REMOTE SENSING FOR RISK ANALYSIS OF OIL SPILLS IN THE ARCTIC OCEAN

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ABSTRACT

Predicted decreases in sea-ice extent and shift from multi-year ice to seasonal ice open up for commercial shipping routes within the Arctic. With expected further growth of maritime activities the potential threat of accidents is increasing. Moreover, there is a lack of information on how an oil spill would affect the Arctic Ocean environment. A robust tool following international risk assessment standards is therefore vital to 1) try to prevent oil spills through use of scenario runs and 2) increase the possibilities to delimit the damage should a spill occur. We use remote sensing images to extract information about oil spill redistribution mechanisms. This combined with information about estimated volume, type of oil and ecotoxicological data enables identification of areas in the Arctic Ocean especially vulnerable to maritime activities. We also include estimates on the probability of an oil spill occurrence.

Key words: Sea ice, Oil spill.

1. INTRODUCTION

Reduced sea ice extent in the Arctic Ocean [3] opens up for an increase in marine activities. The expected growth in shipping is thought to originate from an increased demand for transportation from the Atlantic to the Pacific regions and from an increase in supply and search and rescue ships for the expanding offshore activities in the Arctic [7]. Calculations by [34, 14, 38] show that using the Northeast (or Northern Sea Route (NSR)) could save 40% of the travel distance between London and Yokohama. The shorter distance can be exploited either by reducing speed and maintain travel time or by reducing travel time and maintain speed. The importance of the cross polar transportation routes was identified [27] to depend on opening times of the NSR, the ice-breaker cost for the NSR and the bunker prices. Should the opening times for the NSR and the bunker prices increase it will increase the importance for the polar crossings.

The number of polar crossings has increased since 2009 [37, 31] as has the inter-Arctic transportation [6]. In 2009 the number of passages were four [37] and at the end of July 2013 270 ships had been given permission by the Federal State Institution The Northern Sea Route Administration (http://www.nsra.ru/en/razresheniya/) to transit the NSR in 2013 [32]. However, a majority of the ships moving within the Arctic Ocean are connecting commercial interests within the Arctic with the outside world [6]. Navigation in polar conditions are difficult and the AMSA report of 2009 [2] identified a need for further development of maritime infrastructure in the Arctic ocean to secure safe passages, such as improved navigation charts, improved search and rescue and increased cooperation in oil spill prevention. The increase in shipping exposes the Arctic region to an increased probability of accidents that may release hazardous substance into the environment. Here we focus on a potential oil spill. Risk is defined as the probability of an unwanted event to occur, times the consequence of the unwanted event. To analyse the risks associated with the forecasted increase in maritime activities in the Arctic region, it is also important to know the potential consequences of e.g. an oil spill. A release would most likely not only affect a delimited region but will likely spread to other areas. Furthermore, depending on time of the year an oil spill may have different immediate environmental consequences, e.g. during the Arctic summer the biological productivity peaks, which unfortunately also is the most favourable season for maritime activities such as shipping and exploration of natural resources in the region. The remote location also has consequences on the response time should an accident occur [2].

The need for solid risk assessment, capable of handling the complexity of the system, is obvious to ensure sustainable development of the Arctic region. To describe potential consequences of an oil spill Synthetic Aperture Radar (SAR) images are used to provide input data about the sea ice concentration [4], sea ice drift [5] and wind patterns over open water [10]. Combining this data with information about ocean currents we will make estimates on the redistribution and spread of oil pollution scenarios, which is an important piece of information in the risk analysis and risk assessment.

Proc. 'ESA Living Planet Symposium 2013', Edinburgh, UK
9–13 September 2013 (ESA SP-722, December 2013)

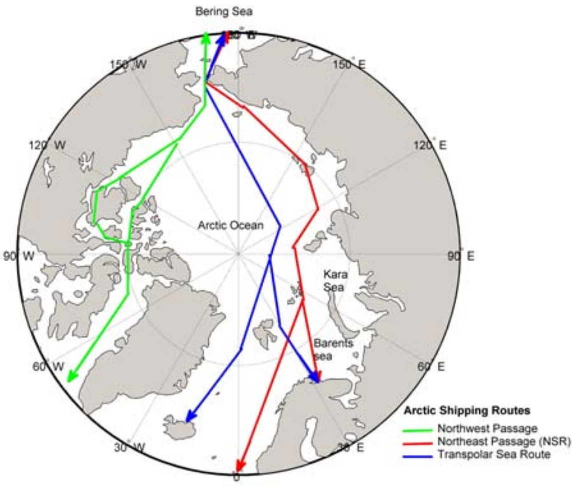

Figure 1: Arctic Ocean with sea routes.

2. STUDY AREA

The Arctic Ocean (Fig. 1) extends north from roughly 75^{o}N and includes for example Barents Sea, Kara Sea and Bering Sea. Satellite observations show that the Arctic sea ice area has decreased since the 1970s [47]. Moreover, the sea ice thickness has reduced since at least the 1980s [23], implying a loss not only in sea ice area but also in sea ice volume. The latter is reflected in the reduced amount of multi-year ice. From a maritime activities perspective the multi-year ice is harder to break and therefore presents a challenge when it comes to navigation [7]. It is therefore important to include not only the sea ice extent but also the age and concentration of the ice for the risk analysis.

The majority of the ships that move in the Arctic Ocean are ships that connect commercially interesting areas within the Arctic with the outside world [6]. However, with reduced sea ice there is an increased interest for cross polar shipping. The number of complete polar crossing passages has increased from 4 in 2009 to 46 in 2012 [37] to 270 approved crossings in end July 2013 [32]. The most known cross Arctic shipping routes are the NSR, Northwest and Transpolar sea routes (Fig. 1). The Northwest shipping route is not expected to be a feasible route within the near time future [40] due to prevailing sea ice and weather conditions. Moreover, as of 2010 the NSR was only open for 30 days. The reduced sea ice opens up for extended opening times for the NSR passage and given model predictions [40] by 2040 the Transpolar sea route will be open for commercial shipping for Polar Class 6 (PC6) classified boats. Assuming the current national sea borders this implies that the route will be on international waters only.

3. DATA SOURCES

The satellite input data to the risk analysis will initially be set up using historical satellite data. Satellite observations dating back to 1978 will be used to follow the trends of sea-ice within the Arctic Region. These data mainly originate from passive sensors and have the advantage of large spatial coverage and high temporal resolution. The lack of daylight during autumn and winter months as well as the occurrence of fog, particularly along the sea ice edge, and low clouds implies that SAR images are necessary to enable tracking of oil spill throughout the year. The passive sensors and the SAR sensors have the same limitation regarding the inability to penetrate the sea ice and enable tracking of oil underneath ice.

The spatial extent of the Arctic region and the need for high temporal resolution has meant that medium spatial resolution such as Envisat ASAR Wide Swath data has been favoured when extracting sea-ice information. Hence, at the initial stages the main focus will be on Envisat ASAR Wide Swath data extracted from the ESA rolling archive. For the surface currents estimates data from Jason 1 and 2 as well as Envisat Radar Altimeter are used. The risk assessment method will be set up to comply with future satellite missions like Sentinel-1, ALOS-2 and the Radarsat Constellation.

4. METHOD AND ALGORITHM DESCRIPTIONS

Arrays of different products extracted from satellite images are used as input data into the risk analysis (Fig. 2) to identify the potential geographical distribution of an oil spill in the Arctic and its consequences. These satellite products are; sea ice extent and concentration, sea ice drift, surface wind and sea surface current.

4.1. Risk analysis

To perform a risk analysis of a hazardous event, in this case an oil spill, the probability of the hazardous event to occur is combined with the potential consequences of the event. The calculated risk is the starting point for a complete risk assessment, which includes risk evaluation to determine whether or not the risk is tolerable and presentation of plausible alternatives for risk reduction. The risk assessment can thereby provide decision support regarding necessary means to control and/or reduce the risk [8]. A number of guidelines describing the process exist and for this study we are using the method outlined by the International Electrotechnical Commission [21].

Both the probability of an oil spill to occur, and the eventual consequences, are dependent on many factors of which at least five can be extracted from remote sensing data; sea ice concentration and extent, sea ice drift, surface winds and currents (Fig. 2).

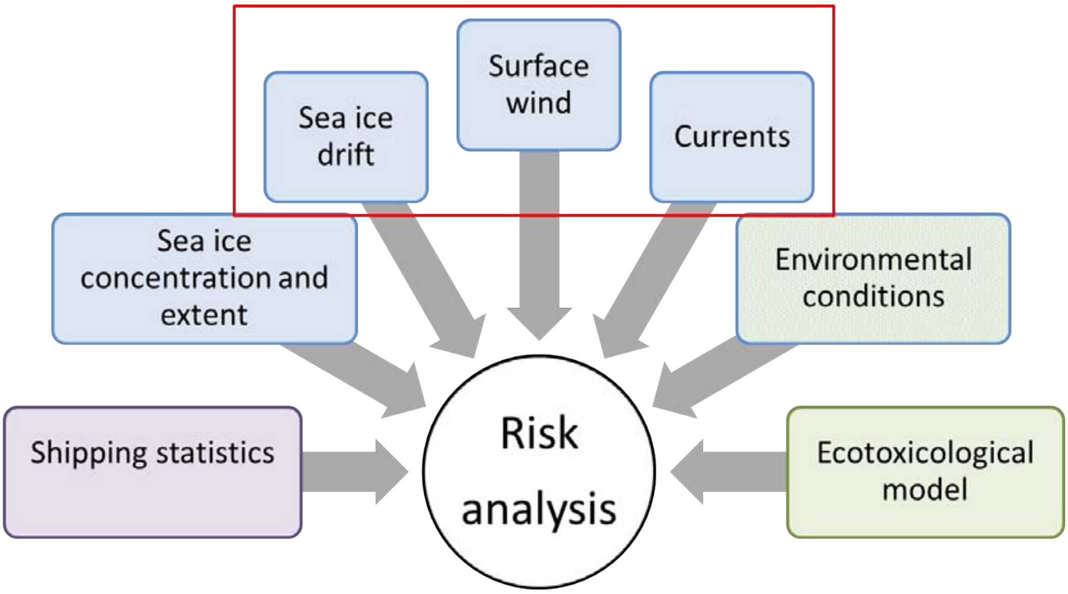

Figure 2: Set up of data needed for the risk analysis. The blue boxes highlight information extracted from remote sensing data. The green box with blue edge highlight information that is partially extracted using remote sensing data, e.g. temperature and biological productivity data. The green box is the ecotoxicological data and the purple box is the shipping statistics. The red box indicate the distribution mechanisms.

The sea ice extent and concentration affects the location of the shipping routes [27]. Sea ice is a threat to shipping and hence years with high sea ice concentration close to or in the shipping routes may have a higher probability of an oil spill. Therefore, within the estimations of the probability of a spill the distance between the shipping routes and the ice edge are included.

Once the potential amount of oil released into the environment has been established the redistribution of said oil is estimated. The spreading mechanisms taken into consideration here are; sea currents, surface wind and sea ice drift (Fig. 2). The spreading mechanisms will also be used to estimate the oil concentration. Results by [25] indicate that even low concentration of polycyclic aromatic hydrocarbons (PAH) will have long-term effects on the benthic community.

Once the oil is distributed ecotoxicological data will be used to assess the effect of the oil on the environment. As the biological production changes during the year, areas of particularly vulnerability may change with time. It is therefore important not to assume a static Arctic environment. Information about the biological production will be taken from chlorophyll and sea surface temperature satellite products and modelling products, this is indicated as environmental conditions within figure 2. Furthermore, certain areas are of particular biological importance as they are regularly used as spawning areas.

4.2. Sea-ice edge and concentration

Sea ice extent and concentration retrieval is done using the algorithm presented in [4]. Sea ice concentration is defined as the fraction of an area that is covered by sea ice. Sea ice concentration has been measured on global daily basis since 1979 [12] and is used on daily basis among ice services around the world, e.g. Danish Meteorological Institute (DMI), Norwegian meteorological institute (Met.no) and Swedish Meteorological and Hydrological Institute (SMHI), for navigation safety as well as weather routing to reduce fuel costs.

The sea ice concentration algorithm has been developed for C-band synthetic aperture radar (SAR) data. Detailed autocorrelation statistics are derived from SAR data for which the ice concentration had been classified manually. The statistics were integrated into the algorithm in order to use autocorrelation as an effective measure of sea ice concentration. The algorithm employs a neural network which was trained against 41 sea ice charts produced by the Swedish Ice Service and with coverage of the Baltic Sea. The method has proven to perform well within open water (94% accuracy) and classification of sea ice pixels has an accuracy of 87% [4]. However, the method performs with a lower accuracy for areas of multi-year ice and regions of open water with small-scale wind features. The problem with multi-year ice is of particular importance in the Arctic region as multi-year ice is a permanent feature there. On the other hand the maritime activities within this region will primarily operate in areas with single year ice and open water.

During melt season the sea ice will most likely be wet at times and streaks of slush ice will likely be present. Such areas are challenging to separate from open water with small-scale wind features. However, such areas are also areas where transportation ships may be moving. Since the method is using a neural network the method can be improved for studies within the Arctic Ocean by further training using satellite images over this area. The problems with multi-year ice may also be rectified by training the algorithm against sea ice charts produced by the DMI and the Met.no. If the problem with multi-year ice and the wet surface still persist the sea ice drift will be incorporated into the sea ice concentration algorithm and within areas with identified sea ice drift an area concentration will be estimated.

4.3. Distribution mechanisms

The distribution mechanisms consist of; sea ice drift, surface wind and surface currents. These types of data will enable estimations of the final location of a potential oil spill and also provide estimates of the oil concentration.

4.3.1. Sea ice drift

Sea ice is a potential redistributor of the oil as oil might get stuck on the ice and then be redistributed with the ice to other areas. Should an oil spill reach ice this might imply that the sea ice can transport oil away from the Arctic or that the oil can be redistributed within the Arctic and then reach potentially more environmental vulnerable areas. The main outlet for sea ice from the Arctic Ocean is through the Fram Strait [36] and should a spill occur there the redistribution might be a substantial problem. It is therefore important to not only look at the location of the ice but also the movement of the ice.

Sea ice drift is estimated using the method described in [5]. The method is a combination of an areal matching method and a feature tracking method. The areal tracking technique uses phase correlation and is based on [42] with the addition of a new rotating resolving module. The feature tracking approach is based on [15] with a new method for image segmentation. The method is developed to not only deal with pack ice but also with the dynamic marginal ice. Shipping may at times be close to the sea ice and accurate information about the sea ice margin is therefore very important when estimating the risk for an oil spill.

Two SAR images are needed by the algorithm and in areas outside the overlap between the two images border effects featuring high drift speeds may occur (Fig. 3). Another possible explanation for high drift speeds at the overlap border is when the first of the two images has a more pronounced wind effect over the open water. This would be interpreted as if the open water has been transported into the sea ice.

4.3.2. Surface wind

The surface wind can also redistribute the oil spill and to estimate the transportation and the concentration both the direction and the speed is needed. Such information can be extracted from scatterometer and SAR sensor data.

Opposed to scatterometer sensors, SAR sensors only use one look angle and it is therefore not possible to extract both wind direction and speed from the inversion of conventional Geophysical Model Functions (GMFs) [33, 19]. Therefore, the wind direction information is normally provided by either the analysis of streaky features aligned with the wind direction [1] in the SAR image [26, 46, 10] or by using estimates from weather prediction models [28, 18]. Due to difficulties of extracting wind direction in coastal areas and areas close to the sea ice [11] we use direction data from the European Centre for Medium-Range Weather Forecasts (ECMWF). The data has a 0.5 degree grid resolution and are used to invert wind speeds from Envisat ASAR data to a resolution of 10 km.

The inversion of the wind speed is accomplished in the following manner [10]. Selecting a GMF, a lookup table of normalized radar cross sections in vertical polarization (VV) is produced for each resolution for the wind direction with respect to the radar look direction (), the incidence angle of the radar (), and the wind directions from ECMWF. Since the selected GMFs are defined for VV polarization, a polarization ratio, PR, is used when the image is in horizontal (HH) polarization. We use the [43] polarization ratio since it have been found to match best with collocated reference measurements [22]. Finally, the wind speed is inverted by applying a linear curve fitting around the value of σ^{o} HH or σ^{o} VV from the available points of the corresponding lookup table.

4.3.3. Surface currents

At present there are four main ways to obtain information about surface current from remote sensing data. These are; 1) geostrophic currents from the mean dynamic topography (MDT) registered by altimeters [29, 45], 2) medium resolution currents (10-20 km) using a maximum cross correlation (MCC) [17, 16], 3) currents derived from the high resolution measurements (0.5-10 km) of the radial component of the current field component (perpendicular to movement direction) from SAR sensors with the Doppler shift (DS) [13] and 4) the along track interferometry (ATI) [35].

The latter three techniques are still under development due to either their restricted applicability due to weather conditions (MCC) or the lack of data availability combined with their restriction to one component of the current field data (DS, ATI). Within this risk analysis we will therefore use geostrophic estimates of the surface current field from the MDT method. The geostrophic data are produced from merged altimeter data of Jason 1 and 2 and Envisat Radar Altimeter, which has been compiled by AVISO into daily 1/3^{o} x 1/3^{o} resolution Mercator grid and is currently available in NetCDF format (http://www.aviso.oceanobs.com/en/data.html).

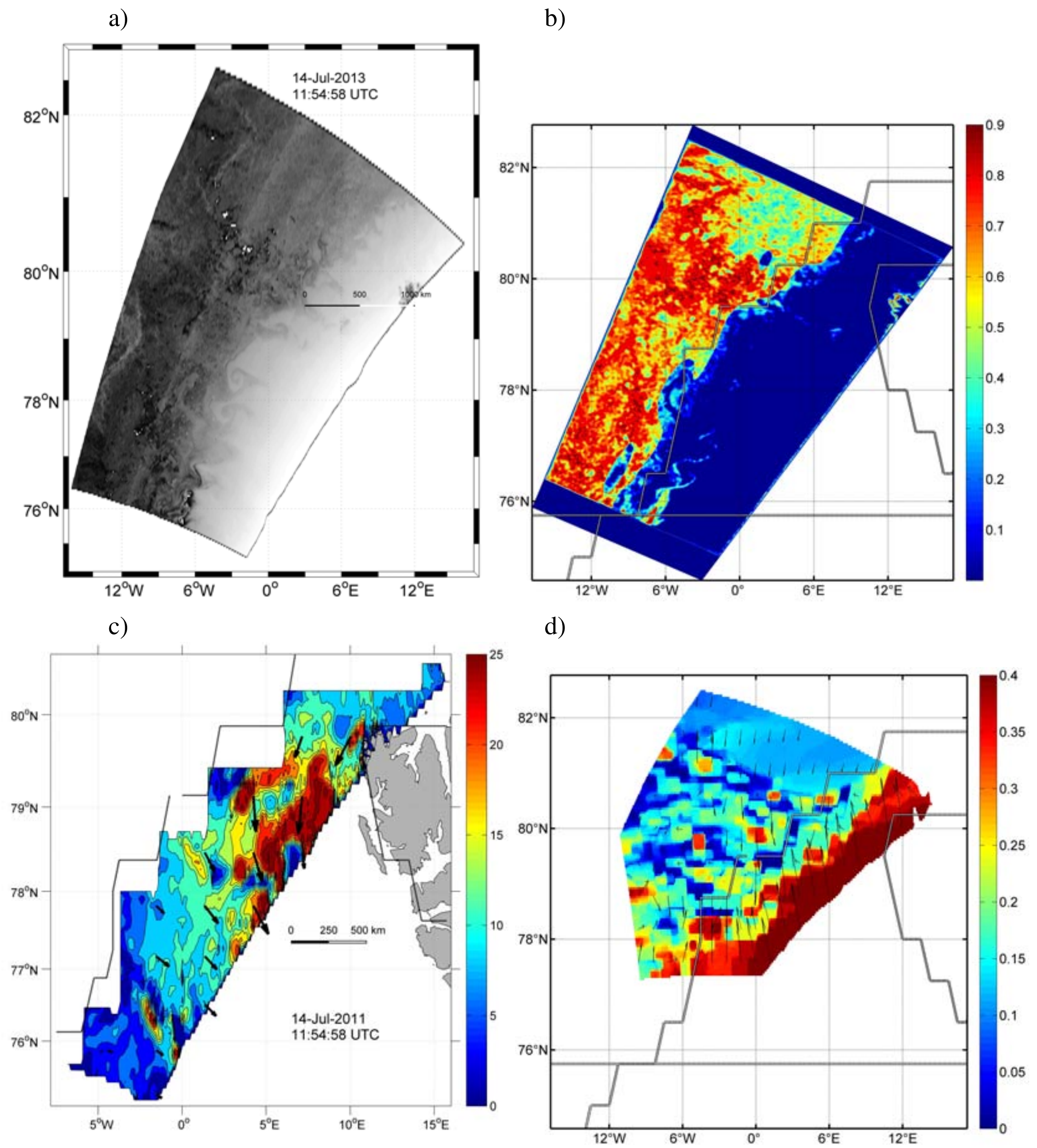

Figure 3: a) Envisat ASAR image from the overpass 2011-07-14. b) Sea ice concentration calculated using the ASAR image shown in a. The ECMWF ice edge extent is the dark grey line and the concentration is given from 0 to 0.9 where 0.9 corresponds to 90% ice cover. c) Surface wind calculated using ASAR image shown in a. The black line illustrates the ECMWF ice edge extent and the arrows shows the ECMWF wind direction. The wind speed is given in m/s. d) Sea ice drift calculated using ASAR images acquired on the 2011-07-14 (seen in a) and 2011-07-16. The ECMWF ice edge extent is the dark grey line and the sea ice drift is given in m/s.

4.4. Ecotoxicologial data

Most available ecotoxicological data on effects of oil in the marine environment concern high concentrations of crude oil. This implies that available risk assessment models also are focused on crude oil. The need for further research on the ecotoxicological effects of low concentrations of refined petroleum products in the Arctic marine environment has therefore been identified as urgent [9].

Our work in temperate waters indicates that there is a cost associated with nature's ability to degrade low concentration of e.g. diesel oil [25]; the biogeochemical cycling of nutrients, one of the most basic supportive ecosystem services, is affected at concentrations in the same range as is allowed for discharge in bilge water today. These findings are also supported by [20], who show similar results from plankton communities in the water column. However, very little is known about these processes in cold climate conditions. Hence, [30] propose the possibility to translate ecotoxicological data from temperate regions to the Arctic marine environment. Available ecotoxicological data from Environment Canada (http://www.etc-cte.ec.gc.ca/databases/oilproperties/) and available scientific literature will be used to rank a set of different oil products.

5. RESULTS AND DISCUSSION

Using a combination of remote sensing products and a risk analysis thought-process we develop a method that tracks a potential oil spill from release to clean-up. Furthermore, the method includes the spills ecotoxicological effects on the environment. In Figure 3 the products used to track the oil spill are shown (Fig. 3c-d) together with the Envisat ASAR image from 2011-07-15 (Fig. 3a) used to extract the products. The sea ice drift product also requires an additional ASAR image, in this case from the 2011-07-16.

SAR images covering the area affected by the oil spill (Fig. 3a) are used to estimate the sea ice extent and concentration (Fig. 3b). If the oil is spread in an area with sea ice the sea ice drift algorithm will be used to detect the movement of the oil (Fig. 3d). Should the spill happen in open water the wind (Fig. 3c) and current (not shown) algorithms will be used to estimate the redistribution of the spill. The redistribution of the spill implies that there may be a cross over between the different algorithm e.g. if the sea ice melts or the wind is pushing the spill onto the sea ice.

Comparisons between the sea ice extent estimate using the method outlined in [4] with the ECMWF (Fig. 3) estimate show reasonably good agreement. The former has higher spatial resolution than the latter and may therefore be used as sea ice extent estimate in the wind retrieval algorithm. The combination of a sea ice concentration algorithm and a wind algorithm enables detection of whether the substance will reach the sea ice. As stated by [44] removal of oil is easier in open water than on sea ice. It may therefore be preferable to prevent the oil from reaching the sea ice when possible. The inability to use SAR images to track oil underneath sea ice is therefore of limited importance. At the end of the summer months there is also formation of new sea ice and by using the sea temperature (one of the environmental conditions in Fig. 2) it is possible to detect if the sea temperature is close to freezing.

In the 17 SAR images presently used in our study the wind patterns followed the same trends; with higher wind speeds closer to the north east corner of Svalbard regardless of the wind direction. Making the spreading of an oil spill more profound within this area. The wind algorithm is only designed to work over open water and hence no indication of the wind patterns over the sea ice can be given. However, given that wind is the main driving force behind sea ice drift with a correlation of R$\sim$0.8 [41] the two products can be combined to show the wind pattern over both the sea ice and the open water areas. The correlation between the wind and the sea ice drift has also been used by e.g. [39] to extend the sea ice drift record back to the 1950s.

As shown by e.g. [39] the sea ice drift is lower during the summer months (June-Aug) compared to the winter months (Dec-Feb). The lower sea ice drift during summer coupled with a smaller sea ice extent is from a risk analysis perspective preferable should an oil spill occur. On the other hand the biological productivity peaks during the summer months. Sea ice export during the summer months of 2004 until 2010 was close to 0 m/s for 2-3 months due to southerly winds [39]. In our comparison of wind and sea ice drift data (July to September 2011) such southerly wind events were observed. However, the winds were predominately northerly. Figure 3 c and d show good agreement regarding direction of the wind and sea ice drift.

The movement of sea ice is also of uttermost importance during clean-up work as sea ice drift may hinder the work. Both from a safety prospective for those working with the clean-up but also prevent ship movements. On the other hand sea ice might prevent an oil spill from reaching the coast and potentially vulnerable areas. In such a scenario it might be preferable to protect the open water. The complexity of the Arctic region is one of the reason for adopting the risk assessment approach in order to ensure a more comprehensive understanding of the system.

6. CONCLUSION

We adopt a risk assessment approach to study the potential redistribution and ecotoxicologial effect of an oil spill within the Arctic Ocean. For this we use remote sensing products to estimate the redistribution of the oil. The products are; sea ice drift, surface wind and surface ocean currents. The oil concentration is estimated and combined with ecotoxicological data. The ecotoxicological data used includes the effect of low concentration refined petroleum products. The combination of different data enables us to assess the most vulnerable areas depending on season and region.

7. ACKNOWLEDGEMENT

SAR data from Envisat were provided by the European Space Agency through the Category-1 Proposal titled Evaluation of Sea and Sea-ice state information for Improved Maritime Security ESSIMS (Proposal ID 5760).

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