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Dispersal of the radionuclide caesium-137 (^{137}Cs) from point sources in the Barents and Norwegian Seas and its potential contamination of the Arctic marine food chain: Coupling numerical ocean models with geographical fish distribution data

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ABSTRACT

Dispersal of ^{137}Cs from the nuclear submarine wrecks *Komsomolets* and *K-159*, which are resting on the seabed in the Norwegian and Barents Seas, respectively, is simulated using realistic rates and hypothetical scenarios. Furthermore, spatiotemporal ^{137}Cs concentrations in Northeast Arctic cod and capelin are estimated based on survey data. The results indicate that neither continuous leakages nor pulse discharges will cause concentrations of ^{137}Cs in cod muscle or whole body capelin exceeding the intervention level of 600 Bq/kg fw. Continuous leakages from *Komsomolets* and *K-159* and pulse discharges from *Komsomolets* induced negligible activity concentrations in cod and capelin. A pulse discharge of 100% of the ^{137}Cs-inventory of *K-159* will, however, result in concentrations in muscle of cod of above 100 times the present levels in the eastern Barents Sea. Within three years after the release, ^{137}Cs levels above 20 Bq/kg fw in cod are no longer occurring in the Barents Sea.

1. Introduction

Radioactive contaminants have been present in the Arctic marine environment for more than 50 years. An updated overview of the most important sources is available in AMAP (2009). The present levels in biota, seawater and sediments in the Barents Sea and adjacent areas are low (e.g., NRPA, 2011; Gwynn et al., 2012). For example, the levels of caesium-137 (^{137}Cs) in muscle of cod (*Gadus morhua* L.) in the Barents Sea have decreased from 0.5 to 1 Bq/kg fresh weight (fw) in the early 1990s to the current level of 0.1–0.2 Bq/kg fw. In comparison, an intervention level for the activity concentration of ^{137}Cs in food, such as muscle of cod, was set to 600 Bq/kg fw by the Norwegian authorities after the Chernobyl accident in 1986.

Around the turn of the millennium, many researchers predicted the environmental impact of potential radioactive leakages from specific point sources, e.g., Baxter et al. (1998; dump sites in the Kara Sea), Blindheim et al. (1994) and Høibråten et al. (2003) (submarine *Komsomolets*) and Amundsen et al. (2002; submarine *Kursk*, which was raised in October 2001). The outcome of the predictions differs for each source. Blindheim et al. (1994) and Høibråten et al. (2003) concluded that *Komsomolets* represents a minor radioactive pollution problem, partly because of the great depth at which the wreck is located (1655 m). Baxter et al. (1998) concluded that the resultant doses from radioactive leakages from dump sites in the Kara Sea are negligible on regional and global scales. However, maximum individual doses could reach higher levels than the limit recommended for the public (1 mSv year^{-1}) on a local scale (e.g., in Abrosimov Bay), but this scenario is regarded as less serious because the bay areas are uninhabited. A source that has obtained less attention than the abovementioned is the Russian nuclear submarine *K-159*, which rests at a depth of 238 m outside of the Murmansk Fjord. This area represents important habitats for commercial fish stocks, e.g., as a spawning and nursery area for capelin (*Mallotus villosus* Müller, 1776) (Hamre, 1994; Sakshaug et al., 1994; Olsen et al., 2010).

The present study assesses the effect of potential long-term leakages and pulse releases of ^{137}Cs from *Komsomolets* and *K-159*, on fisheries resources in the Barents Sea and adjacent areas. The fisheries resources studied here are limited to Northeast Arctic cod and capelin during the autumn and winter, both in the pelagic and benthic parts of the water masses. The approach is generic and

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involves an estimate of the 3-dimensional (3D) dispersal of particles; it represents potential discharges of ^{137}Cs by utilising a numerical ocean model and quantifies the overlap with the observed geographical fish distribution data. Specifically, we would like to answer the following questions: 1) What are the expected activity concentrations of ^{137}Cs in muscle of cod and whole-body capelin given the specific levels of long-term or pulse leakages? 2) How does the concentration of ^{137}Cs in seawater vary spatially and temporally in relation to the timing and location of the discharges? 3) Will the levels of ^{137}Cs in cod and capelin exceed the intervention level of 600 Bq/kg fw?

2. Methods

2.1. The choice of ^{137}Cs as the studied radionuclide

We chose to focus on ^{137}Cs because it is one of the two predominant radionuclides in terms of total activity in the *Komsomolets* and *K-159* reactors (the other radionuclide is ^{90}Sr; Høibråten et al., 1997, 2003; Hermansen et al., 2006) and because ^{137}Cs is the radionuclide expected to have the largest impact on the marine ecosystem. The potential magnitude of this impact is due to the relatively long half-life ($t_{1/2} = 30$ years) of ^{137}Cs, its potential to be transported with ocean currents over large distances, and its transferability through the marine food chain (Avery, 1996; Heldal et al., 2003).

2.2. The point sources and the dominant circulation patterns near the sources

Komsomolets and *K-159* are comparable with respect to radionuclide inventory, but located in different marine environments, which may greatly affect a potential discharge. *Komsomolets* sank on April 7th, 1989, and it is now lying at a depth of 1655 m at 73°43′16″N and 13°16′52″E in the Norwegian Sea (Høibråten et al., 1997, 2003, Fig. 1). Gladkov and Sivintsev (1994) and Høibråten et al. (1997, 2003) estimated the 1989 content of ^{137}Cs as $3.1 \cdot 10^{15}$ Bq, which is used in the scenarios for the present study. *K-159* sank on August 31st, 2003, three nautical miles northwest of the island of Kildin outside of the Murmansk Fjord at a depth of 238 m (Hermansen et al., 2006, Fig. 1). Compared to *Komsomolets*, much less information concerning *K-159* is publicly available. The Norwegian Radiation Protection Authority (NRPA) has estimated that the total radionuclide inventory of *K-159* in 2003 was between $3 \cdot 10^{15}$ and $13 \cdot 10^{15}$ Bq (Hermansen et al., 2006) and that the ^{137}Cs and ^{90}Sr content each accounted for more than 40% of the total inventory. 40% of the total inventory equals to $1.2 \cdot 10^{15}$–$5.2 \cdot 10^{15}$ Bq for ^{137}Cs. We use the latter concentration in the scenarios in the present study.

Komsomolets is located in the continental slope between the shallow Barents Sea (average depth of approximately 230 m) and the deep Norwegian Sea (depth of more than 2000 m). The bottom topography and main currents in the area lead toward the Fram Strait, which connects the Nordic Seas and the Arctic Oceans. The dominating flow direction at greater depths of the slope is expected to be north, but little is known concerning its variability in direction and strength. To the southeast of the site, the Bear Island Trough penetrates the shelf of the Barents Sea. Importantly, this opening is shallower than 500 m and is mainly downstream of this point source. The northward flowing Norwegian Atlantic Slope Current (NASC, temperature > 0 °C and salinity > 35) trapped along the Norwegian continental slope bifurcates at the southern slope of the Bear Island Trough. One branch enters the Barents Sea, and the other branch flows west of Spitsbergen toward the Fram Strait. The eastward flowing branch of the NASC enters the southwestern Barents Sea, with the fresh wedge-shaped Norwegian Coastal Current (NCC) trapped between the NASC and the Norwegian Coast. The circulation pattern near *K-159* is governed by the topography, although the degree depends on the vertical density profile. A strong density gradient may decouple the upper mixed layer and the water below. The currents are rich in mesoscale features at different spatial scales due to the numerous banks and troughs.

2.3. The ocean model ROMS and the transport of particles

The spatiotemporal distribution of ^{137}Cs was simulated with daily mean output of the 3D numerical ocean model ROMS (Regional Ocean Modeling System) (www.myroms.org; Haidvogel et al., 2008) covering the period 1989 until 2008. The model domain is shown in Fig. 1 and is covered by a 4 by 4 km horizontal grid, with 30 sigma-coordinate levels in the vertical. Monthly mean lateral boundary conditions are taken from a global ROMS simulation of 20 by 20 km horizontal resolution, and atmospheric momentum and heat fluxes from ERA40 interim (www.ecmwf.int). Further details of the model setup and comparison with hydrographic and current meter measurements along the Norwegian Coast can be found in Vikebø et al. (2010).

Under the assumption that all ^{137}Cs discharged from *Komsomolets* and *K-159* is dissolved in seawater, the dispersal was modelled by a Lagrangian particle-tracking model (Ramsden and Holloway, 1991) allowing us to follow individual pollution plume parcels. We released a large number of particles (pollution plume parcels),

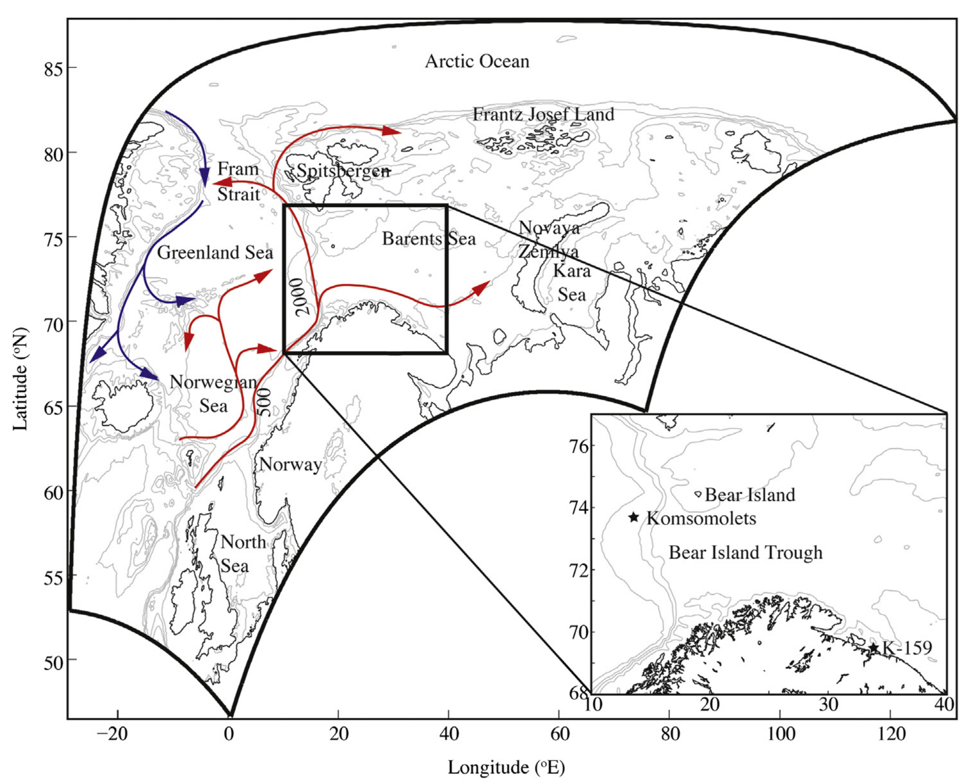

Fig. 1. Model domain covering the Nordic, North, Barents and Kara Seas and parts of the Arctic Ocean. Contours indicate depths of 30, 200, 500, 1000 and 2000 m. The inset shows the positions of the two sunken submarines.