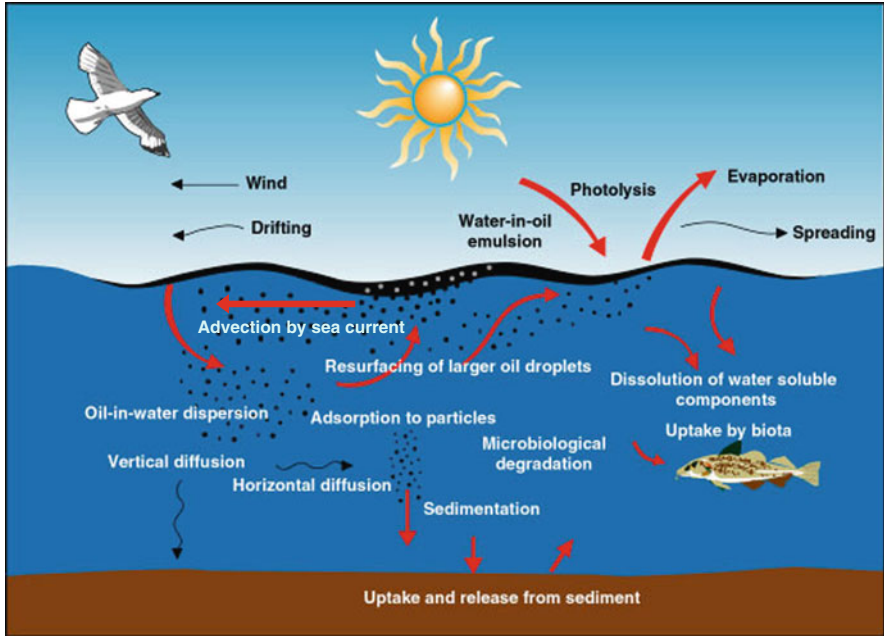
Fig. 9.1 Oil in the sea: main oil transportation and weathering processes. © SINTEF
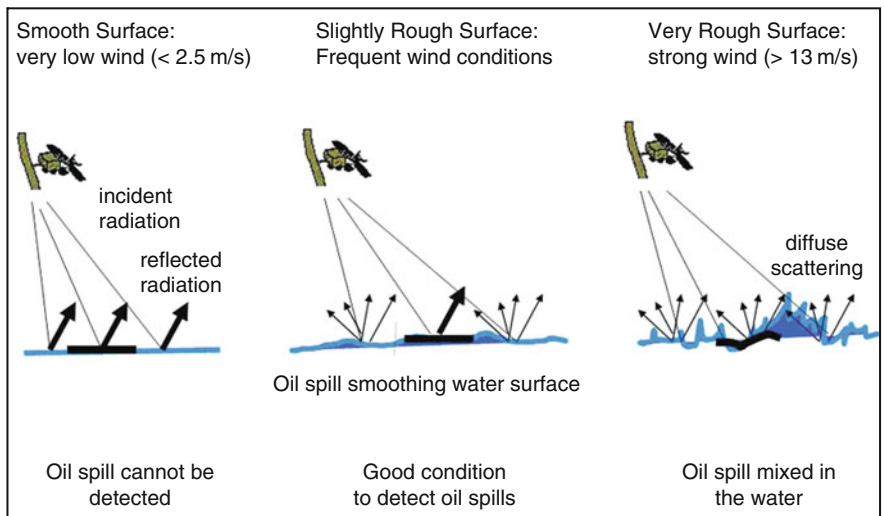

Fig. 9.2 Sea surface conditions and detectability of oil spills
Source: © ESA/Eduspace

(Pavlakis et al., 1996; Gade and Alpers, 1999; Lu et al., 1999; Pavlakis et al., 2001; Ivanov and Zatyagalova, 2008; Shi et al., 2008). In response to the challenges by oil spill in the sea in the 20–21st centuries, a number of projects for utilization of SAR data of different swaths and resolution for oil spill mapping were started since, 1991 (Pavlakis et al., 1996). Many cases of oil spill pollution have been documented and a number of regional monitoring campaigns have been carried out (see, e.g., Bern et al., 1992; Pavlakis et al., 1996; Espedal et al., 1998; Gade and Alpers, 1999; Lu et al., 1999; Pavlakis et al., 2001; Ivanov and Zatyagalova, 2008). Many years of practical research have shown that the SAR is one of the best satellite sensors for oil spill monitoring. Consequently, wide-swath SARs aboard the SAR-equipped satellites have become important tools for control and monitoring of marine environments due to their all-weather and day-and-night capability. They provide high resolution, wide swath and relatively short revisit time coverage, and are the most suitable tools not only for regular monitoring, but also for mapping of oil spills in the sea.

Evidently, oil pollution of the sea is major environmental problem. The first approach to the oil spill mapping problem was developed by Pavlakis et al. (1996), who showed usefulness of a large set of SAR images acquired over the Mediterranean Sea. Gade and Alpers (1999) analyzed more than 400 ERS-2 SAR images covering the North Sea, Baltic Sea and the Gulf of Lions. They concluded that these waters were polluted mainly by shipping. Lu et al. (1999), for the first time compiled a statistical spatial distribution map of oil pollution for the Southeast Asian waters after analyzing 2,500 middle resolution ERS-1/ERS-2 SAR images; they also concluded that the waters were most polluted along main shipping lanes. Finally, it became clear that SAR images are very useful not only for locating the areas where tankers are washed and ships are discharged engine room waters, but for collecting information about spatial distribution of oil films on meso-, and even global scale.

2 Marine Oil Films and Their Role in Ocean-Atmosphere Interaction

Natural and man-made oil slicks affect the physical properties of the air-sea interface, and, in turn, have impact on a number of important processes determining the ocean-atmosphere interaction. Among those are: energy transfer from wind to waves, retardation of evaporation and convective exchange, sea surface temperature (SST) variability, gas exchange, formation of skin-layer and foam on the sea surface and others (Kraus, 1972; Monin and Krasitskii, 1985). Existing knowledge about the effects of oil films on the marine environment, ocean-atmosphere interaction and global warming, in the current circumstances of global changes, is insufficient (Monin and Krasitskii, 1985). These effects are studied only partially and locally. Their global impact and their role in global changes are not well understood. Their regional and global estimates are very approximate, because the real extent and

distribution of oil slicks as well as oil spills in the world's ocean is mostly unknown. These processes have to be re-studied and re-estimated at regional and global scales.

The sea-water surface is always contaminated by oily organic materials of different sorts (Monin and Krasitskii, 1985). Extremely thin layers of natural organic films have thickness comparable to the effective diameter of a single molecule and are formed by surface-active materials, such as some fatty acids and alcohols (Levich, 1962). These materials are made up of molecules with both hydrophilic and hydrophobic parts, and they will spread on the water surface and tend to form a layer one molecule in thickness. These layers continuously change the physical-chemical properties of the air-sea interface (Levich, 1962).

Such a monomolecular layer of some oily substances can prevent the escape of the water molecules into the atmosphere vapor. For example, for a small tank, depending on weather conditions, this can reduce the evaporation rate by more than 50% (Kraus, 1972). But for large water regions this effect is limited by the difficulty of maintaining of unbroken oil layers on large sea surfaces. At the sea surface, in particular at moderate wind conditions, organic films, although never absent from large areas, are always patchy or broken up by currents and surface waves (Monin and Krasitskii, 1985). Their effect on evaporation is also poorly understood (Monin and Krasitskii, 1985). Moreover they may have some effect on SST fluctuations and hence on convection in the low atmosphere and mixing in the upper ocean layer (Monin and Krasitskii, 1985). They also can influence the generation of waves on the sea surface (Alpers and Hühnerfuss, 1989). Organic and oil films change the local gas exchange rates through the water interface (Monin and Krasitskii, 1985).

"Oil" is a general term used to denote petroleum products which mainly consist of hydrocarbons. "Oil spills" is a term that often refers to marine oil spills, when oil is released into the open ocean or coastal waters, due to natural or human activity (ITOPF, 2009). Oil spills consist of liquid petroleum hydrocarbons, and are a form of oil pollution. Ship accidents and operational discharges, river run-off, natural seeps, offshore production, and atmospheric fallout are considerably large sources of oil pollution (Oil in the sea, 2003).

> It is well-known that oil floating on the sea surface originates from different sources. Clemente-Colón and Yan (2000) divided these oil substances into two major categories: natural and man-made (Fig. 9.3). Each category then can be further subdivided into those of biogenic origin and those of mineral origin. Oil films and slicks on the sea surface have been extensively studied theoretically and experimentally starting from the beginning of 60 s (see, e.g., Levich, 1962; Monin and Krasitskii, 1985; Scott, 1986; Alpers and Hühnerfuss, 1989; Ermakov et al., 1992; Gade et al., 1998; Espedal et al., 1998).

Man-made oil slicks are typically caused by accidental spills (collisions and groundings) or by illegal dumping of oil and petroleum products. Most man-made oil pollution comes from different human activities (Fig. 9.4–9.7), but public attention is focused mostly on oil tankers (ITOPF, 2009). Fortunately, there were only 21 major tanker crashes since 1967 with oil spills of over 30,000 tons (ITOPF, 2009). Such spills usually take months or even years to clean up. There is a decreasing number of large spills, and detailed analysis is available for each of them (ITOPF, 2009). From the ITOPF's statistics it is evident that most spills result from routine
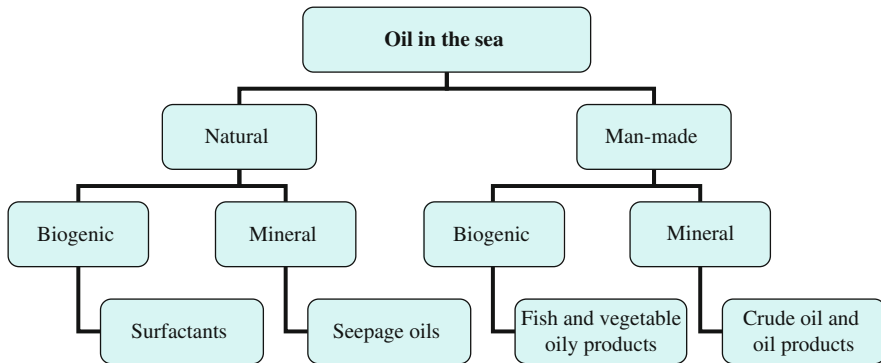
Fig. 9.3 Simple classification of oil products forming oil slicks on the sea surface
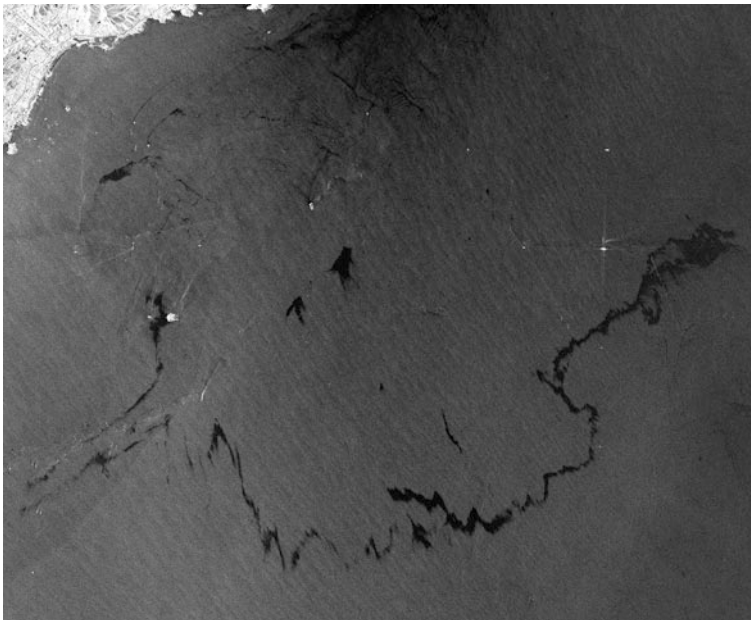

Fig. 9.4 The COSMO-SkyMed SAR image showing oil spill after shipwreck in the Yellow Sea (September 2008). © ASI/Italian MoD

operations such as discharging, loading and bunkering that normally occur at shipping lanes, in roads, ports, or at oil terminals. The majority of these operational spills are small (<7 tons), whereas the number of accidents that generally give rise to much larger spills (>700 tons) has decreased during the last 38 years (ITOPF, 2009).

The mineral oil spills may be of a variety of materials, including crude oil, refined petroleum products (light products: petrol, kerosene, diesel fuel, local fuel blends;
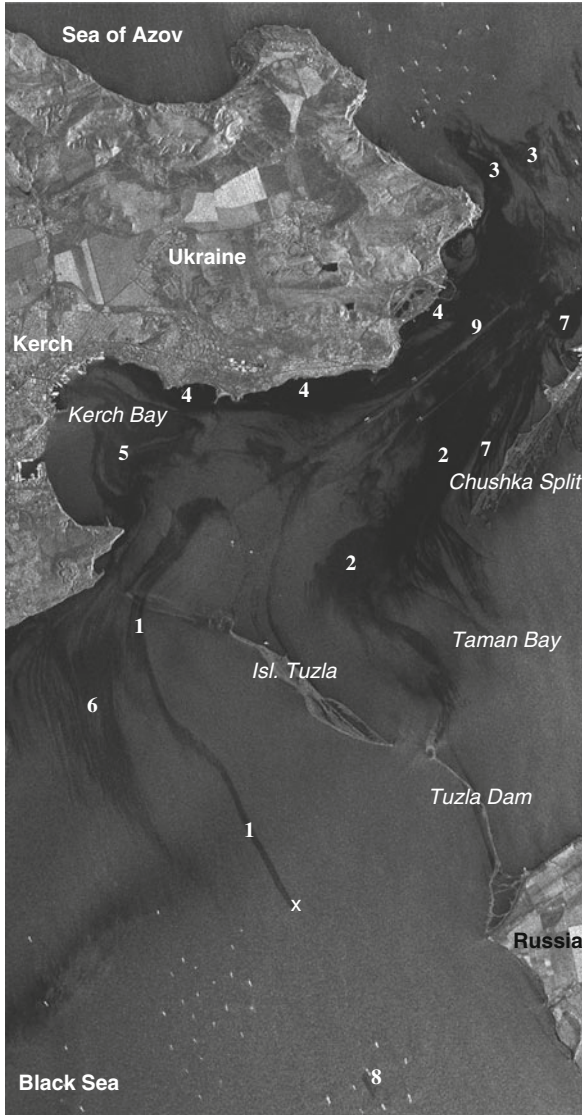
Fig. 9.5 Oil pollution in the Kerch Strait after the Volgoneft-139 tanker shipwreck (about 1,300 tonnes of fuel oil released) as seen on the TerraSAR-X image (16/11/2007, res. 3 m, pol. VV): x – location of the bow of the tanker; 1 – oil trail from the bow penetrating into the Kerch Strait; 2 – oil accumulated in the west part of Taman Bay further propagating into the strait; 3 – oil patches in the Sea of Azov on the exit from the Kerch Strait; 4 – oil pollution along the Ukrainian coast of the strait; 5 – oil pollution accumulated in Kerch Bay; 6 – weathered fuel oil possibly processed by sorbents; 7 – oil patches at the west shoreline of Chushka Split; 8 – ship-made oil spill; 9 – fairway (figure from Ivanov, 2010). © InfoTerra
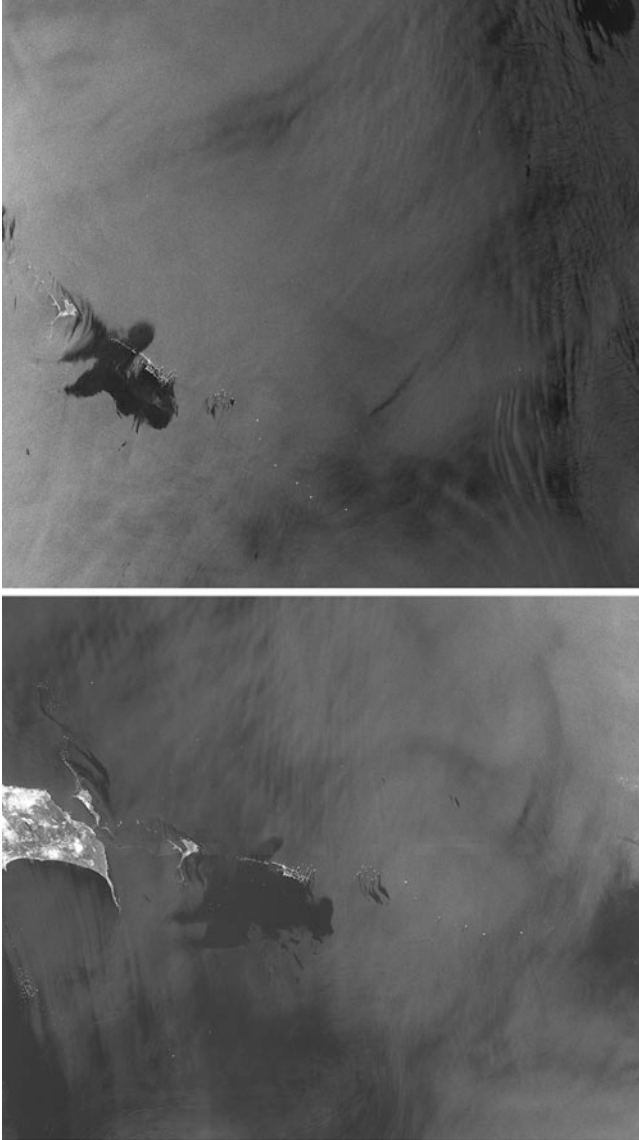
Fig. 9.6 Chronic oil pollution at the oil production site "Oil Stones"(Azerbaijan) in the Caspian Sea as imaged by Radarsat-2 on 11 and 12/07/2009. © MDA/CSA

heavy products: intermediate (IFO) & heavy (HFO) fuel oils) or by-products, ships' bunkers and lubricates, oily refuse or oil mixed waste (CEDRE, 2004). Their appearance, physical characteristics (density, viscosity, pour point) and behavior (e.g., spreading, evaporation, dispersion and emulsification) depend on their composition. Shipping is the main source of oil spills in the open sea (Gade and Alpers,

Fig. 9.7 Ship-made oil spill in the Japan Sea on the ERS-1 SAR image. © ESA
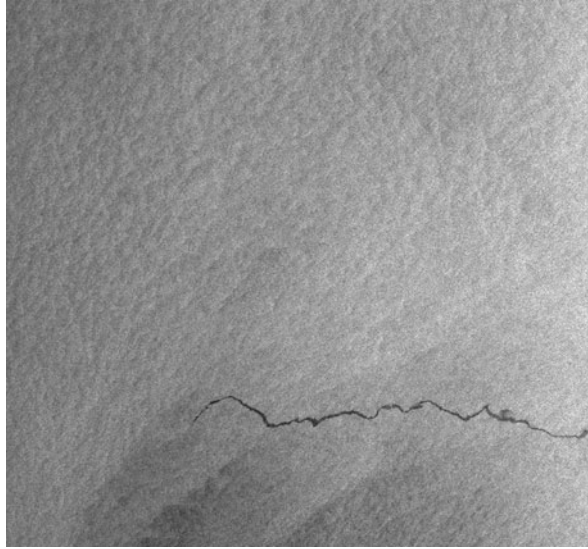
1999; Lu et al., 1999; Pavlakis et al., 2001; Ivanov and Zatyagalova, 2008), but much man-made oil pollution also comes from land-based activity (Alpers and Espedal, 2004). Oil pollution from routine ship operations includes ballast water, tank washing residues and other oil mixtures from the engine room and bilge waters. Such pollution is also known as slops. Sludge includes engine room waste and foul bilge water from all types of ships. Most ships discharge their oily effluents en route, leaving linear spills (Pavlakis et al., 2001; Alpers and Espedal, 2004).

Estimates of total volumes of oils released every year in the marine environment vary widely, but are considered to have decreased from 6.0 million in the early 1970s to 1.3 million tons at present (ITOPF, 2009). However, these estimates are still very uncertain and the real situation is poorly understood, particularly with regard to oil discharges from land-based sources, which is a large and still unknown part of oil pollution (Oil in the sea, 2003).

The spatial distribution of these oil slicks marks the international and domestic shipping lanes and oil producing regions (Lu et al., 1999; Alpers and Gade, 1999; Ivanov et al., 2004; Shi et al., 2008). For this reason, the main problem for ocean remote sensing is to first detect and identify these slicks, and then to map their spatial distribution.

Man-made biogenic oil slicks are produced by the discharge of organic matter resulting from human activities (Fig. 9.8), such as fish and food processing onshore and offshore (Espedal, 1998; CEDRE, 2004; ITOPF, 2009). Fish oils together with fish waste are released directly from fishing vessels or fish processing plants onshore. Vegetable oils are oil extractions from plants and fruits, such as sunflower, soybean, rapeseed, olive, castor, corn, palm nut, etc. According ITOPF (2009),

Fig. 9.8 Spill from a palm oil production plant in Colombia. © Elastec/ITOPF

Fig. 9.9 Seepage slicks in the SW Caspian Sea as imaged by Envisat on 9/08/2003. © ESA

the fate, behavior and environmental impact of vegetable oil spills on the marine environment are not as widely appreciated as the impact of mineral oils.

Natural mineral oil slicks are the result of bottom seepage or oil (hydrocarbon) seeps, which are those places on the seafloor, where liquid or gaseous hydrocarbons come to the sea surface through fractures and holes in the bottom. Oil seeps are quite common and are found in many places of the world's ocean (e.g., in the Gulf of Mexico, Santa Barbara Channel, Caspian Sea; (Oil in the sea, 2003)). Oil, upon reaching the surface after being emitted from the bottom seep, has a tendency to spread out into thin layers, which cause oil slicks on the sea surface (Figs. 9.9 and 9.10) that can easily be detected by remote sensing techniques (MacDonald et al., 1993).

It may seem unusually high, but almost half of the oil detected in the ocean is emitted from natural sources. Kvenvolden and Cooper (2003) report that natural seepage introduces into the marine environment from 0.2 to 2.0 million tons of crude oil per year. This amounts to about 47% of all crude oil currently entering
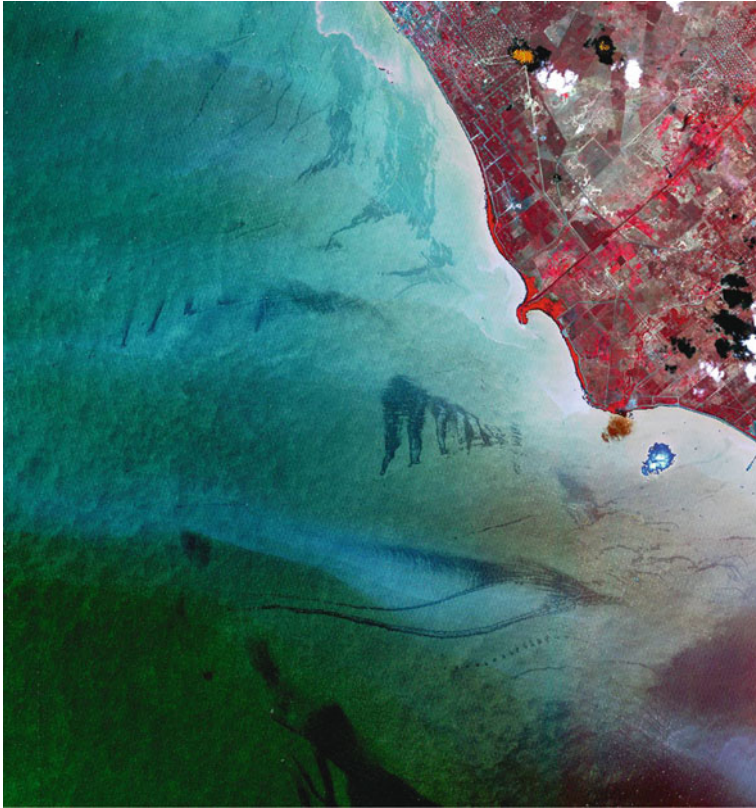

Fig. 9.10 Seepage slicks on Lake Maracaibo (Venezuela) on the Terra/ASTER image
Source: http://earthobservatory.nasa.gov/IOTD/view.php?id=3533

the marine environment, while mankind is responsible for the rest. Tracking and locating these slicks are helpful for two reasons. On the one hand, the seeps can indicate local hydrocarbon deposits, and indeed, a number of oil fields were discovered from observations of oil seeps (Oil in the sea, 2003). On the other hand, on a historic timeline, they may somehow influence the direction and magnitude of climate changes.

Natural biogenic films, also known as surfactants due to their surface-active characteristics, are bio-products of natural life in the ocean. Natural biogenic substances are normally released into the marine environment and produced by plankton organisms and fishes during their life-cycle. They consist of surface-active, mainly organic compounds (hydrolyzed amino acids, proteins, fatty acids and alcohols, lipids, etc.) that are naturally secreted by marine organisms (Monin and Krasitskii, 1985; Alpers and Espedal, 2004). They (also referred as natural slicks) form an extremely thin layer on the sea surface, the so-called "oil microlayer", which can be seen, when the wind is low (2–4 m/s), as patches of mirror-flat water (Monin and Krasitskii, 1985; Alpers and Espedal, 2004). In general, the biogenic films are only
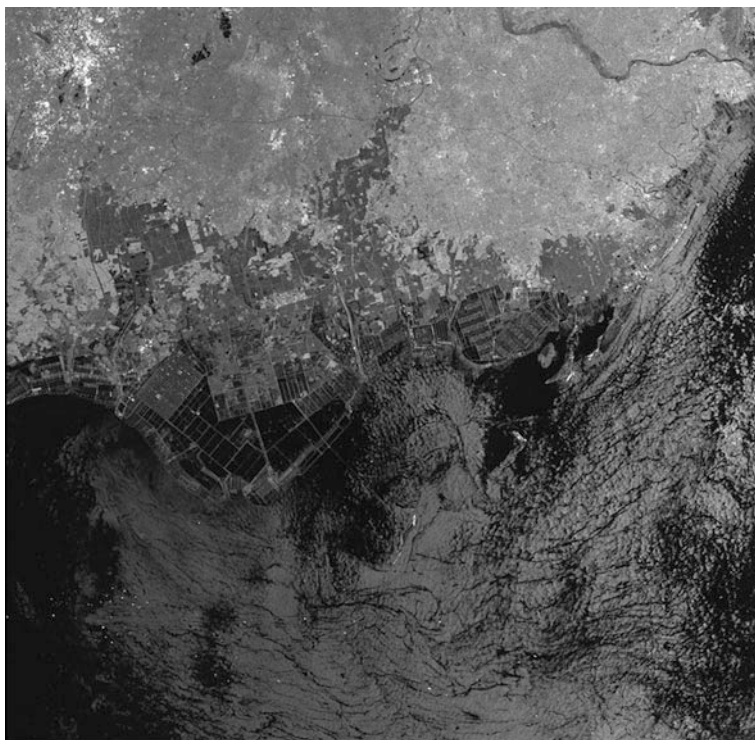

Fig. 9.11 Biogenic slicks in the East China Sea on the Envisat SAR image of 24/08/2005. © ESA

about one molecular layer thick ($\sim 10^{-9}$ m) (Levich, 1962), and only few liters of surface-active material can cover an area of 1 km^2 (Alpers and Espedal, 2004). The probability of encountering natural biogenic films is strongly enhanced, especially at times when the biological productivity is high, i.e., during and after phytoplankton blooms. In some cases the part of the sea covered by natural films can be very large, as it often the case in the inland and marginal seas (Fig. 9.11). When their concentration is very low, surfactants may also be present without directly showing up as slicks (da Silva et al., 2000).

Of course, all these oily substances form layers of different thickness on the sea surface, very efficiently damp the short surface (capillary-gravity) waves and for this reason can be easily detected by remote sensing techniques, primarily by imaging radars.

3 Remote Sensing of Oil Films

Fingas and Brown (1997) reviewed the airborne and spaceborne sensors and evaluated them in terms of their usefulness in responding to oil spills. The remote sensing techniques of marine oil spills include applications of optical (cameras and lasers), infrared (IR) and microwave (radiometers), and radar (real aperture radars – SLAR and synthetic aperture radars – SAR) sensors on board aircrafts or satellites. While airborne sensors are limited by small area of survey and high cost, satellite sensors have other kind of limitations. Satellite systems used visible bands are susceptible to false detections of oil due to sun altitude, clouds, shallow bottom topography and floating seaweeds. Moreover, traditional satellite optical sensors (e.g., SeaWiFS, MODIS, AVHRR) have not been of much use for oil spill detection due to spatial resolution of about 1 km (Fingas and Brown, 1997). Middle-resolution optical sensors (e.g., ETM/Landsat, HRV/SPOT, LISS/IRS etc.) do not provide daily observations, and the data are of limited spatial coverage and expensive (Fingas and Brown, 1997). Nevertheless, under cloudless conditions optical images demonstrate a good capability, as on Terra/ASTER image with seepage slicks on Lake Maracaibo (Venezuela) in Fig. 9.10. Other remote sensors, such as IR (or IR/UV) systems, microwave radiometers and fluorometric lasers have similar inherent weaknesses (lack of sufficient spatial resolution and operational applicability) and can be used on aircraft (Fingas and Brown, 1997).

Therefore, there are situations when these techniques are unable to detect and mapping oil spills. It is in these cases that radar remote sensing is required. On SAR images, the dark signatures can be used to detect oil films on the sea surface and to distinguish them from different non-film phenomena. However, SAR data are not available on daily basis, are limited by wind speed (Bern et al., 1992; Ivanov et al., 1998; Alpers and Espedal, 2004), and have other disadvantages (such as their being costly and prone to many interferences; (Fingas and Brown, 1997)).

SAR systems rely on the detection of variations of the sea surface roughness. The possibility of detecting an oil spill in a SAR image depends on the fact that oil films

decrease the backscattering property of the sea surface, damping the short gravity-capillary waves that results in dark signatures, which contrast with the grey tone of the surrounding, normally backscattering sea surface (Alpers and Hühnerfuss, 1989; Gade et al., 1998). SARs used for monitoring of oil pollution usually operate at incidence angles from 20° to 60°, i.e., at those angles where the radar backscattering can be described by Bragg's scattering theory (Valenzuela, 1978). At wind speeds <2 m/s, the background scattering at the sea surface becomes extremely low, the required contrast is effectively lost, and the oil slicks become undetectable by SAR (Alpers and Espedal, 2004). The minimum wind speed that creates sufficient brightness in the SAR image and makes the oil film visible is between 2m/s and 3 m/s. The optimal wind speed to effectively detect oil films by imaging radars is 3–6 m/s (Bern et al., 1992), whereas thick oil films are still visible at wind speeds of 10–12 m/s (Ivanov et al., 1998; Alpers and Espedal, 2004; Litovchenko and Ivanov, 2006 and Fig. 9.2). When the wind speed is too high (>14 m/s), it causes the oil spill to disappear from the sea surface due to mixing down into the water column. Nevertheless, definite detection is difficult because SAR doesn't measure any film characteristics and detection is possible in a narrow range of wind speeds (Bern et al., 1992).

As previously mentioned, there are three main categories of slicks recognized on SAR images: oil pollution (the thickest slicks), seepage slicks (i.e. created by oil coming from seepages), and natural biogenic films (the thinnest slicks). The signatures of the second and third types can be mixed with those of oil spills produced by vessels, rigs or pipelines (Fig. 9.4–9.7). Discrimination between them and oil spills requires analysis of slick appearance (shape, size, area, dB-contrast, edge type, texture), environmental conditions (wind, currents, precipitation), contextual information about slick position relative to surrounding objects (ships, ship lanes, rigs, platforms, seeps) and other concomitant oceanic and atmospheric phenomena (internal waves, upwelling, grease ice, algae blooms etc.) (Espedal, 1998; Alpers and Espedal, 2004). Discrimination between them is a main and important task of ocean remote sensing (Brekke and Solberg, 2005), especially in the context of global changes.

To sum it up, remote sensing of oil spills with a SAR and their delectability is, to some degree, a combination of: (1) environmental parameters (wind speed and sea state), (2) SAR parameters (frequency, incident angles, polarization, resolution), (3) oil film characteristics (oil type and film thickness), and (4) slick characteristics extracted from a SAR image (contrast, shape and dimension).

Evidently, SAR systems play a major role in remote sensing of oil spills. For detection, a SAR has to have radar frequency, incident angles and polarization, which cover the frameworks of Bragg scattering mechanism. Moreover, resolution and swath width of SAR images have to be sufficient for routine oil spill monitoring.

Wind speed (sea state) considered as critical limitations of SAR seems to be the same for all remote sensing systems. Wind speed >2.5 m/s is sufficient to produce background sea surface roughness allowing an oil spill became detectable. Wind speed >12 m/s, called an upper wind speed limit, prevents the oil spill detection.

Wind strongly affects the shape and appearance of the oil patch (Espedal and Wahl, 1999; CEDRE, 2004).

Oil film characteristics also play important role in spill detection. The thinnest biogenic slicks are visible on the sea surface up to 4–5 m/s, but aren't at wind speed >6 m/s (will tend to mix down into the water column and become undetectable by SAR). Seepage slicks are still detectable at winds of 6–7 m/s. The same is for the oil spills of middle thickness, but heavy oil products and crude oil (the thickest films) can be detectable on the sea surface up to 12 m/s, and even 14 m/s (Ivanov et al., 1998; Alpers and Espedal, 2004). Thus, wind speed can sometimes be a natural filter for oil films. When oil is in the sea, mineral oil films are subject to the actions of the wind, currents, and physical-chemical transformations, called weathering processes (Fig. 9.1). After some time, oil slicks become dispersed and undetectable by remote sensing techniques. This time depends on the type of the oil, its volume and film thickness, and on the wind and wave conditions (Alpers and Espedal, 2004). It usually varies from a half of day for seepage slicks and ship discharges, to several weeks or even months for crude oil.

Slick characteristics visible on a SAR image such as contrast, shape and dimension are very important in remote sensing of oil spills. Apparently, the contrast or oil slick – surrounding ocean backscatter ratio is a complex result of oil film parameters, and wind speed & sea state. Slick shape and size are results of action of currents and winds and their history (Espedal and Wahl, 1999). Thin oil films break up into filaments or windrows due to circulation of currents and wind (Alpers and Espedal, 2004; CEDRE, 2004), whereas crude oil and heavy fuel oils are viscous and usually remain in relatively compact patches. Moreover, all oil patches are subjected to spreading, transportation, mixing with water and weathering processes (Fig. 9.1); they transform and decay by different processes at the air-sea interface. The appearance of seepage slicks and remnant oil pollution sometimes is similar to those of natural biogenic slicks. And sometimes it is not easy to discriminate oil spills from seepage slicks only using backscatter contrast, shape and size (Fig. 9.12). As oil slicks become smaller, thinner and less distinct, classification is less precise, and it is not always possible to understand a definitive origin.

The thinnest biogenic slicks can act as ideal tracers. In convergent zones of currents and eddies they render visible the current patterns. Seepage slicks and oil spills persist over wider wind conditions and for longer time periods than natural biogenic slicks. The thinner oil films the quicker a slick disappears from the sea surface when wind increases. However, in many cases, the discrimination of mineral oil patches from natural surface films is possible by their shape and size (Alpers and Espedal, 2004).

Not only oil films on the sea surface can create dark features in the SAR images of the sea surface. There are a variety of hydrodynamic, aerodynamic and biological phenomena in the upper ocean and the low atmosphere, which damp short surface waves with the strength of the oil and create, the so-called "look-alikes" (Espedal, 1998). The term "look-alikes" unites all slicks that look like oil slicks, which are produced by phenomena in the ocean and the atmosphere, and detected
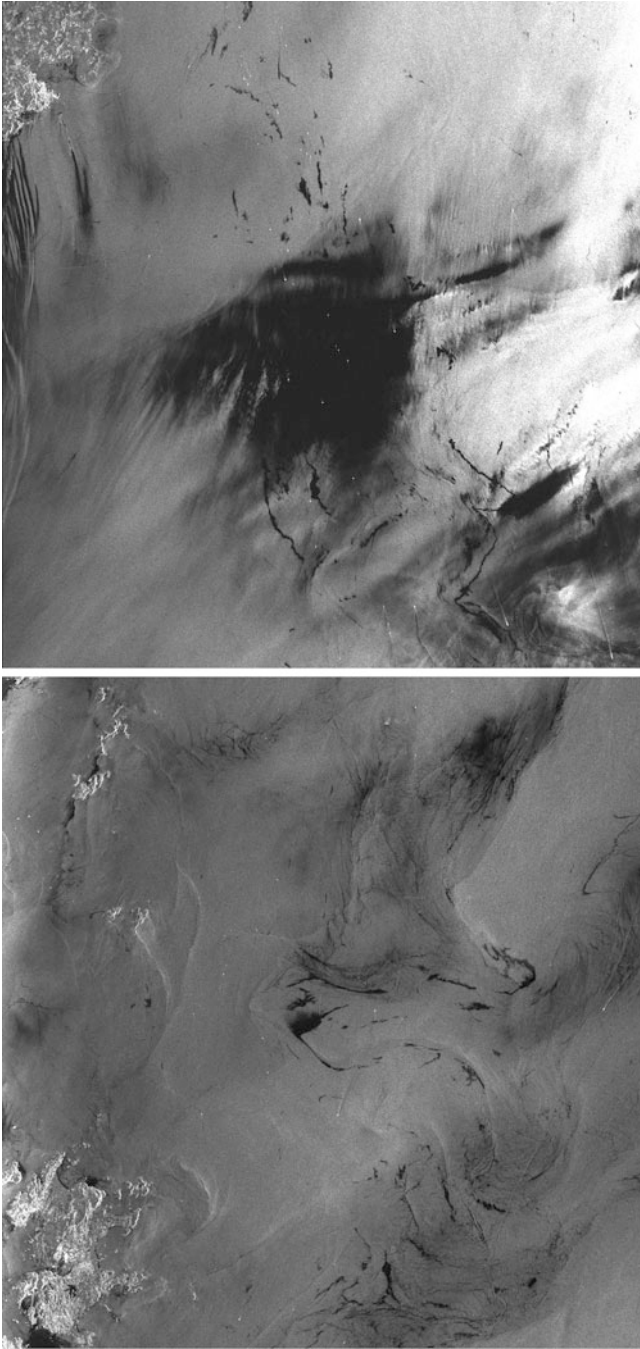
Fig. 9.12 Typical oil pollution from different sources in the Yellow Sea on the ERS-2 SAR images of 13/04/2004. © ESA

by SAR as dark patches. (Espedal, 1998). Typical phenomena producing look-alikes are: currents, upwelling, ship-made turbulence, internal waves, SST and wind stress variations, precipitation, atmospheric gravity waves, grease ice, algae blooms, floating seaweeds, sperm and eggs of marine animals, and shallow bottom topography (CEDRE, 2004; CEDRE, 2007). Under moderate wind conditions surface manifestations produced by these phenomena can be imaged as dark signatures with similar shape and size, and even contrast. Their manifestations on SAR images may cause false detections (Espedal, 1998; Alpers and Espedal, 2004).

Further information and discussions on the typical appearance and detectably of oil spills on SAR images, possibilities to identify man-made oil spills on a complex image background as well as overview on these topics a reader can find, e.g., in Espedal (1998), Alpers and Espedal (2004), CEDRE (2007).

In addition, remote sensing can be a powerful tool to control applicability of international conventions on marine oil pollution. According to the MARPOL Convention's protocols, seagoing ships may discharge oily mixtures into the ocean at a rate of 16 l per km and at a distance longer than 80 km from a shore (MARPOL, 2009). But evidence shows that it is common practice to exceed this limit. The majority of oil pollution incidents takes place just beyond the territorial waters, and therefore beyond the attention of pollution authorities and environmental agencies (Pavlakis et al., 2001).

To sum it up, it should be noted that despite different interferences, ambiguities and look-alikes environmental scientists and oceanographers faced with, a problem of remote sensing of oil films seems to be practically solved. Operational monitoring systems for oil pollution using satellite images are recognized as national/regional priorities. Many national space agencies and pollution authorities demonstrate SAR's potential and use of SAR images to optimize oil pollution control, monitoring and surveillance. The process of oil spill identification consists of several and now well defined steps (Brekke and Solberg, 2005). Image analysts use visual analysis, semi-automatic and automatic methods to detect and identify oil spills and their sources. They provide subsequent users with an accurate and objective first guess at the presence of oil on SAR image/sea surface. By wide use of contextual information about surrounding objects in the sea, a discrimination procedure can be significantly facilitated. Simultaneously wind field and ship positions can be extracted from the same SAR image. Outputs, which are wind, ship and oil spill' distribution maps, are converted in to shape files and than are sent to different catalogues, archives and end users. All these data are available for analysis from the beginning of the 1990s.

4 Mapping of Oil Films in the Context of Climate Changes

A considerable amount of new research over the past 10 years has led to an understanding of vital importance of the interface between the ocean and the atmosphere, and how it may interact with the processes involved in global changes. Recent

research has shown that oil spills, both natural (biology- and geology-made) and man-made, have a far greater impact on a changing climate than previously thought (Kraus, 1972; Monin and Krasitskii, 1985; Liss and Duce, 1997; Toba, 2003). It has been shown that major oil spills may have impact on the marine environment, even at test sites hundreds of kilometers from the accidents. For example, some findings show that oil spills in Europe, such as the Prestige tanker disaster off the coast of Spain in 2002, have consequences on marine environments far from the scene of the initial pollution (Garcia Perez, 2003).

Evidently, prior to the investigation of the climate changes, the detail distribution of oil films over wide areas in the ocean and physical-chemical properties of the air-sea interface under their influence have to be meticulously studied (Monin and Krasitskii, 1985). In this connection, only long-term mapping of oil films enables scientists to see a correlation between total volume and extent of oil films in the ocean and climate changes.

Oil spill researchers also showed that oil spill distribution and extent may have a significant effect on the properties of the ocean-atmosphere interaction (Monin and Krasitskii, 1985). The consistent high changes of a number of phenomena in the climatic system for the past 50 years may be due to human activity-induced oil pollution of the world ocean. If this is the case, it would mean that marine environment is vulnerable to human activities on two counts: directly through oil pollution from illegal discharges and accidents, and indirectly through global climate changes.

As discussed above, biogenic slicks and seepage slicks are natural in the ocean and are permanent factors in the ocean-atmosphere system. Man-made oil pollution comes from a variety of sources, such as routine ship operations and accidents. The first two factors are taken into consideration in global climatic or ocean-atmosphere scales. The last is probably not. This is because the real coverage and spatial extent of oil spills are still not clearly understood. In other words, the distribution of natural oil slicks as well as oil spills is a crucial environmental issue. To understand that, one needs to collect as much data covering the most of seas of the world ocean as possible for at least the last 30 years. This can be realized only though remote sensing and particularly through a GIS, which allows scientists to collect SAR images, manage detected oil spills and link them with appropriate sources (Ivanov and Zatyagalova, 2008).

Evidently, remote sensing is a powerful tool to control better marine oil pollution. To minimize the risks of false identification/classification of dark features on SAR images a number of special algorithms have been developed (see, e.g., reviews by Brekke and Solberg, 2005 and Topouzelis, 2008). These algorithms are based on various features and parameters available from a SAR image and taken into account environmental parameters and contextual information, such as wind, traveling ships, offshore oil and gas objects. This methodology usually uses object-oriented approach and image segmentation techniques (Brekke and Solberg, 2005; Topouzelis, 2008).

Another approach developed worldwide and summarized by Ivanov and Zatyagalova (2008) (see also literature cited herein), called GIS-approach, uses a wide set of detailed geographic & oceanographic (coastline, bottom topography,

wind, currents, etc.), geologic-geophysical (oil and gas formations, oil fields, seepage, etc.) and industrial (onshore and off shore oil & gas infrastructure, shipping infrastructure, etc.) information about a marine basin. All this information can be arranged in a GIS, allowing manipulation of all kind of spatial information including remote sensing images. For example, images of oil spills collected over a long period of time will show in GIS risk zones or hotspots, where chronic oil pollution occurs and accumulates. Moreover, GIS-approach allows scientists to calculate spatial distribution (extent) and total area of detected oil films that, under certain assumptions about thickness of films, can give information about total volumes of spilled oil. Further monthly/annually trends in oil pollution can be analyzed. Finally, knowledge obtained in long-term monitoring based on GIS-approach can be used in climatic models enabling us to see an impact of man-made pollution on trends in climate changes.

GIS-approach is also considered to be a tool for improving oil spill identification and classification in SAR imagery. First of all, a number of limitations of SAR for oil spill detection are being recognized. Second, because operational detection service based on SAR images still depends on an operator's experience, such analysis is considered to help in identification of oil sources. It is proposed, therefore, that GIS-approach and the use of geographic, remote sensing, contextual and other ancillary data and information can make an important aid to interpret correctly the slicks signatures, providing a framework for analysis (Ivanov and Zatyagalova, 2008).

A GIS database for the marine basins can be compiled of data of several sources. Vector shoreline and bathymetric data can be obtained from the national geophysical data centers, by digitizing detailed nautical maps, or extracting from global/regional topographic models. Both oil and gas production infrastructure offshore and industrial/municipal infrastructure onshore can be compiled from data of regional/local archives or corporative databases. Main shipping lanes can be also obtained from nautical maps. Fishing/aquaculture areas, coastal and marine restricted, protected and vulnerable zones are responsibility of corresponding authorities. All datasets and geographic information have to be compiled together and placed into a generally used geographic projection using GIS-software.

Thus, GIS, in providing an efficient storage, retrieval, analysis and visualization of geographic, oceanographic, environmental and industrial information, is considered to support oil spill detection and identification. Fig. 9.13 displays a window of the GIS constructed for oil spill applications in the Yellow Sea and East China Sea. Such GIS was created using different sources, such as maps, charts, satellite images, raster and vector digital data. On Fig. 9.13, only layers related to oil production and transportation, i.e., shipping lanes and oil production platforms are displayed. One can load a set of SAR images into a GIS and display information, which is necessary for the support of identification of oil spill sources, and decision about extent of oil pollution.

In order to validate a methodological approach, a number of projects have been carried out. In these projects, the mapping of oil slicks/spills was undertaken in the Sea of Okhotsk/Japan Sea, Caspian Sea, Black Sea, Yellow and East China Sea, and in the Gulf of Thailand (Ivanov and Zatyagalova, 2008; Shi et al., 2008).
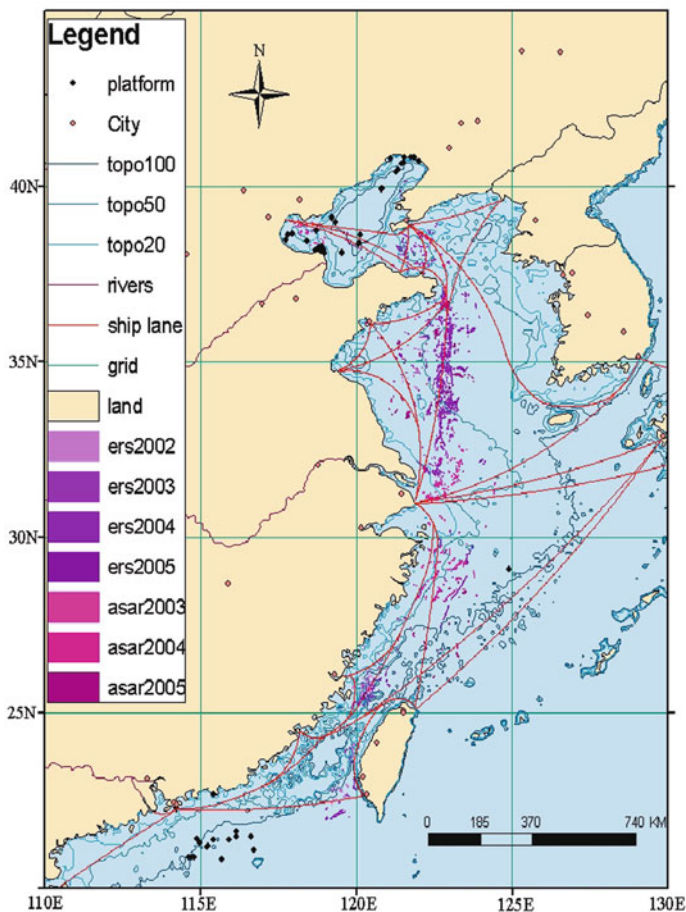
Fig. 9.13 An example of GIS-made oil spill distribution map for the Yellow Sea and East China Sea (main regional/international ship lanes are also shown in red) (figure from Shi et al., 2008)

5 Conclusion

Natural and man-made oil slicks affect the physical properties of the air-sea interface, and, in turn, impact on the processes, which determine the ocean-atmosphere interaction. Among them are: energy transfer from wind to waves, evaporation and convection, SST variability, gas exchange, skin-layer and foam on the sea surface. Existing knowledge about the effects of oil films on ocean-atmosphere interactions and global warming, in the current situation of global changes, is insufficient. Their regional and global impacts are estimated very approximate, because the real distribution of oil slicks as well as of oil spills in the world ocean is indeed unknown.

Significant advances have been made in the last decade both in estimating air-sea interaction over the ocean and in developing methods for detection and identifying of oil spills. Oil films covering the ocean surface can now be resolved with at sufficient temporal and spatial resolution by using remote sensing techniques. It is expected, in the near future, to use satellite-derived oil spill products that have the appropriate resolution instead assimilation products that often do not appropriately resolve oil films variability.

Now remote sensing, being a critical element of any ocean monitoring system, plays an increasingly important role in oil slick monitoring. In its present state, optical satellite imagery does not offer much potential for oil spill remote sensing. The imaging radars have become an important tool in the monitoring of marine oil spills due to their high resolution, all-weather and all-day capability. The potential of spaceborne SARs for oil spill detection has been demonstrated many times in the coastal zones and in the open ocean via observations of oil films floating on the sea surface. In general, this monitoring based on SAR images reveals the dramatic scales of oil pollution in the world ocean. It was also shown that SAR allows detection, localization and furnishing with information on the oil spills. Modern multi-swath, multi-resolution and multi-polarization SAR-equipped satellites, such as Radarsat, TerraSAR-X, COSMO-SkyMed and future Sentinel, will play a significant role in providing not only real data and information on accidents and shipwrecks (Ivanov, 2010), but on oil film extent.

Although conventional oceanographic technologies can provide more of the required data, the remote sensing can provide wider spatial and temporal coverage, new information products and effective solutions for monitoring of natural slicks and man-made oil spills. Through multi-temporal imaging, remote sensing techniques can provide information on slick distribution on a global and regional scale. It seems in the context of global changes only remote sensing can answer a number of questions faced by applying the approaches and methods developed recently. A GIS-approach for the mapping of oil slicks and spills in the sea is becoming an important tool, whereas a set of oil spill distribution maps, when combined and generalized, can be some kind of a response to the challenges of the 21st century.

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