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Simulating pathways of subsurface oil in the Faroe–Shetland Channel using an ocean general circulation model

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ABSTRACT

Little is known about the fate of subsurface hydrocarbon plumes from deep-sea oil well blowouts and their effects on processes and communities. As deepwater drilling expands in the Faroe–Shetland Channel (FSC), oil well blowouts are a possibility, and the unusual ocean circulation of this region presents challenges to understanding possible subsurface oil pathways in the event of a spill. Here, an ocean general circulation model was used with a particle tracking algorithm to assess temporal variability of the oil-plume distribution from a deep-sea oil well blowout in the FSC. The drift of particles was first tracked for one year following release. Then, ambient model temperatures were used to simulate temperature-mediated biodegradation, truncating the trajectories of particles accordingly. Release depth of the modeled subsurface plumes affected both their direction of transport and distance travelled from their release location, and there was considerable interannual variability in transport.

1. Introduction

Modern societies remain largely dependent on crude oil as a material and energy resource. This has pushed the frontiers of oceanic oil drilling to exploit previously inaccessible reserves, for example those found on the continental slope. Deepwater drilling is expanding and programmes exist in various regions worldwide, for example, the USA, UK, Faroe Islands, New Zealand, Norway, Canada, Angola and Brazil (Leffer et al., 2011). The Faroe–Shetland Channel (FSC) has been undergoing development as an area for deepwater drilling for oil since the 1990s (Smallwood and Kirk, 2005). If a prolonged oil spill were to happen in the FSC, complex ocean currents in the region would present challenges to predicting or understanding the impacts of the contamination. Significantly, the FSC is an oceanic region that forms important habitat for a diverse array of benthic marine life (Bett, 2001; Jones et al., 2007). This is partly a result of the habitat heterogeneity in vertical and horizontal temperature gradients that are caused by the influence of cold Arctic bottom water underlying warmer currents at the surface. Several large areas of the FSC have been designated as marine protected areas, for example the North-east Faroe–Shetland Channel (Joint Nature Conservation Committee, a) and Faroe–Shetland Sponge Belt Nature Conservation Marine Protected Areas (Joint Nature Conservation Committee, b).

The 2010 Macondo oil well blowout was the largest accidental release of hydrocarbons into the deep sea from a single incident, with estimates for the total amount of oil spilled reaching 4.9 million barrels (approximately 7.8×10^8 L, McNutt et al., 2011) over the prolonged (86 days) release of crude oil and gas into the deep (~1600 m) waters of the Gulf of Mexico (GoM). Following the incident, there was uncertainty in the true amount of oil spilled, where it went and what effects it had on biota in the deep sea. This was because it became clear that a large proportion of the oil, perhaps >30% of the total amount released (Ryerson et al., 2012; Reddy et al., 2011) never reached the surface, and uncertainties in the oil droplet size distribution complicate the estimation of the amount of subsurface oil (Ryerson et al., 2012). Various mechanisms resulted in oil from plumes of dissolved oil and small droplets reaching the seabed over a wide area, and although some of the impacts of this oil on the resident benthos have been documented (White et al., 2012) the true areal extent of the spilled oil's benthic distribution and effects remain uncertain (Montagna et al., 2013), though is likely to have been considerable (Valentine et al., 2014).

The progression of crude oil leaking from an oil well blowout and the subsequent pathways it takes in the subsurface ocean depends on its buoyancy. This buoyancy in turn depends on the proportion of gas emitted, subsequent gas hydrate formation, and oil droplet size and composition (Johansen, 2003; Yapa et al., 2008; Dasanayaka and Yapa, 2009). Biological and chemical weathering processes change oil composition in the environment and this also has an important effect on its behaviour in seawater. Many of the processes involved in weathering are highly temperature dependent. Oil from the Macondo well blowout

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flowed as a hot (~100 °C), high pressure jet into the much cooler (~4 °C) surrounding ocean (Reddy et al., 2011). As the main column of oil, gas and droplets was propelled rapidly towards the surface, small (<100 μm diameter) droplets of oil were able to form a neutrally buoyant layer of hydrocarbons that remained at between 800 and 1300 m water depth, as predicted by Socolofsky et al. (2011) and observed by Camilli et al. (2010). The use of chemical dispersants at the Macondo wellhead further encouraged the formation of small oil droplets (National Research Council, 2005) and was likely to have supressed biodegradation by microorganisms (Kleindienst et al., 2015). Some lighter molecular weight compounds, including natural gas and monoaromatic hydrocarbons: benzene, toluene, ethyl-benzene and xylene (collectively: BTEX) dissolved in the seawater, contributing to the formation of large, neutrally buoyant, subsurface plumes of dissolved hydrocarbons and droplets. Such plumes provide a route by which spilled oil can be transported on ocean basin scales, with fallout from the plumes potentially contaminating vast areas of the deep ocean, as was observed in the GoM (Valentine et al., 2014).

The GoM plumes triggered blooms of indigenous deep-sea bacteria including γ-Proteobacteria, a group that are related to petroleum degraders (Hazen et al., 2010). The response of deepwater bacterial communities was strong enough to cause appreciable local oxygen anomalies as they respired dissolved methane (Kessler et al., 2011), propane and ethane (Valentine et al., 2010). Temperatures of ~4 °C in the deep GoM appeared to favour certain genera of bacteria (*Oceanospirillales*, *Colwelia* and *Cycloclasticus*) that were found at depth but not in surface slicks of oil (Redmond and Valentine, 2011).

Circulation models helped to advance the understanding of the fate of hydrocarbons following the Macondo spill (Adcroft et al., 2010; Liu et al., 2011a; Mariano et al., 2011; Valentine et al., 2012; Paris et al., 2012; Lindo-Atichati et al., 2014). Ocean circulation models were utilised operationally to simulate the oil's transport, both at and below the surface (Liu et al., 2011b; Mariano et al., 2011). Circulation models were also used to study the potential extent of deep plumes of hydrocarbons following the Macondo spill (Adcroft et al., 2010; Paris et al., 2013; Lindo-Atichati et al., 2014), and to model their effects on resident pelagic microbial communities (Valentine et al., 2012).

As the above outlines, what has been learned about the fate and effects of spilled oil in the deep sea has been concerned largely with the oceanic conditions present in the GoM at the time of the Macondo spill. However, oil drilling is continuing to increase in areas outside the GoM, for example the FSC, where to date there have not been accidental oil well blowouts. Little is known about the potential fate and effects of accidental deepwater releases of oil in this oceanographically contrasting region, although an experiment involving the release oil of at the seabed in 844 m at a site in the Norwegian Sea has provided some data with which to validate models (Johansen et al., 2003).

A particular consideration in the FSC region lies with its circulation. The seabed topography of the Greenland-Scotland ridge gives rise to a complex exchange of water between Nordic seas and the north Atlantic and this presents challenges to the prediction of pathways of subsurface oil in the region. At, and near the surface, water of the North Atlantic Current passes from the Atlantic northwards towards the Arctic in the two branches of the Norwegian Atlantic Current (NwAC, Rossby et al., 2009). The other main near-surface current in the FSC is formed from Modified North Atlantic Water (MNAW), which dominates surface waters of the FSC in areal extent. This current originates from the Atlantic but enters the FSC from northeast of the Faroe Islands. It is then re-circulated to join the NwAC flowing into the Norwegian Sea (Turrell et al., 1999). Hence, very little surface water leaves the FSC to the south.

At depth, however, the circulation is largely in the opposite direction to the surface currents. The warm surface waters of the NwAC cool and lose buoyancy as they progress northwards to the Arctic. These sinking waters form a large proportion of the deep water formed in this region. Subsequently, bottom water formed in the Nordic Seas flows southwards at depth, and FSC Bottom Water is a mix of intermediate water and deep water from the Nordic Seas (mainly Norwegian Sea Arctic Intermediate Water and Norwegian Sea Deep Water). The Wyville Thomson Ridge (WTR), with a sill depth of ~450 m, presents a barrier to southward flow of the cold water mass of the deep FSC. Hence, although bottom water occasionally cascades over the WTR (Sherwin and Turrell, 2005), around 2.7 ± 0.5 Sv flows westward over a sill at ~850 m to enter the Faroe Bank Channel (FBC, Berx et al., 2013).

Three-dimensional ocean general circulation models (GCMs) have been developed to study ocean currents and patterns in transport on regional and global scales. Forced at the surface boundary with atmospheric reanalysis data (Dussin and Barnier, 2013), they provide detailed and realistic representations of the ocean state (Madec, 2008). Through comparison with field observations and exploration of physical processes, GCMs have enhanced our understanding of thermohaline circulation (Lohmann et al., 2014), transport pathways (Blanke et al., 1999) and bulk properties over ocean-basin scales (Marzocchi et al., 2015). However, full simulations of ocean physics and biogeochemistry using GCMs are expensive in terms of both raw computational cost and output storage requirements, especially at high resolution. One alternative approach, particularly in the context of studying transport, is to use Lagrangian particle-tracking algorithms (PTA). These provide a means of studying pathways using existing modelled circulation at a fraction of the cost of the full GCM. Lagrangian PTA releases of passive drifting 'particles' can be applied to study the passage of the currents themselves (Blanke et al., 1999), or indeed anything that can be considered a passive tracer of current flow, such as particulates (Jutzeler et al., 2014) or even small animals (Putman et al., 2012).

Here, output from a 3D GCM is used in conjunction with the 'Ariane' PTA (Blanke and Raynaud, 1997) to model the pathways of subsurface oil plumes emanating from simulated blowouts in the FSC. This study aims to understand the implications of an oil well blowout in the FSC by:

1) Investigating circulation pathways of oil at depths throughout the water column
2) Investigating inter- and intra-annual patterns in circulation pathways, and hence:
3) Highlighting key geographical areas of impact from fallout of contaminated material from near-seabed plumes.

2. Methods

2.1. The NEMO model

The Nucleus of European Modelling of the Oceans (NEMO) is a 'state-of-the-art' modelling framework for simulating ocean dynamics, sea-ice and ocean biogeochemistry (see: http://www.nemo-ocean.eu/). The model is composed of an ocean general circulation model, OPA (Madec, 2008), coupled with the Louvain-la-Nouve Ice Model v2, LIM2 (Timmermann et al., 2005). The version of NEMO used here is v3.5 and is configured at global scale with a horizontal resolution of 1/12° (eddy-resolving), with 75 levels in the vertical increasing from 1 m thickness at the surface to ~200 m at abyssal depths. The model ocean is forced at the surface by DFS reanalysis products developed as part of the European DRAKKAR collaboration, where 1994–2007 uses DFS 4.1 (Brodeau et al., 2010), and 2008 onwards uses DFS 5.1 (Dussin and Barnier, 2013). The full model was simulated from 1994 to 2009, and output, including velocity fields, stored as 5-day averages for this period.

The simulation used here has been extensively described and validated for the North Atlantic, sub-polar region by Marzocchi et al. (2015), who calculated volume transport in the model across five sections marking boundaries to the sub-polar North Atlantic domain, and extracted modelled sea surface temperature (SST) and sea surface salinity (SSS) to compare to UK Met Office datasets. Marzocchi et al. (2015) assessed the realism of large scale surface current patterns by comparing model output with geostrophic velocities derived from satellite