Wind Speed and Instrument Modes Influence on the Detectability of Oil Slicks using SAR Images: a Stochastic Approach

Zhouh Najoui, Benoit Deffontaines, Jean-Paul Xavier, Serge Riazanoff, Guillaume Aurel

Abstract— The detection of marine oil slicks from Synthetic Aperture Radar (SAR) images is considerably hampered by wind conditions and depends on sensing properties. If empirical approaches already exist, this paper has the merit - for the first time - to conduct a statistical study, based on SAR BigData that aims on the one hand, to determine and prove the wind speed range that optimizes the detection of oil slicks in all SAR images, and, on the other hand, to evaluate the behavior of the oil slicks detectability regarding the wind speed intensity. Moreover, it also assesses the influence of the radar instrument mode on slicks detectability. To carry out the present study, a database of 1333 SAR images collected between 1992 and 2015 from three European Spatial Agency (ESA) missions: ERS-1/2, Envisat, and Sentinel-1, has been used. This database which covers four representative large areas of interest has allowed us to perform a dataset of 3903 manually detected oil slicks. The outcome of this manual detection and in particular the number of detected oil slicks, have been linked to the wind speeds computed from observations based on a classic meteorological global model at the time of observation (ECMWF). The analysis of the results of our stochastic approach revealed that the detectability of 95% of oil slicks occurrences, assuming a Gaussian distribution, ranges between 2.09 m/s and 8.33 m/s. By processing a statistical normalization of the wind speed distribution, the analysis revealed also that the detectability - contrary to what is known hitherto - increases almost linearly with the wind speed up to a statistically observed value of 8.25m/s. Moreover, the experimental results obtained on 5 acquisition modes (PRI, APP, IMP, WSM, and IW) demonstrate that the performance of oil slicks detectability depends on the type of modes. Among them, IW mode is far to be the most interesting for oil slicks detection, comes after APP, PRI, IMP, and finally WSM, which seems closely linked to the spatial resolution. Our statistical analysis of the association of the five modes and spatial resolution shows that the detectability is higher under high wind speed for sensor modes with the best spatial resolution (IW).

KEYWORDS

SAR, Oil slick, Detectability, Marine environment, Wind speed, Sensor mode.

1. Introduction

Given the stakes they represent, marine oil slicks (floating oil covering an area of water), and their detection—especially from SAR images—have been the subject of several studies in recent years. The reason being the impact that oil has on marine ecosystems, fisheries and wildlife, but also the economic interest they can represent. Oil slicks have a multitude of sources (natural oil seeps leaked from petroleum reservoir and anthropic oil spills discharged from ship or petroleum platform), and are present in substantial quantities on the sea surface. As an example, in a quantitative way, the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP, 2007), estimated the average total worldwide annual release of petroleum from all known sources to the sea to be 1 245 200 tons per year. According to GESAMP (2007), this amount of oil is divided equally between natural oil seeps and oil spills. All this shows the importance of detecting oil slicks to identify polluted areas and to assess the drift of these slicks in order to protect the coasts. In addition to the environmental application, the detection of oil slicks and especially natural oil seepage is a good indicator to assess the presence and the maturity of an oil reservoir which plays a major role in oil exploration/production.

Marine oil slicks detection represents a key where end users needs and aims. However, if the needs and the aims of the detection of marine oil slicks are clear and well defined, the detection remains a complicated task because of various weather conditions and remote sensing parameters. SAR images have proven to be a useful tool for oil slick mapping due to the dampening effect that oil has on capillary and small gravity waves, called Bragg waves. The latter are generated on water by local winds and they are responsible for the radar backscattering (Gades and Alpers, 1998; Alpers and Espedal 2004; Jackson and Apel, 2004; Mercier and Girard-Ardhuin, 2006; Shu et al., 2010; Xu et al., 2015). As a consequence, oil slicks appear darker compared to the brighter radar backscatter produced by Bragg waves. According to Bragg theory, the backscattered radar power is proportional to the spectral energy density of Bragg waves. Therefore, beyond certain conditions related to the wind speed, oil may become undetectable (Buchroithner, 2001; Brekke and Solberg, 2005).

The capability of a SAR sensor to detect marine oil slicks is a multivariate issue. For instance, it depends on the weather conditions, sensor properties (polarization, signal to noise ratio, incidence angle, spatial resolution, wavelength, etc.), oil properties, seasonality, water temperature, salinity, etc (Skrunes et al., 2012). A variety of studies have been carried out about the range of wind speed that optimizes the oil slicks detection on SAR images. Wind speed requirement has been reported to be 3 to 7-10 m/s (Brekke and Solberg, 2005), 3.5 to 7 m/s (Garcia-Pineda et al., 2009), 1.5-10 m/s (Fingas and Brown, 2014), and 1 to 7°m/s (Marghany,
However, all of these studies are empirical and no explicit statistical study has been presented. Thus, wind data used in some studies are too punctual (from buoys) and consequently are not representative. Furthermore, in an automation perspective of the detection of marine oil slicks on a global scale, the reported wind speed ranges vary considerably and does not take into account the geographical diversity, all oil slick types, seasons, slick age, etc. Our objective is to tackle these gaps by using a stochastic approach based on a high number of samples to give an optimal range of wind speed that optimizes oil slick detection on a global scale and compare the performance of 5 SAR modes on oil slicks detectability under different winds speed.

In this study we focus on the two following parameters, wind speed and sensor mode, which strongly influence the oil slicks detectability using a stochastic approach. So our paper aims at answering the questions: what is the range of wind speed and the SAR modes that optimize the oil slick detection using a statistic study? What other major inputs can we deduce from a stochastic and statistical analysis of a large dataset of radar images? And how the outcome can make more reliable the recognition of marine oil slicks and optimize further automatic detection?

2. Material and Methods

2.1. Data used

2.1.1. SAR dataset

Several spaceborne SAR systems have been used for oil slicks monitoring (Liu et al., 1997; Espedal, 1999; Gad and Alpers, 1999; Solberg et al., 1999; Del Frate et al., 2000; Fiscella et al., 2000; Marghany, 2001; Gasull et al., 2002; Kanaa et al., 2003; Alpers et al., 2004; Brekke and Solberg, 2005; Angiuli et al., 2006; Chang et al., 2008; Garcia-Pineda et al., 2008; Topouzelis, 2008; Garcia-Pineda et al., 2009; Del Frate et al., 2013; Marghany, 2014; Xu and Brenning, 2014; Marghany, 2015; Suresh et al., 2015). In this study we used SAR images from 3 ESA’s missions: ERS-1/2 (1992-2010), Envisat ASAR (2002-2012), and Sentinel-1 (2014-2015). The three sensors operates in the C-band in a wide variety of modes that provide numerous functions such as observations of different polarities of the signal or that combine different polarities, angles of incidence, and spatial resolutions. The following five types of products described below (Table 1) have been used and compared:

- (i) Wide Swath Medium-resolution mode (WSM) gives a 400 km by 400 km wide swath image. It operates in one of two polarizations types, either HH or VV.
- (ii) Alternating Polarization mode Precision image (APP) gives two co-recorded images per acquisition either in HH and VV polarizations, HH and HV or VV and VH.
- (iii) Image Mode Precision image (IMP) generates high-spatial-resolution data products (30 m for precision images) selected from the total of seven available swaths. Its swath width ranges between 56 km (swath 7) and 100 km (swath 1) across-track. It operates in one of two polarizations types, either HH or VV.
- (iv) PRI mode (PRrecision Image) gives a 100 km by 100 km wide swath image with a spatial resolution of 30 m by 26.3 m. It operates in VV polarization.
- (v) Interferometric Wide swath mode (IW) acquires data with a 250 km swath at 5 m by 20 m spatial resolution (single look). IW mode captures three sub-swaths using Terrain Observation with Progressive Scans SAR (TOPSAR). It operates in single (HH or VV) or dual polarization (HH and HV or VV and VH).

In this study, all of the used SAR scenes are co-polarized (HH or VV). The reason is that many studies discuss the potential of sensor polarization for oil slicks detection (Elachi, 1988; Robinson, 1994; Fortuny-Guasch, 2003; Jackson and Apel, 2004) and they highlight that the cross-polarized (VH, HV) ocean backscattering is considerably less efficient than the co-polarized backscattering (VV, HH). In fact, the radar scattering from clean water involves a single, largely polarization-preserving, dominant scattered, yielding cross-polarized returns that are negligible relative to the total returned power (Jones et al., 2011). For most instruments, the cross-polarized signal is below the instrument noise floor for returns from oil on water, making it unobservable (Liu et al., 2011). An example showing the influence of the polarization on the oil slicks detectability is presented in Figure 1 and Figure 2. Figure 1 - (A-1) and (A-2) present two images acquired from Envisat ASAR (C-band, mode APP) on 09 September 2005 at 03:55 UTC respectively with HV polarization (A-1) and HH polarization (A-2). In agreement with the bibliography, one can see that cross polarization (HV) does not provide more results than HH (Figure 1). The oil slicks detected by HH polarization (A-2) are absolutely undetectable using HV polarization (A-1). Figure 2 - (B-1) and (B-2) present two images acquired from Envisat ASAR (C-band, mode APP) on 21 August 2005 at 03:52 UTC respectively with VV polarization (B-1) and HH polarization (B-2). The VV polarization generally gives the same radar backscattering as HH polarization in C-band.

Many studied revealed that there are two backscattering mechanisms: Kirchhoff mechanisms for 0 to 15° incident angle, and Bragg reflection for 20° to 70° angle which allows observing, with Bragg resonance phenomena,
gravity-capillarity waves highly damped by slicks. It has been also highlighted that incidence angle between 20° - 45° was seen to be the most suitable incidence angles for oil slicks detection (Espedal, 1999; De Beukelaer et al., 2003; Girard-Ardhuin et al., 2003; Pellon de Miranda et al., 2004).

As given by Table 1 the incidence angles of the Envisat ASAR, ERS-1/2 and Sentinel-1 are respectively 15° - 45°, 20° - 26°, and 29.1° - 46.0°.

Table 1 Summary of SAR images used in this study (number of scenes) and their characteristics (spatial resolution, pixel spacing, swath width, and incidence angle). The total number of SAR images used is 1333. Spatial resolution is a measure of the system's ability to distinguish between adjacent targets. Pixel spacing is the distance between adjacent pixels in an image, measured in meters. Product overviews: European Space Agency (2016).

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Product type</th>
<th>Spatial resolution (m)</th>
<th>Pixel spacing (m)</th>
<th>Swath width (km)</th>
<th>Incidence angle</th>
<th>Number of scenes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Envisat ASAR</td>
<td>WSM</td>
<td>150*150</td>
<td>75*75</td>
<td>400</td>
<td>15 - 45</td>
<td>636</td>
</tr>
<tr>
<td></td>
<td>APP</td>
<td>30*30</td>
<td>12.5*12.5</td>
<td>100</td>
<td>15 - 45</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>IMP</td>
<td>30*30</td>
<td>12.5*12.5</td>
<td>100</td>
<td>15 - 45</td>
<td>96</td>
</tr>
<tr>
<td>ERS-1/2</td>
<td>PRI</td>
<td>30*26.3</td>
<td>12.5*12.5</td>
<td>100</td>
<td>20 - 26</td>
<td>324</td>
</tr>
<tr>
<td>Sentinel-1</td>
<td>IW</td>
<td>5*20</td>
<td>10*10</td>
<td>250</td>
<td>29.1 - 46.0</td>
<td>231</td>
</tr>
</tbody>
</table>

Total : 1333

Figure 1 The influence of the polarization on the oil slicks detectability. SAR images acquired from Envisat ASAR (C-band, mode APP) on 09 September 2005 at 03:55 UTC with HV polarization (A-1), and HH polarization (A-2). A possible reason for there no oil spill imaged by HV polarization, is the signal level lower than the noise floor.

Figure 2 The influence of the polarization on the oil slicks detectability. SAR images acquired from Envisat ASAR (C-band, mode APP) on 21 August 2005 at 03:52 UTC with VV polarization (B-1) and HH polarization (B-2).

2.1.2. Wind speed data

In order to determine the wind speed range that optimizes the detection of slicks in SAR images, we used wind speed data that comes from the operational Numerical Weather Prediction (NWP) model of the European Centre for Medium-Range Weather Forecasts (ECMWF). ECMWF model has a global spatial coverage. Its wind fields have a
temporal resolution of 6 hours and are defined at 10-m above sea level. According to Dee et al. (2011), used data has a bias of -0.1°m/s that we consider negligible and a normalized standard deviation of 16%.

2.2. Methodology

As previously explained, the detectability of oil slicks on SAR images depends on several parameters; we focus here on wind speed and SAR modes. Indeed, in this paper, we take advantage of over thousand available SAR images from three radar missions (ERS, Envisat, and Sentinel-1) to carry out a stochastic analysis of oil slicks detectability according to wind speed and SAR modes. Beyond the high interest to process a huge amount of radar images, we definitely wanted to apply it to different zones with different meteorological and geographical contexts. Four Areas Of Interest (AOI) have been chosen for this study: North of Peru (that extends over Southern Ecuador and Northern Peru); West African coastline (Gabon, Congo, and Angola); Santa Barbara (Southern California), and southern Caspian Sea. The oil slicks occurring in these four regions come from both natural oil seeps and oil spills. Figure 3 presents the methods of data preprocessing and manual detection which are described below.

![Diagram](image)

**Figure 3** Methodological framework for data preprocessing and manual detection.

2.2.1. Image preprocessing

All radar images have been georeferenced in the geographic coordinate reference system over the WGS84 ellipsoid, datum WGS84. A land mask has been applied and the images have been radiometrically corrected. The radiometric correction consists on correcting the brightness variations due to SAR peculiarities. Indeed, the radar backscattering on offshore area is mainly guided by non-Lambertian reflections (the surface does not reflect the radiation uniformly in all directions). This non-Lambertian reflection leads to heterogeneity of the brightness in the radar image. The major cause of this heterogeneity is the incidence angle dependencies. The radar received signal strength depends on the distance between the satellite and the target (slant range); the reflection backscattering coefficient decreases as incidence angle increases. When the target is close to the nadir (near range), backscatter is stronger which contrast with a far target from the nadir (far range), where backscatter is lower. To overcome this issue a preprocessing method has been applied. This preprocessing method consists on a local stretching. In fact, the images are processed in 16-bits Digital Number (DN). The sea part is stretched linearly with a sliding window. After several tests to overcome the problem of brightness and heterogeneity, the best standard stretching choice in order to equalize all SAR images is a mean of 33410 and a standard deviation of 20560, in all parts of the output image.

The noise floor is an important factor to consider for oil slick detection applications, as the measured normalized radar cross section (NRCS) must be higher than the noise floor to make sure that the signal is not corrupted by noise. For single channel SAR oil slick detection, the signal from the sea needs to lie above the system noise floor.

Our approach in this study was statistical not physical. In fact preprocessing (to correct the incidence angle dependencies) and manual detection (of oil slicks) have been performed on SAR images in digital number in 16bit to preserve their native radiometric dynamic. Consequently, no specific comparison between noise floor and detected oil slicks radar backscattering has been done. However, this can be empirically ensured considering the fact that:

- only co-polarized (HH, VV) images have been used: the signal over the sea is known to be weaker in cross-polarization (HV, VH) compared to co-polarization channels (Brekke et al., 2012). Skrunes et al. (2012) conclude after a signal-to-noise analysis that the co-polarization signal is in most cases not affected by the noise floor. The co-polarization channels are more reliable for oil slicks characterization than cross-polarization channels for which the signal is often hidden below the noise floor (Skrunes et al., 2012).

- only C-band images have been used: Skolnic (1980) notes that the noise floor of C-band is lower than the X-band noise floor.

2.2.2. Manual detection

In addition to oil slicks, many phenomena may appear as dark in SAR images. Non-oil dark patches are termed as look-alikes features that include upwelling, eddies, rainfalls, wind shadows, bathymetry, internal waves, current shear zones, etc. (Espedal, 1999; Brekke and Solberg, 2005; Xu and Brenning, 2014).

Three approaches exist for oil slick detection in SAR images: a manual approach conducted by trained human operators who analyze images to detect oil slicks, the semi-
automatic approach where a computer detects all the dark objects in the SAR image using different techniques of segmentation after which an experienced human operator classifies these objects as slicks or look-alikes, and finally the automatic system that uses complicated image processing and programming techniques to perform both segmentation and classification.

If we did not find examples of manual detection in the bibliography, the semi automatic and automatic segmentation and classification are widely illustrated below. Some used segmentation, or dark spot extraction techniques are adaptive thresholding (Solberg et al., 1999), hysteresis thresholding (Kanaa et al., 2003), edge detection using Laplace of Gaussians or Difference of Gaussians (Chang et al., 2008), wavelets (Liu et al., 1997) and mathematical morphology (Gasull et al., 2002). Neural network based segmentation techniques were demonstrated in Garcia-Pineda et al. (2009), Angiuli et al. (2006), and Del Frate et al. (2013). Some automatic oil slick detection algorithms are "Classifiers" using a Gaussian density function based on statistical model approach (Solberg et al., 1999), a Mahalanobis classifier (Fiscella et al., 2000), neural networks (Del Frate et al., 2000; Garcia-Pineda et al., 2008; Del Frate et al., 2013), texture analysis, (Marghany, 2001), genetic algorithm (Marghany, 2014 and Marghany, 2015), multi-objective entropy evolutionary algorithm (Marghany, 2014) and Automatic Seep Location Estimator (Suresh et al., 2015).

Due to the real unknown accuracy of the semi-automatic and automatic approach, we focus below on a reliable manual detection approach. The manual detection is based on the "Synthetic Aperture Radar marine user's manual" (Jackson and Apel, 2004). Each of the 1333 SAR images has been manually interpreted independently from the others. Each oil slick has been categorized depending on the interpretation based on morphological and textural criteria. Oil slicks are divided into two major categories: biogenic and mineral. Biogenic oil slicks are produced by plankton and fish substances normally released into the environment. The mineral oils are subdivided into those of natural seeps from the sea bottom or anthropogenic oil spills that originate from oil and gas fields, wind fields, bathymetry, etc.). This work let to the constitution of a dataset with 3903 interpreted oil slicks.

3. Results and analysis

3.1. Wind influence

The assessment of the influence of the wind speed on the detectability of oil slicks consists of calculating the probability to detect an oil slick for a given wind speed. To do this, as a first step we calculated the wind speed probability of the 3903 observed oil slicks for all four areas of interest (section 3.1.1). The second step was to calculate the wind speed distribution (probability of occurrence of wind speed) in all areas of interest (3.1.2). The last step was to calculate the probability to detect an oil slick for a given wind speed (3.1.3) as the normalized ratio of the two above probabilities.

3.1.1. Wind speed probability of observed oil slicks: \( p(W/S) \)

Using the ECMWF wind speed model, we got the wind speed of each of the 3903 observed oil slicks all AOI's. Therefore, the distribution of wind speed \( W_i \) of 3903 observed oil slicks \( S \) is a conditional probability and is noted as \( p(W/S) \). In other words, \( p(W/S) \) is the frequency of the occurrences of wind speed of the 3903 observed oil slicks within each wind speed. By analyzing the result given in Figure 4 one can see that the detectability of oil slicks in Peru is high for wind speed equal to and higher than 5.5 m/s. And conversely, a lower detectability is observed in Peru for wind speed lower than 5.5 m/s. A low detectability of oil slicks is observed in the Congo/Angola for wind speed lower than 2.5 m/s and higher than 7 m/s. About 20 % of 682 detected oil slicks in the Caspian Sea are observed at wind speed between 4.5 m/s and 5 m/s. The detectability of Santa Barbara's observed oil slicks remains relatively stable at wind speed between 2.5 m/s and 6.5 m/s. The mean wind speed and the standard deviation were calculated for all oil
slicks of each AOI. By drawing a Gaussian function with the mean and the standard deviation of observations, one may see that 95% observed oil slicks in Peru, Congo/Angola, Caspian Sea, and Santa Barbara range respectively between 2.43 - 8.55 m/s, 2.30 - 7.50 m/s, 1.64 - 8.20 m/s, and 1.03 - 8.23 m/s (see Table 2).

![Wind speed distribution obtained from ECMWF of observed oil slicks (p(W/S)) in Peru (red, 2111 samples), Congo/Angola (blue, 836 samples), Caspian Sea (green, 682 samples), and Santa Barbara (orange, 274 samples). One may note the general Gaussian distribution of the wind speed and the 95% confidence of wind distribution range in between 2 and 8m/s.](image)

**Figure 4** Wind speed distribution obtained from ECMWF of observed oil slicks (p(W/S)) in Peru (red, 2111 samples), Congo/Angola (blue, 836 samples), Caspian Sea (green, 682 samples), and Santa Barbara (orange, 274 samples). One may note the general Gaussian distribution of the wind speed and the 95% confidence of wind distribution range in between 2 and 8m/s.

<table>
<thead>
<tr>
<th>AOI</th>
<th>Number of scenes by sensor mode</th>
<th>Number of observed oil slick</th>
<th>Min (m/s)</th>
<th>Max (m/s)</th>
<th>Mean (m/s)</th>
<th>Standard deviation (m/s)</th>
<th>Wind range 95% (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peru</td>
<td>53 scenes WSM, 46 scenes APP, 96 scenes IMP, 324 scenes PRI, 231 scenes IW</td>
<td>2111</td>
<td>1.1</td>
<td>10</td>
<td>5.49</td>
<td>1.53</td>
<td>2.43 - 8.55</td>
</tr>
<tr>
<td>Congo/Angola</td>
<td>244 scenes WSM</td>
<td>836</td>
<td>0.7</td>
<td>8.2</td>
<td>4.90</td>
<td>1.30</td>
<td>2.30 - 7.50</td>
</tr>
<tr>
<td>Caspian Sea</td>
<td>180 scenes WSM</td>
<td>682</td>
<td>0.9</td>
<td>8.4</td>
<td>4.92</td>
<td>1.64</td>
<td>1.64 - 8.20</td>
</tr>
<tr>
<td>Santa Barbara</td>
<td>159 scenes WSM</td>
<td>274</td>
<td>0.7</td>
<td>9.5</td>
<td>4.63</td>
<td>1.80</td>
<td>1.03 - 8.23</td>
</tr>
</tbody>
</table>
The global wind speed distribution of the 3903 observed oil slicks from all AOI is given in Figure 5. The Pearson correlation coefficient between data (global wind speed distribution) and a Gaussian distribution, calculated as given by Asuero et al. (2006) is high (0.987). Thus, by analyzing the outcome, one may see that 95% of observed oil slicks are detected at wind speed ranging between 2.09 m/s and 8.33 m/s, with a maximal detectability at 4.75 m/s, while the lower and the upper bounds are found to be 0.7 and 10 m/s (Table 2). Above 10 m/s the detection seems practically nonexistent. The few cases with wind speed less than 1 m/s show that oil slicks may be detectible on SAR images beyond the lower bounds reported in the literature (ref. see above).

Figure 6 shows examples of oil slicks detected under different wind speeds. Figure 6A-1 shows an example of oil seep that has been observed in the North of Peru under wind speed of 8.4 m/s. The oil seep has been validated based on a multi-temporal analysis of different SAR images (see Figure 6 A-2). Figure 6B-1 shows some oil slicks that have been observed in Santa Barbara under wind speed of 1.2 m/s. In the same way as A-1, the validation has been done using multi-temporal analysis (see Figure 6B-2). One may see that even for low wind speeds, Bragg waves are present even if they have small amplitude.
3.1.2. Wind speed probability: \( p(W_i) \)

Few oil slicks have been observed outside the range 2.09 - 8.33 m/s. This can be due to the fact that few winds are measured outside this range in our dataset. To assess this eventuality, we calculated the wind speed of each location where an oil slick is observed at the date of observation and at the rest of the dates of our SAR dataset that cover this location. This wind speed distribution is the probability of occurrence of wind speed and is noted as \( p(W_i) \). The \( p(W_i) \) has been calculated per AOI and later for all AOI's where a total of 609220 wind speed occurrences are plotted. The goal here, is to decorrelate (i) the probability to detect an oil slick according to a given wind speed from (ii) the probability of occurrence of this wind speed. The outcome is given in Figure 7. The results are given by AOI in order to differentiate the wind behavior of different geographic, geologic zones. Moreover we added all AOI's results in order to get the global AOI's wind speed distribution. In detail, Peru mean wind speed (4.89 m/s) is higher than that of the other AOI (Caspian Sea: 4.13 m/s, Congo/Angola: 3.28 m/s, and Santa Barbara: 3.21 m/s). The mean wind speed of the total distribution of the four zones is around 4.26 m/s.

Figure 6 Oil slicks detectability under different wind speed. A-1 is an ERS 1 (C-band, mode PRI) SAR image acquired on 07 September 1998 over the North of Peru that shows an example of oil seep that has been observed under wind speed of 8.4 m/s. A-2 shows several oil seeps observed at different dates in the same location as the oil seep observed in A-1. B-1 is an Envisat ASAR (C-band, WSM) image acquired on 31 December 2011 over Santa Barbara that shows some oil slicks that have been observed under wind speed of 1.4 m/s. B-2 shows several oil slicks observed at different dates in the same location as in B-1.
3.1.3. Probability to detect an oil slick for a given wind speed: \( p(S/W_i) \)

The scope of this section is to calculate the probability to detect an oil slick for a given wind speed. This probability can be mathematically presented as a conditional probability noted as \( p(S/W_i) \). As given by Equation 1, \( p(S/W_i) \) is calculated using (i) the probability of occurrence of the wind speed in all locations where an oil slick has been observed \( p(W_i/S) \) (Figure 5), (ii) the probability of occurrence of the wind speed in all acquisitions, in all locations where an oil slick has been observed in at least one acquisition \( p(W_i) \) (Figure 7, right panel), and (iii) the probability for an oil slick to occur on the sea surface. Without any prior knowledge, \( P_s \) can be considered as constant for a given AOI.

\[
p(S/W_i) = P_s \ast \frac{p(W_i/S)}{p(W_i)}
\]

Where:
- \( p(S/W_i) \) is the probability to detect an oil slick \( S \) for a given wind speed \( W_i \)
- \( P_s \) is the probability for an oil slick to occur on the sea surface in a given AOI. Without any prior knowledge, \( P_s \) can be considered as constant for a given AOI.

\( p(W_i/S) \) is the probability of occurrence of the wind speed \( W_i \) in all locations in the single acquisition where an oil slick has been observed.

\( p(W_i) \) is the probability of occurrence of the wind speed \( W_i \) in all acquisitions, in all locations where an oil slick has been observed in at least one acquisition (609220 occurrences).

Figure 8 (left panel) shows \( p(W_i/S) \) (red curve), \( p(W_i/S) \) (blue curve), and \( p(W_i) \) (green curve). The analysis of the outcome shows that the probability to detect an oil slick (red curve) increases with the increase of the wind speed. A maximum probability is reached at 8.25 m/s, above 8.25 m/s, the red curve is in dashed part of the \( p(S/W_i) \) curve and not taken into consideration because of the low number of oil slicks samples. Figure 8 (right panel) shows \( p(S/W_i) \) (red curve) and its linear trend curve (black curve) for the optimal wind speed for the detectability of oil slicks, previously defined (2.09 - 8.33 m/s). One can see that the detectability of oil slicks arises almost linearly with the increase of the wind speed up to 8.25 m/s. Indeed, \( p(S/W_i) \) is well correlated to the linear trend curve (0.953) for wind speed ranging between 2.09 m/s and 8.33 m/s. This finding is important since it contrast with what is known hitherto (Gade and Viebahn, 2000; Bayramov et al., 2015).
right panel); Consequently, the red curve corresponds to the probability \( p(S/Wi) \) to detect an oil slick for a given wind intensity. It is the decorrelation in between the blue and the green curves as it is calculated from the ratio of \( p(Wi/S); p(S/Wi) \). (Equation 1). The dashed part of the red curve is not here taken into consideration because of the low number of oil slicks samples analyzed with strong winds. For the first time, contrasting to previous studies, the red curve prove that the probability to detect an oil slick arises almost linearly with the increase of the wind speed as we observe that the maximum probability is reached at 8.25 m/s

### 3.2. Instrument mode influence

Below we now want to assess the influence of SAR instruments on oil slicks detectability and then to assess this influence under different wind speed with oil slicks detectability. As it’s well known that the detection of marine oil slicks on SAR imagery depends on environment conditions (wind, waves, currents, tides, etc.) as well as radar system parameters (frequency, spatial resolution, polarization, incident angle, etc.) (Gades and Alpers, 1998; Trivero et al., 1998). In order to assess the instrument influence a normalized frequency of oil slicks \( S_f \) is calculated as:

\[
S_f = \frac{S_n}{O_p \cdot GSD}
\]

(Equation 2)

Where:
- \( S_f \) is the normalized frequency of observed oil slicks
- \( S_n \) is the total number of observed oil slicks
- \( GSD \) is the pixel spacing also called the Ground Sampling Distance (GSD). It’s the distance between adjacent pixels in an image, measured in meters.
- \( O_p \) is the total number observed pixels defined by the equation below:

\[
O_p = \sum_{i=0}^{M-1} \sum_{j=0}^{N-1} O_{(l,p)}
\]

(Equation 3)

Where:
- \( O_{(l,p)} \) is the number of scenes (observed at different dates) which pixel(s) fall at \((l,p)\) location.

The normalized frequency of oil slicks has been computed for five types of products (PRI, APP, IMP, WSM, and IW). The result (Figure 9) demonstrate that the performance of oil slicks detectability depends on the acquisition modes in the following decreasing order IW, APP, PRI, IMP, and WSM. By analyzing the Figure 9 (left panel) one can see that the established order seems to be highly correlated with the pixel spacing. In order to characterize this correlation, the normalized frequency of observed oil slicks is calculated according to the pixel spacing (10 m, 12.5 m, and 75 m). The results given in Figure 9 (right panel), show that about 55% of interpreted oil slicks are observed with a pixel spacing of 10 m (IW), 38% with a pixel spacing of 12.5 m (IMP, PRI, and APP), and only 7% with a pixel spacing of 75 m pixel spacing (WSM). This may be explained by the fact that the oil slicks smaller than the spatial resolution of the WSM mode are not detected.

Another explanation is that under high wind speed, oil slicks tend to breakup and may be undetectable by the low pixel spacing WSM. In order to check the influence of the sensor mode under different winds speed, we plotted the normalized frequency of observed oil slicks of the 5 sensors mode according to wind speed. The analysis of the result given on Figure 10 shows that under high winds speed, the normalized frequency of observed oil slicks is the higher for IW mode. So despite the few number of oil slicks observed under strong wind speed, these slicks are detected mainly by

![Figure 9](image-url)  
Normalized frequency of observed oil slicks according to the radar acquisition mode (left panel) and the pixel spacing (right panel). One may notice that IW, APP, IMP, and PRI acquisition modes are more powerful than WSM mode on oil slicks detection because of the higher spatial resolution. It shows that the smaller pixel spacing is, the better the detectability of oil slick is. Remember that small slicks are not detected by WSM mode.
sensors with the higher spatial resolution (IW). By intersecting these results with the earlier ones, one concludes that the high probability to detect an oil slick \( p(S/W_i) \) under high winds speed is due to both the higher amount and pixel spacing of IW, APP, IMP, and PRI scenes on the AOI where the wind is the strongest.

**Figure 10**

Normalized frequency of observed oil slicks \( S_f \) by radar sensor mode according to the wind speed. One may note that all sensor modes present the same response within 1 m/s up to 9 m/s. For the higher wind range only the small spacing resolution sentinel IW sensor mode succeed to reveal oils slicks. We suggest that this is due to the oil slicks fragmentation probably due to breaking through strong winds. In contrast the high value of WSM in the low wind speed value (less than 1m/s) is biased by the absence of radar images of IW, IMP, APP, PRI modes in the Caspian sea, Congo/Angola and Santa Barbara (see table 2).

4. Discussion

This paper is written in the framework of a thesis which aims to automate the detection of natural oil seeps from SAR images in a global scale. The automatic detection can be optimized by eliminating false detections and reducing the process time. Indeed, detection of oil slicks in SAR images is heavily dependent on the prevailing wind speeds at the time of acquisition of the image. Oil slicks are not visible on the ocean surfaces if the contrast between the slick and the surrounding water is not sufficiently high (at low wind speeds) and at high wind speeds, the oil slicks tend to break up into smaller parts thus hindering detectability from SAR sensors. Using wind information can optimize the classification results by increasing the confidence of the estimated slicks locations and reduce false detections in low and high wind regions. In the absence of in situ data in every location of the earth, interpolation from model remains the best approach to the goals we have set.

Our approach to fix the dependency between the oil slicks detectability and wind speed aims to be global and representative of oil slick types and ages, seasonality, geographic contexts, etc. Punctual measures do not respond our need to make a global and representative study. It should also be noted that the ECMWF model has been extensively tested and validated (Dee et al. 2011). We are well aware of the problem of the interpolation from model. However, this problem can be filled by the fact that:

- We use a global model, available with assimilation and homogenization methods validated by experts.
- Statistically, with a large number of observations, errors due to the temporal interpolation will compensate.

Finally, this problem does not call into question our methodology, which as of the existence of more resolved data (wind from SAR data) may be applied.

As a matter of fact, wind speed requirement for oil slicks detectability have been given by several studies and referenced above. However, significant differences, whether in terms of approaches or outcomes, should be taken into consideration:

**Approach:** Previous studies have used empirical approaches while our study is based on a statistical and stochastic approach. In more detail, the referenced studies have merely studied cases of marine oil accidents such as the Deep Water Horizon, whose the oil nature is very peculiar. In the present study, 1333 images and a sample of almost 4000 samples of observed oil slicks (of different natures and origins) were analyzed, which gives the results an exhaustive character.

**Results:**
Here too there have been many advances. The first comes from the approach itself which makes it possible to detect all kinds of oil slicks whatever their origins. The results obtained by the previous studies apply, in fact, to oil spill. In this study, the wind speed range for the detectability of all kinds of oil slicks has been fixed: 2.09 and 8.33 m/s. Beyond these conditions, ie above 8.33 m/s and below 2.09 m/s, there is little chance (5%) to detect an oil slick. The intervals that the literature has given are as follows: 3 to 7-10 m/s (Brekke and Solberg, 2005), 3.5 to 7 m/s (Garcia-Pineda et al., 2009), 1.5-10 m/s (Fingas and Brown, 2014) and 1 to 7 m/s (Marghany, 2014a). The difference is considerable.

The main result of this study, and based on high number of samples (3909 oil slicks), is to quantify the dependency between the oil slicks detectability and the wind speed. And it is this dependency that the paper decorrelates to end in the figure 8 that shows a linear regression between the detectability and the wind speed up to wind speed of 8.25m/s. The stochastic approach based on 3909 observations is higher than all of the observations number cited in the literature (when their number is cited). This large number justifies the two digits placed in decimal part.

Up to a maximum wind speed, the higher wind speed, the higher contrast between oil-covered water and the oil-free water; the higher probability to observe with higher resolution is an assumption which is fully compliant with our statistical results that show that the detectability follows a quasi linear growth in relation to the wind speed up to a statistically observed value of 8.25m/s. However, this fact is not so obvious and does not achieve consensus in the scientific community. The notion of "high wind speed" remains relative. Indeed, Gade and Viebahn (2000) and Bayramov et al. (2015) estimate that the detectability decreases with the increase of wind speed over a given threshold. Thus, Clemente-Colon and Yan (2000) say that "At higher wind speeds (over 5 to 6 m/s), surfactants at the surface layer will tend to mix down into the water column and become undetectable by SAR". So, one of the major outcomes of this paper is to normalize the observations according to wind speed distribution and to obtain this quasi-linearity of the oil slicks detectability up to a statistically observed threshold. Furthermore, under extreme wind conditions oil slicks become undetectable. This may be justified by the fact that the sea waves are stronger than the dampening effect of oil slicks on Bragg waves and consequently oil slicks are broken, degraded, evaporated, remobilized by the waves and they disappear from the sea surface. It is therefore not possible to see oil slicks above a wind speed threshold that we statistically define with this stochastic approach.

It should be noted that wind speed requirement is not the only aspect on which this study has focused. Another result: a performance order of 5 instrument modes has been established (IW, APP, PRI, IMP and WSM). The study shows that the IW mode (Sentinel-1), with a spatial resolution greater than 5x20 m, is the most suitable for detecting an oil slick at high wind speed. Of course it may appear common sense but it was needed to be proved from a stochastic way.

5. Conclusions and perspectives

We are interested, like the numerous previous empiric approaches, in the relations in between the detection of oil slicks from SAR images and wind speeds. But, contrasting with the bibliography, we herein use, for the first time, a stochastic method to assess this relation as it is a very decisive element in the detection of marine oil slicks. After analyzing 1333 SAR images (1992-2015), acquired by three SAR missions on four areas of interest, we achieved this first result: an optimal detectability of oil slicks is ensured when the wind speed is between 2.09 and 8.33 m/s. Beyond these conditions, ie above 8.33 m/s and below 2.09 m/s, there is little chance (5%) to detect an oil slick. Note that intervals have already been announced like 3 to 7-10 m/s (Brekke and Solberg, 2005), 3.5 to 7 m/s (Garcia-Pineda et al., 2009), 1.5-10 m/s (Fingas and Brown, 2014), and 1 to 7 m/s (Marghany, 2014a). Within the same interval, 2.09 and 8.33 m/s, the detectability obviously varies. Contrary to the literature hitherto produced - and this is the most important result - in this interval, the higher the wind speed is the better the detectability is (Figure 8) up to the statistically observed value of 8.25m/s we register in this work.

In addition, a performance order of 5 instrument modes is established (IW, APP, PRI, IMP and WSM). The present study shows that the IW mode (Sentinel-1), with the higher spatial resolution of 5x20 m, is to be the most suitable for detecting an oil slick at high wind speed. This may be due to the fact that the slicks break under the influence of strong winds and that only the higher pixel spacing IW is able to detect them.

Our stochastic study improves and quantifies the dependence of marine oil slicks detectability on wind speed and sensing modes on a global scale. With the challenge of BigData and dealing with lots of data, these findings help to optimize the automatic detection of oil slicks. Optimization consists on eliminating false alerts that make ambiguity between slick and areas of low wind. For high wind areas where the detection of slicks is not possible, further process optimization is to minimize the processing time by the non consideration of the very low and high wind speed. We recommend extending this study by taking into account the influence of seasons, more wavelengths, and oil properties. Also, for more accurate wind data we recommend the use of local wind models or a large number of in situ observations using our statistical methodology.

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