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Impacts of offshore oil spill accidents on island bird communities: A test run study around Orkney and Svalbard archipelagos[☆]

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ABSTRACT

The sea area around the Orkney archipelago, Scotland is subjected to substantial maritime shipping activities. By contract, the Svalbard archipelago, Norway currently has a rather low marine traffic profile. Future projections, however, indicate that the Trans-Arctic route might change the whole transportation picture and Svalbard may be at the centre of maritime activities. Both archipelagos have sensitive environmental resources at sea and inland, including bird communities. There are, for instance, 13 Red Listed species present in Orkney and 2 in Svalbard. In this regard, it is important to address oil spill risks along existing and projected shipping routes. Hypothetical spills were simulated in twelve scenarios for both the Orkney and Svalbard archipelagos with the OpenDrift open-source software. The results indicate risks to seabird communities. For Orkney, the spills resulted in the most extensive contamination of the sea and land environments in autumn. For Svalbard, autumn spills on the contrary presented the lowest risk to seabirds. Based on the simulations, we recommend increased caution for shipping activities in the problematic seasons, improved local readiness for ship accidents and sufficient pre-incident planning.

1. Introduction

The 1970s and 1980s were remembered by oil spill response professionals with global average numbers of approximately 80 and 45 spills a year. Clearly, there has been improvement in incident prevention in oil and gas industry. As the International Tanker Owners Pollution Federation reports, the number of spills in the 2000s and 2010s were respectively about 18 and 6 spills per annum (ITOPF, 2023). In addition, oil spill response preparedness has been enhanced. Apart from technological instrumental progress, a set of oil trajectory modelling tools is currently available (Keramea et al., 2021). However, accidents, where oil spills are involved, do still occur and consequences to the environment may be severe.

Large oil spills and disasters can result in high mortalities of seabirds (Piatt & Ford, 1996; Munilla et al., 2011; Fraser et al., 2022). Individuals can directly suffocate in oil, or ingest toxic oil, for example in attempts to clean feathers through preening. These effects are especially problematic for diving species, and those spending significant amounts of time on the sea surface. Oiled feathers increase the chances of hypothermia, which is especially prevalent in northern latitudes, but hyperthermia may also occur. In addition, seabirds suffer increased energy demands as a consequence of oiling, as activity such as flying and/or swimming during foraging trips are more demanding, whilst changes in buoyancy impacts swimming and diving ability (King et al., 2021). Indeed, seabird prey species and the foraging grounds themselves may be impacted, forcing individuals to be displaced. Seabirds may also be impacted by chronic oil pollution, with frequent and persistent release of relatively smaller volumes oil causing lethal or sub-lethal effects to seabirds (Belanger et al., 2010; Camphuysen, 2007). The cumulative effect of oil on individuals can impact the population as a whole, with reduced survival rates of adults, and lower reproductive rates observed long after oil spill events (Votier et al., 2005; Votier et al., 2008).

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Abiotic factors are likely to play a part in the way in which oil impacts seabirds. For instance, in colder waters some types of oil (e.g. medium crude and heavy fuel oils) may persist for longer on the sea surface and in the water column owing to increased viscosity. At the same time, in colder environments seabirds will be under increased thermal stress and are therefore more vulnerable to the effects of oil (Wiese & Ryan, 2003; Fraser & Racine, 2016).

The focus of this work is to localize potential oil trajectories and study spill impacts in remote regions which can be characterized by the following prerequisites. These are present and projected high maritime traffic, proximate sensitive ecological areas and low capacity of oil spill response infrastructure. Two study locations were taken into account in distinctively different climatic zones but similar peripheral conditions: Orkney and Svalbard archipelagos. The first one is situated at the 58th latitude in the North Sea – north of mainland Scotland. The second one is at the 78th in the Barents Sea – north of Norway. Both areas are far from the main population centres, sparsely populated and suffer from the challenges of small island economy. Besides, there are noticeable high impacts of climate change and a proven abundance of natural resources in the environment – oftentimes considered pristine (NPA, 2016). This unique combination of conditions results in challenges, which both archipelagos can find themselves in. One of these challenges is the risk of oil spill accidents at sea, and its potential environmental damage to bird communities. The main research questions of this paper are, what are the potential trajectories of oil spills in these study areas, and what could be the local consequences for the seabird species.

Several oil spill modelling tools have been actively used in global research and industrial applications to simulate the evolution of an oil spill. These models have a range of complexity: starting from simple vector-based computations and ending with state-of-the-art numerical models, based on meteorological and oceanographic models, which can provide forecasts of oil transport and fate in high-resolution and with high precision. There are commercial oil spill models, for instance – OILMAP and OSCAR, and ones with open access – e.g. MEDLISK-II and OpenDrift. For example, in a review work conducted by Keramea et al., 2021, there was a comparison of 18 widely used deterministic trajectory models, 15 of which include a stochastic component. This component helps to demonstrate the probability of an oil spill affecting a particular area within predefined time intervals. This is achieved by running the model multiple times, generating numerous trajectories under different meteorological and oceanic conditions using historical data. The resulting outputs depict the marine areas and coastlines that are most susceptible to oil contamination during different seasons. Oil spill models are crucial for contingency planning, emergency response, and environmental impact assessment in the event of accidental oil releases.

Oil spill models can be broadly classified into two types: Eulerian and Lagrangian models. Eulerian models focus on mass and momentum conservation equations to describe the behaviour of oil slicks, including spreading and advection through currents and wind (Zodiatis et al., 2017). Lagrangian models track numerous particles representing the oil slick, considering the combined effects of winds, waves, and currents, as well as dispersion. Lagrangian models are often preferred for prompt simulations during oil spill accidents due to their efficiency and computational cost-effectiveness (Barker et al., 2020; Zafirakou, 2018). The majority of present Lagrangian oil spill models are surface models. These models discretize the oil slick into particles and simulate their movement based on various physical processes. The precision of the particle positions depends on initial conditions, reliable forecasting from coupled metocean models, and the incorporation of relevant physical mechanisms. The most crucial oil weathering processes are advection, spreading, diffusion, beaching, dispersion, evaporation, resurfacing, emulsification, sedimentation, dissolution, biodegradation, vertical turbulent mixing, and photo-oxidation. As a general rule, the last four processes are lacking in the majority of existing oil spill models. Oil spill models require input data such as oil spill scenario details, oil properties, metocean data (e.g., currents, winds, temperature, salinity), and output requirements (Keramea et al., 2021). The accuracy of oil spill predictions relies on understanding oil behaviour, interaction with the marine environment, and the inclusion of sophisticated weathering algorithms.

There are several examples of widely-used and extensive Lagrangian models for simulating oil spills, including SIMAP, OSCAR, OILMAP, MOHID, MEDSLIK, MEDSLIK-II, and OpenDrift. The scientific community extensively utilizes two open-source Lagrangian models, namely OPENOIL and MEDSLIK-II. OpenDrift is a comprehensive oil spill model that encompasses the transport and weathering of oil spills in the marine environment. It incorporates crucial mechanisms for vertical mixing of oil and various parameterizations for the size distribution of dispersed oil droplets. Conversely, the horizontal movement of oil spills depends on factors such as oil type, meteorological data, and turbulence levels. According to Keramea et al., 2021, OpenDrift was called an “all-inclusive” oil drift model. Regarding MEDSLIK-II, it is another freely available open-source model for tracking particles using the Lagrangian method. It has been widely employed in operational scenarios during numerous oil spill incidents in recent times.

In this study, OpenDrift was used as a modelling tool, as it has global coverage and is openly accessible. In addition, it is a well-recognized, flexible and tested ocean trajectory model system which has been used in a large number of publications (Dagestad & Hope, 2020). For example, the OpenOil module has been validated against observations of real oil spills in Brekke et al., 2021; Hole et al., 2019. The model has demonstrated a great agreement with satellite observations of the Deepwater Horizon oil slick. OpenDrift incorporates algorithms for processes such as wave entrainment, vertical mixing, resurfacing based on buoyancy, and emulsification of oil properties. OpenDrift has been applied as an operational tool in Norway for oil spill contingency and as a search and rescue model. It can utilize high-resolution ocean circulation and meteorological models for forecasting. It integrates with the ADIOS Oil Library, with almost 1000 oil types, for oil properties and can use coarser resolution forecasts from CMEMS and NOAA as well (Keramea et al., 2021).

2. Case study areas: Orkney and Svalbard archipelagos

Despite remoteness from the large economic centres of London and Oslo, Orkney and Svalbard archipelagos are rather frequently visited sea areas. According to the Marine Traffic online portal with the 2021 density map of global shipping traffic, both study areas lie within popular shipping routes – especially when it comes to the fishing fleet. Fig. 1 demonstrates vessel presence by type: fishing, cargo and passenger vessels as well as oil tankers. The maps include only vessels where automatic identification system is fitted aboard.

Marine pollution risks are associated with the main traffic routes that cross the seas as well as lane crossings. Among common causes of spill accidents are groundings, collisions at intersections, overtaking and head-on collisions (Marchenko et al., 2018). Based on qualitative observations of the maps, between the sea areas of the Orkney and Svalbard archipelagos, the Scottish north exceeds the Barents Sea in terms of the number of vessels crossing its waters. (Marine Traffic, 2022) For instance, passenger, cargo and tanker vessels have much higher presence in the North Sea in comparison with the Barents Sea. Except for several tankers, cargo and passenger vessels annually visiting Svalbard towns for the regular supply, no other transit ships stay within the archipelago. However, as indicated by Nyman et al. (2019), there are projections that Svalbard may become a popular shipping destination in the future. The reason may be the development of the Trans-Arctic Route and related potential shipping opportunities.

2.1. Orkney

Environmental background. *Geography, climate and oceanography.* Bordered by Scotland, Norway, Sweden, Denmark, Germany, the

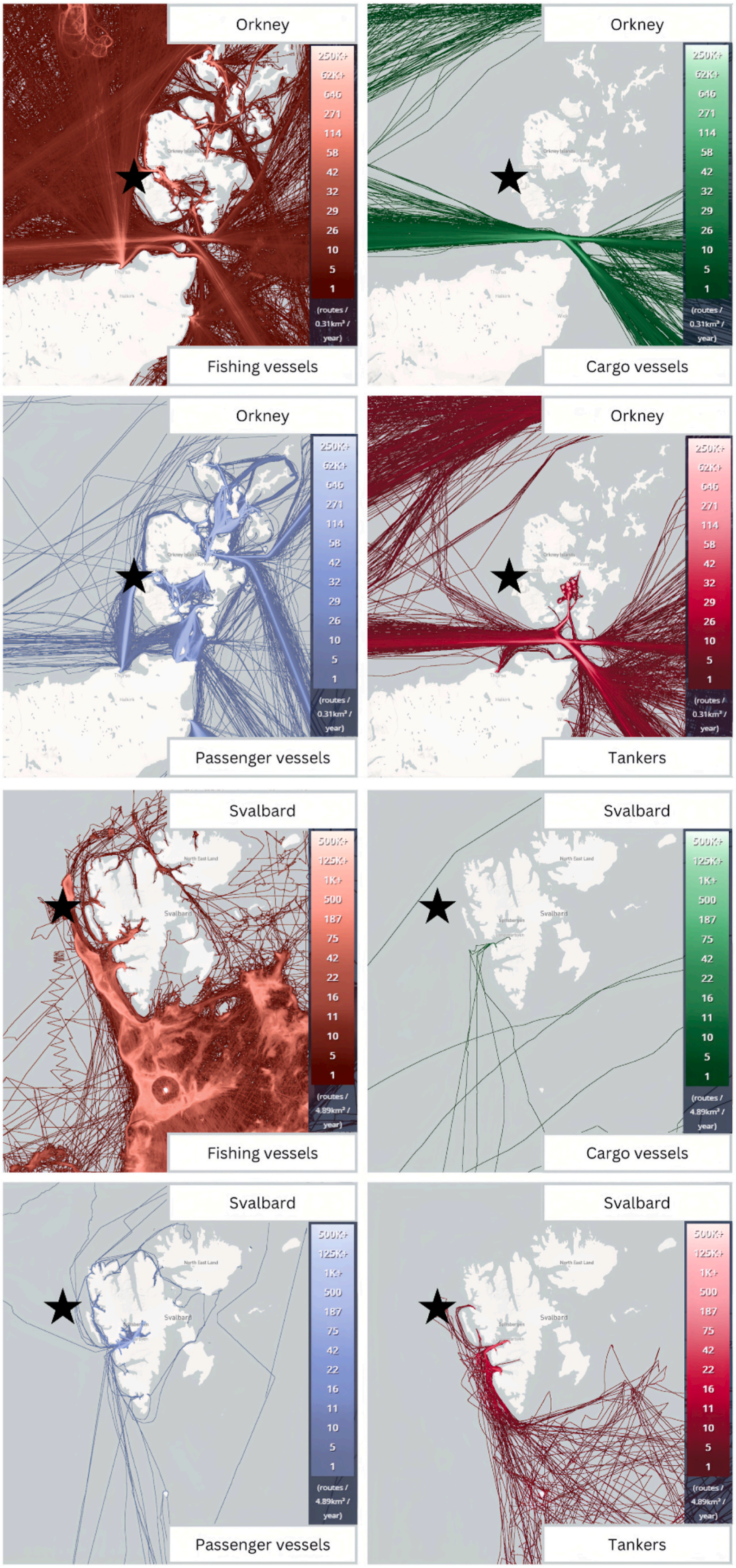

Fig. 1. Density of marine traffic in the Orkney and Svalbard archipelagoes shown by vessel type. Black star is the initial spill location.

Netherlands, Belgium, France and England, the North Sea provides not only maritime connection for the countries but also one of the most important fishing grounds. The sea is young and rather shallow, with an average depth of 90 m. There is a large influence from the Atlantic Ocean, hence its rich biodiversity and extremely high productivity. According to European Environment Agency, 2002), pollution in the region, including, but not limited to nutrients, oil, and plastics has been reported and considered for many years due to concerns for ecological and human health. Although the situation has been normalizing over the past two decades, large anthropogenic impacts remain. Current problematic pollution mostly comes from fisheries and agricultural activities causing eutrophication due to nutrient inputs with river flows. (EEA, 2002) The sea water is moderately warm: ranging between 7 and 13 °C (WST, 2023a). Salinity levels stay usually between 32 and 35 ppt in open water. The shoreline is affected by rivers making waters sweeter – down to 25 ppt. (EEA, 2002) Plots showing the mean fields of ocean currents are presented in Fig. 2.

Protected areas. There is a number of various international agreements protecting land and maritime areas around the North Sea (EEA, 2002). In the study area, around northern mainland Scotland and Orkney, there are several marine protected areas with the closest one being the North-west Orkney marine protected area (MPA). This MPA was designated due to the area's importance for sand eels, a key food source for marine life in the region, particularly seabirds. Regarding terrestrial protected areas of local natural heritage, about 35% of the archipelago is covered by nature reserves. (UNEP-WCMC and IUCN, 2019).

Bird communities. Orkney is an important hotspot for breeding seabirds in the UK, with 11 Special Protection Areas (SPAs) designated specifically for large numbers of breeding seabirds, including Red-throated Loon (*Gavia stellata*), Great Cormorant (*Phalacrocorax carbo*), European Shag (*Phalacrocorax aristotelis*), Northern Fulmar (*Fulmarus glacialis*), Northern Gannet (*Morus bassanus*), European Storm Petrel (*Hydrobates pelagicus*), Leach's Storm Petrel (*Hydrobates leucorhous*), Arctic Jaeger (*Stercorarius parasiticus*), Great Skua (*Catharacta skua*), Great Black-backed Gull (*Larus marinus*), Black-legged Kittiwake (*Rissa tridactyla*), Common Murre (*Uria aalge*), Razorbill (*Alca torda*), and Atlantic Puffin (*Fratercula arctica*) (JNCC, 2019). Therefore, there is a high density of seabirds around the Orkney islands during the breeding season, with high species richness (Critchley et al., 2018; Waggitt et al., 2020). Fig. 3 illustrates species density around the Orkney and Svalbard archipelagos. Coastal areas are inhabited the most being more sensitive to oil spill impacts.

Economic activities and marine traffic. *General trends.* Orkney, with a population of 22 000 people, has a unique feature. It has the largest natural harbour in the northern hemisphere and the second largest natural harbour in the world – Scapa Flow. This competitive advantage makes Orkney an attractive destination for many sorts of marine economic activity, and Scapa Flow - one of the three largest operating harbours in Scotland. Among the activities of all Orkney harbours are the share of fisheries, supportive port services for the oil and gas industry and other sectors, as well as tourism. In fisheries, there is a slow but steady decline in the number of registered fishing boats. In 2017, there were 128 fishing vessels reported operational. This is 27 units less in the fleet than in 2007 (OICHA, 2019). As a harbour service, Orkney offers ship-to-ship transfer to oil tankers. There is also an oil terminal (Flotta) on the archipelago and offshore platform mooring activities. In 2017–2018, 2.72 million tons of crude oil were transferred in the oil port, with 33 export and 32 import tankers using the service. During the same period, approximately 4.5 million tons of crude oil were loaded from the oil terminal. Regarding tourism, Orkney is one of the most popular cruise ship destinations in Scotland, with the number of passengers averaging approximately 115 000 people a year. About 140 cruise ships visited the archipelago in 2017/2018 season, which has almost doubled since 2013. Apart from international tourism, local transportation services are also well organized, with the annual number of ferry passengers close to 330 000 people.

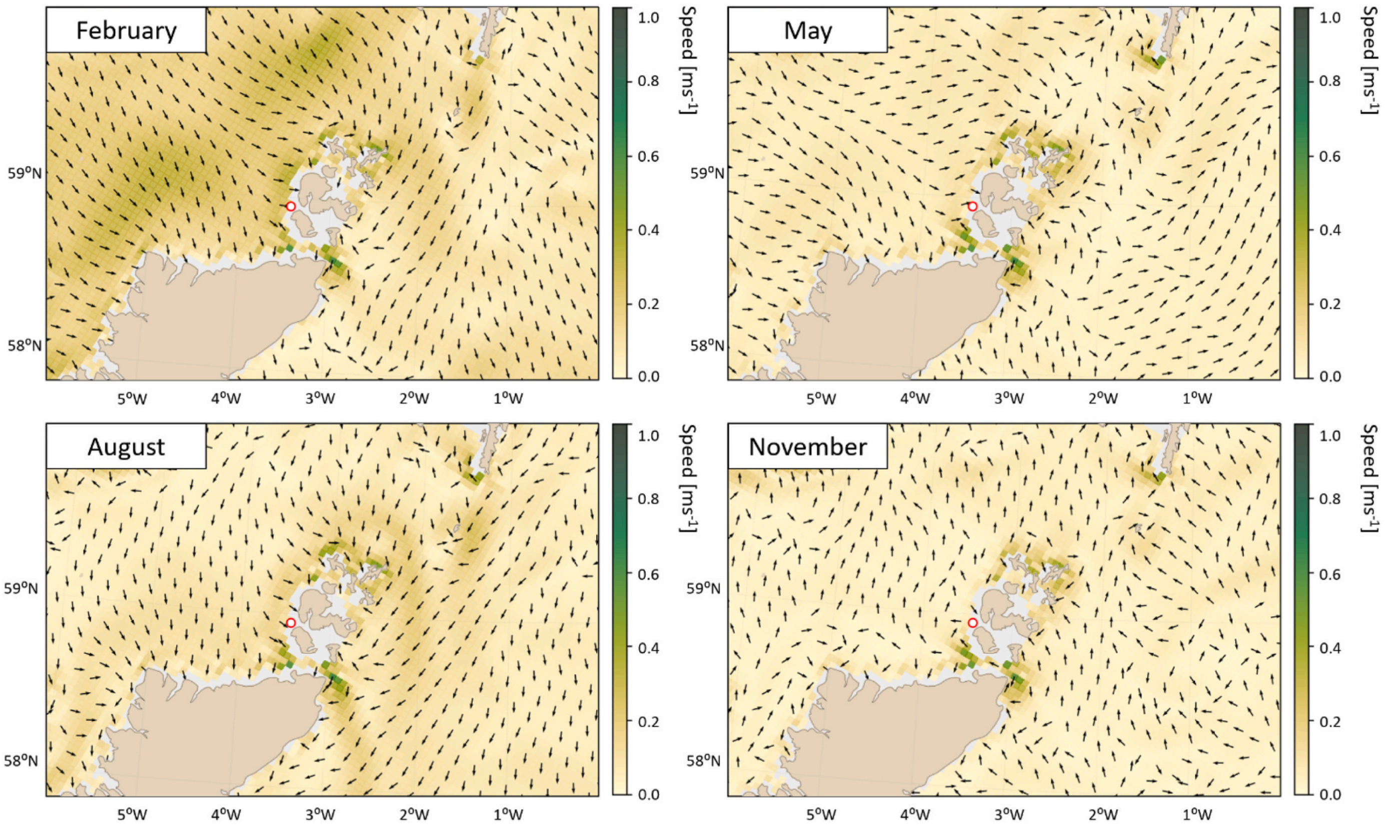

Fig. 2. Ocean currents in the North Sea near the Orkney archipelago, normalized by the speed.

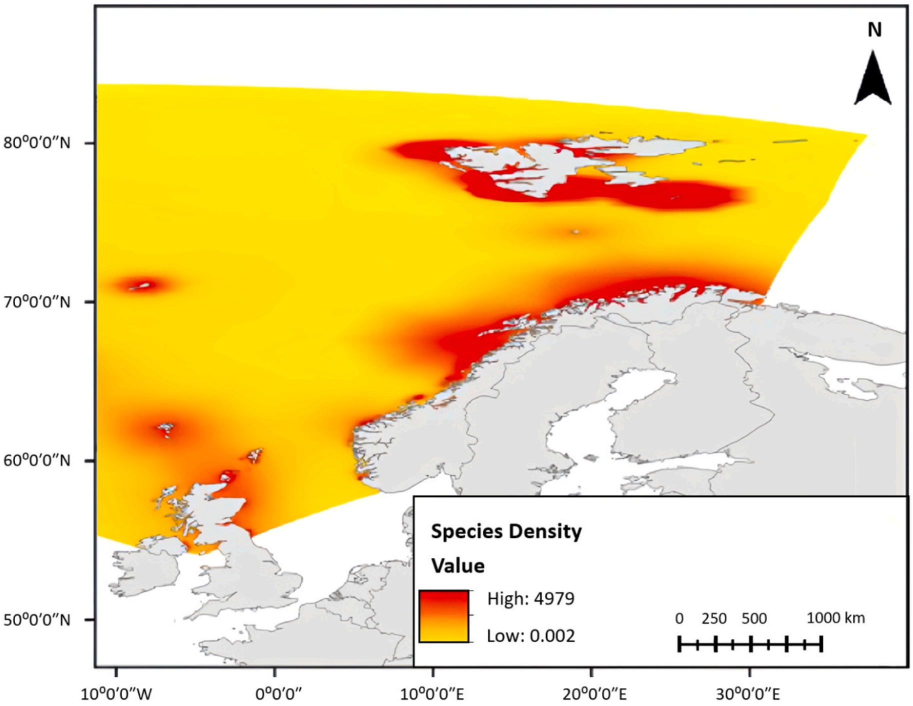

Fig. 3. Seabird distribution around the Orkney and Svalbard archipelagos.

Future projections. The oil and gas industry is projected to decrease its presence in the area. According to annual statistical data, from 1998 to 2013 there was a constant decline in the terminal loading: from 10 to 0.7 million tons of crude oil. More recently, however, this trend has reversed, with terminal loading of 3.6–4.5 million tons for the years 2015–2017. However, the harbour authority recognises that the importance of the terminal will inevitably slow down. They are in the process of diversification to other economic activities, both within the energy sector (oil and gas, renewables, low carbon economy) and also cruise tourism. Ferry transportation is expected to maintain its levels in the future. (OIC & OICHA, 2018).

2.2. Svalbard

Environmental background. *Geography, climate and oceanography.* The sea surrounding Svalbard is located in the northern hemisphere and is managed by Norway and Russia. Its northern location determines the prevalent Arctic climatic and oceanographic conditions. One of the main recognized features is its harsh environment and shallow waters. The water of the Barents Sea is with 2–10 °C range (WST, 2023b). From four months of the non-stop polar day, there can be 120 days of pitch-black visibility conditions. Shorter cold summers are changed by longer freezing and stormy winters (Dobrovolsky and Zalogin, 1982). The average sea depth is about 350 m, which is close to the Arctic Ocean mean value – of 200 m (EPPR, 2015 a, b). Due to the warm influence of the Atlantic Ocean waters, the sea is mostly ice-free in winter and has a salinity of about 35 ppt (Matishov et al., 2004). Fig. 4 shows the mean fields of ocean currents and sea ice concentrations near Svalbard. Biological productivity and an abundance of fish resources are characteristic features of the area, whilst most of its waters are characterized as pollution-free (Kulakov et al., 2004).

Protected areas. According to UNEP-WCMC and IUCN, 2019 and its global map of protected areas, a large part of Svalbard is a nature reserve. Indeed, more than 50% of the archipelago's territory is protected. There is a number of flora and fauna protective regulations. The Polar Bear, as the main fauna representative, is emphasized to a great degree as a protected species. Vegetation is rather limited. Many territories are preserved by environmental regulations to avoid negative impacts caused by both local domestic and touristic activities (CAFF, 2002). There are also two MPAs, Svalbard East and Svalbard West designated for significant populations of Thick-billed Murre (*Uria lomvia*), Ivory Gull (*Pagophila eburnea*) and Black-legged Kittiwake (OSPAR, 2019).

Bird communities. In the Barents Sea, Svalbard is a particularly important location for breeding seabirds, with 18 seabird species breeding across the islands, with the largest breeding colonies located along the west coast of Spitsbergen (Bakken, 2002). Breeding Little Auks (*Alle alle*) and Thick-billed Murres are particularly numerous, but also Northern Fulmar, Glaucous Gulls (*Larus hyperboreus*), Black-legged Kittiwakes, Ivory Gull, Arctic Tern (*Sterna paradisaea*), Common Murre, and Razorbill (Bakken, 2002). Therefore, high densities can also be found around Svalbard during the breeding season, likely associated with the region's high productivity. Bird densities are shown in Fig. 3.

Economic activities and marine traffic. *General trends.* With a population of 10 times lower than in Orkney (approximately 2200 people) and its remoteness, being 850 km from the mainland, Svalbard is a rather detached community. Since the towns are isolated, external supplies play an important role. On a regular basis, there are two cargo ships visiting Longyearbyen. Six other vessels can visit the archipelago occasionally. Overall, these count for about 20 visits per year, plus an additional three by bulk careers (Global Fishing Watch, 2019; Marchenko et al., 2015). With the largest town of 2000 individuals in Longyearbyen, there are several distinguishable activities involving the local population. Historically, the main activity on the remote archipelago of Spitsbergen – the second name of Svalbard – was mining, but more recent it is mostly research, tourism, fishing and local businesses (Nyman et al., 2019). In Longyearbyen, there is a university centre where marine-related studies are conducted year-round with up to two research vessels operating near the archipelago (Marchenko, 2015; UNIS, 2019). In terms of maritime activities, the share of research vessels in the study area is steady but minor, and unlikely to have a devastating impact on the environment in case of an accident. Svalbard has been an attractive touristic cruise destination since the 1870s. Today, it has reached an unprecedented scale. Annually, up to 10

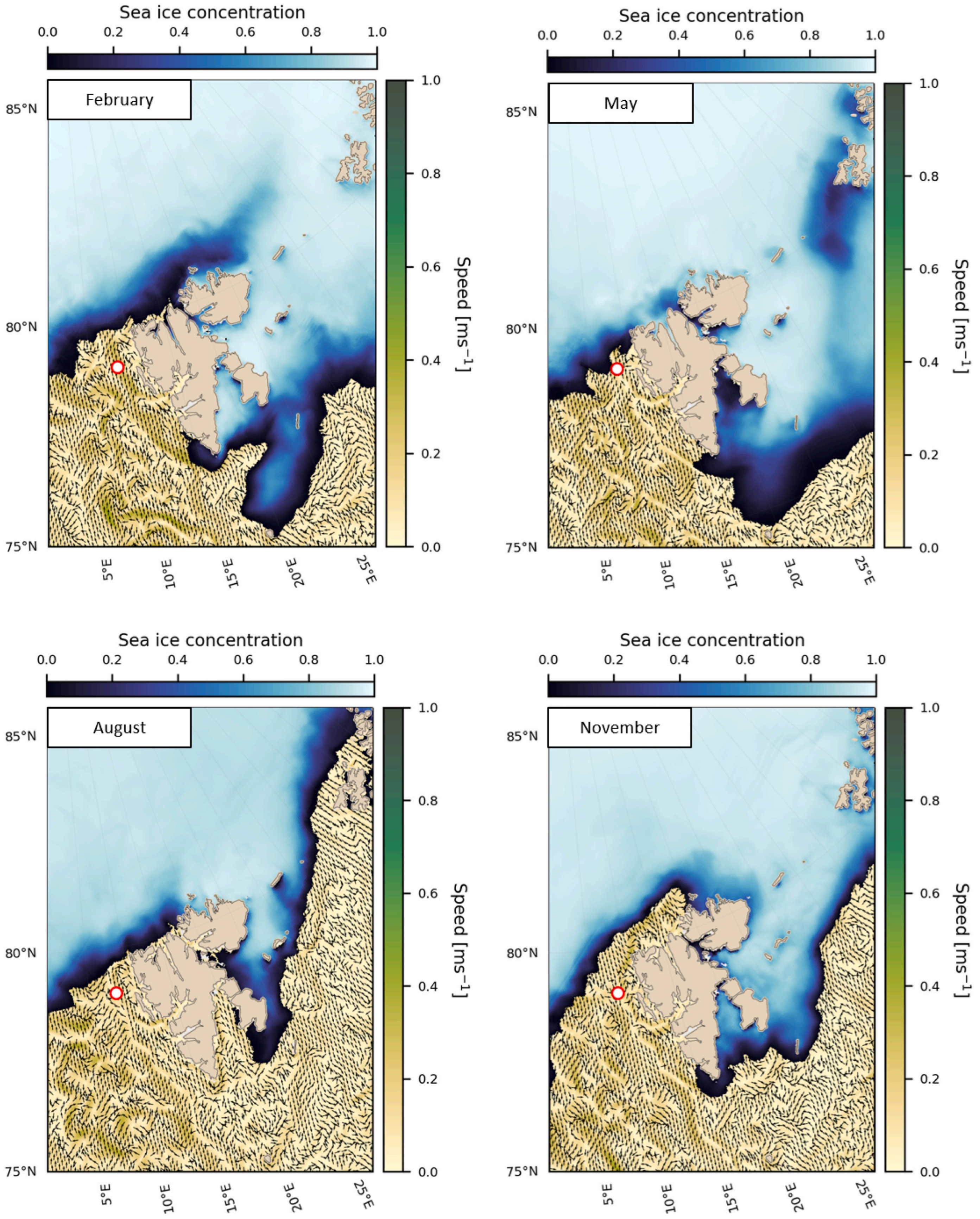

Fig. 4. Ocean currents and sea ice concentration in the Barents Sea near the Orkney archipelago, normalized by the speed.

international cruise ships with more than 4000 passengers onboard moor in the port of Longyearbyen. The interest towards the archipelago has been steadily increasing, almost doubling in the period from 2011 to 2016 (Nyman et al., 2019). This is 30 times less than passenger traffic in Orkney but still remarkable for such a remote area. There are about 10 vessels which serve as support or supply for cruise liners when they are in the harbour (Marchenko et al., 2015). Since the Barents Sea is one of the most productive seas of the Arctic Ocean, fishing is a traditional and well-established activity (Kulakov et al., 2004). Hence, it is not a surprise that fishing vessels are the most present sea visitors in the study area. The high season corresponds to the time from July to November. At its peak, up to 60 vessels are fishing: e.g. in the month of September. In low season, about 10 fishing vessels are reported to be operational at sea. As fish require fridges to keep it and make it possible to deliver to other seaports, several freezer vessels are found in the area all year round.

Future projections. Apart from current economic activities, there are existing projections about the future of the archipelago and Longyearbyen. According to Nyman et al., (2019), due to the unique geographical location, predicted ice-free Arctic conditions, lack of strict regulations, and value-added taxation of Svalbard, it can be an interesting investment opportunity for certain private parties, which seek economic benefits thanks to the development of the main port. It is primarily connected to the far-seeing expectation that the Arctic cap will completely melt off and the Transpolar or Trans-Arctic Route becomes available as a straight-line connection between Europe and Asia (Nyman et al., 2019). If by 2050 a major proportion of bulk carriers with liquid and dry cargo onboard would shift from the Suez Canal or the North Sea Route to the Trans-Arctic scenario, the role of Svalbard would increase noticeably. Hence, there is a potential future risks of oil spill accidents in the area.

3. Methods and materials

Geographical location. Two geographical locations were chosen for this study: lat 58.95, lon −3.45 in Orkney; and lat 78.97, lon 8.29 in Svalbard archipelagos. Oil and gas development and transportation activities are conducted in both locations. Regarding wildlife, there are many seabird colonies living on the nearest islands: Bear Island of the Barents Sea and Orkney Islands of the North Sea. Fig. 5 illustrates the approximate location of the studied areas: Orkney and Svalbard respectively. The nearest OSR centres in the North Sea are Scapa, Aberdeen, Edinburgh and Glasgow, with Scapa being the nearest – at 30 km from the hypothetical accident spot. In the Barents Sea, there are at least seven OSR authorities – Vadsø, Hammerfest, Longyearbyen, Tromsø, Lødingen, Bodø, Sandnessjøen, with the one in Longyearbyen being as far as 230 km away from the studied spill location.

Scenarios. In both of the locations, 12 study spill scenarios were simulated. They comprise of the combination of four seasons with three oil types. The hypothetical spills occurred in February, May, August and November, from the 10th to the 20th for each month. The annual seasons were taken in order to provide more data about possible impacts and define tentatively what time of the year is the worst for an oil spill accident. The data for these dates were taken from the year 2019. Three oils with different physicochemical nature were addressed: IFO-180LS (2014), Volve (2006) and Marine diesel (ESSO). The reported ambient conditions for all 24 scenarios are given in Table 1 (CMC, 2016; PacIOOS, 2020; PO. DAAC, 2020).

Wind speed together with air and sea temperature affect oil spill behaviour in water – its spreading, emulsification, dispersion, evaporation, dissolution, oxidation, biodegradation and sedimentation (Vadla & Sörheim, 2013). The Barents Sea has cold climatic conditions: the air temperature of February, May and November can be below zero, except August when the range is from 2 to 5 °C. The lowest air temperature in the North Sea is slightly less than 5 °C and the warmest – about 15 °C. Similar tendency is observed with sea temperatures: the annual range for the Barents Sea is from 2 to 7 °C, the North Sea – from 7 to 14 °C. Wind patterns have similarities between the two seas: the wind speeds can reach up to 15–20 m/s at both areas. The presented data is for 2019.

Table 1
Ambient conditions at the site of the studied scenarios in 2019.

Month	Environmental parameter	**Value range**	
		North Sea	Barents Sea
February	Air temperature, °C	4.72–10.59	−19.15––5.04
	Sea temperature, °C	7.64–7.95	2.54–3.70
	Wind speed, m·s^{-1}	1.69–21.47	2.77–14.59
May	Air temperature, °C	7.08–14.91	−2.11–3.63
	Sea temperature, °C	8.70–9.76	3.25–7.01
	Wind speed, m·s^{-1}	0.67–11.86	1.03–11.63
August	Air temperature, °C	11.05–15.17	2.12–5.15
	Sea temperature, °C	13.25–14.01	6.32–7.01
	Wind speed, m·s^{-1}	2.48–14.64	2.55–12.45
November	Air temperature, °C	5.97–9.05	−8.99–2.57
	Sea temperature, °C	10.17–10.72	1.88–4.27
	Wind speed, m·s^{-1}	0.89–14.88	0.36–15.95

Fig. 5. Baseline about the studied location: the North and Barents Sea.

Methods. The oil drift simulations were performed with OpenOil, an open-source transport and weathering Lagrangian framework (Röhrs et al., 2018). Part of OpenDrift (Dagestad et al., 2018), OpenOil contains tabulated oil information provided by the Norwegian Clean Seas Association for Operating Companies (NOFO) and ADIOS (https://github.com/NOAA-ORR-ERD/PyGnome). OpenDrift and the OpenOil module is described in detail in Röhrs et al. (2018); Dagestad et al. (2018); Brekke et al., 2021; de Aguiar et al., 2023. Oil entrainment due to wave energy dissipation is parameterized according to Li et al. (2017). The horizontal drift is computed as the vector sum of ocean currents and Stokes drift caused by surface gravity waves. An additional wind drift component of 2% of the wind speed at 10 m/s (e.g., Jones et al., 2016) has to be added to the surface velocity. This compensates the fact that typical ocean models do not account for the intense shear observed in the upper few decimeters of the ocean (Laxague et al., 2018; van der Mheen et al., 2020). The same is necessary when retrieving the surface current from a near-surface drifter. Together with the Stokes drift (typically 1.5% of the wind at the surface), this wind drift combines to about 3.5% of the wind speed, as found by several empirical studies (Röhrs et al., 2018; Schwartzberg, 1971). The forcing which was used in the simulations also covers coastal areas. The virtual particles get stranded once they reach the coastline. Oil spill was released daily on a continuous basis, 1000 oil particles per day during the selected study period (240 h). The exchange between surface and submerged particles, mixing schemes and droplet radius distributions can be found in Röhrs et al. (2018). For each scenario, 1 t of oil was released and tracked for 10 days. For the weathering processes, evaporation, emulsification and biodegradation were considered. The predicted oil drift and mass balance are presented in Figs. 6, 7, 9 and 10. The figures support discussion of potential negative impacts of environmental character. They could also help in preparing oil spill response operations of contaminated areas. Model output for atmospheric and oceanographic modelling originate from the National Centres for Environmental Prediction Global Atmospheric Model and the ROMS Nordic-4km Model, respectively. In this work, only four test runs with 240 h simulations for each location were conducted to indicate a need or its absence for further research. This implies running OpenDrift to create probability maps based on historical data: 10–30 years.

Seabirds. To assess the potential impact of oil spills on seabird populations from the simulations, we collated information on the seabird species present in the breeding and non-breeding seasons in Svalbard and Orkney regions. This included auks, cormorants, gulls, gannets, phalaropes, skuas, terns and tubenoses as categorised according to Gaston (2004). Species presence was determined using distribution data from Birdlife International (2022) and included those present on land in Svalbard and Orkney, and on land and at sea in areas in which oil was distributed according to the spill simulations. Seabird species were categorised according to conservation status. All species present in either Svalbard and/or Orkney were categorised according to the International Union for Conservation of Nature (IUCN, 2022) Red List of Threatened Species. Species present in Svalbard were additionally categorised according to the Red List Evaluations for Svalbard as part of the Norwegian Red List for Species (The Norwegian Biodiversity Information Centre, 2021). Seabirds present in Orkney were further categorised according to the Birds of Conservation Concern 5 (Stanbury et al., 2021). There were some inconsistencies between distribution data and conservation status, for instance the Razorbill is not present in Svalbard according to distribution data from Birdlife International (2022) but is classified as endangered by The Norwegian Red List of Species (The Norwegian Biodiversity Information Centre, 2021) in Svalbard, with a small population (200 breeding individuals) reported in 2013. In such instances we included species as more localized data was deemed to be more representative of the species present.

Materials. Three oil types were taken from the database for this research work. In descending order from the most dense to the least dense material, it is IFO-180LS (2014) – 975.8 kg/m^3, Volve (2006) – 892 kg/m^3 and Marine diesel (ESSO) – 852.1 kg/m^3. Depending on the type, all behaviour at sea is predicted to be different. For example, lighter oils undergo faster evaporation compared to heavier oils (Antigoni, 2018). On the other hand, heavier oils tend to preserve well in the marine environment with slower biodegradation, dissolution and other weathering processes resulting in larger quantities present in the water days after the spilling accident. From this point of view, a range of oils will give more interesting and diverse results in sense of possible negative impacts on the environment. It will also cover more transporting scenarios of oil-carrying vessels with different petroleum products. Simulation configurations are presented in Table 2.

Both geographical locations, amount of spilt oil, start and end of spill remained constant during simulated scenarios. The duration of each spill was set at 240 h or 10 consecutive days. The total amount of oil is likely to be spilled due to accident involving oil tanker. This can be a case, for example, with a tanker of 70 000 t deadweight that can lead to up 3200 t of spill due to board damage.

4. Results and discussion

Oil behaviour with its spreading patterns at sea, at times reaching the land, is demonstrated for Orkney (Figs. 3 and 4) and Svalbard cases (Figs. 6 and 7). Two sets of twelve scenarios are presented in a grid format: three columns with four rows. Each column, from left to right, describes the oil type: heavy crude [IFO-180LS (2014)], medium crude [Volve (2006)] and light oil product [Marine diesel (Esso)]. Each row corresponds to the studied month as a test sample for each annual season. From top to bottom, it is February, May, August and November of the year 2019. Five types of marks are used to visualize specific behavioural patterns of the oils. A black star serves as an original geographical starting point for each simulated spill. Grey trajectories on Figs. 4 and 6 show oil horizontal spreading movement on water. Red dots stand for stranded oil polluting coastline areas. White-to-green points, according to the colour palette under each figure, illustrate the depth of oil in water at the final time step of simulations. It ranges from 0 to 50 m below sea surface. Light beige areas at the maps limited by black uninterrupted line mark islands and the studied archipelagos: Orkney and Svalbard.

4.1. Orkney

OIL BEHAVIOUR. The most remarkable and concerning feature in Fig. 6 is the high number of particles stranded onshore regardless of the month and oil type. Although some behavioural variability is present due to wind directions, as discussed later, only negligible characteristics of oil spill trajectory can be highlighted due to the rapid particles stranding at the coastal areas.

February. As illustrated in the top row of Fig. 6, the same environmental and climatic conditions can cause different behavioural patterns of different oil types. Thus, heavy crude IFO-180LS (2014) had less extensive horizontal spreading trajectory in comparison with medium and light oil types: Volve (2006) and Marine diesel (ESSO). Although wind barbs, represented in Supplementary Fig. S1, were same in all three cases, oil drifted and stranded differently. Marine diesel travelled mostly northeast with the largest share of oil particles being stranded. Both other oils also eventually stranded but on different islands and with less oil amount. The furthest horizontal spreading was reported by Marine diesel, the closest – by IFO-180LS. In all three February cases, oil slick reached the islands of Hoy, Mainland, Rousay, Westray, Eday, and Sanday: covering more than 50 km of the coastal line. The radius of impact from oil spill incident initial point exceeded 100 km for Volve and Marine diesel.

May. This month is characterized by the least noticeable trajectory pattern with all three studied oil types out of all four seasons. All oils stranded almost entirely on one island – Hoy, in particular its eastern side. In case of Marine diesel in the rightmost figure, some particles

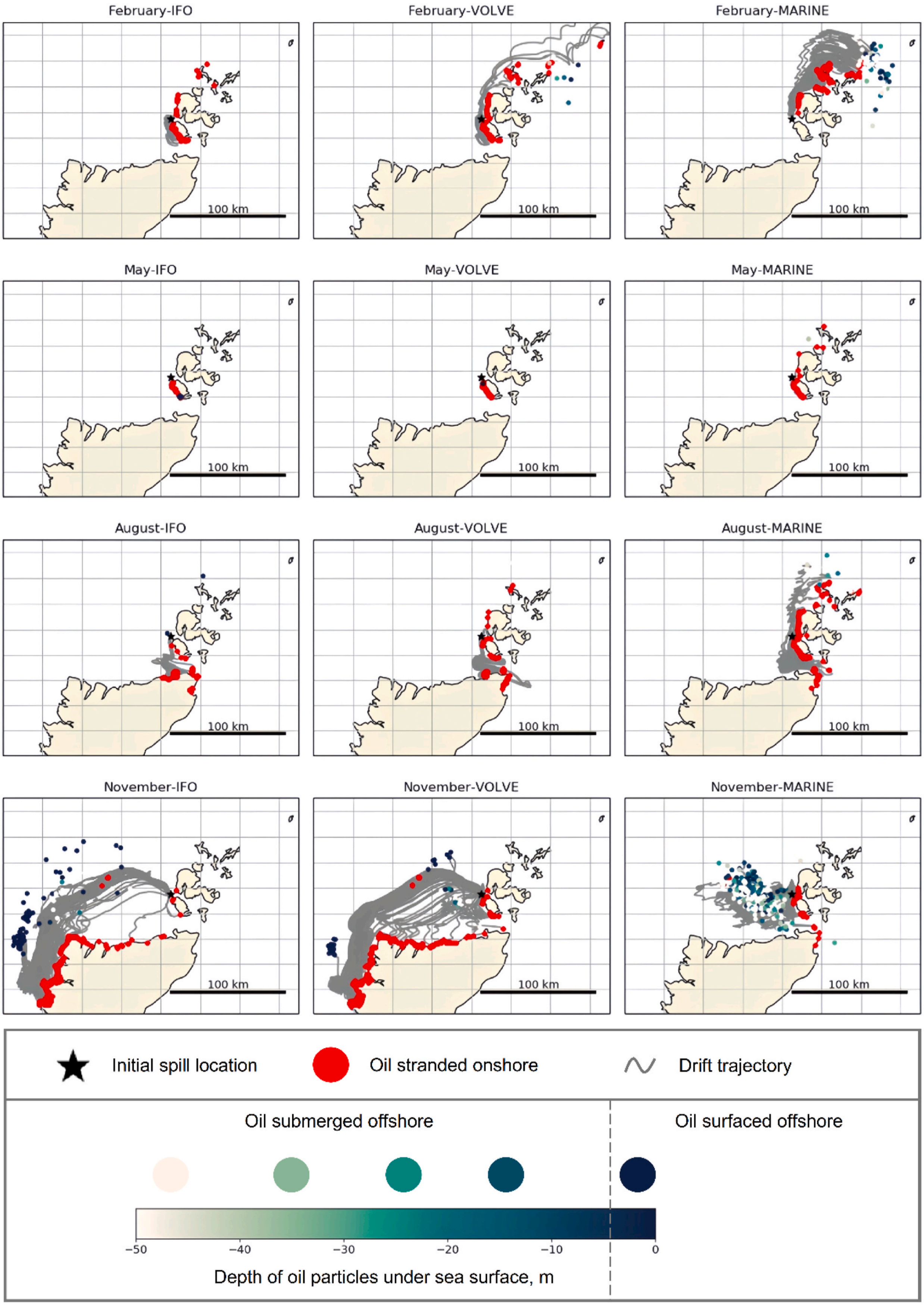

Fig. 6. OpenDrift simulations for Orkney with three studied oils and four selected months: IFO-180LS (2014), Volve (2006) and Marine Diesel (Esso), and February, May, August and November in 2019. Maps show trajectory movement of hypothetically spilled oils in the North Sea – lat 58.95, lon −3.45.

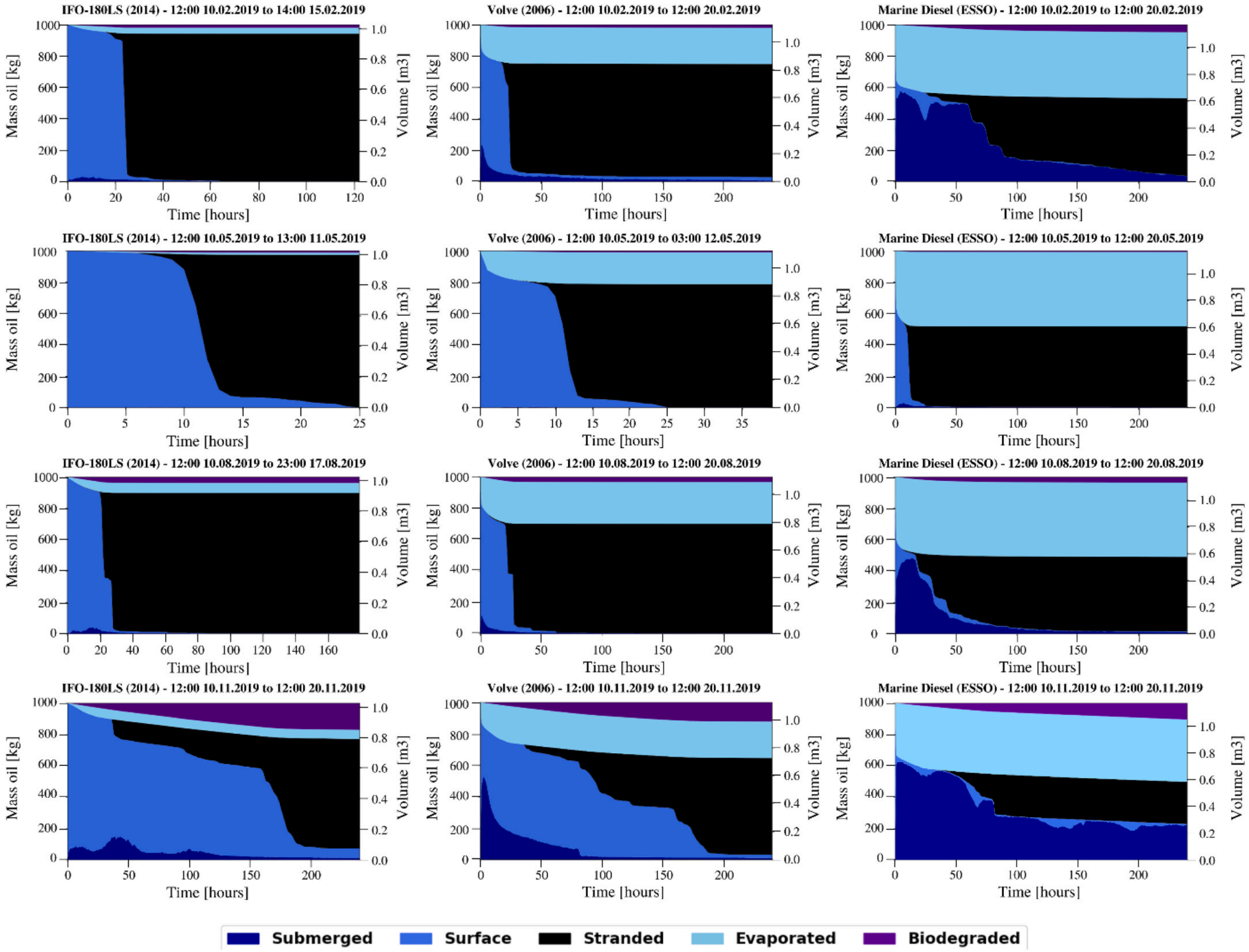

Fig. 7. Oil mass temporal balance for each type of oil in case of Orkney: left column – heavy crude [IFO-180LS], middle column – medium crude [Volve (2006)], right column – light oil [Marine diesel (Esso)]. Among four represented months of the year 2019 are February (top row), May and August (mid rows), and November (bottom row). The number of time-steps (240) is presented in the x-axis.

Table 2

Constant and variable values for OpenDrift: 24 simulated scenarios.

Inputs for OpenOil	Values
Oil types	IFO-180LS (2014) Volve (2006) Marine diesel (ESSO)
Time of the year: months in 2019	February May August November
Location 1	Barents Sea: lat 78.97, lon 8.29
Location 2	North Sea: lat 58.95, lon −3.45
Oil amount, t	1000
Start of spill	12.00 (noon), 10th of the month
End of spill	12.00 (noon), 20th of the month
Duration, h	240

drifted further towards northeast direction and stranded there on Mainland, Rousay and Westray – having a larger spreading in the studied area. Overall, potential impact from the May spills is the most localized out of all Orkney scenarios. The length of area covered with oil in produced simulations is within the range of 15–20 km.

August. Oil slicks reached out the north of Scotland's mainland. Oil stranded on the coast between Thurso and Wick as well as covered some parts outside the towns. In case of Marine diesel, the largest area was covered. This comes to the entire eastern side of the archipelago, including its northern and southern areas. Hoy, Mainland, Rousay, Westray, Eday, Sanday and South Ronaldsay can be observed with stranded oil particles. August and February can be characterized with the largest land stranding of Marine diesel among all other simulated seasons.

November. The horizontal spreading of oil was the most massive out of all 12 graphs. Besides its profound stranding patterns, much of oil also stayed surfaced or submerged in the marine environment. This is more visible on mass balance graphs in Fig. 7. As noted before, despite same wind conditions, different oil types showed different behavioural patterns. While heavier oils such as IFO-180LS and Volve travelled further in a south-western direction, the light type did not follow the same trajectory but stayed in the water column, as visible on the depth palette. IFO-180LS and Volve presented the largest coverage of coastal mainland areas. As generated trajectories demonstrated, almost all northern coast of Scotland – more than 150 km – experienced oil stranding. With Marine diesel, the marine area of impact is the most extensive – being approximately 1500 km^2.

MASS BALANCE OF THE OIL SPILL. As a comparison between the studied oil types, the largest effect of evaporation process was observed in case of Marine diesel – a lighter oil type. Fig. 7 demonstrates the growing effect of evaporation with decreasing oil density: light blue colour shows share of the weathering process in all three types within the 10-day simulation. As mentioned earlier, the prevalent weathering process in all 12 Orkney scenarios was stranding of oil slick onshore. By the end of almost all simulations – except minor amounts of surfaced and submerged oil in November – the initial 1000 t ended up onshore.

February. Marine diesel evaporated the most in comparison with other oil types. This can be seen in the top right graph of Fig. 7. Light blue illustrates the evaporation weathering process. In all 12 graphs, it has the strongest influence with Marine diesel, the weakest – with IFO-180LS. In all three February graphs, black colour is prevalent – meaning stranding. However, in case of IFO-180LS, it took less than 10 days until all spilled oil was finally onshore. According to the generated simulation, it was within 5 days, or 120 h.

May. The second row in Fig. 7 shows oil weathering for May. Stranded oil, indicated by the black colour, is the dominant fate for this month across all oil types. It took 25 h for IFO-180LS to be completely stranded onshore, and about 35 h – for Volve. In addition to stranding, there is a reportable share of evaporation, especially with Marine diesel weathering patterns. It is the second largest physicochemical process influencing oil mass balance.

August. The pre-described pattern of stranding is also maintained in this scenario. The heavier the oil type, the greater mass of oil predicted to strand onshore. This can be seen in the graphs and its black colour gradually decreasing from left to right: from IFO-180LS to Volve and Marine diesel. On the other hand, the influence of evaporation (the light blue) is increasing in the same direction. Besides surfacing, these two are the dominant processes, as was also visible in May simulations. The exception is noticeable with Marine diesel in August. Some part of it had been undergoing submersion during the first 100 h. This is also explicit in both February and November series.

November. Simulations demonstrated significant presence of biodegradation weathering process. Much less oil was stranded. Instead, it was either surfaced or submerged in the water column.

4.2. *Impacts to bird populations*

There are 41 species of seabirds present in Orkney in either the breeding or non-breeding seasons, with 18 of these species present all year round (Fig. 8, Table S1). Of the seabirds commonly present, 13 species are on the Red List of the Birds of Conservation Concern (BoCC), with 21 and 7 species on the Amber and Green Lists respectively.

During the breeding season there are 27 species of seabirds commonly present in the Orkney region. The populations will tend to be concentrated around breeding sites, with frequent foraging trips requiring travel and time at sea, and the return journeys to nesting sites on land.

In the non-breeding season, there are 32 species present in the Orkney region. Although there are more species present in the non-breeding season, they will be predominantly on the water, and at lower densities compared to the breeding season.

February. This is the non-breeding season for seabirds in the region and therefore the birds would be away from their colonies and not restricted by the need to return to their nests. However, non-migratory inshore species such as Black Guillemots (*Cepphus grylle*) and European Shags use inshore waters during winter, as do seaducks such as Long-tailed Duck (*Clangula hyemalis*), and divers/loons. Therefore, as most particles stranded and stayed nearshore, this would be a cause for concern regarding these species. This is especially true for Long-tailed Duck which is categorised as vulnerable on the IUCN red list and red in BOCC.

May. Most particles stranded on the coast of Hoy which is an important area for seabirds including great skua. Hoy hosts colonies representing approximately 12% of the global population of Great Skuas, which also use the areas nearby during the breeding season (Wade et al., 2014). Therefore there would be a potential impact of oil spills for this species in particular.

August. The particles drift up to Marwick Head and down to East Caithness Cliffs, both of which are important areas for seabirds and designated Special Protection Areas (SPAs). August is post-breeding for most seabird species in the UK however if the breeding season was particularly late then this could overlap with breeding birds still being restricted in their movements to areas near the colonies. Additionally, even if post-breeding it is likely that birds will remain close to the colony before undertaking migration. A concern for auks such as Common Murre, Razorbill, and Black Guillemot is the fact that during their post-breeding moult which can commence late August to September, they undergo simultaneous loss of flight feathers which means they are restricted to the water (Ewins, 1988; Harris & Wanless, 1990).

November. For IFO and VOLVE particles strand along the coasts of Caithness and Sutherland as well as down the west coast. This would again be potentially harmful for inshore species such as Black Guillemots and European Shags, as well as seaducks and divers/loons.

4.3. *Svalbard*

OIL BEHAVIOUR. The first observation with Svalbard simulations in Fig. 9 is how the dispersed oil trajectories relate to the wind, both in direction and intensity. Unlike the Orkney case, few particles near Svalbard reached the shore and were stranded. It was vivid only in one scenario: November, in series with Marine diesel. Otherwise, both heavy and medium crudes drifted away from coastal areas of the archipelago in all simulated months. May and August runs for Marine diesel were also without any stranding.

February. The top rows of Fig. 9 and S1 – representing February series – one can clearly observe the response of the oil spills, especially the particles on the sea surface, to the wind pattern. In Fig. S1, for the period

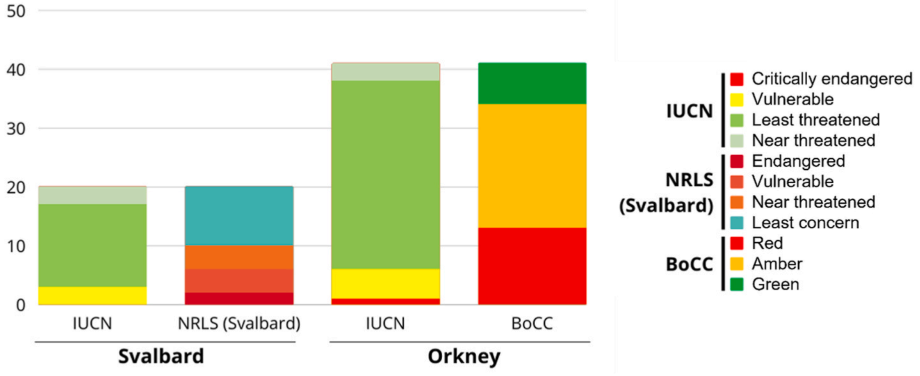

Fig. 8. Number of seabirds species present in Svalbard and Orkney, categorised according to conservation status. All species present in either Svalbard or Orkney are categorised according to the global conservation status from the International Union for Conservation of Nature (IUCN) Red List of Threatened Species. Species present in Svalbard are categorised according to the Red List Evaluations for Svalbard (NRLS Svalbard) as part of the Norwegian Red List for Species by the Norwegian Biodiversity Information Centre. Conservation status for species present in Orkney use the Birds of Conservation Concern 5 (BoCC). Colours represent those used by the respective conservation status lists. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

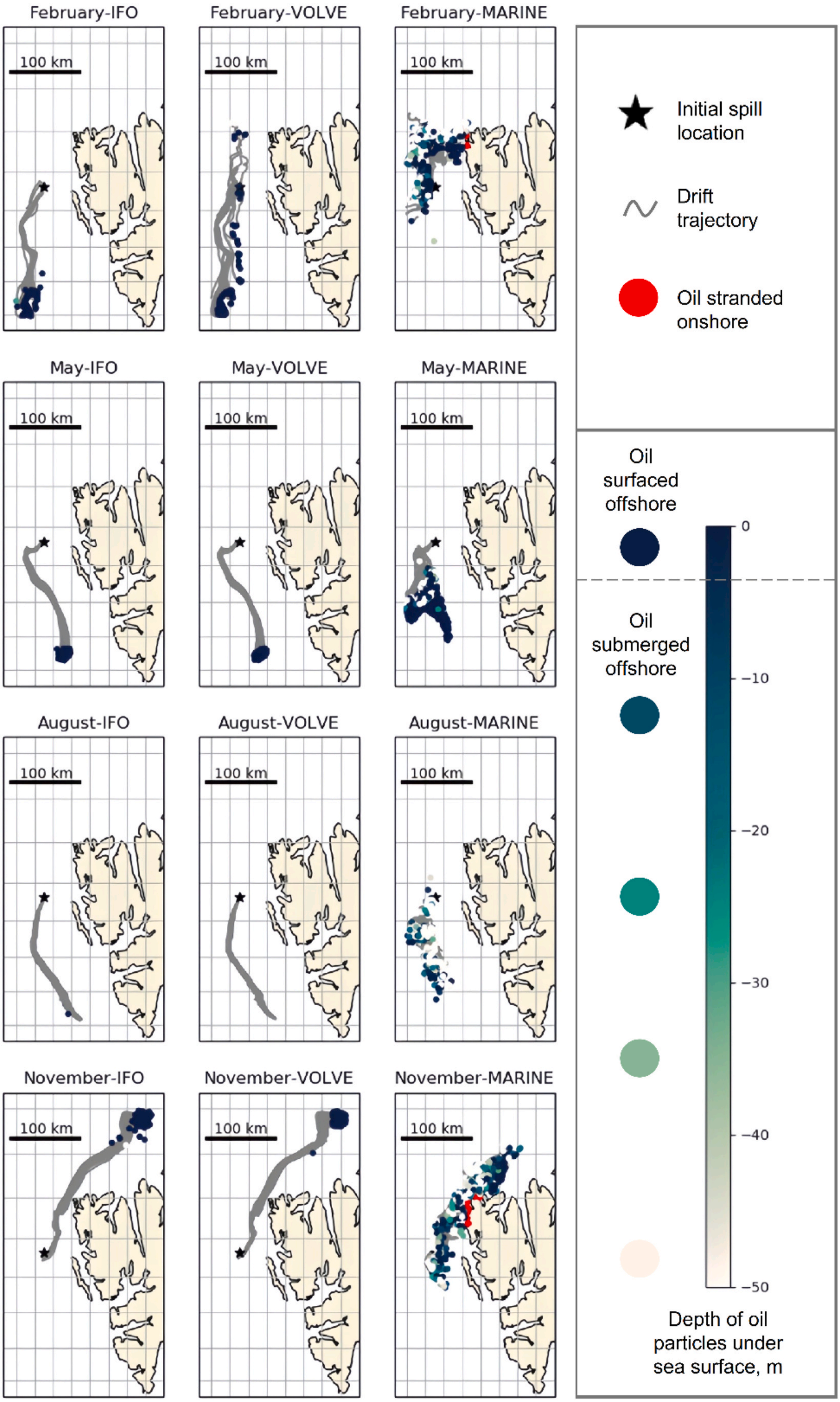

Fig. 9. OpenDrift simulations for Svalbard with three studied oils and four selected months: IFO-180LS (2014), Volve (2006) and Marine diesel (Esso), and February, May, August and November in 2019. Maps show trajectory movement of hypothetically spilled oils in the Barents Sea – lat 78.97, lon 8.29.

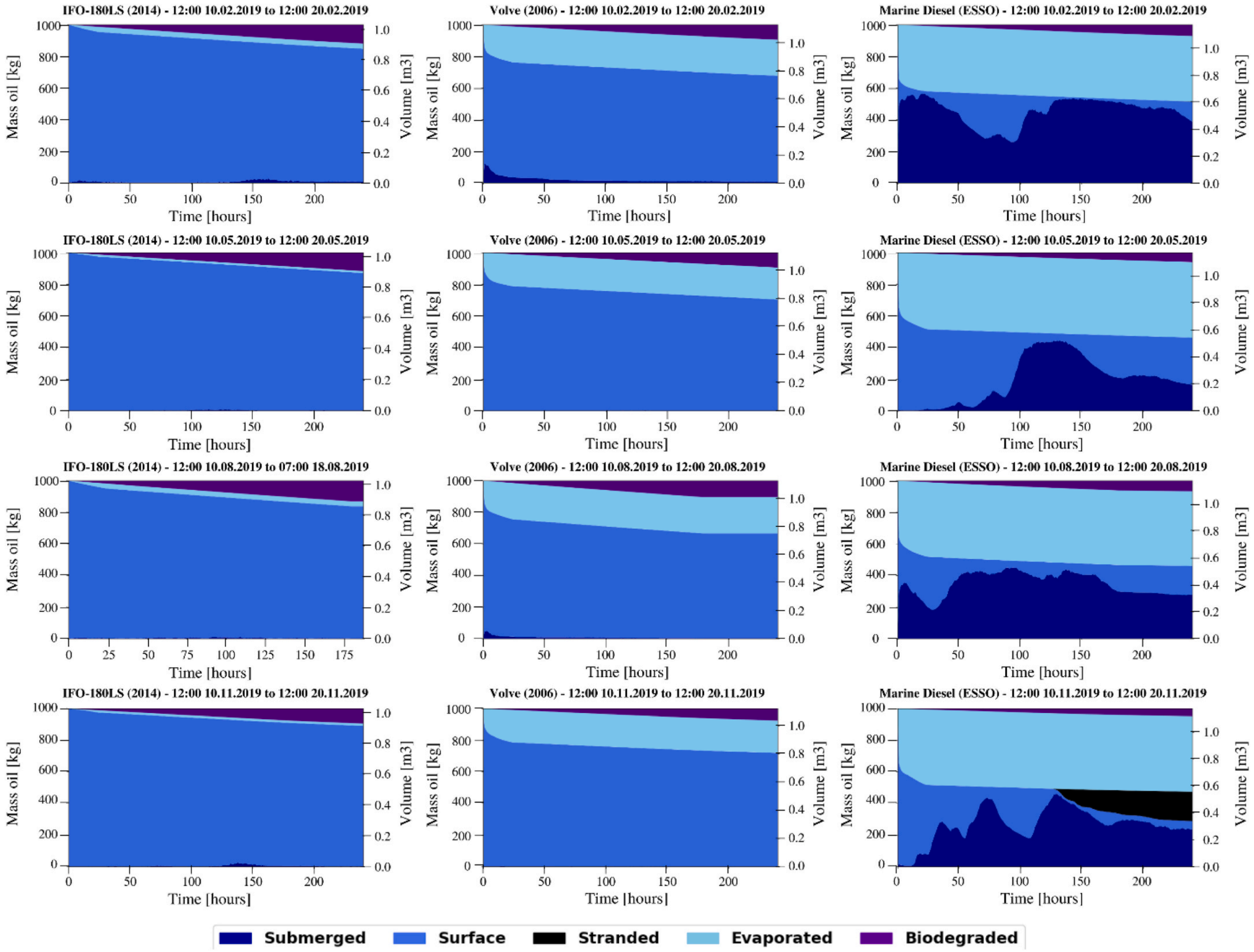

Fig. 10. Oil mass temporal balance for each type of oil in case of Svalbard: left column - heavy crude [IFO-180LS], middle column - medium crude [Volve (2006)], right column - light oil [Marine diesel *(ESSO)]. Among four represented months of the year 2019 are February (top row), May and August (mid rows), and November (bottom row). The number of time-steps (240) is presented in the x-axis.*

between February 10, 2019 until February 12, 2019, the wind is mainly southward with an average speed of 11.3 m s^{-1}, and thus oil trajectories share the same direction. Despite a change in the wind direction (northward) and decrease in intensity (average of approx. 6 m s^{-1}) – which might be observed between February 12, 2019 noon and February 14, 2019, the oil particles continued drifting south. This is the prevalent mean direction of the movement in this case which is in accordance with the wind barb pattern. As for oil coverage, the largest area can be attributed to Marine diesel. This oil type spill caused a cloud-like spreading pattern both with floating and submerged oil. It covered a marine area of about 5000 km^2. This scenario also resulted in negligible stranding of the north-western point of Svalbard, which is not reflected in Fig. 10 of oil mass balance.

May-August. Although the previous observations describe results of particles horizontal dispersion in February, they are also representative for the other months except November. Both May and August simulation runs demonstrate similar oil behaviour to the one observed in February: with certain resembling tendencies of the heavy and medium crude oil types of IFO-180LS and Volve, and distinctive pattern of the light oil – Marine diesel. In this regard the presence of the West Spitsbergen Current (WSC) flowing northward along the west coast of Svalbard means that particles spread towards south, aligned to the wind direction. Even in February, when the WSC reaches 20 Sv, its maximum volume transport – oil still drifts southward (Fahrbach et al., 2001). Minor oil slick coverage is observed in cases of IFO-180LS and Volve. Both have very concentrated cluster of oil trajectory at sea. Marine diesel represents a spill spreading south direction in a wide cloud: with oil particles both above and under water surface. The area of oil coverage at sea is approximately the same in both cases, being about 6000 km^2. No oil stranding was observed.

November. Both IFO-180LS and Volve still follow the wind barbs rather dependently. The dominant direction of drifting is towards the north: at times north-west, but mostly north-east. In case of Marine diesel, the direction is kept, however, the spreading is more homogenous, wide and inconsistent. Some of oil is surfaced, some is submerged as visible from the depth bar on the right in Fig. 9. This irregular trajectory causes some stranding at the archipelago: its north-west side. Unlike the Orkney series, November simulations on Svalbard represented vast impact only in one case: Marine diesel. It caused as twice as much coastal territory covered with oil as in February: more than 20 km of the shoreline. As an intriguing fact, there is an observable formation of 7000 km^2 sized slick drifting near the shore – north-west of Svalbard.

MASS BALANCE OF OIL SPILL. *February*. The same visual comparison and oil type different behaviours can be expanded to the oil mass budgets presented in Fig. 10. As mentioned previously, two distinct wind regimes are observed during the first 4 days of the February runs:

southward and relatively intense winds (February 10, 2019–February 12, 2019) and approximately northward and less intense winds (February 12, 2019 at noon - February 14, 2019). Under the stronger wind regime, oils with lower densities are submerged to a much higher extent. Its maximum is observed at about 24 h later, coinciding with the wind speed local peak (13.17 m s^{-1}). After that, the wind speed decreases and reaches a minimum value (2.24 m s^{-1}) within the second period (69 h later). Hence, due to buoyancy, heavy and medium oils fully resurface, whereas approximately half of the remaining Marine diesel migrates towards the surface, and the other half – stays under it.

The same patterns, i.e. the horizontal spreading and vertical movements discussed above, were also observed by Röhrs et al. (2018). The authors indicate that submerged particles are less affected by key surface driving forces such as Stokes drift and wind drag, and hence tend to drift mainly with ocean currents.

May-August-November. Fig. 10 also depicts how weathering processes – for this work evaporation and biodegradation – act differently on light, medium and heavy oils. As mentioned before, lighter oil products are more susceptible to evaporation due to high proportions of light and volatile compounds of oil. Furthermore, this process might be enhanced due to the action of winds and currents (Antigoni, 2018). This might reduce the initial volume of light oil between 40 and 75% within two to a few days, whereas the volume of medium and heavy crude oils are reduced between 15 to 40% and 5%–15% with the same period, respectively (Fingas, 1994 & 1996). Indeed, as illustrated in Fig. 10, Marine diesel was the one most weathered by evaporation independently of the season.

Biodegradation, on the other hand, seems to play a major role on IFO-180LS and be suppressed by evaporation on the other two cases. As expected, and in agreement with the values presented in Table 1, biodegradation presented a more significant role in August and a minor influence in November, similarly to the evaporation process pattern.

There are 20 species of seabirds present in either the breeding or non-breeding seasons in Svalbard, with 6 of these species present all year round (Fig. 8). Of the seabirds commonly present, 2 species, Sabine's Gull (*Xema sabini*) and Razorbill, are classified as endangered in the Red List Evaluations for Svalbard as part of the Norwegian Red List for Species. In addition, 4 seabirds are classified as vulnerable, 4 as near threatened, and 10 as least concern. No species present in Svalbard has a conservation status currently classified as critical. In the breeding season 16 seabird species are commonly present in Svalbard, whilst 6 species are present in the non-breeding season.

February. There are relatively few species present in this month in Svalbard, as it is in the non-breeding season. However, three species of auks are present, namely the Atlantic Puffin, Black Guillemot, and Little Auk, with the latter the most numerous species present in Svalbard with over 2 million breeding individuals, in over 200 colonies. The three auk species may be particularly vulnerable to oil, as they spend a significant amount of time on the water, and dive and swim in search of food. In particular, Marine diesel is of particular concern for these auks, as a significant proportion of this oil type remains submerged. Black Guillemots can dive to depths of over 40 m (Masden et al., 2013), whilst Atlantic Puffins can reach down to 120 m (Piatt & Nettleship, 1985). Therefore, increased sub-surface Marine diesel is likely to increase exposure during foraging dives, or displace individuals from the local habitat.

May. The particles are predicted to remain at sea in the simulations, meaning that there is no direct threat to colonies in Svalbard. However, in the breeding season more species are likely to be affected by oil spills, as there are over three times as many species present in comparison to the non-breeding season. In particular, auks, including Thick-billed murre and Razorbills which are present in high and low numbers respectively, seaducks (Common Eider (*Somateria mollissima*), and Long-tailed duck), and gulls, which feed on fish and crustaceans, are likely to be impacted by oil during foraging trips. The high proportion Marine diesel that is submerged is a particular risk to diving species. The Razorbill (200 breeding individuals) and Sabine's gull (20–150 breeding individuals), are classified as endangered on the Red List Evaluations for Svalbard (The Norwegian Biodiversity Information Centre, 2021), and are therefore particularly vulnerable to the effects of oil. Both species nest in areas in relatively close proximity to the oil spill simulations. Sabine's gull has been known to breed at Isfjorden, on the west side of Svalbard, with other known locations to the north and east, although they can be present at sea and along the coast. Meanwhile, Razorbills nest predominantly on the western side of Svalbard.

August. The oil particulars are predicted to remain at sea, whilst the majority of chicks are likely to have fledged by this time. However, the auks, gulls, and seaducks remain at the highest risk of the effects of oil. In particular, species that undergo post-breeding moult may be particular vulnerable to the effects of oil. Razorbills, Black Guillemot, Common Murre, and Atlantic Puffin, for example, are flightless during the post-breeding moult (Harris & Wanless, 1990), and are therefore more susceptible to the effects of oil including changes in buoyancy, waterproofness, and thermoregulation. The high proportion of submerged Marine diesel is a particular threat to diving species.

November. For the IFO-180LS and Volve oils, the particles are predicted to remain at sea. As this is the non-breeding season, and most individuals are likely to have completed post-breeding moults, the risk is lower. However, there would still be a risk to the 6 resident species present in the area, including the diving species of Atlantic Puffin, Black Guillemot, and Little Auk. Also, the Ivory Gull (*Hydrocoloeus minutus*), which is classified as vulnerable on Red List Evaluations for Svalbard is also present all year round (The Norwegian Biodiversity Information Centre, 2021). Although also a scavenger, the Ivory Gull is a surface feeder, primarily predating zooplankton and small fish, and its therefore likely impact by surface oil, as seen in all three oil simulations, or be displaced and need to seek alternative foraging habitats. As with other seasons, the high proportion of Marine diesel that remains submerged is likely to affect diving species to a greater degree, either through increased exposure, or through displacement.

5. Conclusions

Associated with vast regional fishing grounds, large densities of seabirds can be found around both studied archipelagos. Apart from fishing vessels – which are the largest share of maritime shipping – oil tankers, cargo and passenger ships are also present in the marine waters around Orkney and Svalbard. This involves a potential risk of oil spill accidents in the North and Barents Seas. This could be a cause of concern regarding present seabird species: about 40 and 20 species respectively in Orkney and Svalbard.

Orkney archipelago is home and feeding ground to 41 species: 27 species are present during the breeding season, and 32 – during non-breeding time, 18 species are in Orkney all year round. The breeding season (including spring and summer) is more important for consideration since higher densities of seabirds are present at sea and on land. Out of all studied months, May seems to be the one with least possible damage for seabird populations. The only substantial loss will be among Great Skuas, which can be endangered due to the accident. In other months, the threat to species is much higher.

For Orkney, the simulations showed predominantly rapid oil stranding. If the spill is not detected and localized by OSR centres within the first 24 h, then on Day 2 it starts to pollute the nearest shorelines. On Day 5, it can be already late, and almost all spilled oil would end up entirely on the coast: e.g. the case of heavy crude oil in February. In May, it was even earlier: complete stranding was observed after 25 h for heavy crude oil, and after 35 h – for medium crude.

All oil types had stranding as part of their after-accident effect. The light oil evaporated with the highest intensity, and almost none of it was on the surface during the simulated spills. Instead, submersion was relevant, and one could observe oil in water column in three cases out of four. In contrast, submersion did not occur for the medium and heavy crude types; surfacing did – most vividly in two cases out of four during the 10 days of the spill. From this perspective, incidents with vessels carrying light oils may cause fewer negative impacts due to lower volumes stranding after evaporation, and absence of surfacing.

Regarding seasonality, this exploratory study found that spills in the spring pose the lowest risk, since the horizontal spreading trajectory is very limited, and the accident scale can be classified as local. The most extensive contamination of the sea and land environments was observed in autumn. Winter and summer come somewhat between spring and autumn in terms of their impacts. Thus, the recommendation is increased caution for shipping activities in the autumn and sufficient pre-incident planning.

For Svalbard, out of 12 simulated scenarios, only one case resulted in land pollution: in November, in the case of light oil spill. The other 11 visualisations demonstrated mainly oil surfacing and partly submerging. Surface spreading of the spill was attributed to the heavy and medium crude oil types, which both had only negligible oil amounts in the water column. Both surfacing and submerging occurred with the light oil. However, it is worth highlighting that significant amount of light oil had undergone evaporation. The loss corresponds to more than 40% of the initial spill volume. Based on these findings, it is fair to confirm that lighter oils would be a preferred fuel for maritime shipping – judging by the possible consequences of their spill.

Svalbard hosts 20 seabird species: 16 species in the breeding season and 6 – in the non-breeding period, while 6 species are in the archipelago all year round. The lowest risk to the seabirds was observed in November. It helps that there are fewer species present during the non-breeding season. However, the aforementioned 6 species under risk include Atlantic Puffin, Black Guillemot, Little Auk and a vulnerable Red listed Ivory gull. We encourage to focus on increased level of readiness to combat ship-related oil spill accidents in winter, spring, and summer.

Recommendation for further research. This was an exploratory study to highlight the importance of seabird species present in the studied areas and demonstrate their vulnerability in case of oil spill accidents. To expand the knowledge, increase awareness about sensitive areas and provide more tangible results, one can generate probability maps of oil spreading in the studied locations within the considered seasons. This will give a clearer picture, especially when taking a rather long period of time: 5, 10, and more years. The seasonal oil spill behaviour would then be more visible. Inclusion of oil vulnerability indices and/or overlapping local sensitivity maps with the produced oil probability maps would yield more precise conclusions. As for the seasons with higher risks of environmental pollution, we recommend more studies to be conducted, focusing on of pre-incident planning and improving local oil spill response preparedness.

Author contributions statement

Victor Pavlov, Conceptualization, Visualization, Methodology, Writing- Original draft preparation, **Victor Cesar Martins de Aguiar** Software, Visualization, Data curation, Methodology, Writing- Original draft preparation, **Lars Robert Hole**, Supervision, Software, Methodology, **Neil James**, Visualization, Data curation, Methodology, Writing-Original draft preparation. **Elizabeth Masden** Data curation, Methodology, Writing- Original draft preparation. **Henrikki Liimatainen** Supervision, Validation, Writing- Reviewing and Editing. **Eva Pongrácz**, Supervision, Validation, Writing- Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2023.122193.

References

Barker, C.H., Kourafalou, V.H., Beegle-Krause, C.J., Boufadel, M., Bourassa, M.A., Buschang, S.G., Androulidakis, Y., Chassignet, E.P., Dagestad, K.-F., Danmeier, D.G., 2020. Progress in operational modeling in support of oil spill response. J. Mar. Sci. Eng. 8, 668.

Belanger, M.P., Tan, L., Askin, N., Wittnich, C., 2010. Chronological effects of the Deepwater Horizon Gulf of Mexico oil spill on regional seabird casualties. Journal of Marine Animals and Their Ecology 3 (2), 10–14.

Birdlife International, 2022. IUCN Red List for Birds.

Brekke, C., Espeseth, M.M., Dagestad, K.-F., Röhrs, J., Hole, L.R., Reigber, A., 2021. Integrated analysis of multisensor datasets and oil drift simulations—a free-floating oil experiment in the open ocean. J. Geophys. Res.: Oceans 126, e2020JC016499. https://doi.org/10.1029/2020JC016499.

Camphuysen, C.J., 2007. Chronic Oil Pollution in Europe. IFAW, Brussels, Belgium.

Canada Meteorological Center (CMC), 2016. GHRSST Level 4 CMC0.1deg Global Foundation Sea Surface Temperature Analysis (GDS Version 2). CA, USA. Last accessed 10th Jan 2020 at.

Conservation of Arctic Flora and Fauna (CAFF), 2002. Protected Areas of the Arctic: Conserving a Full Range of Values (Ottawa).

Critchley, E.J., Grecian, W.J., Kane, A., Jessopp, M.J., Quinn, J.L., 2018. Marine protected areas show low overlap with projected distributions of seabird populations in Britain and Ireland. Biol. Conserv. 224, 309–317.

Dagestad, K.-F., Röhrs, J., Breivik, Ø., Ådlandsvik, B., 2018. OpenDrift v1.0: a generic framework for trajectory modelling. Geosci. Model Dev. (GMD) 11, 1405–1420. https://doi.org/10.5194/gmd-11-1405-2018.

Dagestad, K.F., Hope, G., 2020. Publications. Introduction to OpenDrift. https://opendrift.github.io/references.html.

de Aguiar, V., Röhrs, J., Johansson, A.M., Eltoft, T., 2023. Assessing ocean ensemble drift predictions by comparison with observed oil slicks. Front. Mar. Sci. 10, 1122192 https://doi.org/10.3389/fmars.2023.1122192.

Dobrovolsky, A.D., Zalogin, B.C., 1982. USSR seas (Моря СССР). http://ashipunov.info/shipunov/school/books/dobrovolskij1982_morja_sssr.pdf.

European Environment Agency (EEA), 2002. Seas around Europe. The North Sea. https://www.eea.europa.eu/publications/report_2002_0524_154909/regional-seas-around-europe/NorthSea.pdf, 26th Nov 2019.

Emergency Prevention, 2015a. Preparedness and response (EPPR) working group of the arctic council. In: Guide to Oil Spill Response in Snow and Ice Conditions. https://oaarchive.arctic-council.org/handle/11374/403.

Emergency Prevention, 2015. Preparedness and response (EPPR) working group of the arctic council. Reykjavik, Iceland, december. In: 2015b). Impact of Metocean Conditions on Oil Spill Response Viability in the Arctic (Previously Named Circumpolar Oil Spill Response GAP Analysis), 2-3. http://arctic-council.org/eppr/wp-content/uploads/2015/06/2015_11_16_COSRVA_Analysis_Update.pdf.

Ewins, P.J., 1988. The timing of moult in black Guillemots cepphus grille in shetland. Ringing Migr. 6, 5–10.

Fahrbach, E., Meincke, J., Østerhus, S., Rohardt, G., Schauer, U., Tverberg, V., Verduin, J., 2001. Direct measurements of volume transports through Fram Strait. Polar Res. 20 (2), 217.

Fingas, M., 1994. Evaporation of oil spills. J. ASCE.

Fraser, G.S., Racine, V., 2016. An evaluation of oil spill responses for offshore oil production projects in Newfoundland and Labrador, Canada: implications for seabird conservation. Mar. Pollut. Bull. 107 (1), 36–45.

Fraser, G.S., Robertson, G.J., Stenhouse, I.J., Ellis, J.I., 2022. Estimating the numbers of aquatic birds affected by oil spills: pre-planning, response, and post-incident considerations. Environ. Rev. 30 (2), 323–341. https://doi.org/10.1139/er-2021-0121.

Gaston, A.J., 2004. Seabirds: a Natural History. Yale University Press, New Haven, CT.

Global Fishing Watch, 2019. Global Fishing Watch Map. https://globalfishingwatch.org/map/, 3rd Sep. 2019.

Harris, M.P., Wanless, S., 1990. Moult and autumn colony attendance of auks. Br. Birds 83, 55–66.

Hole, L.R., Dagestad, K.F., Röhrs, J., Wettre, C., Kourafalou, V.H., Androulidakis, Y., et al., 2019. The DeepWater Horizon oil slick: simulations of river front effects and oil droplet size distribution. J. Mar. Sci. Eng. 7 (10), 329. https://doi.org/10.3390/jmse7100329.

IUCN, 2022. The IUCN Red List of Threatened Species. Version 2022-1. https://www.iucnredlist.org.

King, M.D., Elliott, J.E., Williams, T.D., 2021. Effects of petroleum exposure on birds: a review. Sci. Total Environ. 755 (1), 142834.

Keramea, P., Spanoudaki, K., Zodiatis, G., Gikas, G., Sylaios, G., 2021. Oil spill modeling: a critical review on current trends, perspectives, and challenges. J. Mar. Sci. Eng. 9, 181. https://doi.org/10.3390/jmse9020181.

Kulakov, M.Yu, Pogrebov, V.B., Timofeyev, S.F., Chernva, N.V., Kiyko, O.A., 2004. In: Robinson, A.R., Brink, K.H. (Eds.), Chapter 29. Ecosystem of the Barents and Kara Seas, Coastal Segment (22, P). President and Fellows of Harvard College, Cambridge, pp. p1135–p1172. The Sea.

Li, Z., Spaulding, M., French-McCay, D., 2017. An algorithm for modelling entrainment and naturally and chemically dispersed oil droplet size distribution under surface breaking wave conditions. Mar. Pollut. Bull. 119, 145–152. https://doi.org/10.1016/j.marpolbul.2017.03.048.

Marchenko, N.A., 2015. Ship traffic in the Svalbard area and safety issues. In: Proceedings of the International Conference on Port and Ocean Engineering under Arctic Conditions.

Marchenko, N., Andreassen, N., Borch, O.J., Kuznetsova, S., Ingimundarson, V., Jakobsen, U., 2018. Arctic shipping and risks: emergency categories and response capacities. TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation 12 (1), 107–114. https://doi.org/10.12716/1001.12.01.12.

Marchenko, N., Borch, O.J., Markov, S.V., Andreassen, N., 2015. Maritime Activity in the High North—the Range of Unwanted Incidents and Risk patterns.Marine Traffic. *Density Maps.* Available:

Masden, E.A., Foster, S., Jackson, A.C., 2013. Diving behaviour of Black Guillemots Cepphus grylle in the Pentland Firth, UK: potential for interactions with tidal stream energy developments. Hous. Theor. Soc. 60 (4), 547–549.

Matishov, G., Golubeva, N., Titova, G., Sydnes, A., Voegele, B., 2004. Barents Sea, GIWA Regional Assessment 11. http://www.unep.org/dewa/giwa/areas/reports/r11/giwa_regional_assessment_11.pdf, 3rd Feb 2017.

Munilla, I., Arcos, J.M., Oro, D., Álvarez, D., Leyenda, P.M., Velando, A., 2011. Mass mortality of seabirds in the aftermath of the Prestige oil spill. Ecosphere 2 (7).

Northern Periphery and Arctic Programme Secretariat (NPA), 2016. Northern Periphery and Arctic Programme 2014-2020. Available: http://www.interreg-npa.eu/fileadmin/Programme_Documents/Approved_Cooperation_Programme_Jan2016.pdf.

Nyman, E., Galvao, C.B., Mileski, J., et al., 2019. Maritime Studies. https://doi.org/10.1007/s40152-019-00143-4.

Orkney Islands Council Harbour Authority (OICHA), 2018. Annual Report 2017-2018. Available:

Orkney Islands Council Harbour Authority (OICHA), 2019. Fishing and fish farms. https://www.orkneyharbours.com/sectors/fishing.

Piatt, J.F., Ford, R.G., 1996. How many seabirds were killed by the Exxon Valdez oil spill. In: Rice, B.A.W.S.D., Spies, R.B., Wolfe, D.A. (Eds.), Proceedings of the Exxon Valdez Oil Spill Symposium, Anchorage, Alaska, 2– 5 February. American Fish Society, Bethesda, Maryland, USA, pp. 712–719, 18.

Piatt, J.F., Nettleship, D.N., 1985. Diving depths of four alcids. Auk 102, 293–297.

Röhrs, J., Dagestad, K.-F., Asbjørnsen, H., Nordam, T., Skancke, J., Jones, C.E., Brekke, C., 2018. The effect of vertical mixing on the horizontal drift of oil spills. Ocean Sci. 14, 1581–1601. https://doi.org/10.5194/os-14-1581-2018.

Stanbury, A., Eaton, M., Aebischer, N., Balmer, D., Brown, A., Douse, A., Lindley, P., McCulloch, N., Noble, D., Win, I., 2021. The status of our bird populations: the fifth Birds of Conservation Concern in the United Kingdom, Channel Islands and Isle of Man and second IUCN Red List assessment of extinction risk for Great Britain. Br. Birds 114, 723–747.

The International Tanker Owners Pollution Federation Limited (ITOPF), 2023. Oil Tanker Spill Statistics 2022. Available: https://www.itopf.org/knowledge-resources/data-statistics/statistics/.

The Norwegian Biodiversity Information Centre, 2021. Results from the 2021 red list for species. In: The Norwegian Red List of Species 2021. http://www.biodiversity.no/Pages/135386/Results_from_the_2021_Red.

The University Centre in Svalbard (UNIS), 2019. UNIS Annual Report 2018. https://www.unis.no/about-unis/annual-reports/.

UNEP-WCMC, IUCN, 2019. Protected planet: the world database on protected areas (WDPA). https://www.protectedplanet.net.

Vadla, R., Sörheim, K.R., 2013. Oseberg Öst Crude Oil - Properties and Behavior at Sea. SINTEF.

Votier, S.C., Birkhead, T.R., Oro, D., Trinder, M., Grantham, M.J., Clark, J.A., McCleery, R.H., Hatchwell, B.J., 2008. Recruitment and survival of immature seabirds in relation to oil spills and climate variability. J. Anim. Ecol. 77 (5), 974–983.

Votier, S.C., Hatchwell, B.J., Beckerman, A., McCleery, R.H., Hunter, F.M., Pellatt, J., Trinder, M., Birkhead, T.R., 2005. Oil pollution and climate have wide-scale impacts on seabird demographics. Ecol. Lett. 8 (11), 1157–1164.

Wade, H.M., Masden, E.A., Jackson, A.C., Thaxter, C.B., Burton, N.H.K., Bouten, W., Furness, R.W., 2014. Great skua (Stercorarius skua) movements at sea in relation to marine renewable energy developments. Mar. Environ. Res. 101, 69–80.

Waggitt, J.J., Evans, P.G.H., Andrade, J., Banks, A.N., Boisseau, O., Bolton, M., Bradbury, G., Brereton, T., Camphuysen, C.J., Durinck, J., Felce, T., Fijn, R.C., Garcia-Baron, I., Garthe, S., Geelhoed, S.C.V., Gilles, A., Goodall, M., Haelters, J., Hamilton, S., Hartny-Mills, L., Hodgins, N., James, K., Jessopp, M., Kavanagh, A.S., Leopold, M., Lohrengel, K., Louzao, M., Markones, N., Martínez-Cedeira, J., Cadhla, O.Ó., Perry, S.L., Pierce, G.J., Ridoux, V., Robinson, K.P., Santos, M.B., Saavedra, C., Skov, H., Stienen, E.W.M., Sveegaard, S., Thompson, P., Vanermen, N., Wall, D., Webb, A., Wilson, J., Wanless, S., Hiddink, J.G., 2020. Distribution maps of cetacean and seabird populations in the North-East Atlantic. J. Appl. Ecol. 57 (2), 253–269.

Wiese, F.K., Ryan, P.C., 2003. The extent of chronic marine oil pollution in southeastern Newfoundland waters assessed through beached bird surveys 1984 – 1999. Mar. Pollut. Bull. 46, 1090–1101.

World Sea Temperature (WST), 2023a. Orkney Sea temperature. https://www.seatemperature.org/europe/united-kingdom/orkney.htm.

World Sea Temperature (WST), 2023b. Teriberka Sea temperature. https://www.seatemperature.org/asia/russia/teriberka.htm. (Accessed 24 January 2023).

Zafirakou, A., 2018. Oil spill dispersion forecasting models. In: Monitoring of Marine Pollution. IntechOpen, London, UK.

Zodiatis, G., Lardner, R., Alves, T.M., Krestenitis, Y., Perivoliotis, L., Sofianos, S., Spanoudaki, K., 2017. Oil spill forecasting (prediction). J. Mar. Res. 75, 923–953.