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Model analysis of worst place scenarios for nuclear accidents in the northern marine environment

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ABSTRACT

The North and Nordic Seas contains some of the world's most important fishery resources and is an area of significant traffic involving nuclear powered vessels and transports of nuclear and radioactive materials. Consumer awareness to even rumors of radioactive contamination imparts a special vulnerability to this region. The effective assignation of emergency resources, design of monitoring programs and provision of information regarding accidents relies upon an a-priori analysis of potential impacts. To this end, an adjoint sensitivity analysis regarding potential impacts on the most important regional fishery was conducted with a view towards development of a system capable of providing information regarding potential contaminant dispersal from any point within the North and Nordic Seas. Results indicate that the area is potentially vulnerable to releases of radioactive materials over a much wider area than has previously considered.

1. Introduction

As evidenced by events over a number of decades, the general public has been, and remains, acutely aware of potential radioactive contamination of the marine environment which has the potential to generate socio-economic impacts that extend far beyond any impact that may arise from any actual contamination. This awareness of potential contamination was especially apparent after the sinking of the “Komsomolets” in international waters of the Norwegian Sea (73°43′16″ N and 13°16′52″ E) on the 7th of April 1989 (see: Høibråten et al., 1997) and the sinking of the “Kursk” on the 12th of August 2000 in the Barents Sea (see: Amundsen et al., 2002) and more recently in the aftermath of the Fukushima Accident in Japan. Public unease has, in recent years, focused again on the transport of nuclear material by sea as a cause of concern despite there never having been a significant release from a marine vessel carrying nuclear waste or spent fuel (IAEA, 2001) and the stringent international and national regulations under which such transports are conducted.

Although land based facilities have been and are the greatest contributors to radioactive contamination of the area known as the Northern Seas (see Eldevik et al., 2014) the region is also vulnerable to marine releases from vessels carrying or powered by nuclear materials (AMAP, 2010). The civilian transport of nuclear fuel cycle materials has been conducted along routes through this area for many years. These transports involve materials from all stages of the fuel cycle and occur between a number of countries involved in the production and use of nuclear fuels, both European and as far afield as the United States, South America, Russia and Asia. Transports of nuclear materials may be conducted by vessels of dedicated fleets such as that operated by Pacific Nuclear Transport Limited (PNTL), by individual vessels owned by nuclear operators or by vessels operated by service companies or other carriers. A useful overview of the transport of nuclear materials within European waters including statistics and routes is provided by Gaffney (2011).

Nuclear powered vessels, both civilian and military, have operated in the Northern Seas for many decades. These vessels have

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been primarily those of the Russian Northern Fleet and other nations naval forces and civilian nuclear icebreakers and service ships operated by Russia. While the routes and itineraries of civilian nuclear vessels are relatively open information, similar information for military vessels is less available and it may be assumed they may be found at any point within the overall area. A useful overview of accidents and incidents involving nuclear powered vessels may be found in Ølgaard (1996, 2001).

A third category of nuclear transport that has been the focus of some concern belongs neither to nuclear powered vessels or transport of materials of the nuclear fuel cycle. This category involves shipments conducted under the broad umbrella of various threat reduction initiatives which include the repatriation of research reactor fuels to the countries of origin – the United States and Russia. The repatriation of Russian-origin HEU fresh and spent fuel from research reactors in countries such as Poland, Germany, Ukraine, Romania, Bulgaria, Latvia and countries of the former Yugoslavia has resulted in a number of shipments of nuclear material taking place over the past years of relevance to northern waters. Given the nature of the cargoes carried, *a priori* information regarding such shipments tends to be relatively scarce although such shipments have attracted significant public attention. In 2010 the MV Puma carried a load of spent nuclear fuel from a research reactor in Belgrade along the Norwegian coastline to the Russian port of Murmansk. The same year, the MCL Trader transported HEU from Poland along the same route, the Polish material having been transported under a 2009 agreement between Poland and Russia facilitating the transport of all HEU in Poland to Russia over a period of twenty years. Czech spent nuclear fuel was transported aboard the MV Mikhail Dudin to Murmansk early in 2013. More comprehensive overviews of transports under such repatriation programmes may be found in, amongst others, IAEA (2009) and Messick and Galan (2012). These transports and a diverse range of other incidents such as the outbreak of fire onboard the MV Parida carrying radioactive wastes in waters off the north coast of Scotland in October of 2014, have served to raise the issue of sea transport of such materials once again in the public eye and focus attention on implications of a possible release to the marine environment.

Although the entire northern area has rich fisheries, the waters of the Lofoten archipelago (Fig. S1) between 68° and 69° N are of special value (Olsen et al., 2010). . Of the 3 million tonnes of fish extracted yearly from the Barents and Norwegian Seas, approximately 70% have spawning grounds in the Lofoten area or utlise the area during their early life stages. The area is especially important for Northeast Arctic cod (*Gadus morhua*) and Norwegian spring-spawning herring (*Clupea harengus* L.), which constitute the largest populations (IMR, 2013). Other species for which the area is equally important but which are in themselves not as economically vital as the previous two species, include Northeast Arctic haddock (*Melanogrammus aeglefinus*), Northeast Arctic Pollock (*Pollachius virens*), deepwater redfish (*Sebastes mentella*), tusk (*Brosme brosme*) and ling (*Molva molva*). In total these species represent an equivalent economic importance to either herring or cod alone (Olsen et al., 2010).

The combination of heightened public awareness, ongoing nuclear traffic and the presence of a valuable economic resource pose challenges for effective and efficient emergency response capabilities in relation to the management of a potential release scenario in the Northern Seas. Compared to releases from fixed position land based facilities, potential releases from nuclear transports and nuclear powered vessels present an additional layer of complexity in that a release may occur at any point along the route of the vessel which is, in the case of military vessels and some transports, often unknown. In addition, the variation in ocean currents with time means that potential releases from the same location but at different points in time may result in different dispersion patterns.

In order to improve predictive capabilities and response planning capacities in relation to incidents involving the release to water of radioactive materials, an adjoint sensitivity analysis was conducted over the entire domain of the NAOSIM and ADNAOSIM models (see Fig. S2). The aim of this analysis was to attempt to categorize different areas of the Northern Seas with respect to their potential importance for a major fishery in the event of an accidental releases. The analysis provided, in a highly efficient manner, the change of the concentration in the waters of the Lofoten fishery with respect to a unit amount of a conservative, passive tracer released anywhere in the adjacent seas. The main purpose of this analysis was to highlight which geographic areas constituted the most risk to the target Lofoten area during the target time-period from March to April.

2. Methods

A version of NAOSIM (North Atlantic/Arctic coupled Ocean Sea Ice Model), which covers the Northern Seas plus the central Arctic and northern North Atlantic, was used to ensure a correct embedding into the important large-scale circulation of the northern marine area. NAOSIM has previously been successfully used for studies in a number of applications focusing on Northern Sea circulation and tracer dispersion (see e.g. Karcher et al., 2004, 2012; Gerdes et al., 2001). NAOSIM has been validated extensively for the representation of circulation, propagation of anomalies as well as for sea-ice cover in the model domain (e.g. Karcher et al., 2003; Kauker et al., 2003; Drange et al., 2005). The model version used for this study has a horizontal resolution of 0.5° (roughly 46 km) in a rotated grid. Open boundaries in the Northern North Atlantic and the Bering Strait are implemented with climatological hydrographic data for inflow conditions based on a temperature and salinity climatology (PHC) (Steele et al., 2001) and a prescribed total volume inflow through Bering Strait of 0.8 Sv. The model is initialized from PHC and driven by daily atmospheric surface data from the NCEP/NCAR reanalysis from 1948 to 2012. The sensitivity of the tracer concentration at a particular target area and time period with respect to a release at any prior time and any location is most efficiently analyzed by means of NAOSIM's adjoint model (ADNAOSIM) (Kauker et al., 2009). In a similar way as a back-trajectory calculation, all these sensitivities are provided by a single run of ADNAOSIM, which propagates the sensitivity information backwards in time from the target area. ADNAOSIM has been successfully applied to the analysis of the origin of the ice extent minimum in the Arctic in September 2007 (Kauker et al., 2009). The target area for this study was an area west of the Lofoten comprising a (target) volume of 1620 km^3 from sea surface to a depth of approximately 60 m (Figure S1). The variable of interest (target variable) was the mean concentration, c, of a conservative, passive radionuclide in the target volume, averaged from March to April. ADNAOSIM was used to calculate dc/dq, the sensitivity of c with respect to a hypothetical release q. Since the unit of the concentration is moles/$m^3$and that of the release moles, the unit of dc/dq is $1/m^3$. ADNAOSIM was run for 28 months providing dc/dq sensitivity maps beginning at the target period (March/April) and extending back in time over a 28 month period, data being stored at monthly intervals. Since these sensitivities depend on the state of the ocean (e.g. circulation and hydrography) which in turn depends upon, among other factors, the atmospheric conditions during the time period of the backward calculation, the natural variability of the physical system imposes some limits because it is *a priori* not clear which circulation regime would prevail at the moment of a potential release. To address this aspect of the problem, ADNAOSIM