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1 **Monitoring of natural oil seepage in the Lower Congo Basin using**

2 **SAR observations**

3 Romain Jatiault <sup>a, b\*</sup>, Damien Dhont <sup>a</sup>, Lies Loncke <sup>b</sup>, Dominique Dubucq <sup>a</sup>

4 <sup>a</sup> Total SA, Centre Scientifique et Technique Jean Feger (CSTJF), Avenue Larribau, 64018 Pau, France

5 <sup>b</sup> University of Perpignan Via Domitia, Centre de Formation et de Recherche sur les Environnements Méditerranéens (CEFREM), UMR 5110, 52 Avenue Paul

6 Alduy, 66100 Perpignan, France

7 \*Corresponding author. University of Perpignan Via Domitia, Centre de Formation et de Recherche

8 sur les Environnements Méditerranéens (CEFREM), UMR 5110, 52 Avenue Paul Alduy, 66100

9 Perpignan, France. Tel.: +334 68 66 20 98

10 E-mail adresses: [romain.jatiault@univ-perp.fr](mailto:romain.jatiault@univ-perp.fr), [romain.jatiault@total.com](mailto:romain.jatiault@total.com) (R. Jatiault)

## 11 **Abstract**

12 Synthetic Aperture Radar (SAR) is a spaceborne tool allowing near real-time imagery over large  
13 ground footprints of areas hundreds of kilometres wide. SAR also allows persistent observations  
14 of the process of oil discharges, benefiting from (1) day and night observations, (2) independence  
15 of cloud cover and (3) high revisiting frequencies. The interpretation of 82 SAR scenes over the  
16 Lower Congo Basin for the 1994-2012 period allowed the recognition of 1400 natural seepage  
17 slicks associated with 102 individual seep sites. We acquired an additional SAR data set with a  
18 short revisit time over a selected prolific area. The data set consisted of 22 SAR scenes acquired  
19 over a 10-day period, meaning a maximum revisiting period of 12 hours between subsequent SAR  
20 acquisitions. The short-term approach shows that seepage slicks were detected with wind speeds  
21 between 1.5 and 6.5 m/s (2.91 to 12.63 knots). Both long-term and short-term monitoring  
22 evidences that seepage events are intermittent, with the occurrence rate of oil release ranging from  
23 5 to 80%. Short-term monitoring shows that the seepage pace is independent between seep sites,  
24 suggesting contrasted controlling factors. It also shows that the residence time of seepage slicks is  
25 systematically shorter than 12 hours, which is far below reported values. Understanding the  
26 seepage slick residence time is essential to provide an accurate estimation of the fluid flow and to  
27 compute the volumetric outflow. The integration of in-situ mooring points measuring the current  
28 velocity 10 m below the sea surface, in addition to local wind field and slick length, allowed us to  
29 more accurately estimate the residence time of oil slicks at the sea surface before vanishing. The  
30 results show that the sea surface residence time of oil slicks is limited to a few hours, with a  
31 median value of 3h15min. These new residence time estimations allowed us to propose a  
32 quantification of the regional oil output in the Lower Congo Basin, estimated at 4380 m<sup>3</sup>/year.  
33 This area may therefore be considered as the world's third biggest oil-supplying province from  
34 natural leakages.

## 35 **1. Introduction**

36 Natural discharges of hydrocarbon fluids occur in most of the world's petroleum basins  
37 (Kvenvolden and Cooper, 2003; National Research Council, 2003; Kvenvolden and Rogers, 2005;  
38 Etiope, 2015). Because of its sensitivity to centimetre wavelengths (e.g., McCandless and  
39 Jackson, 2003), Synthetic Aperture Radar (SAR) is a remotely operated tool widely used in ocean  
40 studies for the recognition of sea surface patterns. Satellites with an on-board SAR system are  
41 used to detect natural liquid hydrocarbon seepage at the sea surface (Johannessen et al., 2000;  
42 Espedal and Johannessen, 2000; MacDonald et al., 2002; Brekke and Solberg 2005; Garcia-  
43 Pineda et al., 2009, Fingas and Brown 2014) in complement to spaceborne optical data  
44 (MacDonald et al., 1993; Macdonald et al., 2002; Hu et al., 2009; Chen and Hu, 2014). The  
45 presence of oil flattens the sea surface and significantly reduces the amount of energy  
46 backscattered to the satellite (Fresnel specular reflection) compared to the surrounding free water.  
47 Sea surface covered by oil seepage appears as black streaks on SAR images (Johannessen et al.,  
48 2000; Espedal and Johannessen, 2000; Williams and Lawrence, 2002; Ivanov et al., 2007;  
49 Zatygalova et al., 2007; Garcia-Pineda et al., 2009; Körber et al., 2014). Up to now, research on  
50 sea surface manifestations of thermogenic seeps has focused on a few case studies, including the  
51 Caspian Sea (Ivanov et al., 2007; Zatygalova et al, 2007), the Black Sea (Körber et al., 2014) and  
52 the Gulf of Mexico (Garcia-Pineda et al., 2014, Macdonald et al., 2015). The SAR method also  
53 serves as a primary tool for the evaluation of released volumes of heavy hydrocarbon discharges  
54 (MacDonald et al., 1993; Mitchell et al., 2000; Garcia-Pineda et al., 2014), even if quantifications  
55 may have been potentially underestimated with this technique (Hu et al., 2009; Garcia-Pineda et  
56 al., 2010; Smith et al., 2014). Oil seep systems are usually accompanied by gas escapes (Solomon  
57 et al., 2009; Hu et al., 2012) originating from the thermal cracking and the second methanogenesis  
58 from anaerobic biodegradation (Head et al., 2003; Peters et al., 2007). For environmental  
59 purposes, quantifying natural hydrocarbon escapes is therefore compulsory to understand their  
60 implications on the global carbon budget. Understanding the amount of expelled hydrocarbon at

61 the regional scale along continental margins also presents great implications for petroleum  
62 systems evaluation. The sea surface residence time of oil slicks is an important input parameter  
63 for the quantification of oil output but still remains poorly documented due to low revisiting  
64 frequencies of SAR data. The Lower Congo Basin is considered as an active petroleum province  
65 where geophysical investigations of the seafloor have allowed the recognition of high-density  
66 fluid flow features (Gay et al., 2003; Gay et al., 2006a, b, c; Gay et al., 2007; Andresen et al.,  
67 2010; Andresen and Huuse, 2011; Anka et al., 2013) of probable thermogenic origin (Gay et al.,  
68 2002; Gay et al., 2006b; Andresen 2012; Anka et al., 2013). Natural oil seepage slicks have been  
69 recognised at the sea surface at the regional scale in the Lower Congo Basin from observation  
70 using SAR images (Williams and Lawrence 2002; Dhont et al., 2013; Deffontaines et al., 2014)  
71 confirming that this area is a major active thermogenic fluid releasing domain and an excellent  
72 natural work site for studying regional fluid release dynamics and associated expelled  
73 hydrocarbon volumes.

74 The aim of this paper is to combine short-term and long-term SAR monitoring to compare the  
75 pace of thermogenic seeps distributed along the Lower Congo Basin and to quantify the volumes  
76 of expelled hydrocarbons. The study comprises an extensive archive comprising 82 SAR scenes  
77 acquired between 1994 and 2012 used to detect and map seepage slicks and to determine the  
78 location of recurrent oil seep sites. From these long-term observations, we assessed the activity of  
79 individual active seeps in order to quantify expelled oil volumes. To address the question of the  
80 seep lifespan, we set up a short-term monitoring with the acquisition of 22 SAR scenes every 12  
81 hours during 10 days over a specific area recognised as a major active seeping province. The  
82 tasking of overlapping SAR scenes over an active seeping area with a half day revisiting period  
83 constitutes a first order approach to study the recurrence and synchronicity of fluid discharges at a  
84 regional scale. For the first time, this study allows us to compare simultaneously the activity of  
85 several active oil seeping sites, benefiting from a minimum of two SAR scenes each day. The  
86 comparison between the local wind fields derived from SAR data and the occurrence of oil slicks

87 also helps to improve our knowledge of the relationships between slick detection and weather  
88 conditions. In addition, the assessment of short-term seepage pace is decisive to categorise the  
89 active, dormant and passive seep sites for research teams and exploratory cruises.

## 90 **2. The Lower Congo Basin**

### 91 **2.1. Geological context**

92 The Lower Congo Basin is located in offshore Angola, in the southern part of the Congo Delta  
93 (Fig. 1A). The study area is located on a passive margin resulting from the opening of the South  
94 Atlantic domain initiated during the Early Cretaceous (Duval et al., 1991; Cainelli and Mohriak  
95 1999; Browfield and Charpentier, 2006). During the Neocomian to Barremian, the development  
96 of syn-rift lakes gave rise to the prolific mudstone source rocks of the Bucomazi formation  
97 (Burwood 1999). During the late Aptian, the post-rift shallow environments allowed the  
98 development of thick hypersaline deposits overlaying a sag basin under conditions of regional  
99 thermal subsidence (Marton et al., 2004; Brun and Fort, 2004; Fort et al., 2004; Beglinger et al.,  
100 2012). During the Albian, sedimentation was characterised by carbonate ramp development (Da  
101 Costa et al., 2000; Anka et al., 2009; Beglinger et al., 2012). As thermal subsidence and  
102 progressive basin deepening continued, post-rift salt tectonics triggered by high sedimentation  
103 rates caused strong deformation of the overburden. Subsequent evolution of the margin was  
104 controlled by salt tectonics. The study area is sub-divided into three main provinces (Fig. 1B): an  
105 internal extensional area where the salt layer has been extremely thinned, a mid-slope transitional  
106 province where post-salt sedimentary series have been translated towards the basin, and a  
107 compressive domain consisting of a wide area dominated by severe deformation associated with  
108 salt diapirism, followed by a basinward compressive toe with extensive salt napes (Brice et al.,  
109 1982; Duval et al., 1991; Schoellkopf and Patterson, 2000; Marton et al., 2004; Brun and Fort,  
110 2004; Anka et al., 2013). The seaward part of the basin deformed by salt tectonics is delimited

111 from the abyssal plain by a distal compressive salt front (Anka et al., 2009). Intra-saliferous basins  
112 are infilled with turbidites and display an alternation of mudstone, claystone, shale and sandstone.

## 113 **2.2. Seafloor manifestation of fluid vents**

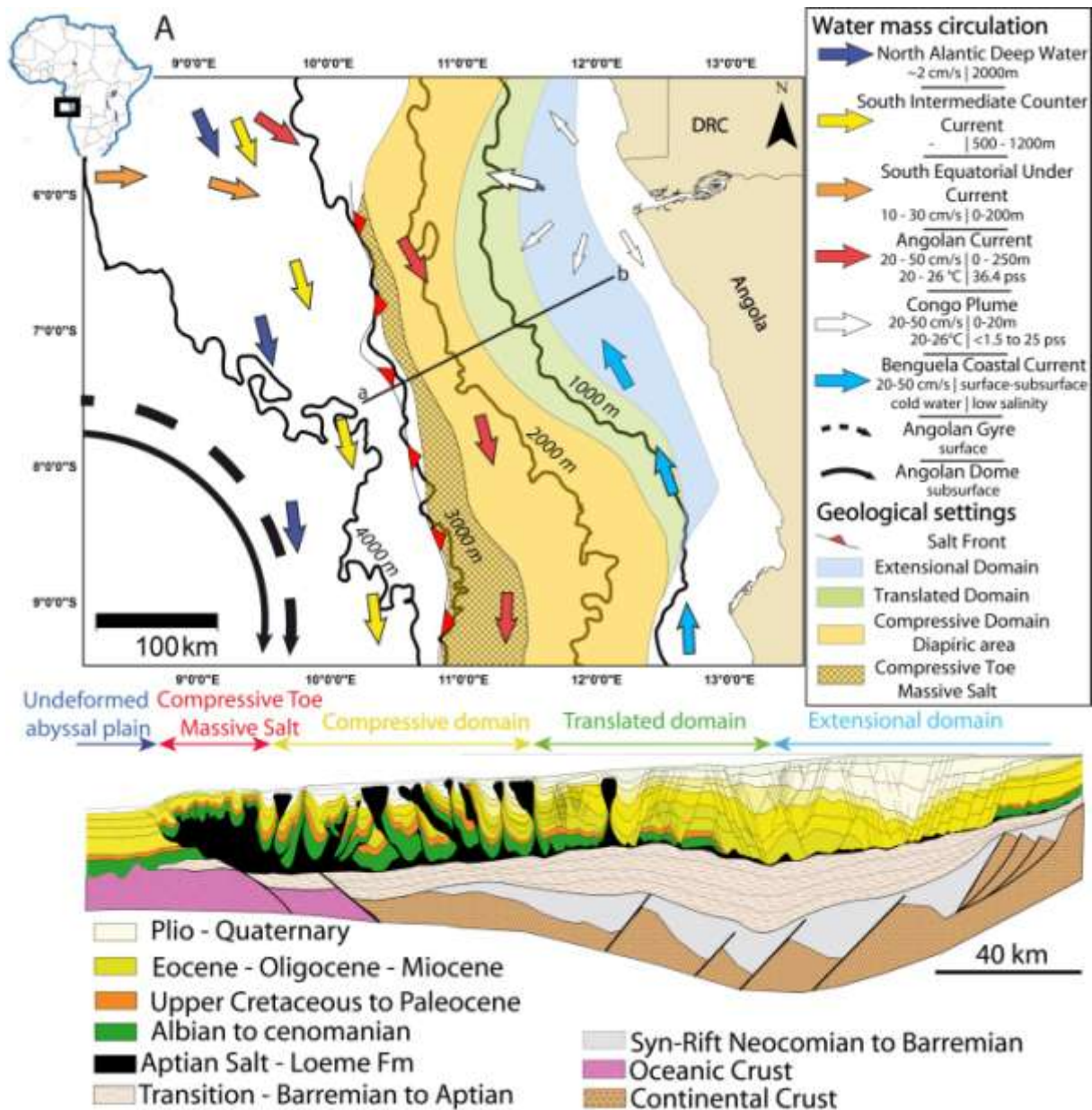
114 Geophysical investigations in the Lower Congo Basin report fluid escape features occurring as  
115 focused depressions on the seafloor and sub-seafloor fluid migration chimneys (Gay et al., 2003;  
116 Gay et al., 2007; Sahling et al., 2008; Anka et al., 2013). A large variety of pockmarks, defined as  
117 seafloor expressions of focused fluid flows (King and McLean., 1970), have been described with  
118 diameters varying from 30 m (Gay et al., 2007) up to 3150 m (Charlou et al., 2004; Ondreas et al.,  
119 2005; Gay et al., 2006c). The Aptian salt withdrawal and associated gravitational deformation  
120 greatly influenced the location of thermogenic seeps by creating efficient migration pathways  
121 along salt flanks as demonstrated by several publications (e.g. Gay et al., 2007; Andresen et al.,  
122 2010; Andresen and Huuse, 2011; Andresen, 2012). Wenau et al. (2014a, b) described active  
123 escape features on the seafloor expelling gas bubble trains imaged from side scan sonar at the salt-  
124 induced deformation front. From their fauna inventory, Jones et al. (2014) showed abundant  
125 seafloor topographic reliefs, consisting of biodegraded oil which forms asphalt mounds with  
126 diameters ranging from 0.5 to 50 m in the compressive salt province.

## 127 **2.3. Oceanographic context**

128 Understanding water mass movements is necessary for seepage studies because the strength of  
129 underwater currents steers the trajectory of oil droplets in the water column, whilst sea surface  
130 currents and wind determine the shape and lifespan of the oil slicks. The Fig. 1A displays a  
131 summary of oceanographic transport along the Angolan coast. Surface water circulation is  
132 prominently dominated by the southward Angolan Current (AC) (Moroshkin et al., 1970,  
133 Hardman-Mountfort et al., 2003), which results from the combination of different surface and  
134 subsurface currents, including the South Equatorial Under-Current (SEUC), Equatorial Under  
135 Current (EUC), the steady state surface Angolan Dome (AD) (Doi et al., 2007), and the

136 subsurface Angolan Gyre (AG), which are respectively surface and subsurface permanent gyres  
137 whose depth influence reach 500 m (Peterson and Stramma, 1991; Schneider et al., 1996; Holmes  
138 et al., 1997; Stramma and England, 1999). The AC is bordered to the south by a frontal  
139 convergence area with the Benguela current (Shannon, 2001), namely the Angolan-Benguela  
140 Front Zone (ABFZ) (Lass et al., 2000; Boyer et al., 2000), roughly located along the Angolan-  
141 Namibian frontier. However, the coastal and surfacing component of the Benguela Coastal  
142 Current (BCC) bypasses the ABFZ, resulting in a current flowing towards the north along the  
143 Angolan coasts (Hopkins et al., 2013). The Congo River outflow also inflects water circulation in  
144 the northern area. Seasonal variations are characterised by two warm periods from February to  
145 April and from September to November (Hardman-Mountford et al., 2003), alternating with two  
146 cold periods characterised by strong upwellings. Intermediate water circulations are controlled by  
147 the extension of the SICC to the south (Southern Intermediate Countercurrent) for water depths  
148 comprised between 500 and 1200 m (Stramma and England, 1999; Stramma and Scott, 1999).  
149 The main orientation of deepwater currents along the Angolan coast is controlled by the North  
150 Atlantic Deep Water known to occur at 2000 m depth (NADW; Stramma and England, 1999;  
151 Arhan et al., 2003) and flowing to the south at 2 cm/s (Lynn, 1971).





152

153 **Fig. 1. A:** Location map of the study area (see the African map within the black frame in the top  
 154 left corner) superimposed with an overview of main oceanic currents and geological settings. The  
 155 orientation of coloured arrows represents the directions of the hydrodynamic components of the  
 156 basin. The characteristics of each current, including velocity, depth influence, temperature and  
 157 salinity, appear in the legend when available. **B:** Geological cross-section of the Lower Congo  
 158 Basin (a-b on Fig. 1A) including pre-rift, syn-rift, transitional and post-rift series (modified from  
 159 Guilbot et al., 2012). See location of the section from the black line in Fig. 1A.

## 160 **3. Dataset and methods**

### 161 **3.1. SAR acquisition parameters for oil slick detection**

162 Synthetic Aperture Radar (SAR) is sensitive to centimetre-scale capillary waves induced by the  
163 local wind at the sea surface (Franceschetti et al., 2002; McCandless and Jackson, 2003). Oil  
164 surfactants smooth the sea surface and significantly reduce capillary waves, which triggers a  
165 contrast in roughness between oil-covered areas and free water. A minimum wind speed is  
166 required to trigger capillary waves and therefore to identify seepage slicks. The lower wind speed  
167 limit for seepage slick detection varies between case studies and authors, from 1.5 m/s (Skrunes,  
168 2014, Fingas and Brown, 2014), 2-3 m/s (Espedal and Wahl, 1999; Johannessen et al., 2000;  
169 Girard-Arduin et al., 2005, Brekke and Sölberg, 2005) to 3.5 m/s (Garcia-Pineda et al., 2009). In  
170 case of strong winds, natural oil slicks are also affected by capillary waves, which prevents the  
171 detection of oil at the sea surface. Seepage slicks from natural discharges are considered to be  
172 detectable up to 6-7 m/s (Bern et al., 1992; Espedal and Wahl, 1999). Some authors consider that  
173 thicker slicks can be identified for higher wind speeds (Alpers and Espedal, 2004; Brekke and  
174 Sölberg, 2005; Körber et al., 2014). In addition to the sea surface currents, it is assumed that 3%  
175 of the wind speed accounts for the oil slick drift velocity (Bern, 1992; Espedal and Wahl, 1999;  
176 Kim et al., 2014). Previous studies demonstrated that short wavelengths of the X- (2.5 to 3.75  
177 cm), C- (3.75 to 7.5 cm) and Ku-bands (1.6 to 2.5 cm) are more efficient in detecting oil slicks at  
178 the sea surface (Gade et al., 1998; Espedal and Wahl, 1999; Espedal and Johannessen, 2000;  
179 Johannessen et al., 2000; Alpers and Espedal, 2004; Brekke and Sölberg, 2005; Girard-Arduin et  
180 al., 2005; Skrunes, 2014). According to Bragg's reflection theory, the backscattered signal  
181 decreases with increasing incidence angles between 20° to 70° (Alpers and Espedal, 2004). Ideal  
182 incidence angles for slick detection range from 20° to 45° (Girard-Arduin et al., 2005; Brekke and  
183 Sölberg, 2005; Garcia-Pineda et al., 2010). Vertical SAR polarisation (VV) is the most efficient  
184 mode to detect oil slicks at the sea surface (Brekke and Solberg, 2005).

185 **3.2. SAR dataset**

186 **3.2.1. Long-term acquisitions**

187 Satellite SAR sensors are deployed on polar orbiting platforms, which enables worldwide  
188 observations with a rapid repeat rate. The SAR operational mode allows day and night imagery,  
189 regardless of cloud cover, which is one of the main advantages compared to passive optical  
190 imagery. In order to find oil seep sites, we gathered a collection of 82 SAR images from different  
191 satellite sensors (Fig. 2A). Archive data acquired from 1994 to 2012 were used to detect recurrent  
192 oil slicks and afterward to identify the sea surface location of natural oil seepage.

193 The dataset provided by the European Space Agency (ESA) is composed of ASAR data  
194 (Advanced Synthetic Aperture Radar) acquired in Image Mode Precision (IMP) by the European  
195 Remote Sensing satellites (ERS 1 and 2) between 1994 and 2001 and Wide Swath Mode (WSM)  
196 Envisat scenes acquired between 2002 and 2012, both operating in C-Band (Table 1). We  
197 complemented this dataset with RADARSAT, TerraSAR-X and Cosmo-SkyMed data. The map  
198 of SAR coverage density varies between 40 to 70 scenes (Fig. 2A). SAR scenes were converted  
199 from N1 raw format to 8-bit geoTiff format, displayed in greyscale for visual interpretation with  
200 GIS software (ArcInfo, ESRI). Scenes were kept speckled to preserve whole details. We applied  
201 linear stretching to counterbalance signal loss with increasing incidence angle from the orbital  
202 path.

203 **Table 1**

204 SAR data used for oil slick mapping during both long-term and short-term monitoring.

Satellite/ Sensor	Band/ Wavelength	Pixel Spacing (m)	Amount of SAR data	
			Long-term monitoring (1994 - 2012)	Short-term monitoring (12 - 22/10/2012)
Envisat /WSM	C (5.8 cm)	75	46	0
ERS/IMP	C (5.8 cm)	12.5	17	0
Cosmo-SkyMed	X (3.1 cm)	3-15	13	15
TerraSAR – X	X (3.1 cm)	20	2	4

<b>RADARSAT-2</b>	<b>C (5.3 cm)</b>	<b>25-50</b>	<b>4</b>	<b>3</b>
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205 **3.2.2. Short-term monitoring**

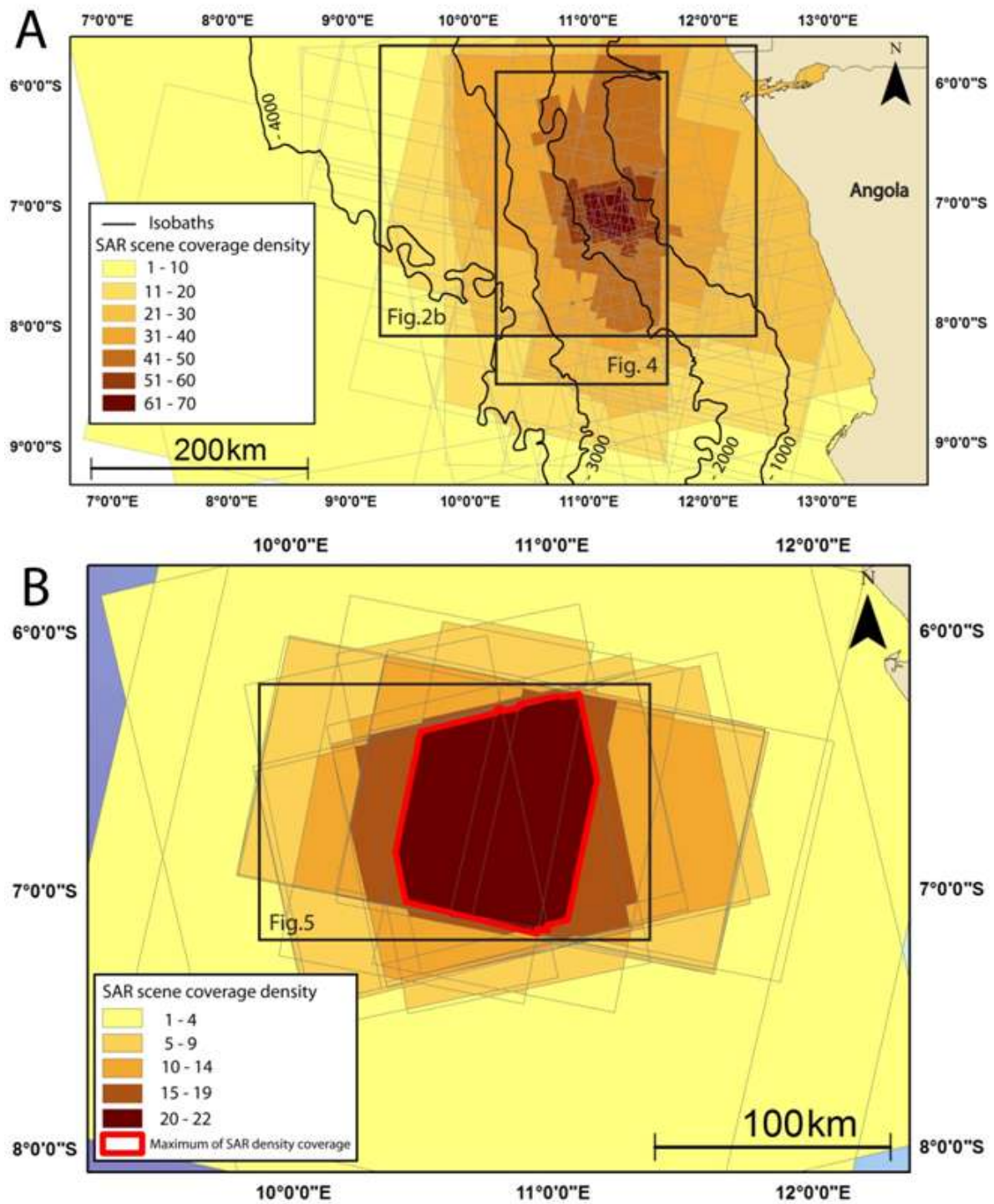
206 In order to investigate the seepage recurrence, synchronicity and lifespan on sea surface, we  
207 performed a short-term monitoring based on the tasking of SAR images during a restricted period  
208 of 10 days. We focused this monitoring on the area recognised for the largest amount of expelled  
209 oil, located 135 km from the Angolan coast to the southwest of the mouth of the Congo River  
210 (Fig. 2B). Tasking of 22 satellite images during 10 days provided at least one image every 12  
211 hours (Table 2). The dataset consists of a combination of X-band (TerraSAR and Cosmo-  
212 SkyMed) and C-band (RADARSAT) data. The radar density coverage constructed from the stack  
213 of multi-temporal images varies spatially, including a central area of maximum coverage density  
214 imaged by a series of at least 20 images out of the 22 tasked.

215 **Table 2**

216 Listing and characteristics of SAR scenes acquired during short-term monitoring

<b>Scene number</b>	<b>Date (dd/mm/yyyy)</b>	<b>Time (hh:mm)</b>	<b>Sensor</b>	<b>Scene number</b>	<b>Date (dd/mm/yyyy)</b>	<b>Time (hh:mm)</b>	<b>Sensor</b>
<b>1</b>	12/10/2012	05:40	Cosmo-SkyMed	<b>12</b>	18/10/2012	05:22	Cosmo-SkyMed
<b>2</b>	13/10/2012	04:58	RADARSAT - 2	<b>13</b>	18/10/2012	16:47	Cosmo-SkyMed
<b>3</b>	13/10/2012	16:53	Cosmo-SkyMed	<b>14</b>	18/10/2012	17:37	TerraSAR - X
<b>4</b>	13/10/2012	17:28	TerraSAR - X	<b>15</b>	19/10/2012	05:40	Cosmo-SkyMed
<b>5</b>	15/10/2012	05:06	TerraSAR - X	<b>16</b>	19/10/2012	16:47	Cosmo-SkyMed
<b>6</b>	15/10/2012	05:40	Cosmo-SkyMed	<b>17</b>	20/10/2012	04:54	RADARSAT - 2
<b>7</b>	15/10/2012	16:41	Cosmo-SkyMed	<b>18</b>	20/10/2012	16:35	Cosmo-SkyMed
<b>8</b>	16/10/2012	05:34	Cosmo-SkyMed	<b>19</b>	21/10/2012	04:58	TerraSAR - X
<b>9</b>	16/10/2012	17:42	RADARSAT - 2	<b>20</b>	21/10/2012	05:28	Cosmo-SkyMed
<b>10</b>	17/10/2012	05:34	Cosmo-SkyMed	<b>21</b>	21/10/2012	16:53	Cosmo-SkyMed
<b>11</b>	17/10/2012	06:53	Cosmo-SkyMed	<b>22</b>	22/10/2012	06:53	Cosmo-SkyMed

217



218

219 **Fig. 2.** A. Map of coverage density of Synthetic Aperture Radar scenes from 1994 to 2012. B.  
 220 Coverage density of Synthetic Aperture Radar tasked during the short-term monitoring. The  
 221 maximum coverage density of SAR scenes tasked during short-term monitoring occurs within the  
 222 red polygon outline and covers 6736 km<sup>2</sup> with a water depth ranging from 1000 to 2750 metres.

### 223 3.2.3. *Wind and current assessments*

224 In order to observe the wind effect on slick detection, we compared the regional wind field with  
225 the number of slicks detected and their size with the local wind field extracted at the location of  
226 the oil slicks. Real-time wind field measurements are not available over the study area, hence we  
227 used the regional wind field provided by the European Centre for Medium-Range Weather  
228 Forecasts (ECMWF). The wind field is calculated every 6 hours with a spatial resolution of the  
229 grid of  $1/8^\circ$  (~14 km). The forecasted wind field has been averaged over 24 hours for better  
230 comparison with the number of slicks detected in each image. In order to observe small-scale  
231 variations of the wind field, we assessed the local wind from SAR scene derivation with the  
232 scatterometer technique. Spatial resolution is 1150 m with a maximum speed uncertainty of 2 m/s  
233 and  $15^\circ$  in direction (for details see Johannessen et al., 2000 and Zecchetto, 2015). The wind  
234 dataset is composed of discrete data including forecasts and SAR-derived wind fields which  
235 represents a certain limit for the understanding of the wind effect on slick dissipation between two  
236 SAR acquisitions.

237 The current velocity is measured from ADCP (Acoustic Doppler Current Velocity) tools that use  
238 particle displacement to quantify current speed (Rowe and Yound 1979; Gordon and RDI, 1996).  
239 The data were collected during 6 months of mooring between January 2009 and July 2009 at a  
240 depth of 10 m below the sea surface. The current velocity was not available during short-term  
241 monitoring, but the integration of predated mooring data represents a good proxy to approach the  
242 current velocity distribution.

### 243 **3.3. Identification of natural leakages at the sea surface**

244 Sea surface smoothing may be induced by a wide collection of look-alike seep features. Table 3  
245 sums up look-alikes found during SAR scene interpretation.

#### 246 **Table 3:**

247 Overview of look-alike features detected on SAR scenes and dismissal features

<b>Look-alike type</b>	<b>Origin</b>	<b>SAR features</b>	<b>Dismissal method</b>	<b>References</b>
<b>Low Wind Areas</b>	Insufficient wind speed to trigger capillary waves	Extensive dark patches	Masking of the affected region	Espedal and Wahl (1999)
<b>Bioturbations</b>	Surface covered area smoothes the sea surface	Threadlike extensive and scattered films	Masking of the affected region or SAR scene dismissal	Gade et al. (1998) Espedal and Johannessen (2000)
<b>Boat spill</b>	Ship hold cleaning	Straight slick caused by moving source, shining point at boat location	Slick mapping with appropriate "spill" rank attribution	Espedal and Wahl (1999)
<b>Platform/ Pipeline spills</b>	Accidental/operational production pollution	Petroleum infrastructure data integration (IHS) and shining platform	Slick mapping with appropriate "spill" rank attribution	Trivero and Biamino (2010)
<b>Rain cells</b>	Local opposite winds at the edge of rain cells cause roughness wipeouts	High roughness values in the internal cell area compared to free water and rounded features	Masking of the affected region	Espedal and Johannessen (2000)
<b>Solitons or Internal waves</b>	Decrease backscattered energy associated with wave-related slopes	Multiple parallel trends interspersed by greater backscattered values	Visual dismissal	Jackson et al. (2013)

248

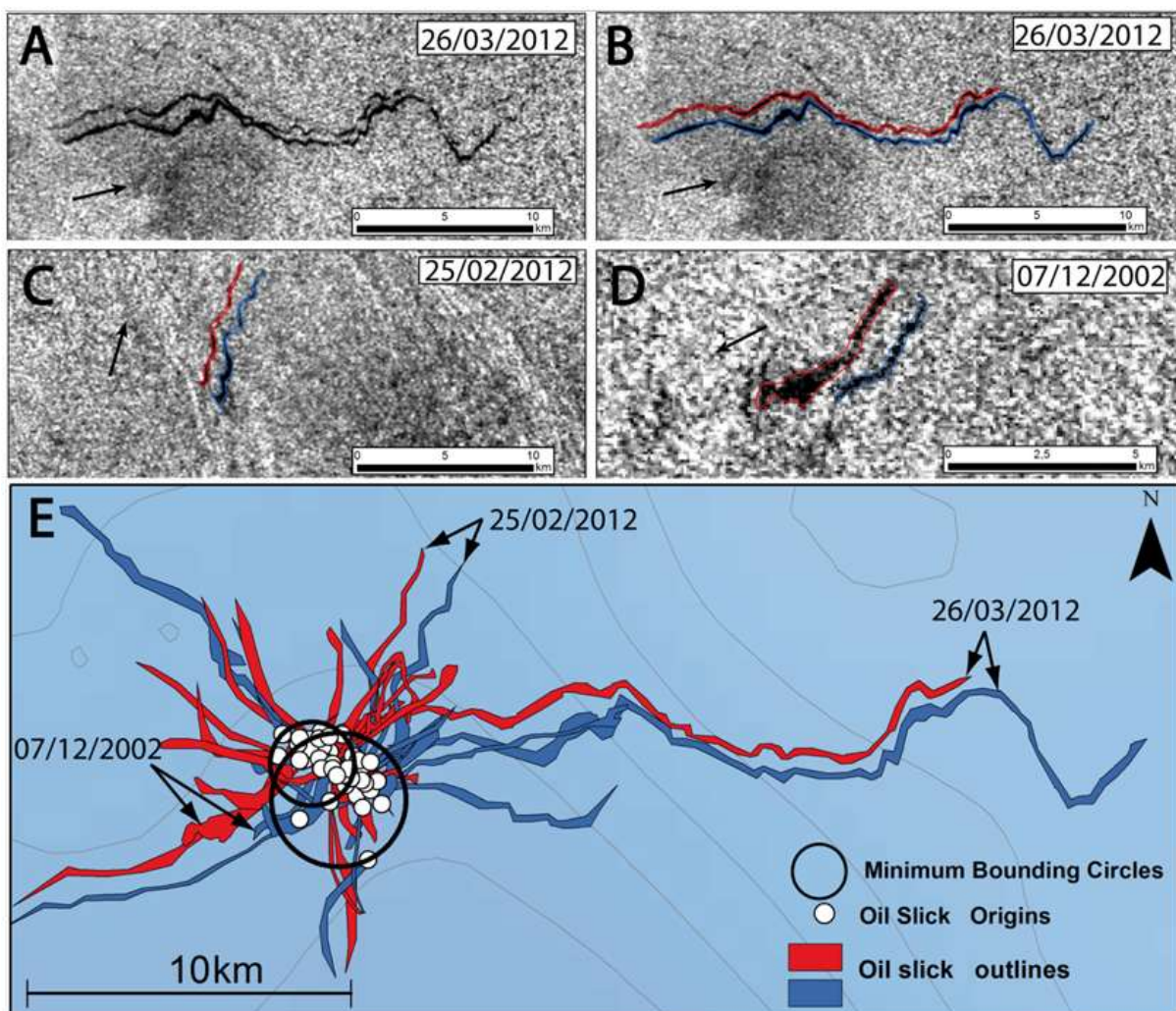
249 Petroleum infrastructure database integration (IHS) helps to discard leakage originating from  
250 pipes and/or petroleum platforms. In addition, boats or platforms appear as shiny diffracting  
251 points on SAR data, which make a distinctive feature compared to natural slicks. Spills from  
252 anthropogenic activities represent about 15% of the total surfacing oil in this study. Rain cells and  
253 solitons were occasional, in contrast to bioturbations which forced us to dismiss about 20% of  
254 SAR scene collection. Regions of SAR scenes containing low wind areas, rain cells or  
255 bioturbations were removed from the data collection to preserve the SAR coverage density which  
256 is used to quantify the seepage activity. The shape of natural oil slicks is induced by the strength  
257 and orientation of the wind and surface currents (Espedal and Wahl, 1999). Wind and surface  
258 currents induce short-term variations of sea surface motion. The sinuosity of black patterns is a  
259 first-order criterion to detect oil content slicks (Fig. 3 A - D). Sharp radiometric contrast between  
260 oil-covered areas and the surrounding free water correspond to the sideward detectable edge of the

261 slicks and allowed us to identify the extent of individual seepage slicks (see examples in Fig. 3 A  
262 and B). Computer-based automatic picking (Brekke and Solberg, 2005; Garcia-Pineda et al.,  
263 2009) certainly provides a quick way to delineate dark features but is still not able to distinguish  
264 natural seepage from anthropogenic pollutions or look-alikes (Suresh et al., 2013). Garcia-Pineda  
265 et al. (2009) showed that the classification using neuronal networks between dark areas and free  
266 water is equivalent to manual picking. In our case, visual interpretation is more powerful, as the  
267 input of the photo-interpreter allows a confidence rank attribution which prevents the over-  
268 interpretation of dark features. Therefore, we based our interpretation on manual picking instead  
269 of computer-based automatic detection. We compiled on a map the outlines of each high-  
270 confidence slick identified on each SAR image (Fig. 3E). Once mapped, diverging black streaks  
271 evidence active seeping areas of thermogenic fluids (Kornacki et al., 1994; MacDonald et al.,  
272 1996; de Beukelear et al., 2003; Zatyagalova et al., 2007; Garcia-Pineda et al., 2010; Garcia-  
273 Pineda et al., 2014; Körber et al., 2014). The centre of each diverging structure corresponds to the  
274 probable impact area of the fresher oil droplets at the sea surface. The Oil Slick Origin (OSO,  
275 Garcia-Pineda et al., 2010; Körber et al., 2014) is visually drawn for each seepage slick from the  
276 location of the proximal detectable edge of the slick to the seeping area (see white dots in Fig.  
277 3E). Diverging slicks allowed us to sort seepage slicks and associated OSOs between recurrent  
278 seep sites. We associated nearby and recurrent double-pattern slicks as being associated with two  
279 different seep sites (Fig. 3).

280 From the location of each OSO, we computed the kernel density with the ArcGIS toolbox in order  
281 to better display areas of active seepage. We also calculated the geometric mean centres (Garcia-  
282 Pineda et al., 2010) for each diverging structure, corresponding to mean values of each OSO  
283 location. The spatial dispersion of the OSOs generated by a single seep and detected in multiple  
284 SAR images is related to the horizontal deflection of the oil plume through the water column. We  
285 drew the minimum size circles encompassing each single OSO expelled from individual seep sites  
286 to evaluate the offset range values generated by underwater deflection (Garcia-Pineda et al., 2010)



287 by using the minimum bounding geometry tool of the ArcGIS toolbox (Fig. 3E). The radius  
288 serves as a proxy to quantify the horizontal deflection of oil droplets in the water column when  
289 rising towards the sea surface. We also computed the ratio between the number of oil slicks  
290 detected and the SAR scene coverage density, namely the occurrence rate, which gives an  
291 indication of the frequency and release activity of each seep. Compared to SAR data coverage,  
292 seep sites with high occurrence percentage frequently expel oil slicks, conversely to the low  
293 occurrence percentage that corresponds to weaker seeping sites with few slicks detected during  
294 the monitoring interval. We assessed the average oil volume at the sea surface from the method  
295 developed by MacDonald et al. (2015), who gridded their area and considered the total surfacing  
296 volume divided by the SAR coverage density for each cell.



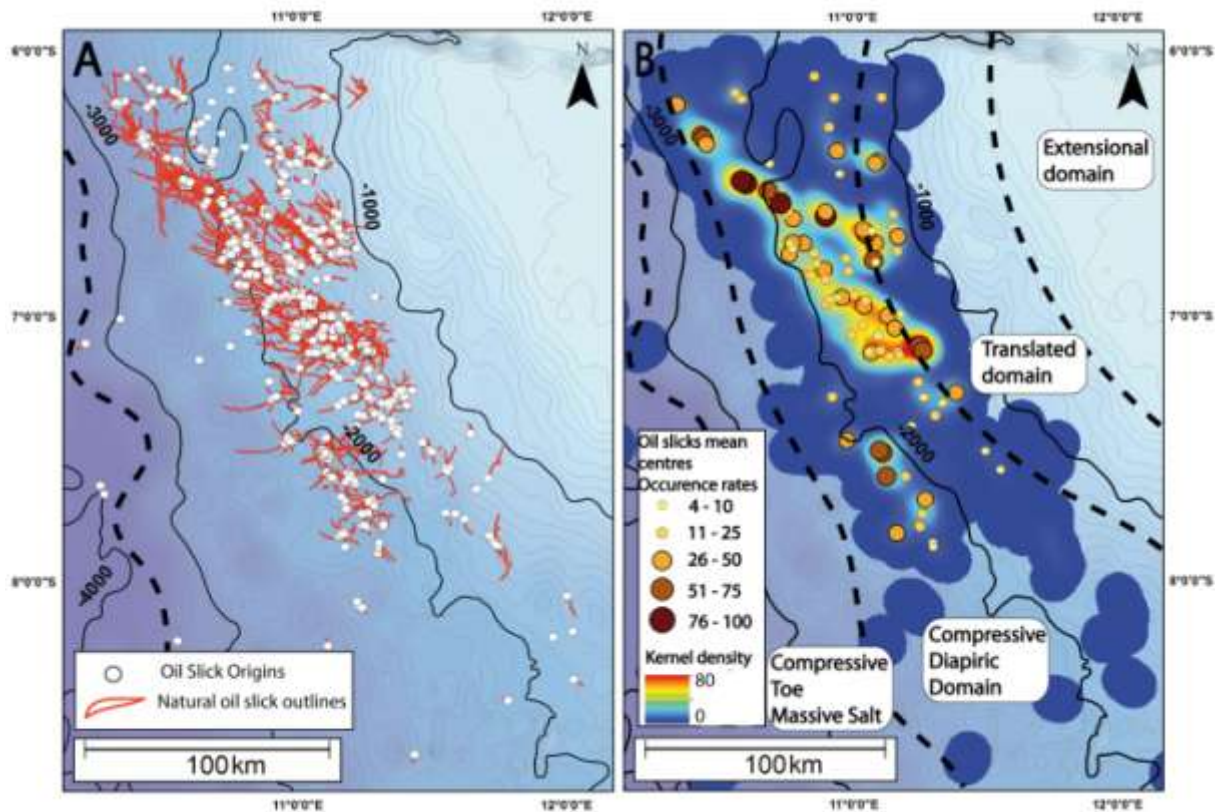
297

298 **Fig. 3.** A. Extract from SAR WSM scene dated 26/03/2012. Grey speckled background represents  
299 backscattered energy from sea surface free water. Black streaks depict the location of seepage  
300 slicks. B. Same SAR image extract complemented with manual picking. C and D. ASAR WSM  
301 SAR sub-scenes respectively dated 25/02/2012 and 07/12/2002 superimposed with manual  
302 picking of oil slicks. The three different SAR extracts overlap at a common spatial location. Black  
303 arrows show the flow direction of surface currents during SAR scene acquisition. E. Compilation  
304 map of oil slick outlines mapped from the entire dataset, including slicks displayed in A., B., C.  
305 and D. at two major seep sites. All scenes are provided by the European Spatial Agency (ESA).

## 306 **4. Oil seep analysis and results**

### 307 **4.1. Long-term observations**

308 We mapped a total of 1600 oil slicks interpreted from the analysis of the 82 SAR data over 18  
309 years. The integration of the IHS international exploration & production database and the  
310 recognition of diffracting points associated with the boat or platform location allowed us to  
311 remove about 200 slicks associated with anthropogenic activities. The remaining 1400 seepage  
312 slicks are displayed in Fig 4A. Among them, 1240, i.e. 90%, of the slicks are recurrent, forming  
313 diverging patterns on the compilation map. The length of the slicks varies from a few hundred  
314 metres to 45 km. We recognised 102 active seep sites whose geometric mean centres are  
315 displayed in coloured dots in Fig. 4B. The water depth of the seeping province ranges roughly  
316 from 1100 to 2600 m at a distance of 130 to 200 km from the Angolan coastline. Active seep sites  
317 are distributed all along the southern part of the Congo Basin over an area of 21,000 km<sup>2</sup>. The  
318 seeping province is well delimited from the basinward edge of the translated province and mainly  
319 included in the compressive province associated with salt diapirs (Figs. 1 and 4). Occurrence rates  
320 range between 5% for the weakest seeps and 80% for the most active (Fig. 4B), suggesting that  
321 the flux of fluid differs between seep sites.



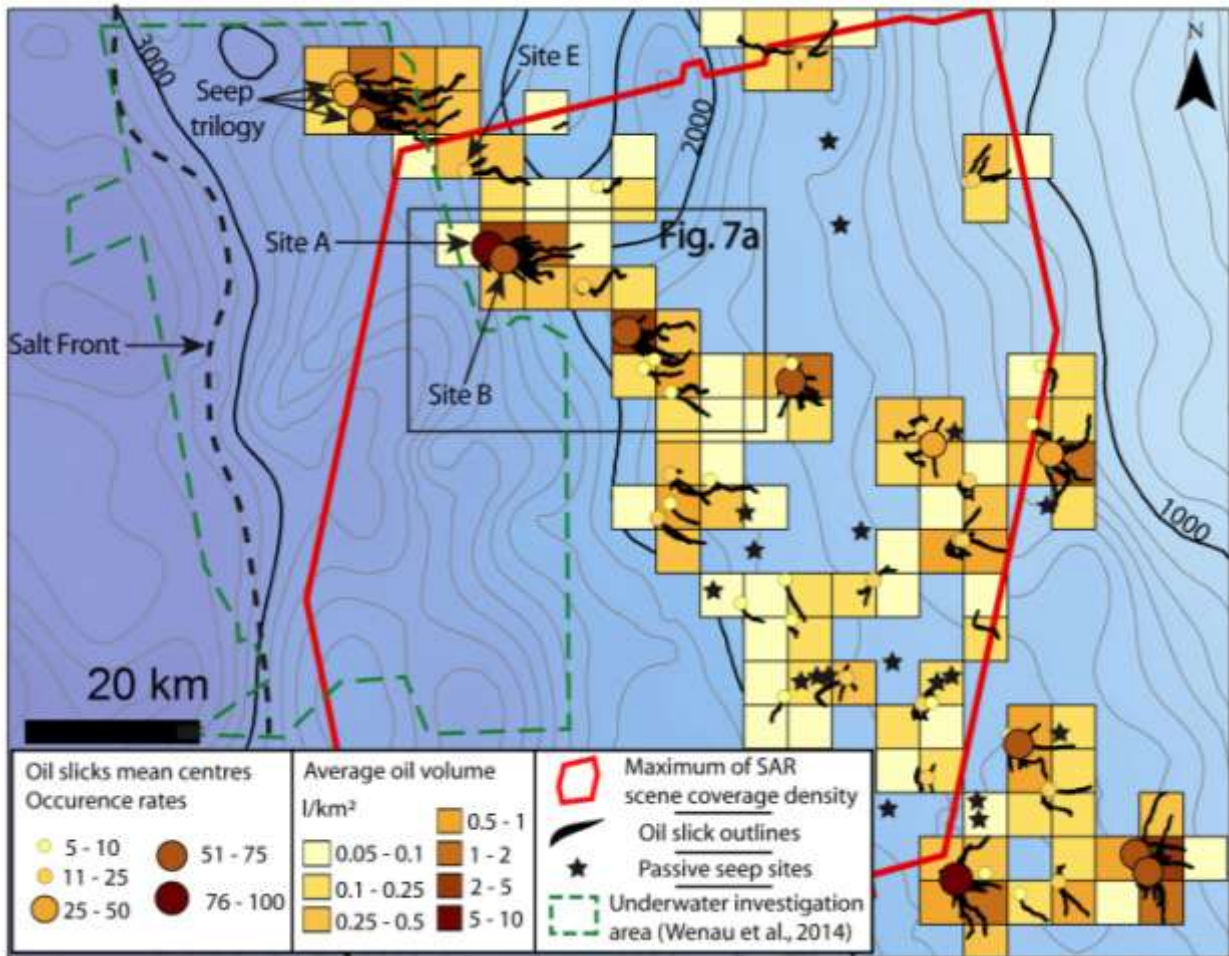
322

323 **Fig. 4.** A. Compilation map of oil slick outlines in red polygons superimposed with Oil Slick  
 324 Origins in white dots (see details in text). B. Kernel density computed from the density of seepage  
 325 slicks. Coloured dots show the location of geometric mean centres of OSOs. The dashed black  
 326 lines indicate the boundaries of each province related to the salt tectonics presented in Fig. 1B.

327 **4.2.Short-term monitoring**

328 **4.2.1. General observations**

329 We identified a total of 231 high-confidence oil seepage slicks from the interpretation of the 22  
 330 tasked scenes. The locations of recurrent seep sites are consistent between the two monitorings.  
 331 Recurrent slicks during short-term monitoring are associated with 53 seep sites identified from  
 332 long-term monitoring (coloured dots in Fig. 5 - see location in Fig. 2). A total of 102 oil seep sites  
 333 were mapped from long-term monitoring, suggesting that about 50% of seeping sites were passive  
 334 during short-term monitoring (black stars in Fig. 5).



335

336 **Fig. 5.** Compilation map of oil slick outlines (black polylines) mapped from SAR scenes tasked  
 337 during short-term monitoring and focused on the maximum coverage density area (see location in  
 338 Fig. 2A). Coloured dots represent geometric mean centres of OSOs expelled from individual seep  
 339 sites. Size and colours correspond to the occurrence percentages. Inactive seepage site locations  
 340 during short-term monitoring are displayed as black stars. The salt tectonic boundary is displayed  
 341 as a black dashed line. Background continuous lines are 100 m isobaths.

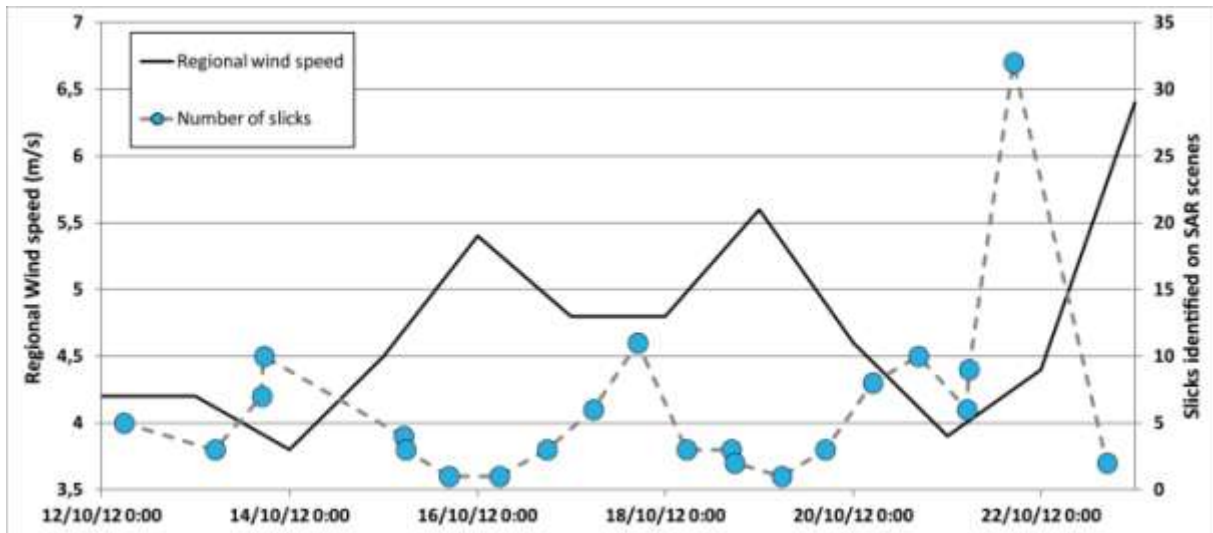
342

343 The area of highest radar coverage, defined as the area imaged by a minimum of 20 images out of  
 344 the 22 tasked scenes, encompasses the 51 seeping sites observed during long-term monitoring  
 345 (inside the red frame in Fig. 5).

346 In this area, 130 slicks with lengths varying from 1000 to 16,000 metres are associated with 33  
347 geometric mean centres or active sites (Fig. 5). The spatial spreading of OSOs retrieved from the  
348 computation of minimum bounding circles for each seep sites provides the estimation of the  
349 deflection offset in the water column. The spatial dispersion of surfacing slick areas varies  
350 between 80 and 1020 m, which remains low compared to the water depth of the seeping province  
351 (from 1100 to 2600 m). As shown by the Fig. 1, the regional hydrodynamics involves multiple  
352 oceanic components with various speed and depth influences. The horizontal deflection of oil  
353 droplets in the water column is directly influenced by this hydrodynamic complexity. The linear  
354 law between the water depth and the horizontal deflection established in the Gulf of Mexico  
355 (Garcia-Pineda et al., 2010) does not apply for the Lower Congo Basin. As a matter of fact, the  
356 greatest OSO dispersion values account for shallower areas in this study where the AC meets the  
357 BCC's influence, probably resulting in greater current variability, whereas the deepest seep areas  
358 are associated with restricted OSO spatial spreading.

#### 359 4.2.2. *Correlation with the wind field*

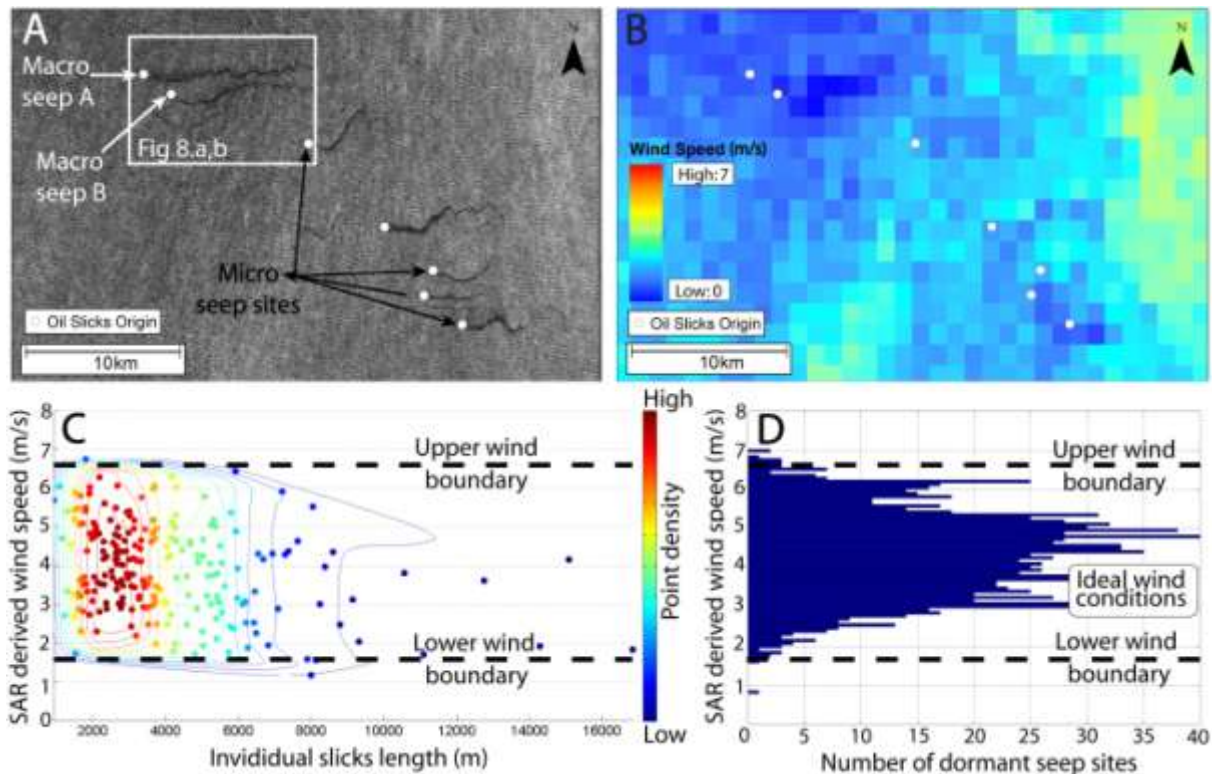
360 The study of seepage recurrence requires good knowledge of the wind speed to ensure the  
361 consistency of the detection. As a first approach, we used the wind speed field forecasted at the  
362 regional scale (ECMWF) to confirm that weather conditions were suitable all along the 10-day  
363 acquisition period (Fig.6). The reported values of suitable wind speed for the detection of oil  
364 slicks (Espedal and Wahl, 1999; Alpers and Espedal, 2004; Girard-Arduin et al., 2005; Brekke  
365 and Sölberg, 2005; Garcia-Pineda et al., 2009; Fingas and Brown, 2014) confirm that the weather  
366 conditions were suitable during short-term monitoring (from 3.7 to 6.5 m/s (Fig. 6) for the  
367 recognition of oil slicks on SAR data.



368

369 **Fig. 6.** Superimposed graphs of modelled regional wind speed (ECMWF) displayed in black line  
 370 and the number of slicks in the high-density SAR coverage area.

371 The two curves displaying the wind speed and the number of slicks show an anti-correlation,  
 372 where higher wind speeds correspond to fewer detected slicks and vice versa. The curve  
 373 displaying the number of detected slicks through time reveals three peaks characterised by an  
 374 increase of the number of detected slicks (scenes 3 to 4, scenes 9 to 11, scenes 17 to 21 - see  
 375 Table 2). These periods are interspersed by stages of low detection of slicks on SAR scenes  
 376 especially at the following scenes: 5 to 8, and 12 to 16. These stages correspond to periods of  
 377 regional wind speed intensification.



378

379 **Fig. 7.** A. Extract from the SAR scene dated 21 October 2012, 16:53 (scene 21). Black streaks  
 380 show the location of oil slicks at the sea surface. B. Local wind values are retrieved from SAR  
 381 scene derivation at the locations of OSOs displayed as white dots. C. Plot of the length of  
 382 individual slicks and the local wind speed value at the location of OSOs. The colour of the dots  
 383 ranging from red to blue respectively represents high to low point density. D. Histogram of the  
 384 distribution of local wind values at the location of recurrent oil seeping areas revealed from long-  
 385 term monitoring and measured during dormant stages in short-term monitoring. The vertical black  
 386 dashed lines correspond to the probable ideal boundaries for seepage slick detection.

387 Even though the modelled wind provides a regional assessment of weather conditions, the  
 388 applications related to local wind quantification remain questionable. Therefore, in order to  
 389 quantify more accurately the ideal weather conditions for slicks in the study area, we integrated  
 390 the local wind measurement extracted from SAR scenes from the scatterometer technique at the  
 391 location of seepage slicks (Fig. 7A, B). Local wind values vary between 1.5 and 6.5 m/s at the

392 slick locations (Fig. 7C). This observed detectability agrees with lower and upper values reported  
393 in the literature.

394 The information related to the population density of slick lengths shows that most of the slicks  
395 (137 out of 231) were detected with lengths ranging from 1000 to 4000 metres. The population  
396 density progressively decreases with the increase of the slick length. Slicks longer than 8000 m  
397 were occasional and exclusively associated with local winds between 2 to 4 m/s, meaning that no  
398 elongated slicks were detected with wind speeds above 4 m/s during the 10 days of monitoring  
399 (Fig. 7C).

400 We then plotted the number of dormant seep sites on the SAR-derived winds (Fig. 7D).  
401 Considering that ideal wind values range from 1.5 to 6.5 m/s in the study area, dormant seep  
402 phases clearly occur during periods of ideal wind conditions. Only a restricted portion of dormant  
403 seep sites (~5%) occur outside the ideal detection boundary conditions (Fig. 7D). This shows that  
404 the disappearance of slicks at recurrent seep sites is associated with short-term intermittence.

#### 405 4.2.3. *Macro-seepage sites*

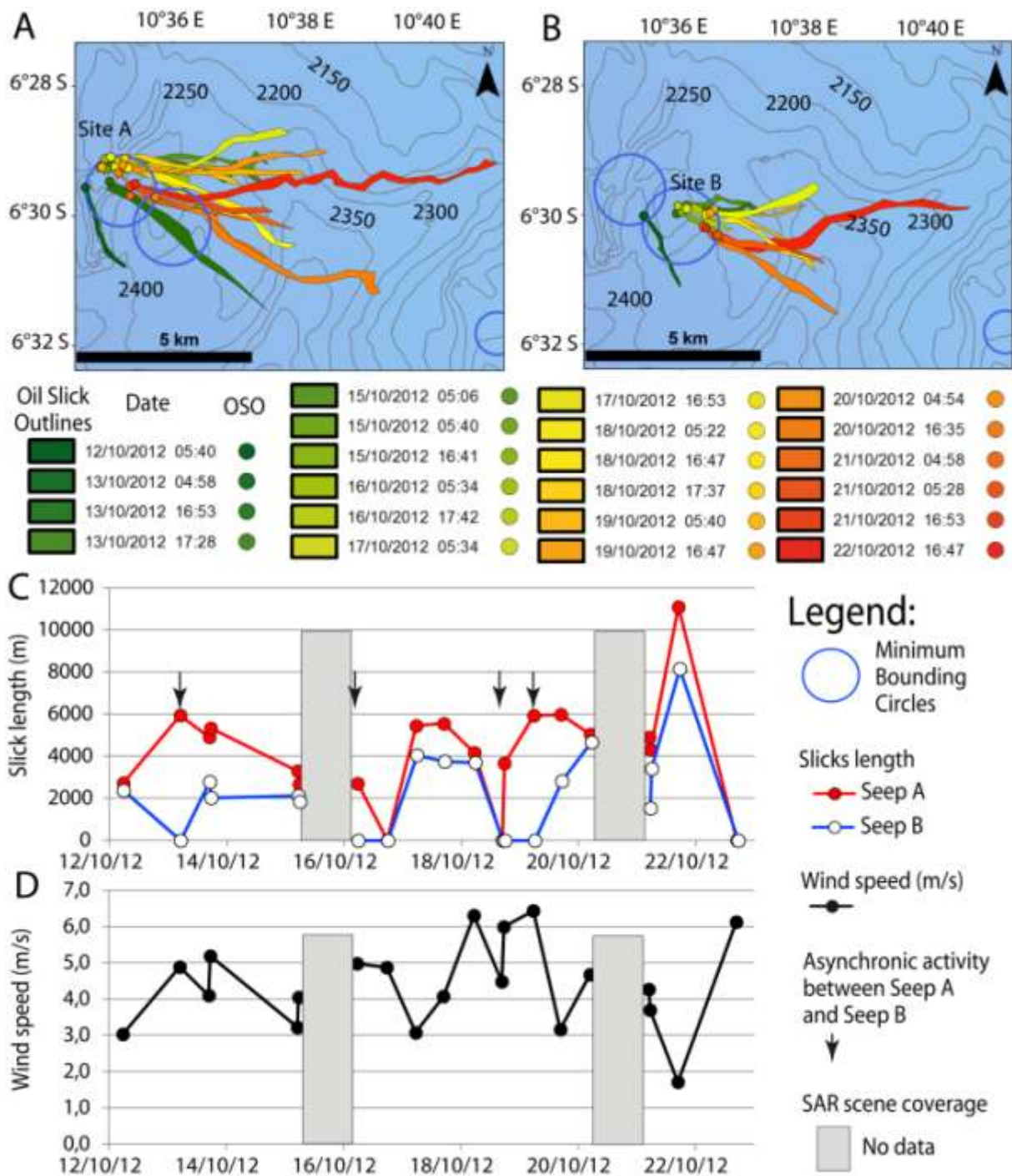
406 We defined macro-seepage sites as prolific leaking spots with occurrence rates above 50%.  
407 Within the area of SAR maximum coverage density, the acquisition of SAR data simultaneously  
408 at the nearby major seep sites allowed us to study the seepage pace for major seep sites during  
409 short-term monitoring. Seep sites A and B are distinct seepage sites, as the identification of  
410 recurrent double-pattern slicks allowed us to distinguish slicks expelled from one site to the other  
411 (Fig. 7A). The two sites are only 2250 m apart; this proximity constitutes a first-order benefit to  
412 compare the pace of two different seeps, independently of weather conditions (Fig. 8 A, B). Most  
413 of the time, sites A and B were both active, as seepage slicks were identified at both sites for 13  
414 scenes out of 20 (Fig. 8 C).

415 We also identified asynchronous active phases from the recognition of isolated seepage slicks on  
416 4 images at macro-seep A, while macro-seep B was dormant (pinpointed with black arrows in Fig.



417 8). Based on previous works showing that oil slicks are best detected for wind speeds less than 6-  
418 7 m/s (Bern et al., 1992; Espedal and Wahl, 1999), the maximum wind value of 6.5 m/s at these  
419 specific sites during short-term monitoring cannot be considered as the factor controlling the  
420 absence of seepage (Fig. 8D). In addition, the fact that oil slicks are observed for higher wind  
421 speeds during the monitoring period implies that weather conditions were suitable for slick  
422 detection. To summarise, all the conditions were satisfied during the three common and  
423 asynchronous cessation events for an optimal detection of oil slicks.

424 Furthermore, based on the fact that the disappearance of the seepage slicks is observed between  
425 two consecutive SAR acquisitions implies that oil dispersion is effective in less than 12 hours.  
426 The reappearance of oil slicks on the following image also indicates that cessation of oil release  
427 can occur under restricted time scales.



428

429 **Fig. 8.** A, B. Compilation of oil slick footprints and associated OSOs revealed from short-term  
 430 monitoring for macro-seep sites A and B. Colour scale refers to subsequent acquisition dates and  
 431 is applied for both seepage slicks and OSOs. Blue circles are the deflection offset computed from  
 432 individual OSO locations. C. Red and blue graphs display the length of individual seepage slicks  
 433 for seep site A and B respectively. D. Graph of the local wind values derived from SAR scenes.

434 Non-imaged areas were masked with grey squares. Black arrows pinpoint SAR scenes where  
435 seepage slicks were only visible from one of the two sites A and B.

#### 436 **4.2.4. *Transience and persistence at micro-seepage sites***

437 A micro-seepage is defined here as a seeping spot with an occurrence rate below 50%. A large  
438 number of micro-seepage sites (~1/3) are only associated with a single active event that occurred  
439 during the acquisition of SAR scene No. 21 (see yellow dots in Fig. 5). Isolated slick detection  
440 occurred during a period of regional increase in the amount of detected oil, while roughly 60% of  
441 seeping sites were active. Wind values varied between 1.2 and 6.1 m/s at the OSO location, which  
442 is slightly below observed average weather conditions (Fig. 7). Apart from lower occurrence rates,  
443 oil slicks expelled from micro seepage sites are revealed by shorter and narrower slicks, showing  
444 that the amount of oil released is weaker (Fig. 7A).

445 Micro-seep E identified from 3 recurrent and diverging slicks appears as a new seepage feature on  
446 the compilation map that we confidently ranked as natural slicks (Fig. 5). Prior to short-term  
447 monitoring, the area was passive, as the SAR data coverage reaches 40 overlapping scenes  
448 between 1994 and 2012 (Fig. 2A), but none revealed the presence of seepage slicks at this  
449 location. The slicks are characterised by typical curvilinear shapes that have similar trends to the  
450 neighbouring slicks on the images, which comforts our presumptions on the natural origin of  
451 expelled slicks. This example corresponds to the minimum period of seepage activity observed  
452 during the short-term monitoring, revealing that oil release can be ephemeral and temporally  
453 constrained to a few days.

## 454 **5. Discussion**

### 455 **5.1. Wind requirements for seepage slick detection**

456 The weather requirements for slick detection have been reported by different authors to be 3 to 10  
457 m/s (Espedal and Wahl, 1999; Alpers and Espedal, 2004; Girard-Arduin et al., 2005; Brekke and

458 Sölberg, 2005), 3.5 to 7 m/s (Garcia-Pineda et al., 2009) and 1.5 to 10 m/s (Fingas and Brown,  
459 2014). During the short-term monitoring, regional wind values ranged among the most restrictive  
460 conditions as reported by Garcia-Pineda et al. (2009). The results from seepage studies in the  
461 Lower Congo Basin show that weather requirements are constrained between 1.5 and 6.5 m/s  
462 (Fig. 7C). Such differences are presumably associated with seepage slick characteristics such as  
463 the slick thickness or the oil type (API gravity) that largely varies between petroleum provinces.  
464 The wind is also known to affect seepage slicks by separating heavy and light components of oil  
465 slicks and spreading oil at the sea surface (Alpers and Espedal, 2004; Marmorino et al., 2008).  
466 SAR scene No. 21 records the greatest number of seepages, where two thirds of the imaged sites  
467 were active (Figs. 6 and 8). The SAR acquisition was predated by low weather conditions, with  
468 regional wind speed around 4 m/s during the 24 preceding hours (Fig. 6). This suggests that ideal  
469 weather requirements for seepage slick detection might call for regional low wind conditions not  
470 only during, but also predating the SAR acquisition.

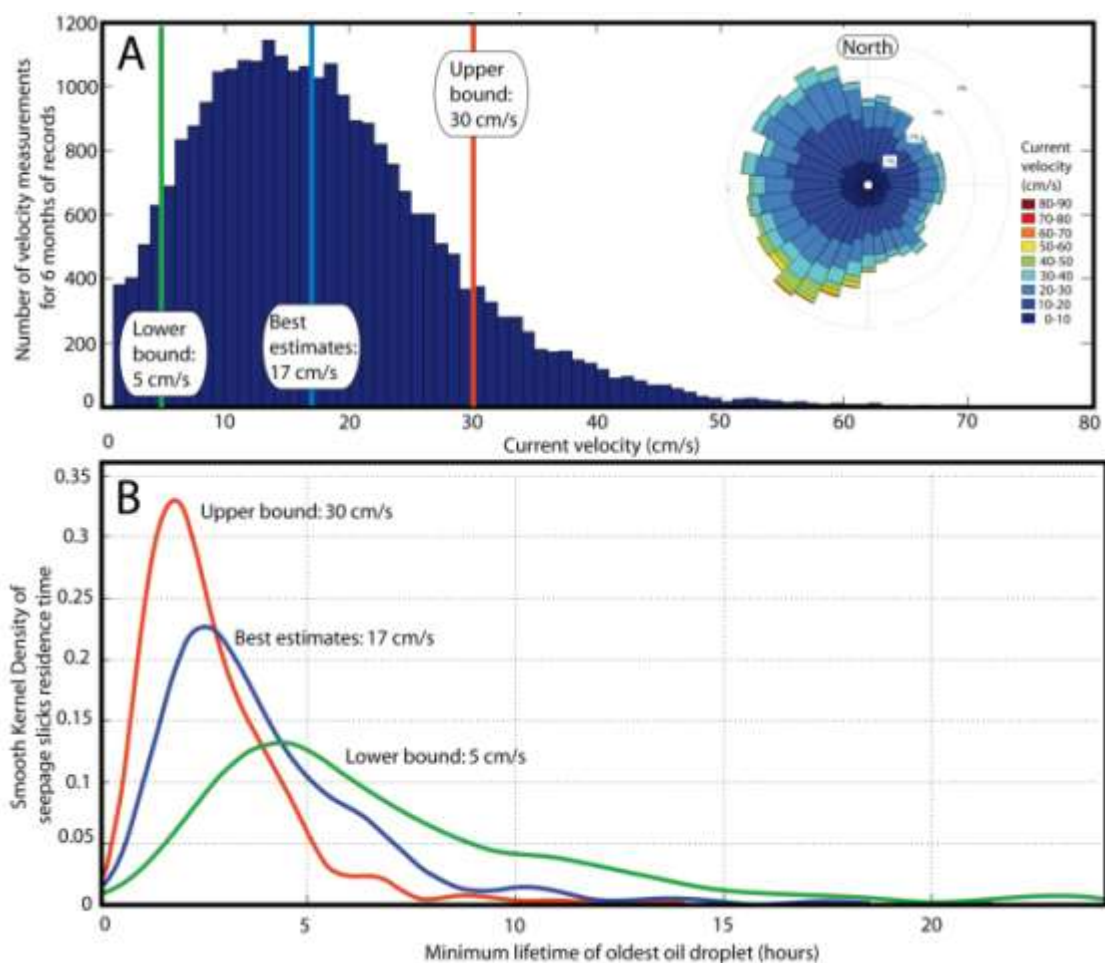
## 471 **5.2.Seepage slick residence time**

472 Seepage slick residence time was defined from the estimated age of the oil droplet at the distal  
473 edge of the slicks (De Beukelear et al., 2003). The restricted length of oil slicks, in addition to  
474 brief variations of slick orientation prevent seepage shapes from being fitted between subsequent  
475 scenes. This suggests that oil slick dissipation is effective between the acquisitions of two  
476 subsequent SAR scenes, typically separated by 12 h.

477 The residence time is approached from the individual slick length divided by the sea surface drift  
478 velocity (Macdonald et al., 2015). The velocity of the surface slick displacement is inferred to be  
479 induced by 100% of the surface currents in addition to 3% of the wind speed (Kim et al., 2014).  
480 The current measurements were not available during short-term monitoring and large scale  
481 oceanographic models are unsuitable to characterise local dynamics of the sea surface. We

482 integrated mooring data to characterise the distribution of the surface/subsurface current velocity  
483 (Fig. 9A).

484 The mooring data were recorded from January 2009 to July 2009, i.e. three years before short-  
485 term monitoring. The integration of ADCP data allowed us to compute a statistical study of the  
486 residence time of oil slicks at the sea surface during short-term monitoring using the near surface  
487 velocity of the current (10 m below the sea surface) and the local wind from derived SAR scenes.  
488 Surface velocity ranged between 0 and 81 cm/s during the 6 months of mooring. Among this  
489 range, 85% of measured velocity lies between 5 and 30 cm/s with a median velocity value of 17  
490 cm/s. We made three estimations of residence time considering a lower bound for a conservative  
491 current velocity of 5 cm/s, an upper bound for an overstating current velocity of 30 cm/s and a  
492 best estimate for the median current velocity of 17 cm/s (Fig. 9B).



493

494 **Fig. 9.** A: Histogram of the distribution of current speed recorded from 6 months of mooring  
495 measurements 10 m below the sea surface. We considered an upper and a lower bound from the  
496 overall distribution of the current velocity. The wind rose to the right shows the distribution of  
497 current orientation and speed. B: Smooth kernel density of the distribution of the minimum  
498 residence time of the oldest oil droplet of individual slicks mapped during short-term monitoring.  
499 The residence time computation considers the local wind value at the location of OSOs, surface  
500 current velocity and slick length.

501 The estimation of theoretical residence times shows that their distribution gathers around the  
502 median value for the upper, median and lower bound. The distribution progressively decreases  
503 from this median value. The median residence time value for the upper bound at 30 cm/s is  
504 2h15min, 3h15min for the median value of 17 cm/s and 5 h 30min for the lower bound at 5 cm/s.  
505 The slick residence time for median estimates is mostly distributed between 1 and 7 hours.

506 The natural seepage residence time was inferred to be comprised between 8 and 24 h by Mitchell  
507 et al. (2000) and MacDonald et al. (2015) for the Gulf of Mexico. Seepage residence time in this  
508 study is lower than previously suggested, as best estimates suggest that median residence time is  
509 3h15min. The residence times from this study are rather in agreement with Marmorino et al.  
510 (2008), who suggested that they concentrate below 5 hours. Restricted residence time has great  
511 implication on the hydrocarbon flux and therefore on quantifications of the regional oil output.  
512 The short lifetime of seepage slicks can be explained from the relative expelled amount that is  
513 probably lower in the Lower Congo Basin than in the Gulf of Mexico, but also by severe  
514 weathering conditions along warm Angolan coasts (Hardman-Mountford et al., 2003) that largely  
515 contribute to spill dispersion (Leifer et al., 2012).

516 However, these observations refer to short-term monitoring, where the length of the oil slicks  
517 varies between 1000 and 17,000 m (Fig. 7), yet seepage slicks were mapped with greater lengths  
518 during long-term monitoring (Fig. 3A and B). Observations of slicks greater than 30 km long

519 remained unusual (less than 1% of slick collection) but suggest that slick residence time can  
520 occasionally be greater than values computed from short-term monitoring. Such exceptional  
521 observations of lengthened slicks could also be explained by a substantial increase in surface  
522 displacement velocity or predating by consistent low wind conditions before SAR acquisition.

### 523 **5.3. Evidence of leakage interruption**

524 The non-detection of seepage slicks on SAR scenes can either be explained by unsuitable wind  
525 conditions or as an evidence of a consistent decrease of the amount of expelled oil that prevents  
526 the detection of slicks by the SAR system. The comparison between the distributions of local  
527 wind values at recurrent seep sites between active and dormant stages remained concordant (Fig.  
528 7). The wind distribution at the location of recurrent sites during dormant periods were imaged  
529 during the ideal weather conditions (Fig. 7D) which demonstrates that the non-detection of  
530 seepage slicks is associated with a short-term intermittence.

531 It was established in the Black Sea (Greinert et al., 2006) and Gulf of Mexico (Garcia-Pineda et  
532 al., 2010) that gas seepage rates from cold seeps may be highly variable over time. Leifer et al.,  
533 (2004) and Garcia-Pineda et al. (2016) also demonstrated this variability for oil seepage in the  
534 Santa Barbara basin and the Gulf of Mexico, respectively.

535 Concordant observations performed from long-term and short-term monitoring suggesting that oil  
536 seepage is also discontinuous in the Lower Congo Basin are listed below:

537 - The great variability of occurrence rates values ranging from 5 to 80% shows that the amount of  
538 released oil significantly differs between seeping sites, suggesting recurrent interruption of oil  
539 release with varying frequencies between seep sites.

540 - Recurrent twin slicks were identified at the location of the two macro-seep sites A and B, which  
541 are separated by a distance of 2250 m. The identification of concordant shapes for neighbouring  
542 slicks on SAR data (Figs. 3 and 8) proves that they are expelled simultaneously from distinct

543 sources (MacDonald et al., 1993; Garcia-Pineda et al., 2010; Körber et al., 2014). Therefore, the  
544 identification of a single seep suggests the leakage interruption of one of the two sites instead of  
545 unsuitable meteorological conditions (Fig. 8).

546 - Seep site E (see location in Fig. 6) was characterised by a restricted active period of a few hours.  
547 The observations of recurrent slicks over a restricted period can be either explained as associated  
548 with ephemeral seep sites or with a consistent increase in the amount of expelled oil.

549 - The seep triplets in the northernmost area (Fig. 6) lie in the underwater investigation area studied  
550 by Wenau et al. (2014). The detection of acoustic anomalies is commonly used to identify seepage  
551 bubble trains in the water column (De Beukelear et al., 2003; Körber et al., 2014). The area was  
552 considered as inactive, as the water column records did not reveal any typical acoustic anomaly at  
553 this location. This demonstrates that the three oil seeps were dormant during the few days of  
554 underwater investigations and further supports the hypothesis of intermittent seepage activity.

555 The integration of SAR data characterised by a swath several hundred of kilometres wide provides  
556 an interesting means to monitor several oil seeps simultaneously. Mesoscale events, such as  
557 seismic events (Zatyagalova et al., 2007) or hydrostatic variation of pressure (Boles, 2001; Glasby  
558 et al., 2001; Chanton et al., 2003; Rollet et al., 2006) were demonstrated to be associated to a  
559 variation of the amount of expelled fluids. Conversely, our results regarding the regional seepage  
560 pace indicate that individual seep sites can have their own periodicity (see examples of seep sites  
561 A and B) with miscellaneous active and inactive stages.

#### 562 **5.4. Insights on seepage pace from short- and long-term monitoring**

563 The short-term pace of seepage activity appears highly variable. The maximum duration of  
564 seepage activity was observed for Seep A, where slicks were detected on six consecutive scenes  
565 showing that they remained active during at least 3 days. In addition, inactive periods of macro-  
566 seep sites are restricted to daily periods (Fig. 9), revealing that the seeping mechanism may be  
567 transient at a daily scale. The recurrent lack of seepage slick detection above macro-seepage sites



568 suggests at least a great decrease of both the volume of expelled oil and the slick thickness  
569 preventing the slick detection from SAR scenes detectability threshold.

570 Among the 102 seep sites (Fig. 4), 48 minor seep sites (occurrence rate lower than 30%) were  
571 passive during the short-term monitoring acquisitions (black stars in Fig. 5), revealing that  
572 inactive stages can be longer than 10 days. Occurrence rates of macro-seep sites are consistent  
573 between short-term monitoring and long-term monitoring. This suggests that the relative macro-  
574 seep activity observed over the short-term period remain constant over decades.

575 In addition, non-recurrent slicks were observed from 140 seepage slicks (10%) during long-term  
576 monitoring (isolated white dots in Fig. 4A). Assuming that the acquisition frequency of SAR  
577 scene acquisitions was low between 1994 and 2012 (4 to 5 scenes each year in average), non-  
578 recurrent slicks detected during the long-term monitoring are presumably associated with  
579 ephemeral expulsions sites, as demonstrated by the short-term monitoring (seep site E). The high  
580 variability of the amount of expelled oil suggests that the evaluation of the seepage activity during  
581 scientific exploration campaigns should be based on a consistent period of underwater records.

## 582 **5.5. Oil output quantification**

583 From oceanographic investigations and SAR observations, the minimum detectable thickness for  
584 oil film can be estimated at 0.1  $\mu\text{m}$  (Allen, 1970; Macdonald et al., 1993; Mitchell, 2000;  
585 Macdonald et al., 2002; Garcia-Pineda et al., 2009). From the Bonn agreements (2009), which  
586 established a relationship between the visual aspect of oil slicks and their thickness in the offshore  
587 domain, Garcia-Pineda et al. (2013) considered that the thickness of an oil slick is 1  $\mu\text{m}$  for 5% of  
588 the fresher slick surface and 0.1  $\mu\text{m}$  for the remaining 95% of the surface. Based on this  
589 assumption, a slick of 1  $\text{km}^2$  may therefore contain 145 l of oil. Considering this thickness, the  
590 sum of oil-covered surface within each grid cells gives a total average amount of 1625 litres at the  
591 sea surface (Fig. 5). Considering a median residence time at the sea surface computed with the  
592 subsurface current (Fig. 9) and the local wind velocity (Fig. 7), we performed a volumetric

593 computation of regional oil output for the 102 natural seeps along the Angolan coasts (Table 4).  
 594 The median estimate, considered as the best estimate and computed using an average surface  
 595 current velocity (Fig 9), indicates that 500 litres are expelled each hour, which represents an  
 596 annual amount of 4380 m<sup>3</sup> of oil naturally expelled in the Lower Congo Basin.

597 **Table 4**

598 Estimation of the regional output of oil from the 102 natural seeps along the Lower Congo Basin,  
 599 assessed from average surface oil and SAR data coverage.

Average surface oil volume (l)	Lower Bound	Median estimate	Upper bound
Considered subsurface current velocity (cm/s)	5	17	30
Median residence time	5h30min	3h15min	2h15min
Average output (l/h)	295.45	500	722.22
Annual amount (l/yr)	2.58*10 <sup>6</sup>	4.38*10 <sup>6</sup>	6.32*10 <sup>6</sup>
Annual amount (bbl/yr)	1.62*10 <sup>4</sup>	2.75*10 <sup>4</sup>	3.97*10 <sup>4</sup>

600  
 601 To give a comparison, Macdonald et al. (2015) assessed the annual output across the entire Gulf  
 602 of Mexico as between 25,300 m<sup>3</sup> and 94,800 m<sup>3</sup> per year. Hornafius et al. (1999) estimated oil  
 603 seepage along the Santa Barbara basins around 5840 m<sup>3</sup>. For the southwestern Caspian Sea,  
 604 Zatygalova et al. (2007) evaluated a minimum natural seepage rate of 1700 m<sup>3</sup>. Estimations  
 605 performed by Körber et al. (2014) suggest that about 360 m<sup>3</sup> are expelled for the eastern Black  
 606 Sea. The most accurate estimation presented in this paper therefore rank the Lower Congo Basin  
 607 as the third biggest oil-supplying area in the world. The computations of expelled volumes based  
 608 on the gridded method developed by Macdonald et al. (2015) are detached from the dimensions of  
 609 the study areas. The orders of magnitude of the surface oil volume are comparable between the  
 610 Gulf of Mexico (<15 l/km<sup>2</sup>) and the Lower Congo Basin (<10 l/km<sup>2</sup>), where oil seep systems are  
 611 related to salt tectonics in both cases. The seepage intensity per unit area should be compared for  
 612 miscellaneous geological contexts to understand bypass system efficiency. Thermogenic seep

613 sites are also associated with a consistent methane flux (Solomon et al., 2009; Hu et al., 2012),  
614 benefiting from both thermal cracking and biodegradation (Head et al., 2003; Peters and  
615 Moldowan, 2007). Even if the gas quantification associated with oil escapes remains an open  
616 question, this amount is presumably considerable. The assessment of contemporary seepage  
617 volumes also provides calibration tips for the evaluation of fossil seep systems. Ongoing work  
618 integrating the SAR dataset together with subsurface geophysical imagery will help to associate  
619 sea surface evidences of oil leakage with seafloor venting features.

## 620 **Conclusions**

621 This study integrates a combination of long-term (82 images over 18 years) and short-term (22  
622 images over 10 days) monitoring of SAR scenes to understand the seepage situation in the Lower  
623 Congo Basin. The compilation map of recurrent seepage slicks forms diverging oil slick patterns  
624 from the central origin area, which allowed the recognition of 102 recurrent oil seeping sites. The  
625 seeping area is constrained to the compressive and translated salt-related structural domains,  
626 where salt diapirs create efficient oil migration pathways to the sea surface. It was demonstrated  
627 that the occurrence rates strongly vary between seeping sites, ranging from 5 to 80%. The  
628 correlation of SAR observations with wind speeds showed that slick detection is possible for wind  
629 values ranging from 1.5 to 6.5 m/s. Local winds at dormant sites remain within ideal weather  
630 conditions demonstrating the intermittent activity and the high variability of seepage flow rates  
631 over short periods. This allowed the identification of macro-seep sites of high occurrence rates  
632 and micro-seepage sites releasing hydrocarbons sparsely or ephemerally towards the sea surface.  
633 Merely half of the seeping sites revealed from 18-year long-term monitoring were active during  
634 10-day short-term monitoring, suggesting that the remaining half remained dormant. Short-term  
635 monitoring shows that the slick residence time is low, as the seepage signal is lost between two  
636 consecutive SAR scenes separated by 12 h. Sea surface speed displacement estimated from the  
637 integration of local winds and subsurface current measurements, coupled with slick lengths

638 allowed us to provide for the first time a statistical study and a quantitative approach to assess the  
639 surface slick residence time. This distribution concentrates around a median value of 3h15min.  
640 The best estimates of the volumetric outflow give an annual volume of 4380 m<sup>3</sup> of oil naturally  
641 expelled in the Lower Congo Basin.

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