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Operational oil spill trajectory modelling using HF radar currents: A northwest European continental shelf case study

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A B S T R A C T

This paper presents a novel operational oil spill modelling system based on HF radar currents, implemented in a northwest European shelf sea. The system integrates Open Modal Analysis (OMA), Short Term Prediction algorithms (STPS) and an oil spill model to simulate oil spill trajectories. A set of 18 buoys was used to assess the accuracy of the system for trajectory forecast and to evaluate the benefits of HF radar data compared to the use of currents from a hydrodynamic model (HDM). The results showed that simulated trajectories using OMA currents were more accurate than those obtained using a HDM. After 48 h the mean error was reduced by 40%. The forecast skill of the STPS method was valid up to 6 h ahead. The analysis performed shows the benefits of HF radar data for operational oil spill modelling, which could be easily implemented in other regions with HF radar coverage.

1. Introduction

Oil spill pollution and its impact on coastal and marine environments have led to a growing concern regarding oil spill preparedness and response. Over the last decade, many operational oceanographic systems that are based on oil spill numerical models coupled to hydrodynamic and meteorological models have been set up in order to provide decision makers with oil spill trajectory forecasting. Recent oil spill incidents, such as the *Prestige* incident in Spain (2002) and the *Deepwater Horizon* oil spill in the Gulf of Mexico (2010), have demonstrated that forecasting oil spill trajectory is fundamental for planning and mitigation strategies (Castanedo et al., 2006; Liu et al., 2011a, b, c). Besides forecast applications, Lagrangian trajectory models have been used and incorporated into operational systems which are run backwards in time, with the purpose of detecting likely release sites, illegal discharges and potential polluters (Ambjörn, 2008; Christiansen, 2003; Abascal et al., 2012).

The accuracy of the simulations provided by these oil spill simulation systems is highly dependent on the accuracy of the met-ocean forcing data used to force the oil spill model. These forcing data are usually provided by hydrodynamic and atmospheric models, which have associated uncertainty which may affect the accuracy of the oil spill forecast and backtracking simulation (Edwards et al., 2006; Price et al., 2006). Such uncertainty becomes greater in ocean circulation modelling of coastal areas, where the complex patterns that characterize coastal hydrodynamics complicate the forecasting of the current field. High frequency (HF) radar systems become an alternative for the provision of accurate surface current maps in near coastal environments. HF Radar is nowadays the only technology capable of providing real time surface currents continuous in space and time for wide areas, from a few kilometers to up to 200 km offshore. In the last few years, several studies have been carried out to validate this technology (e.g. Graber et al., 1997; Kaplan et al., 2005; Hubbard et al., 2013; Lorente et al., 2014) and to assess the effectiveness of using HF radar currents for trajectory analysis (e.g. Ullman et al., 2003; O'Donnell et al., 2005; Ullman et al., 2006; Abascal et al., 2012; Liu et al., 2014).

Recent experiments, such as the NOAA sponsored Safe Seas 2006 exercise (Long and Barrick, 2007) and the Galicia HF Radar Experience (Abascal et al., 2009), have shown the benefits that HF radar currents can provide for the tracking and simulation of oil spills. However, a

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possible limitation to the use of HF radar for this purpose arises from the data gaps that HF radar, as any other remote sensing system, is subject to. Data gaps are predominately due to environmental effects, such as increased external noise or low signal due to ocean surface conditions. Many applications of HF radar surface current data require these gaps to be filled, such as Lagrangian numerical models used to estimate material transport and dispersion. Several studies have proposed different methodologies to accurately reconstruct hourly HF radar surface current data to provide gap-free current fields, e.g. Open-Boundary Modal Analysis (OMA) (Lekien and Gildor, 2009; Barrick et al., 2012; Roarty et al., 2016).

In order to increase the benefits of this technology for search and rescue, safety in navigation, and oil spill modelling, and to improve trajectory forecasts during emergency-response situations, recent studies have successfully provided accurate short term current forecasts based on assimilation of HF radar currents into coastal ocean models (Breivik and Sætra, 2001; Oke et al., 2002; Paduan and Shulman, 2004; Hoteit et al., 2009). Efforts have also been made to use longer time series of HF radar surface current maps to make short-term forecasts (Zelenke, 2005; Frolov et al., 2011). Whereas these forecast methods using HF radar data employed methodologies that relied on a month or more of historic data to forecast tides and background residual circulation, this will not be possible in the scenario of a rapid deployment of an HF radar system to a new area in an oil spill emergency situation. To overcome this limitation, Barrick et al. (2012) designed and validated a real-time gap-filling technique for HF radar data and a short-term prediction system (STPS) methodology that relied only on 12 h of HF radar currents from a system deployed in Norway.

Despite its potential, developments that make use of the information provided by HF radar technology, translating it into added value products to support decision making in oil spill response or oil and gas platform operation, are currently scarce. While HF radar systems have been mainly used for search and rescue emergencies (Barrick et al., 2012; Breivik et al., 2013), there is a lack of operational applications for oil spills, especially in Europe.

To study the benefits which an HF radar system could bring to the UK coast, the Brahan Project (http://www.thebrahanproject.com/) was carried out in northern Scotland as a joint effort between several public institutions and oil and gas companies (Turrell et al., 2014). The main goal of this project was to provide a fully operational Long Range SeaSonde HF radar system in the Shetland-Orkney area (Fig. 1) to measure surface currents in near real time.

Within the framework of the project "NEw MetOcean Tools for the Oil and Gas Industry" (http://www.nemot4ogi.com), an oil spill forecasting and backtracking system was implemented in the Brahan study area to show the capabilities of HF radar systems for oil spill preparedness and response. The system integrates Open Modal Analysis (OMA), Short Term Predicted algorithms (STPS) and an oil spill numerical model to simulate oil spills in real time into a web-based information system. The oil spill forecasting capability of the system was extensively validated by means of a set of 18 drifting buoys released in the study area. A sensitivity analysis was carried out to assess the accuracy of OMA and STPS velocity fields for oil spill simulations and to evaluate the benefits of HF radar data compared to the use of HDM currents.

2. Study area

The Orkney Islands are situated directly north of the Scottish mainland, separated by the ca. 10 km wide Pentland Firth. The Shetland Islands are to the north west of Orkney, separated by a channel approximately 80 km wide, the Fair Isle Gap (FIG), named after the small island (Fair Isle) in the middle. Water depths around and between Orkney and Shetland (collectively known as the Northern Isles) are generally < 100 m, compared to slightly deeper waters in the northern North Sea to the east and the continental shelf to the west. The island chain made up by Orkney and Shetland, and the relatively shallower ridge of the FIG create a natural physical border which, to some extent, presents a barrier to the exchange of water with the North Atlantic (Turrell, 1992a; Huthnance, 1997). However, this is an important area of water inflow into the northern North Sea. Waters enter the North Sea from the North Atlantic through the northern open boundary via three main routes (Otto et al., 1990; Svendsen et al., 1991; Turrell, 1992b): through the FIG, around the north and east of the Shetland Islands (the East Shetland Atlantic Inflow, ESAI) and along the western side of the Norwegian Trench (Norwegian Trench inflow). The northern North Sea ecosystem variability (including regime shifts) has been linked to changes in the Atlantic inflow (e.g. Beaugrand, 2004). The Brahan HF Radar system covered the FIG and adjacent waters to the east and west; the radar sites were located at North Ronaldsay (Orkney) and Sumburgh (Shetland), with coverage with an average range of > 100 km (see below). The FIG is an important maritime transport corridor, including for oil tankers (the MV *Braer* ran aground on the southern tip of Shetland in 1993, spilling 85,000 t of Norwegian Gullfaks crude oil) and the waters around the Northern Isles are subject to a wide range of important socio-economic activities such as shipping, tourism, aquaculture, fishing and oil and gas extraction.

3. Description of the operational system

The main goal of our operational system is to provide short term (12–48 h) oil spill trajectory forecasting and backtracking. The system is comprised of three components: 1) Met-ocean Data Module that provides hourly surface currents with ~4 km spatial resolution and gap-free HF radar surface currents based on Open Modal Analysis. This module also integrates wind forecast from the Global Forecast System (GFS) model (NOAA) (Environmental Modeling Center, 2003); 2) Numerical Module that includes: i) a Short Term Prediction System that provides 12 h forecast currents using HF radar measurements and ii) an oil spill transport and fate model, TESEO (Abascal et al., 2007); and 3) Web-based Information System that is able to provide all relevant information, in an operational way to the end user, which is needed to support decision making for the purposes of oil spill response.

In the case of an oil spill, the system allows the user: 1) to forecast the transport and fate of the spill with a forecast horizon of 12 h, using GFS wind and STPS surface currents and 2) to perform trajectory backtracking with a simulation horizon of 48 h, using OMA surface currents and GFS winds.

A general overview of the system is displayed in Fig. 2 and its description is presented below.

3.1. Met-ocean data module

3.1.1. HF radar currents

The HF radar technology works on the principle of Bragg scattering where the transmitted electromagnetic radio waves are reflected by resonant ocean surface waves with half of the incident radar wavelength (Barrick et al., 1977). An HF radar system consists of a transmitter antenna transmitting high-frequency (3–50 MHz) electromagnetic waves over a conductive ocean surface and receiver antennas capturing the backscattered signal with a Doppler frequency shift resulting from the moving ocean surface due to waves and underlying (surface) currents. The main data product is 2-D surface current maps, which require two or more radars with overlapping coverage (Barrick et al., 1977; Lipa and Barrick, 1986). HF coastal radars have evolved over the past 40 years into worldwide operational networks that provide real time data to a variety of end users (Harlan et al., 2010).

HF radar surface currents used by the Operational Oil Spill Modelling System were provided by two CODAR HF radar stations that were installed in Northern Scotland as part of the Brahan project: one at Sumburgh lighthouse (Shetland), and one at North Ronaldsay light-