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Consequence assessment of nuclear-powered vessel accidents and floating nuclear power plant transit accidents in the Arctic region

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KEYWORDS: nuclear-powered vessel, floating nuclear power plant, protective actions, emergency preparedness, JRODOS, operational intervention levels, dose criteria

Abstract

Radiological consequence assessment of atmospheric releases of radioactive materials due to accidents on Nuclear-Powered Vessel (NPV) and during a transit of Floating Nuclear Power Plant (FNPP) were performed. The assessment was performed using a probabilistic approach for open sea locations in the Gulf of Finland and near the Norwegian coast in the Barents Sea, and coastal locations nearby the city of Tromsø and the Kara Strait on the Northern Sea Route. The dose rates and radiation doses to emergency workers and people close to the accident site were estimated, and needed protective actions were evaluated.

The decision support system JRODOS was used to model the dispersion and deposition of radioactive substances in atmospheric release and to estimate dose rates and the doses to people and emergency workers. The modelling applied previously published radionuclide inventories and release fractions, and NOMADS weather data from the year 2021.

The results showed that for the NPV accidents, external dose rate of 100 µSv/h, effective dose of 100 mSv, and thyroid equivalent dose of 100 mSv are exceeded nearby the accident locations. Thus, in case there is habitation in the vicinity of the scene, different protective actions are needed downwind from the accident location to protect people. It was estimated that the recommendation to limit being outside is needed up to 10 km, sheltering indoors up to 3 km and evacuation up to 2 km. Furthermore, the iodine prophylaxis for adults may be needed up to 5 km, and rough estimate revealed that iodine prophylaxis for children and pregnant females is needed up to 10 km.

Based on the analyses, emergency workers should wear Personal Protective Equipment (PPE) up to about 5 km from the accident site due to the elevated external dose rates. Furthermore, the emergency workers should take iodine prophylaxis if the air contains radioactive iodine, working hours should be recorded, and alarming external dose rate meters and dosimeters should be used. In prolonged situations, the shift work arrangements should also be considered up to 1 km to limit total working time. It is not likely that the higher Operational Intervention Levels (OIL) of 1000 or 10000 µSv/h are exceeded in the considered NPV accident.

In the FNPP transit accident, the effective and thyroid equivalent doses remain below 0.1 mSv and 1 mSv, respectively. Furthermore, the external dose rate of 1 µSv/h was not exceeded in any of the analyzed release scenarios. It was concluded that it is highly unlikely that any of the protective actions would be needed for the people or emergency workers due to the considered atmospheric releases from the considered FNPP transit accident. Note that the results given are dependent on initial assumptions and are likely to change with assumptions.

AVAINSANAT: Ydinkäyttöinen alus, kelluva ydinvoimalaitos, suojelutoimenpiteet, valmius, varautuminen, JRODOS, ohjeelliset toimenpidetasot, annoskriteerit

Tiivistelmä

Työssä arvioitiin ydinkäyttöisen aluksen (NPV) onnettomuuksien ja kelluvan ydinvoimailaitoksen (FNPP) kuljetusonnettomuudesta aiheutuvan radioaktiivisen ilmakehäpäästön seurauksia. Seurausarvio tehtiin hyödyntäen tilastollisia menetelmiä Suomenlahdella ja Barentsinmerellä Norjan rannikolla sekä Tromsøn ja Karan salmen alueilla Pohjoisella merireitillä. Annoslaskennan perusteella arvioitiin päästön aiheuttamaan ulkoista annosnopeutta sekä pelastushenkilöstön ja väestön mahdollista säteilyaltistusta. Lisäksi arviointiin mahdollisien suojelutoimien tarvetta.

Päästön leviämis- ja laskeumamallinnus sekä annoslaskenta suoritettiin käyttäen JRODOS-ohjelmistoa. Mallinnuksessa hyödynnettiin aiemmin julkaistuja tietoja laivareaktoreiden radionuklidi-inventaarille ja päästöosuuksille sekä globaalia NOMADS-säädataa vuodelta 2021.

Tulokset osoittivat, että NPV-onnettomuuksissa ulkoinen annosnopeus ylitti 100 µSv/h ja efektiivinen ja kilpirauhasen ekvivalentti annos ylittivät 100 mSv onnettomuuspaikan läheisyydessä. Jos alueella on asutusta, tuulen alapuolella onnettomuuspaikan lähellä tarvitaan erilaisia suojelutoimenpiteitä ihmisten suojelemiseksi. Arvioitiin, että suositus ulkona olon rajoittamisesta tarvitaan 10 km:iin, sisälle suojautumiseen 3 km:iin ja evakuoimiseksi 2 km:iin saakka. Lisäksi joditabletteja tarvitaan aikuisille 5 km:iin sekä lapsille ja raskaana oleville 10 km:iin saakka.

Arvioiden perusteella säteilytyöntekijöiden tulisi käyttää henkilökohtaisia suojavarusteita noin 5 km etäisyydelle saakka onnettomuuspaikasta korkean ulkoisen annosnopeuden takia. Lisäksi hätätyöntekijöiden tulisi ottaa joditabletti, jos päästö sisältää radioaktiivista jodia, työtunnit tulisi kirjata ja ulkoisen annosnopeuden mittareita ja dosimetrejä tulisi käyttää. Pitkittyneissä tilanteissa työaikaa alle 1 km etäisyydellä tulisi rajoittaa hyödyntäen työvuoroja. On epätodennäköistä, että päästön seurauksena ylittyisi korkeammat ulkoisen annosnopeuden toimenpiderajat (1000 tai 10000 µSv/h).

Havaittiin, että FNPP-onnettomuudessa efektiivinen annos jää alle 0,1 mSv:n ja kilpirauhasen ekvivalentti annos jää alle 1 mSv:n. Analyysin perusteella, ulkoisen annosnopeuden arvo ei ylittynyt 1 µSv/h minkään analysoidun päästön seurauksesta. Voidaan todeta, että on epätodennäköistä, että FNPP-onnettomuuden seurauksena mikään asetetuista annosrajoista tai ohjeellisista toimenpiderajoista ylittyisi laitoksen ulkopuolella.

NYCKELORD: kärnkraftsfartyg, flytande kärnkraftverk, skyddsåtgärder, beredskap, JRODOS, operativa interventioner nivåer, doskriterie

Sammanfattning

Radiologisk konsekvensbedömning av atmosfäriska utsläpp av radioaktivt material på grund av olyckor på kärnkraftsfartyg (NPV) och under en transitering av flytande kärnkraftverk (FNPP) utfördes. Bedömningen utfördes med en probabilistisk metod för platser i öppet hav i Finska viken och nära norska kusten i Barents hav, och kustnära lägen i närheten av staden Tromsø och Karasundet på den norra sjövägen. Doshastigheter och stråldoser till räddningspersonal och personer nära olycksplatsen uppskattades och nödvändiga skyddsåtgärder utvärderades.

Beslutsstödssystemet JRODOS användes för att modellera spridningen och depositionen av radioaktiva ämnen i atmosfäriska utsläpp och för att uppskatta doshastigheter och doserna till människor och räddningspersonal. Modelleringen tillämpade tidigare publicerade radionuklidinventeringar och frisättningsfraktioner och NOMADS väderdata från år 2021.

Resultaten visade att för NPV-olyckorna överskrids extern doshastighet på 100 µSv/h, effektiv dos på 100 mSv och sköldkörtelekvivalentdos på 100 mSv nära olycksplatserna. Således, om det finns bosättning i närheten av platsen, krävs olika skyddsåtgärder i medvind från olycksplatsen för att skydda människor. Det uppskattades att rekommendationen att begränsa vistas utomhus behövs upp till 10 km, skydd inomhus upp till 3 km och evakuering upp till 2 km. Dessutom kan jodprofylax för vuxna behövas upp till 5 km, och en grov uppskattning visade att jodprofylax för barn och gravida kvinnor behövs upp till 10 km.

Baserat på analyserna bör räddningspersonal bära personlig skyddsutrustning (PPE) upp till cirka 5 km från olycksplatsen på grund av de förhöjda externa doshastigheterna. Vidare bör akutpersonalen ta jodprofylax om luften innehåller radioaktivt jod, arbetstimmar bör registreras och alarmerande externa doshastighetsmätare och dosimetrar bör användas. I en långvarig situation bör skiftarrangemangen också övervägas upp till 1 km för att begränsa den totala arbetstiden. Det är inte troligt att de högre Operational Intervention Levels (OIL) på 1000 eller 10000 µSv/h överskrids i den aktuella NPV-olyckan.

I FNPP-transitolyckan förblir den effektiva dosen och sköldkörtelekvivalentdosen under 0,1 mSv respektive 1 mSv. Vidare överskreds inte den externa doshastigheten på 1 µSv/h i något av de analyserade utsläppsscenarierna. Man drog slutsatsen att det är högst osannolikt att någon av skyddsåtgärderna skulle behövas för människorna eller räddningspersonalen på grund av de övervägda atmosfäriska utsläppen från FNPP-transitolyckan. Observera att resultaten som ges är beroende av initiala antaganden och sannolikt kommer att förändras med antaganden.

Contents

1 Introduction

The risks of different nuclear and radiological emergencies in the Arctic region have been assessed in the Arctic Council publication "Radiological / Nuclear Risk Assessment in the Arctic" - EPPR Consensus Report (EPPR, 2021). Four events were assessed to have a higher probability in the future (increasing risk trend) in the Arctic region: a Nuclear-Powered Vessel (NPV) accident, accident during transit of a Floating Nuclear Power Plant (FNPP), a Small Modular Reactor (SMR) accident, and an accident during the transport of nuclear materials. In the EPPR Consensus Report, the likelihoods of these accidents were perceived to be increasing due to increasing use of nuclear technology in the Arctic region. The risks of the NPV and the FNPP transit accidents were assessed as moderate while the risks of the SMR and transport of nuclear materials accidents were assessed as low. The radiological consequences of the events with moderate risks and increasing trend (the NPV accident and transit of FNPP accident) were analyzed in this study.

Based on the estimation performed by Reistad et al. (2008), the mean time between failures on NPV is 893 ± 138 vessel operating years. Note that a failure does not necessarily lead to atmospheric release. In their analysis, they considered the known failures of Russian nuclear-powered vessels and submarines. These failures include 14 loss of coolant accidents (LOCA) and 7 criticality events that have occurred between 1959 and 2007.

Even though the possibility of an NPV accident in the Arctic region is recognized, number of publicly available full-scope consequence assessments are limited. While the inventory and source terms of decommissioned reactors and vessels in operation have been estimated (Reistad et al. 2006a), the assessments of the radiological consequences of the NPV accidents in the Arctic region are lacking. Previous consequence assessments have concentrated mainly on the releases from sunken submarines (Bartnicki et al. 2016) or atmospheric releases from decommissioned submarines (Takano et al. 2001, Mahura et al. 2005). Furthermore, the Australian Radiation Protection and Nuclear Safety Agency has performed consequence analyses of reference accident scenarios for two types of NPVs (submarines and small surface vessels, aircraft carriers) visiting in Australian ports (Arpansa 2001). They estimated that evacuation may be needed up to 0.8 km and sheltering up to 1.9 km due to a severe reactor accident with atmospheric release from an NPV.

Consequences of a LOCA accident of the FNPP Academic Lomonosov, nearby the coast of Norway, have been studied by Berge et al. 2021. However, the initial events that could cause the LOCA accident during transit of the FNPP are unlikely. More probable release scenarios would be related to a fire on the FNPP e.g., due to a collision with another ship or running aground.

The aim of the present work is to estimate the immediate effects to people and the short-term effects to environment caused by these accidents using probabilistic methods. The focus is on the scenarios in the Arctic environment with atmospheric release of radioactive substances. Radiation doses to the emergency workers and radiation hazards during the accident are also evaluated. Long-term consequences to the terrestrial and marine environment, and dose estimates through ingestion as well as consequences for personnel onboard, are excluded from the analyses.

2 Accident scenarios

There are multiple initial events that can lead to atmospheric release of radioactive substances in the considered scenarios. The probabilities of the initial events are not estimated in this work. It must be noted, however, that their probabilities are extremely low. We describe some events that may lead to atmospheric release, estimate potential inventories, and release fractions using publicly available information.

2.1 Nuclear-powered vessels

NPVs sail in Arctic waters and radioactive release from an accident may potentially impact arctic areas of Canada, Iceland, the Kingdom of Denmark, Norway, the Russian Federation, and the USA (EPPR, 2021). Furthermore, Russian NPVs often visit the Baltic Sea and an accident during the visit may impact all countries in the area.

A NPV would have to experience a severe accident (damage to nuclear fuel and loss of containment integrity) to impact the Arctic. A potential initiating event could be: 1. collision of two vessels that compromises the safety of the reactor, 2. vessel runs aground, and reactor safety is compromised, or 3. technical problems in the reactor. The first two accident types can cause a strong mechanical impact affecting cooling and containment of the vessel's reactor. A significant atmospheric release can take place only when the integrity of the nuclear fuel elements and the reactor coolant circuit are compromised and the active and/or passive safety systems are not working properly. Previously estimated inventory and release fractions (Reistad et al. 2006a) are applied in the consequence assessment (see Appendices A and B). NPVs that could be affected by these initial events include civilian and military surface vessels and submarines.

In this study, we have used parameters determined for the Russian KLT-40 reactor design as a reference for the marine applications. However, the results can be used to estimate consequences from other types of reactors, e.g., by scaling ratio of heat power. The KLT-40 is a pressurized water reactor with thermal power varying from 135 MWt to 171 MWt (Reistad et al. 2006b). The core of the KLT-40 contains about 170 kg of uranium in total with U-235 enrichment of 90% (ca. 150 kg). The KLT-40 reactor is used in the icebreaking freighter Sevmorput that often operates over the Northern Sea Route and regularly visits the Baltic Sea. Furthermore, the Russian Taymyr class icebreakers use a modified version of the KLT-40 reactor with increased power (KLT-40M).

2.2 Floating nuclear power plant

The Russian FNPP Akademik Lomonosov is not self-propelled, and it requires towing between the operation and maintenance sites. The towing distance for FNPPs can be thousands of kilometers in Arctic weather conditions. States whose Arctic areas are potentially impacted due to the currently existing FNPP are limited to Norway and the Russian Federation (EPPR, 2021). However, due to increasing interest in FNPPs in energy production in remote locations, the number of potentially impacted states may increase in the future.

The reactors of an FNPP are in a sub-critical state during the towing but nuclear fuel needs to be cooled due to decay heat production. A potential initiating event for an accident during the towing of an FNPP could be 1. collision of two vessels that compromise the safety of reactor and a storage of spent nuclear fuel, or 2. vessel runs aground and reactor safety and a storage of spent nuclear fuel are compromised. A significant atmospheric release could take place if the accident also involves an extensive fire on the vessel. Such fire could be initiated by collision of an FNPP and an oil tanker. The radionuclide inventory of an FNPP is broadly similar to that of an NPV. It is assumed that the reactor is in shutdown mode and the reactor has been cooling down for a period of 100 days before the accident. During the shutdown, the short-lived radionuclides have decayed (see Appendix A). A hypothetical FNPP containing two reactors with fuel cycle of three years and four cycles before larger maintenance is assumed. Thus, the transiting vessel contains also spent nuclear fuel with decay times of 3, 6, and 9 years. Note that the reactor of the FNPP might have a slightly different inventory than those of nuclear powered vessels due to e.g., different enrichment of the fuel. However, the other uncertainty sources of the release are large compared to the uncertainties in inventory and using the inventory of the NPV can be considered as a fair approximation. The release fractions given by Compton et al. (2003) for low-temperature fires are applied in this work (see Appendix B).

Currently, the only FNPP in operation is the Russian Academic Lomonosov, which contains two KLT-40S reactors that are modified versions of the KLT-40. The publicly available references offer a limited amount of information about the KLT-40S reactor and its inventory of radionuclides. However, the thermal power (150 MWt) and the amount of U-235 (179 kg) are similar to those of the KLT-40 (IAEA 2013).

2.3 Location of the accidents

In principle, an accident involving an NPV could happen in any Arctic location with accessible waterways. Civilian and military vessels, and submarines operate regularly in the Arctic region and the Northern Sea Route is one of the most popular routes for nuclear-powered vessels. Furthermore, the only FNPP currently in operation is docked in the Pevek harbor on the coast of the East Siberian Sea and is planned to be towed to another location when larger maintenance of the FNPP is needed.

Three marine locations were selected to be analyzed for an NPV accident and two for a transit of an FNPP accident (see Figure 1). The locations were chosen so that they represent coastal and open sea locations where such accidents could occur. The consequence analyses of

NPV accidents were performed on the Barents Sea, the coast of Tromsø and the Gulf of Finland while consequences of FNPP transit accidents were analyzed on the Barents Sea and in the Kara Strait. The locations have been selected to represent various Arctic weather conditions, and the results could be utilized for other Arctic locations if needed.

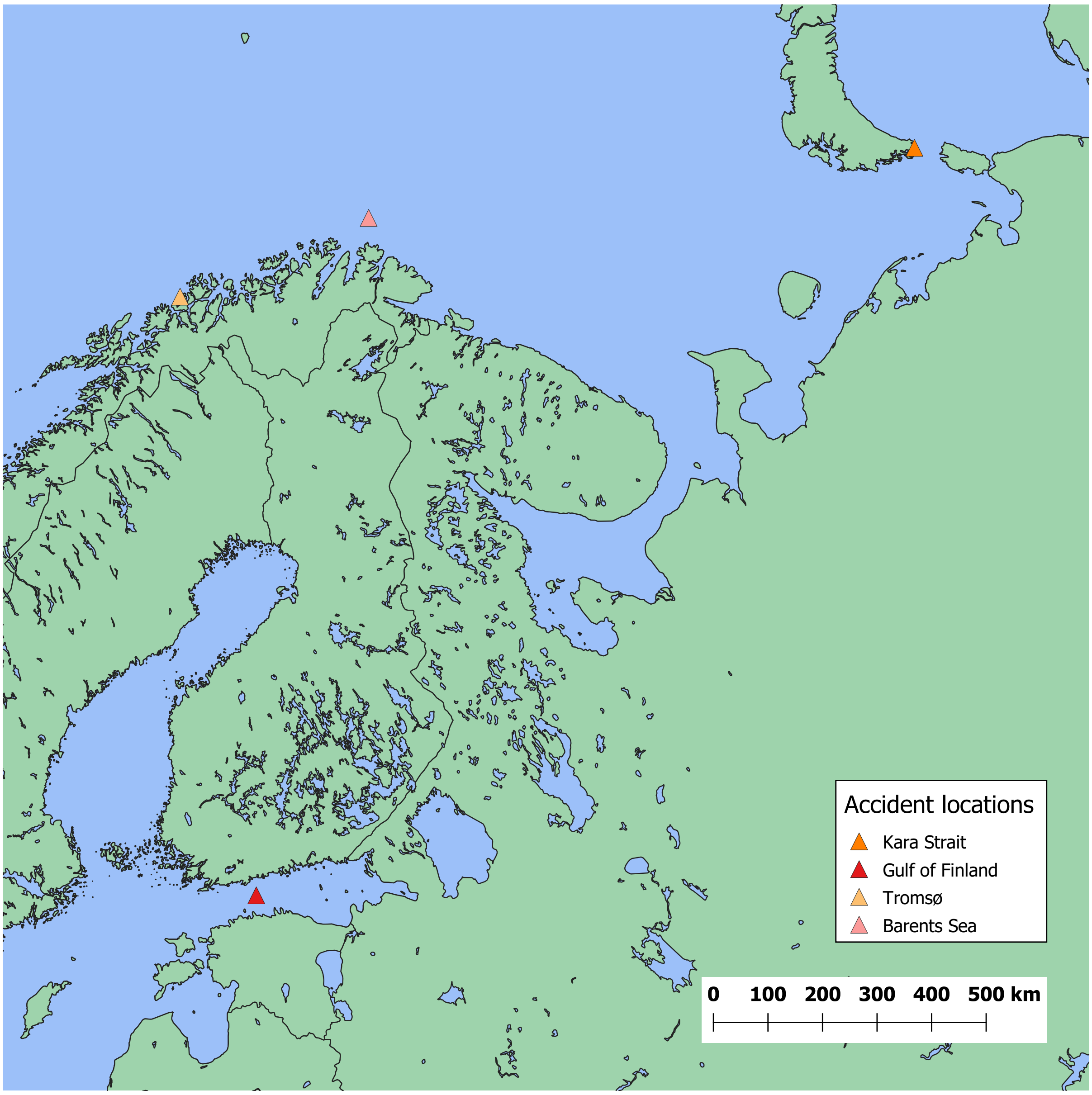

FIGURE 1. Selected accident locations include open sea locations in the Gulf of Finland and near the Norwegian coast in the Barents Sea, and coastal locations nearby the city of Tromsø and the Kara Strait on the Northern Sea Route.

3 Preparedness and radiation safety

3.1 Preparedness in the Arctic

The main aim of Search And Rescue (SAR) operations, including radiological or nuclear (RN) incidents, is to save lives and minimize health effects while, in the longer term, the aims are to minimize consequences to maritime and terrestrial habitat and reduce the socio-economic and psychosocial impact to the society. An RN emergency has multiple different factors which do not feature in operations without radiation. The RN emergencies organization, situation assessment and decision making must be adjusted accordingly. Furthermore, personal protective equipment (PPE) of rescuers and decontamination of persons and equipment brought from contaminated areas are required. (Aas-Hansen et al. 2022)

First responders for an RN accident in the maritime environment may not be familiar with details of the NPV or FNPP and need general information for rescuing the people on board. The information needed include the type of the vessel, reactor and accident, capabilities of personnel on board, weather conditions, and estimation of atmospheric dispersion when atmospheric release of RN substances is possible. Risk of atmospheric release and meteorological conditions should be considered when defining restriction areas, deciding the location of the on-site coordination center and direction of evacuation, and planning measurements and monitoring. Furthermore, help from radiation experts should be requested to gain situation awareness and control and assessment of potential doses to rescue personnel and other people involved. Radiation measurements using simple hand-held devices or drones are also crucial.

First responders working outside should wear PPE to minimize contamination and the radiation dose to skin, airways, eyes, nose, and mouth. Overalls and full-face masks of first responders give external protection against alpha radiation and mostly against beta radiation while external gamma radiation penetrates through these PPEs and forms the main part of the dose to protected responders. For unprotected persons, most of the radiation dose accumulates via inhalation and thus the face mask is the most important PPE when radioactive substances have been released to the atmosphere. The respirators have different Assigned Protection Factors (APF). For example, FFP3, Half-face mask with P3 filter, full-face mask with P3 filter, and have APFs of 20, 30, and 500, respectively (TTL 2007, STUK 2022). Note that these APFs apply only for particulates. For example, in nuclear accidents, part of iodine is released in molecular and organic forms that are not filtered by standard filters without special iodine filtering. In addition, the responders should have personal dosimeters to alarm when set limits for external dose rate and effective dose are exceeded. Military vessels likely have sophisticated capabilities for working in contaminated environments providing good protection to the crew inside.

3.2 Protective actions

Protective actions can be ordered to ensure the safety of the population and emergency workers, the functioning of the society, and the continuation of business activities. Predefined dose criteria and operational intervention levels (OIL) are set to help decision making during a nuclear or radiological emergency. The protective actions, dose criteria and OILs in Finland are described in detail in the Guide VAL1 (STUK 2022). Protective actions of people in a nuclear emergency include sheltering indoors, the recommendation to limit being outside, iodine prophylaxis, access control and evacuation. Furthermore, there are protective actions related to foodstuff production (i.e. protecting primary foodstuff production and protecting foodstuff production facilities) and restricting land usage (i.e. restricting use of public and natural recreational areas).

The summary of protective actions and related dose criteria for effective and thyroid dose, and OIL for external dose rate in the early phase of an emergency are given in Table 1 and in the intermediate phase in Table 2. More detailed descriptions of other OILs are given in the Guide VAL1 (STUK 2020).

TABLE 1. Protective actions in the early phase of a nuclear emergency, and the dose criteria and operational intervention levels (OIL) related to the actions in Finland. (STUK 2022)

Protective action	Dose criteria / OIL
Sheltering indoors	Effective dose > 10 mSv in 2 days*
	External dose rate > 100 µSv/h
Recommendation to limit being outside	Effective dose 1 - 10 mSv in 2 days*
	External dose rate > 10 µSv/h
Iodine prophylaxis (adults)	Thyroid equivalent dose > 100 mGy
	External dose rate > 100 µSv/h
Iodine prophylaxis (children and pregnant females)	Thyroid equivalent dose > 10 mGy
	External dose rate > 10 µSv/h
Evacuation	Need of sheltering indoors for more than 2 days
Protecting primary production of foodstuff	External dose rate > 1 µSv/h
Protecting production facilities of foodstuff	External dose rate > 10 µSv/h

* For unprotected people

** Please see further details from Preparedness Guide (STUK 2022)

TABLE 2. Protective actions in the intermediate phase of a nuclear emergency, and the dose criteria and operational intervention levels (OIL) related to the actions. (STUK 2022)

Protective action	Dose criterion / OIL
Sheltering indoors	Effective dose > 10 mSv in 2 days*
	External dose rate > 100 μSv/h
Recommendation to limit being outside	Effective dose > 10 mSv in 7 days but < 10 mSv in 2 days*
	External dose rate > 10 μSv/h but < 100 μSv/h
Evacuation	Effective dose in first week after the accident > 20 mSv*
	External dose rate > 100 μSv/h for over 2 days
Temporary relocation	Monthly effective dose > 10 mSv after a month from the accident*
	External dose rate > 10 μSv/h regardless of decontamination
Permanent relocation	Annual effective dose > 50 mSv after a year from the accident*
Restricting use of public recreation areas	External dose rate > 1 μSv/h
Restricting use of natural recreation areas	External dose rate > 10 μSv/h

* For unprotected people

Protective actions are also implemented for the emergency workers to avoid unnecessary radiation exposure. However, an emergency worker participating in the management of a radiological accident is allowed to be exposed to radiation more than a member of the public. The general objective is that the annual effective dose to an emergency worker does not exceed 20 mSv. Furthermore, there are multiple protective actions including wearing dust-proof protective clothing and respirators, iodine prophylaxis, using alarming dose rate meters and dosimeters, and arrangements to work in shifts to reduce radiation exposure of the emergency workers. The OILs for external dose rate and corresponding protective actions of emergency workers are given in Table 3. More detailed descriptions of other OILs are given in the Guide VAL1 (STUK 2022).

TABLE 3. Protective actions of emergency workers for different OILs for external dose rate. (STUK 2022)

External dose rate	Protective actions
10–100 µSv/h	• Wear dust-proof protective clothing and respirators • Iodine prophylaxis if the air may contain radioactive iodine. • Working hours and location details are recorded as accurately as possible • The external dose rate is recorded if a dose rate meter is available. • Personal or group-specific dosimeters are used if they are available.
100–1000 µSv/h	• All above • Shift work arrangements to limit total working time if the situation prolongs.
1000–10000 µSv/h	• All above • staying in a contaminated area is limited where possible without impeding urgent protective actions • Radiation surveys and other measurement activities are not performed
> **10000 µSv/h**	• All above • Only absolutely necessary work to ensure the safety of the public is conducted

In a rescue operation the effective dose should remain, whenever possible, below 1 mSv for public and 20 mSv for an emergency worker. If it is not possible to adhere to these limits in the emergency situation, higher reference levels can be applied. In such conditions, the effective doses of the emergency workers should be kept below 100 mSv, except for situations related to the prevention of severe health effects due to radiation, life-saving measures, or the prevention of the aggravation of an accident. In the case of such measures, the doses should be kept below 500 mSv. (STUK 2022)

For accidents taking place in open sea, far from coastal regions and inhabited areas, many of the protective actions stemming from doses resulting from deposited radionuclides would be unnecessary as they would mix and disperse in vast quantities of sea water. However, for accidents taking place due to running aground or near coastal regions, consequences of deposition would need to be considered. Estimation of the deposition might also be relevant when assessing potential contamination of vessels involved in SAR operation and if the sea is frozen.

4 Methods

4.1 Dispersion modelling and dose assessment

The global NOMADS weather forecast data by NOAA (NOAA 2021) and dose conversion factors included in the JRODOS (Ievdin et al. 2019) were applied in the modelling. The releases from NPV accidents were modelled using 80 km × 80 km area with a resolution of 100 m close to the release location. The resolution of the grid is increased stepwise within distance from the release point (resolution/distance: 100 m/1 km, 200 m/4 km, 400 m/10.4 km, 800 m/20.8 km and 1600 m/40 km). The releases from FNPP accidents were modelled using 40 km × 40 km area with a resolution of 50 m close to the release location. Here the resolution is increased similarly stepwise within the distance from release point (resolution/distance: 50 m/0.5 km, 100 m/2 km, 200 m/5.2 km, 400 m/10.4 km and 800 m/20 km). Duration of releases was set to 12 hours and dispersion will be modelled for 48 hours. Representative weather data of the studied accident locations are shown in Figure 2 for wind fields and in Figure 3 for precipitation rate. For each scenario, about 200 releases were modelled using the NOMADS weather forecast data for 2021. The releases were started every 43 hours to cover daily and seasonal variation of the weather. This enabled usage of probabilistic approaches with representative weather conditions.

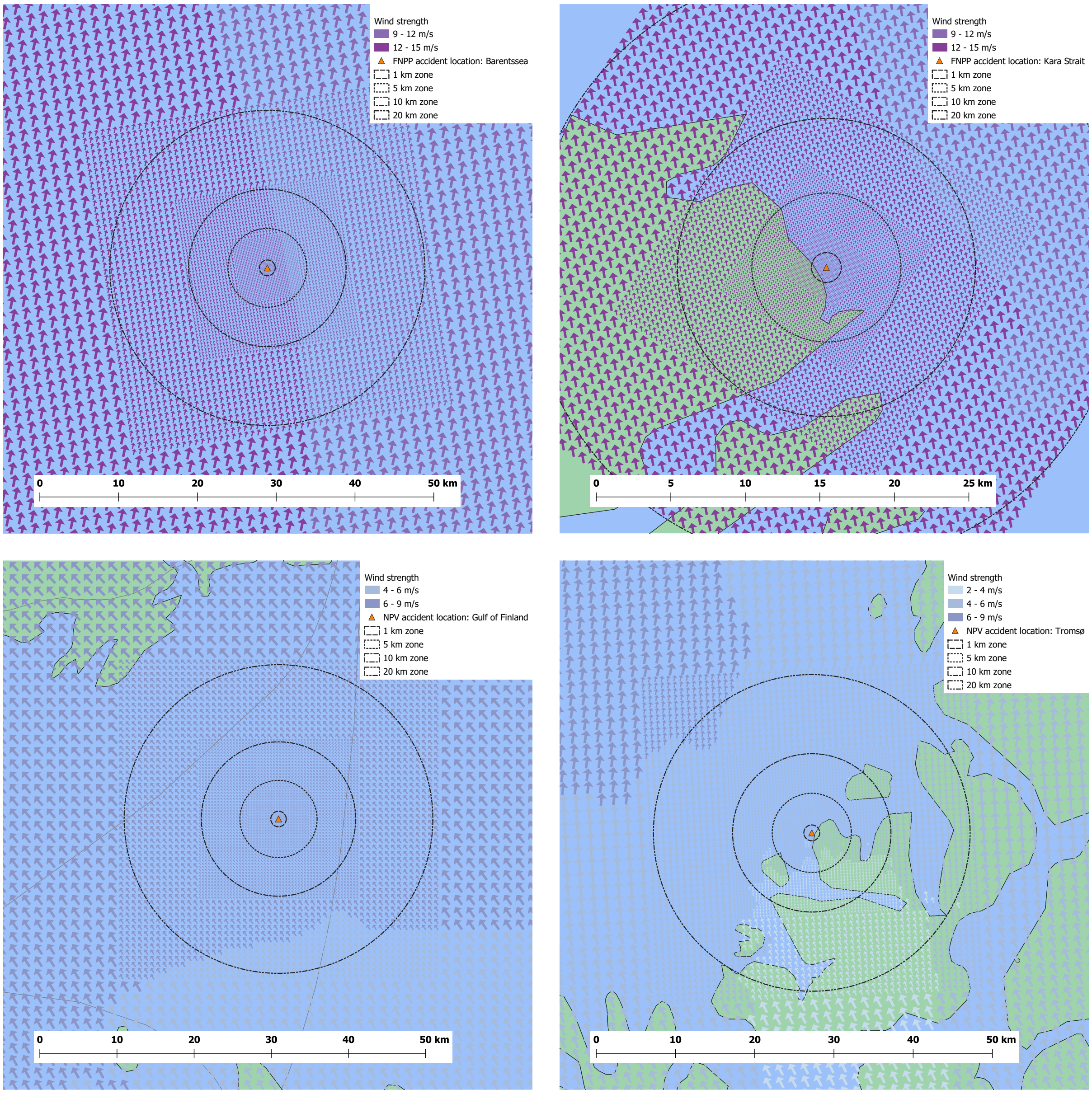

FIGURE 2. Visualizations of individual realizations of wind fields in the considered locations at the Barents Sea (upper left), the Kara Strait (upper right), the Gulf of Finland (lower left), and coast of Tromsø (lower right).

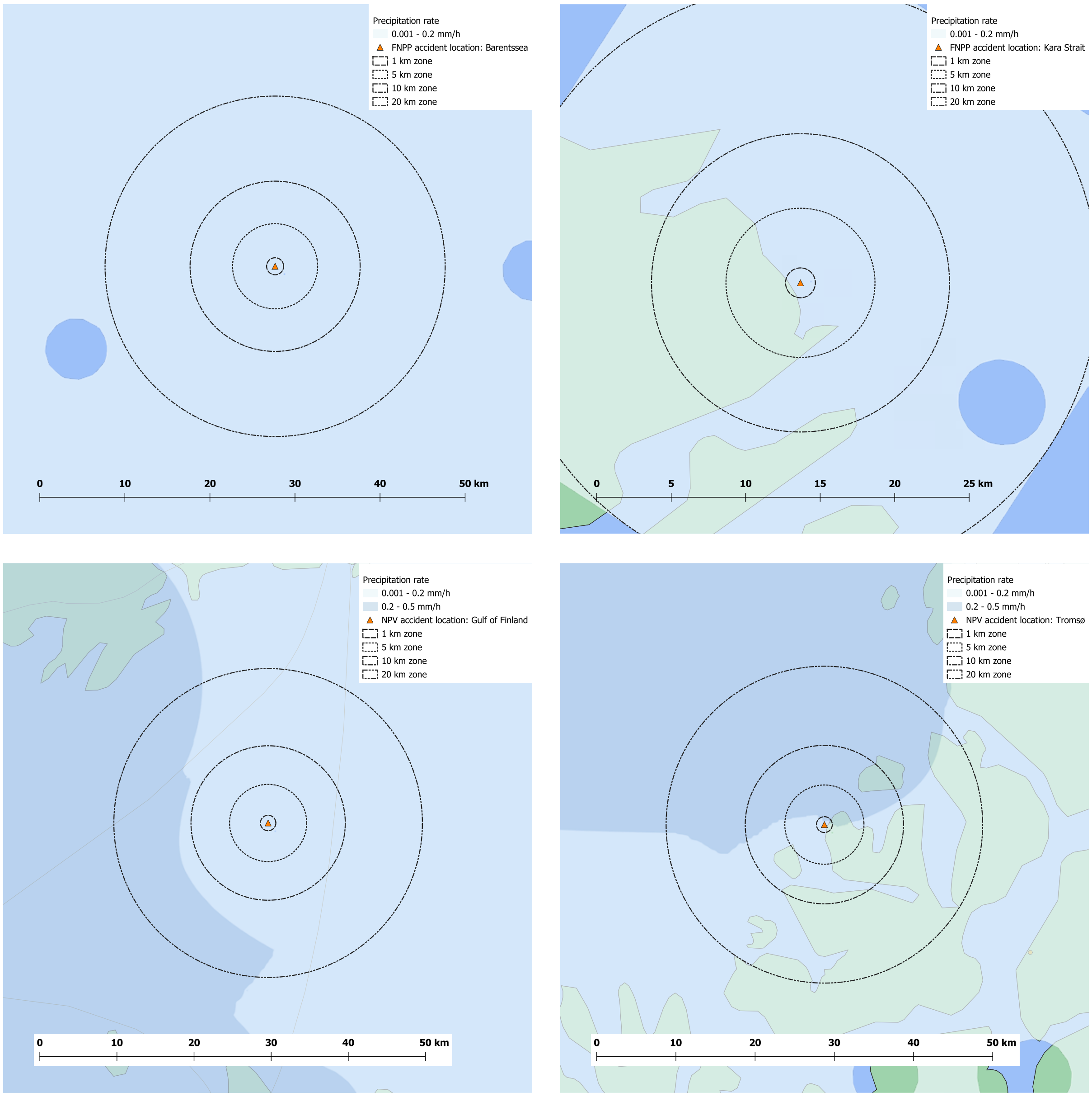

FIGURE 3. Visualizations of individual realizations of precipitation rates in the considered locations at the Barents Sea (upper left), the Kara Strait (upper right), the Gulf of Finland (lower left), and coast of Tromsø (lower right).

The atmospheric dispersion modelling and dose calculations were performed using the JRODOS and RIMPUFF dispersion model included in JRODOS (Karlsruhe Institute of Technology 2021, Thykier-Nielsen et al. 1999). Representative effective dose data within 48 h are shown in Figure 4 for each of the studied scenarios.

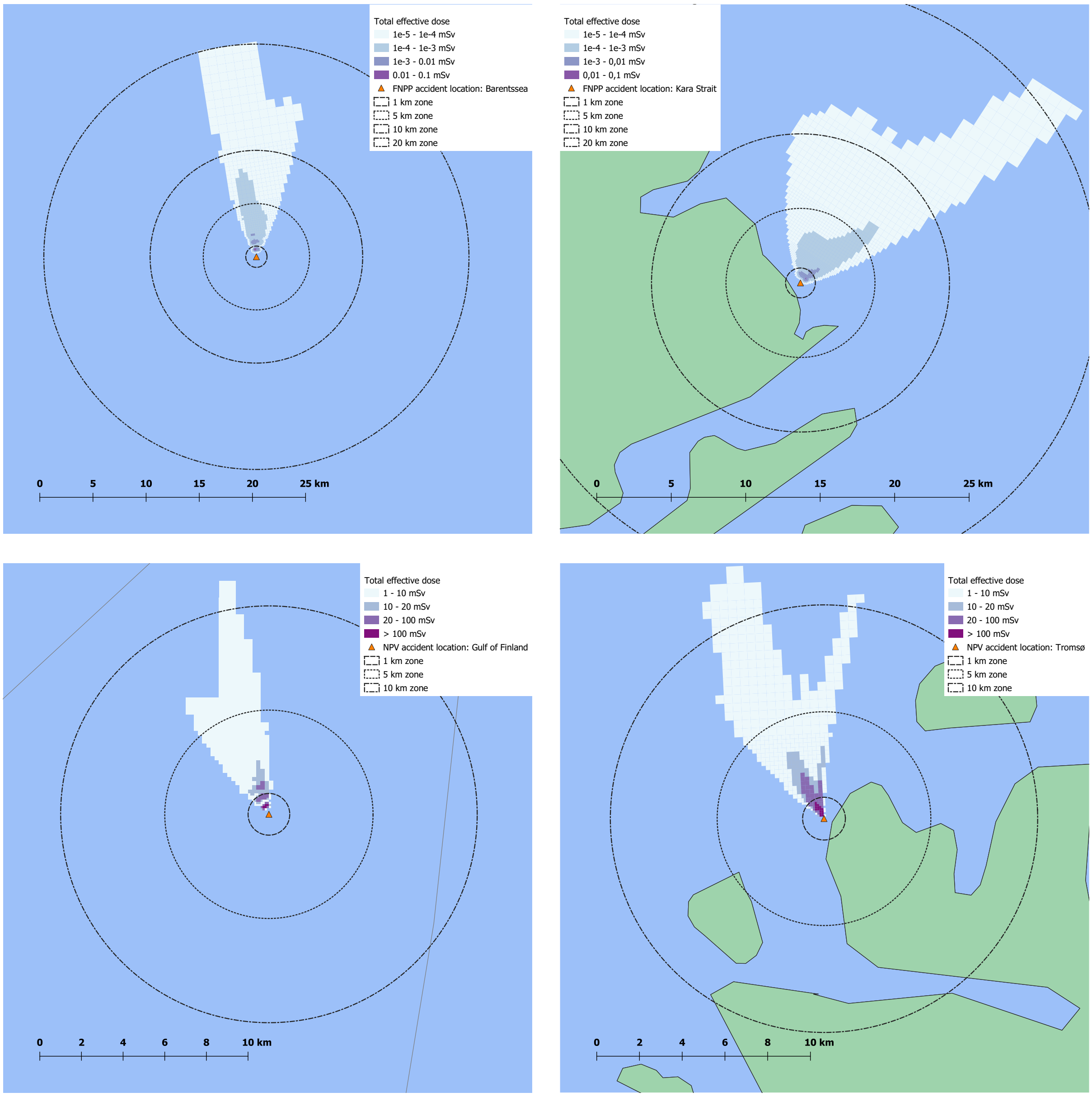

FIGURE 4. Effective doses of representative release scenarios from the FNPP accidents (upper row) at the Barents Sea (left) and the Kara Strait (right), and the NPV accidents (lower rows) at the Gulf of Finland (left) and the coast of Tromsø (right). Note the different scales used for the effective doses for the FNPP and NPV releases.

4.2 Processing of model results

The data was post-processed statistically using Python scripts and visualized using a geographic information system software QGIS (2023). In the consequence analyses, inhalation and external doses are estimated. A cloud and deposition are both considered in the external dose, which can be considered as a conservative dose estimate in a marine environment where deposition is not formed everywhere. External dose from deposition can, however, be formed on shore, sea ice and surfaces of the vessels. Note that the shape of the NPV or FNPP or external dose from upper layers of atmosphere are not considered in the model. Furthermore, thyroid doses are estimated for the releases that contain radioactive iodine isotopes and duration for external dose rates exceeding the OILs given in Tables 1–3. The analyses have been performed for unprotected adults assuming that the airway, eye, nose, or mouth protective equipment is not worn, and the skin dose or external beta and alpha doses are not considered. The results of the dose assessment are compared with the dose criteria for the different protective actions given by IAEA (2015) and Radiation safety authorities of Nordic countries (2014).

5 Results

Consequence assessments of NPV and FNPP accidents were performed using external dose rate, effective dose, and thyroid equivalent dose. Note that in the accident, the numerical values given in the section are valid only downwind from the accident location. In stable weather conditions, the elevated external dose rates or doses are not anticipated in other directions. Note that the doses on the NPV and FNPP are not considered in this work and that onboard the doses may be higher than the analysis shows.

5.1 Consequences of nuclear-powered vessel accidents

External dose rate is a key factor when taking protective actions in early phase of the accident as it can be directly measured by fixed monitoring networks, hand-held radiation protection instruments, and personal alarming dosimeters. The durations when the external dose rate exceeds 1, 10 and 100 µSv/h were estimated for three marine NPV accident locations (see Figure 5). It is not likely that the higher OILs of 1000 or 10000 µSv/h (see Table 3) are exceeded in the considered NPV accident.

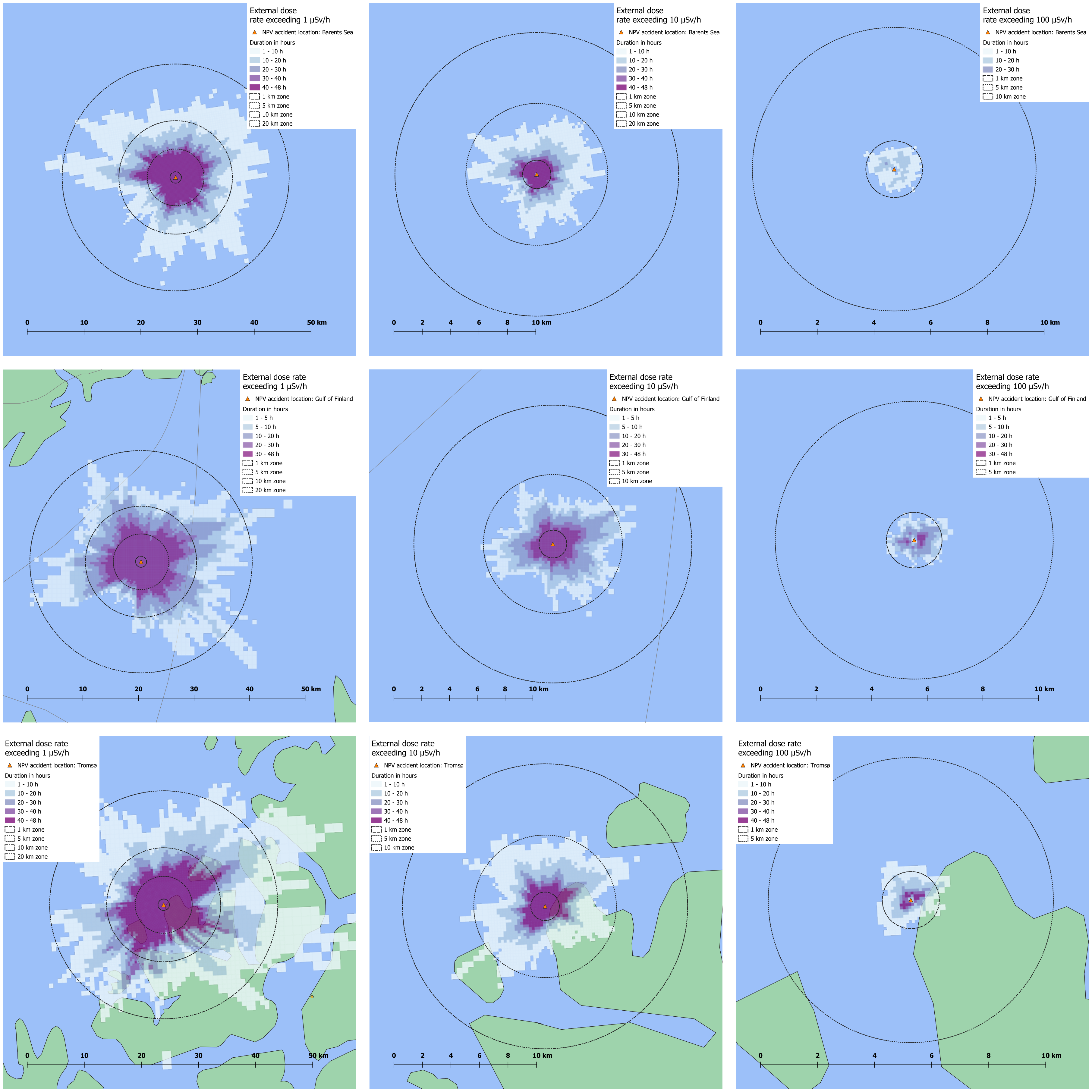

FIGURE 5. The durations for external dose rate exceeding 1 µSv/h (left column), 10 µSv/h (middle column) and 100 µSv/h (right column) for 95th percentile of data due to releases from NPV accidents at the Barents Sea (upper row), the Gulf of Finland (middle row), and the coast of Tromsø (lower row).

At open sea locations in the Barents Sea and the Gulf of Finland the OILs of 1 µSv/h, 10 µSv/h and 100 µSv/h may be exceeded up to about 20 km, 5 km, and 1 km, respectively. While at a coastal location nearby Tromsø, the same OILs may be exceeded at slightly larger distances due to lower wind strengths on the continent and higher precipitation rates. As the duration of releases was set to 12 hours, the longer durations in Figure 5 are caused by deposition. Thus, on sea, these durations can be considered as conservative estimates. The deposition maps of Cs-137 and I-131 are shown in Appendix C.

Recommendation to limit being outside and iodine prophylaxis for children and pregnant females may be needed up to about 5 km from the accident site. Sheltering indoors may be needed up to about 1 km. These protective actions are needed only in case there is habitation in the vicinity of the accident location. Emergency workers should wear protective equipment up to about 5 km from the accident location due to elevated external dose rate. Furthermore, the emergency workers should take iodine prophylaxis (if the air contains radioactive iodine), working hours should be recorded, and alarming external dose rate meters and dosimeters should be used if they are available. In prolonged situations, the shift work arrangements should also be considered up to 1 km to limit total working time. Especially in open sea conditions, radiation exposure can be limited by staying upwind from the accident site.

The effective and thyroid equivalent dose includes radiation doses accumulating directly from the cloud and deposition, and via inhalation. The doses of the first 2 days after the release were estimated for three marine NPV accident locations for the 95th percentile of data (see Figures 6 and 7). The doses for an unprotected adult were considered.

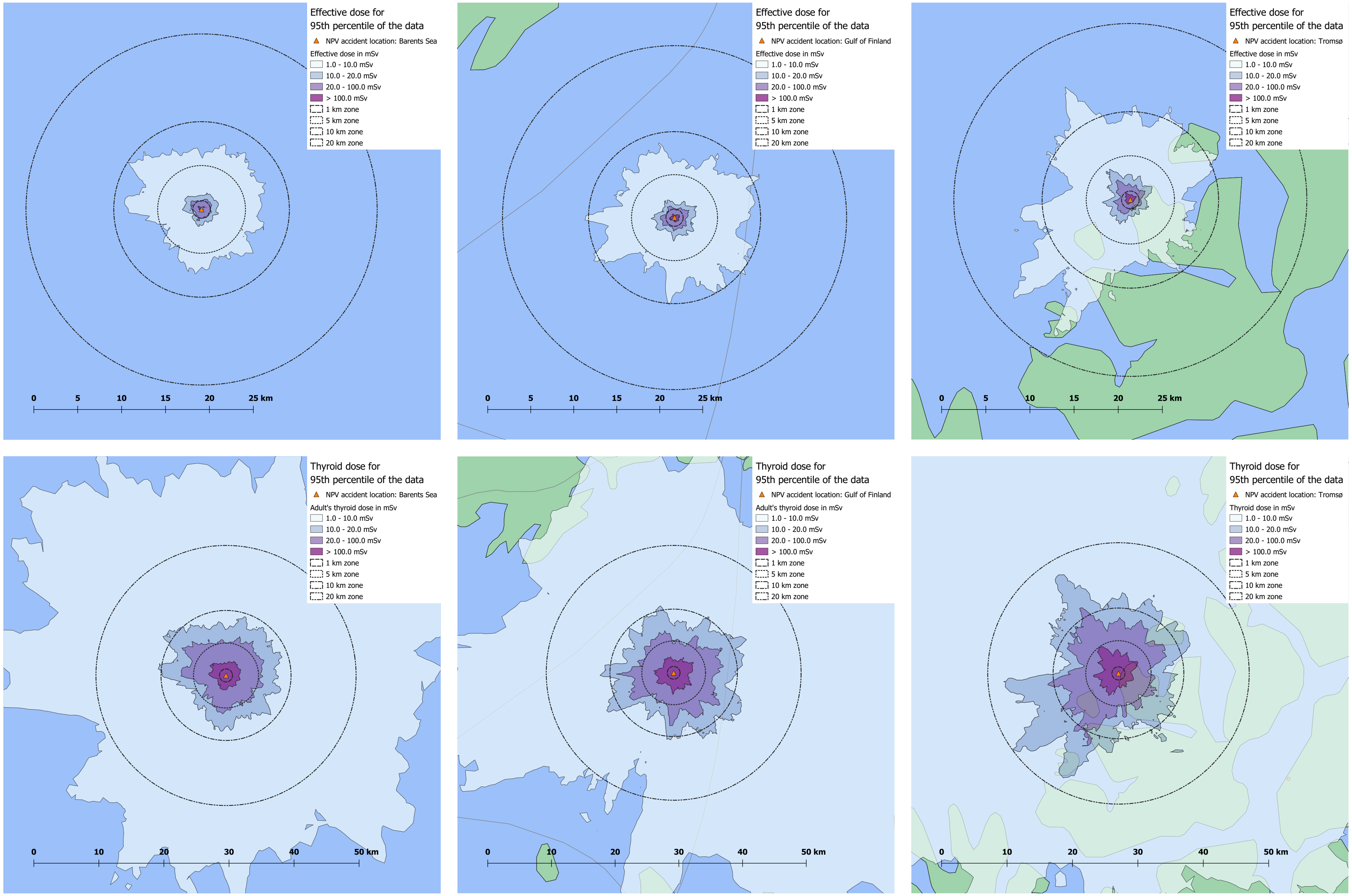

FIGURE 6. Effective (upper panels) and thyroid (lower panels) equivalent doses for 95th percentile of the data for releases from NPV accidents at the Barents Sea (left), the Gulf of Finland (middle), and the coast of Tromsø (right).

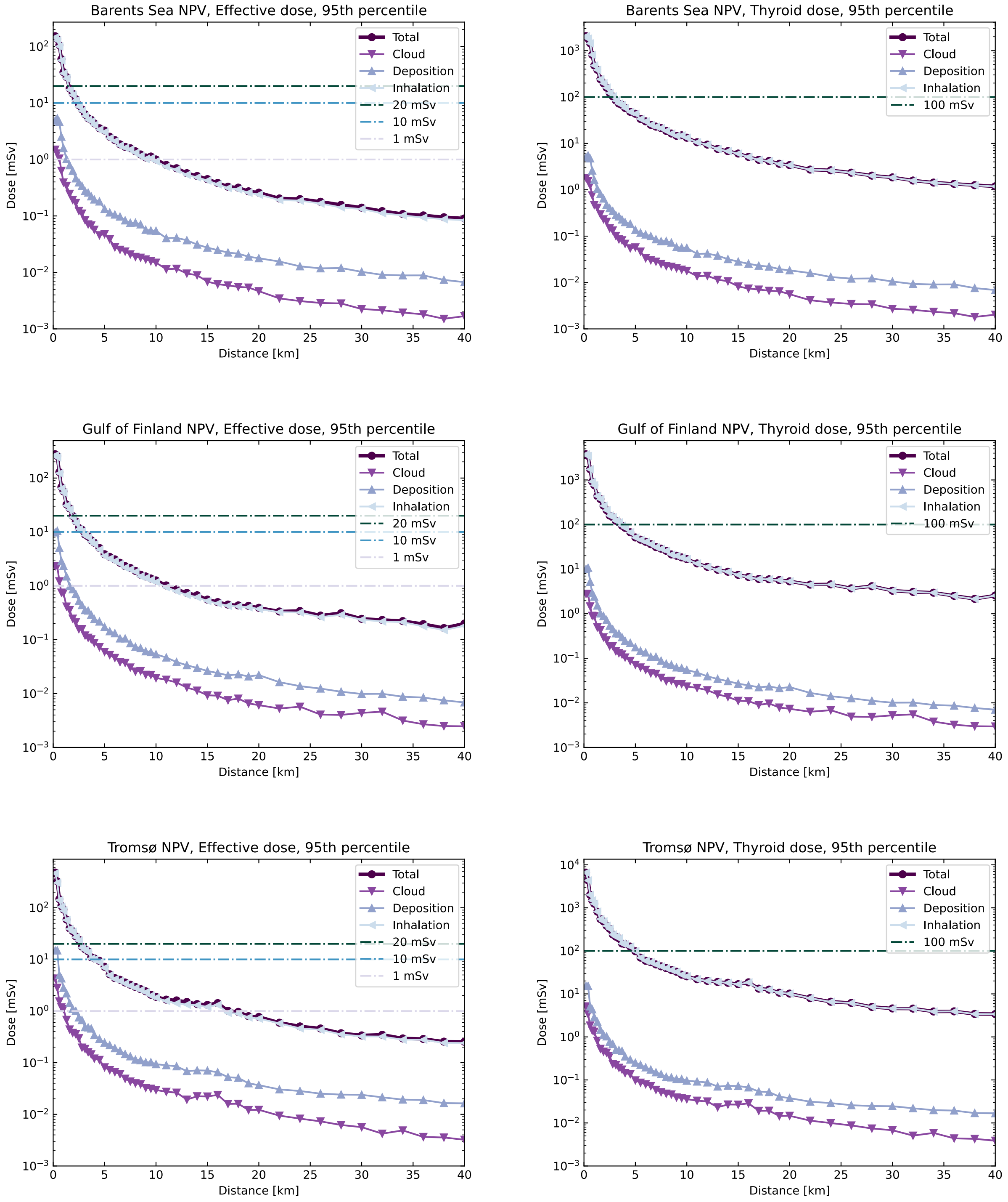

FIGURE 7. Maximum effective dose (right) and thyroid equivalent dose (left) as function of distance for the 95th percentile of data due to releases from NPV accidents at the Barents Sea (upper), the Gulf of Finland (middle), and the coast of Tromsø (lower). The total effective dose (●) is built up from components formed by cloud dose (▼), deposition dose (▲), and inhalation dose (◀). Horizontal lines show the dose limits of 1, 10, 20 and 100 mSv.

At open sea locations in the Barents Sea and the Gulf of Finland, the dose criteria of 1 mSv, 10 mSv, 20 mSv, and 100 mSv for effective dose may be exceeded up to about 10 km, 3 km, 2 km, and a few hundred meters, respectively. At a coastal location nearby Tromsø, the same dose criteria may be exceeded at slightly greater distances, due to lower wind strengths near the continent. Recommendation to limit being outside, sheltering indoors and evacuation are needed to protect people in areas where dose criteria of 1 mSv, 10 mSv and 20 mSv, respectively, are exceeded.

At open sea locations in the Barents Sea and the Gulf of Finland, the dose criteria of 100 mSv for thyroid equivalent dose may be exceeded up to about 3 km, and up to about 5 km on the coast of Tromsø. In these areas, thyroid prophylaxis would be needed as protective action. Dose criterion for thyroid prophylaxis for children and pregnant females was not analyzed precisely. Based on the analysis performed for adults, however, it can be concluded that iodine prophylaxis for children and pregnant females would be needed at least up to 10 kilometers.

The graphs in Figure 7 show that the majority of the effective dose is accumulated via inhalation (94%). The radionuclides in deposition and cloud form about 4.6% and 1.4%, respectively, of the effective dose. Effective dose from inhaled substances forms even a bigger part of thyroid equivalent dose (99.6%), as inhaled iodine isotopes accumulate into the thyroid. The radionuclides in deposition and cloud form only about 0.3% and 0.1%, respectively, of the thyroid equivalent dose.

The effective dose can also be analyzed based on different nuclide groups. Typically, in nuclear reactor accidents, the majority of dose is accumulated by different isotopes of iodine, cesium, and noble gases (see Figure 8). In the considered NPV accidents, iodine isotopes form the majority of the total effective dose (72.5%) while cesium isotopes and noble gasses form about 5.4% and 0.5%, respectively. The fractions of different nuclides are given with more detail in Appendix D.

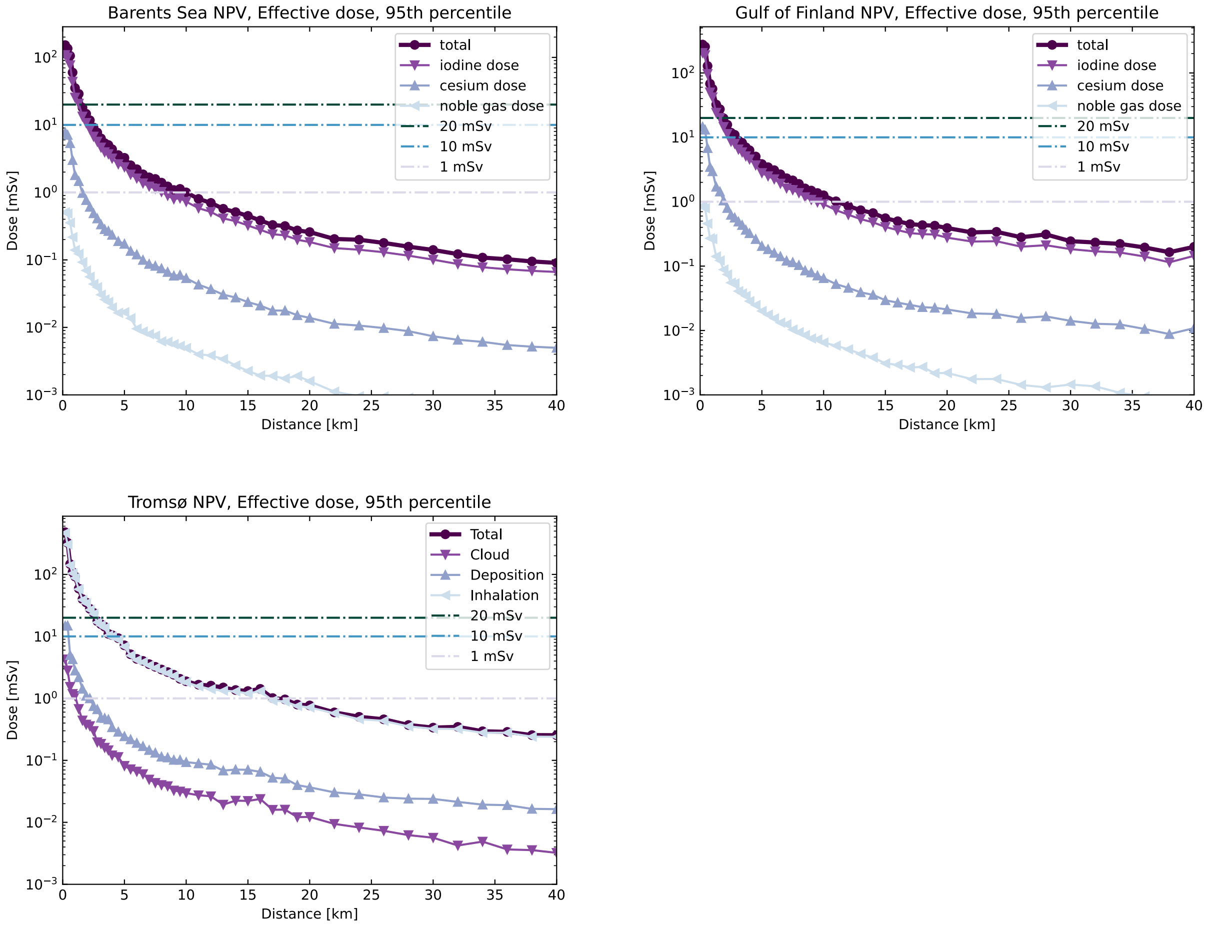

FIGURE 8. Maximum effective dose as function of distance for the 95th percentile of data due to releases from NPV accidents at the Barents Sea, the Gulf of Finland, and the coast of Tromsø. The total effective dose (●) is built up from components formed by iodine dose (▼), cesium dose (▲), and noble gas dose (◀). Horizontal lines show the dose limits of 1, 10 and 20 mSv.

Typically, this kind of probabilistic analyses of atmospheric releases are performed using 95th percentile of the data. However, using multiple percentiles it is possible to estimate and visualize probabilities for exceeding different dose criterion at different distances from the accident location. The probabilities for effective and thyroid dose exceeding the different dose criteria in NPV accidents at the Barents Sea, the Gulf of Finland, and the coast of Tromsø are shown in Figures 9–11.

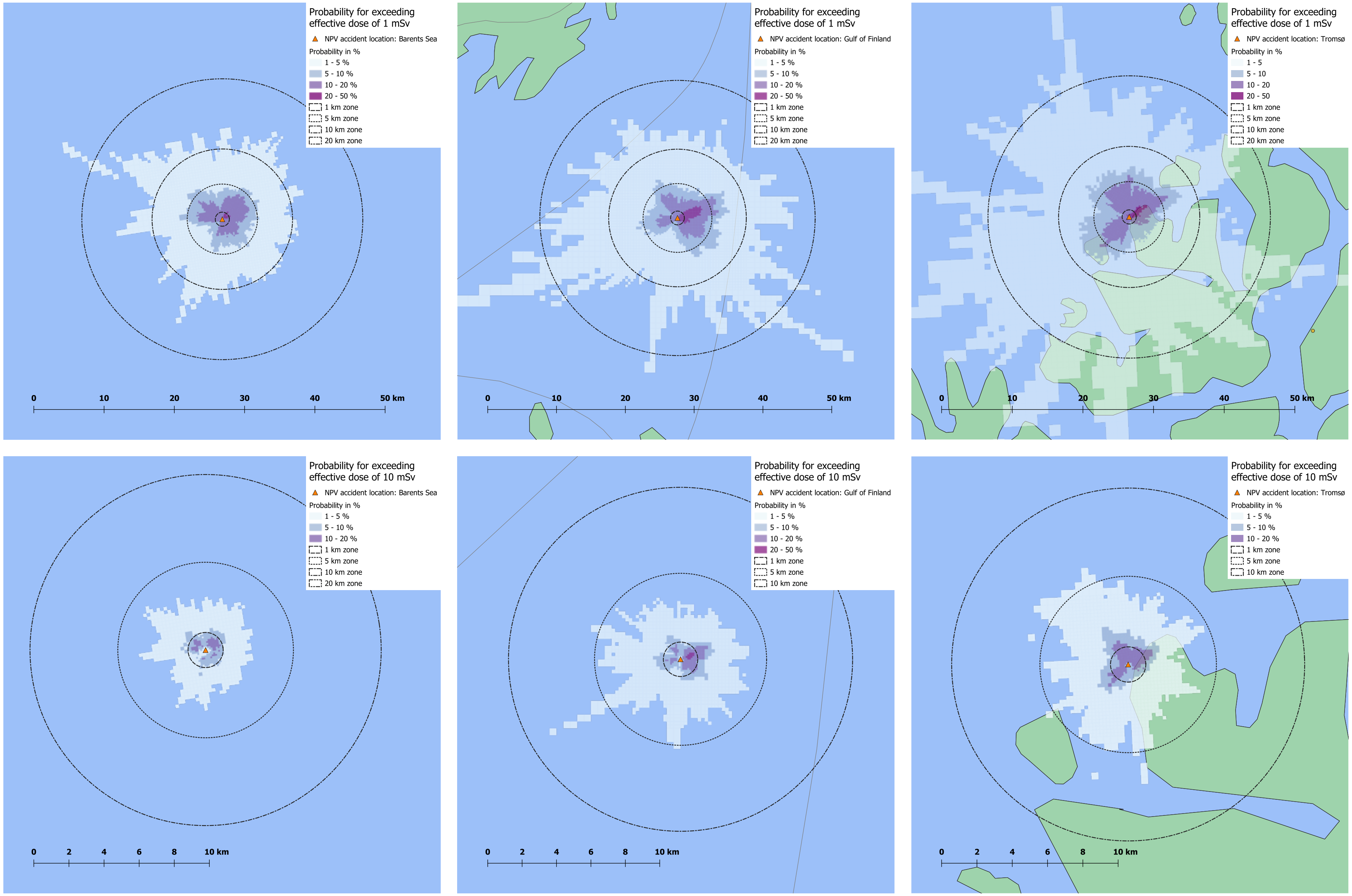

FIGURE 9A. The probabilities for effective dose exceeding 1 (upper) and 10 (lower) mSv due to releases from NPV accidents at Barents Sea (left column), the Gulf of Finland (middle column), and the coast of Tromsø (right column)

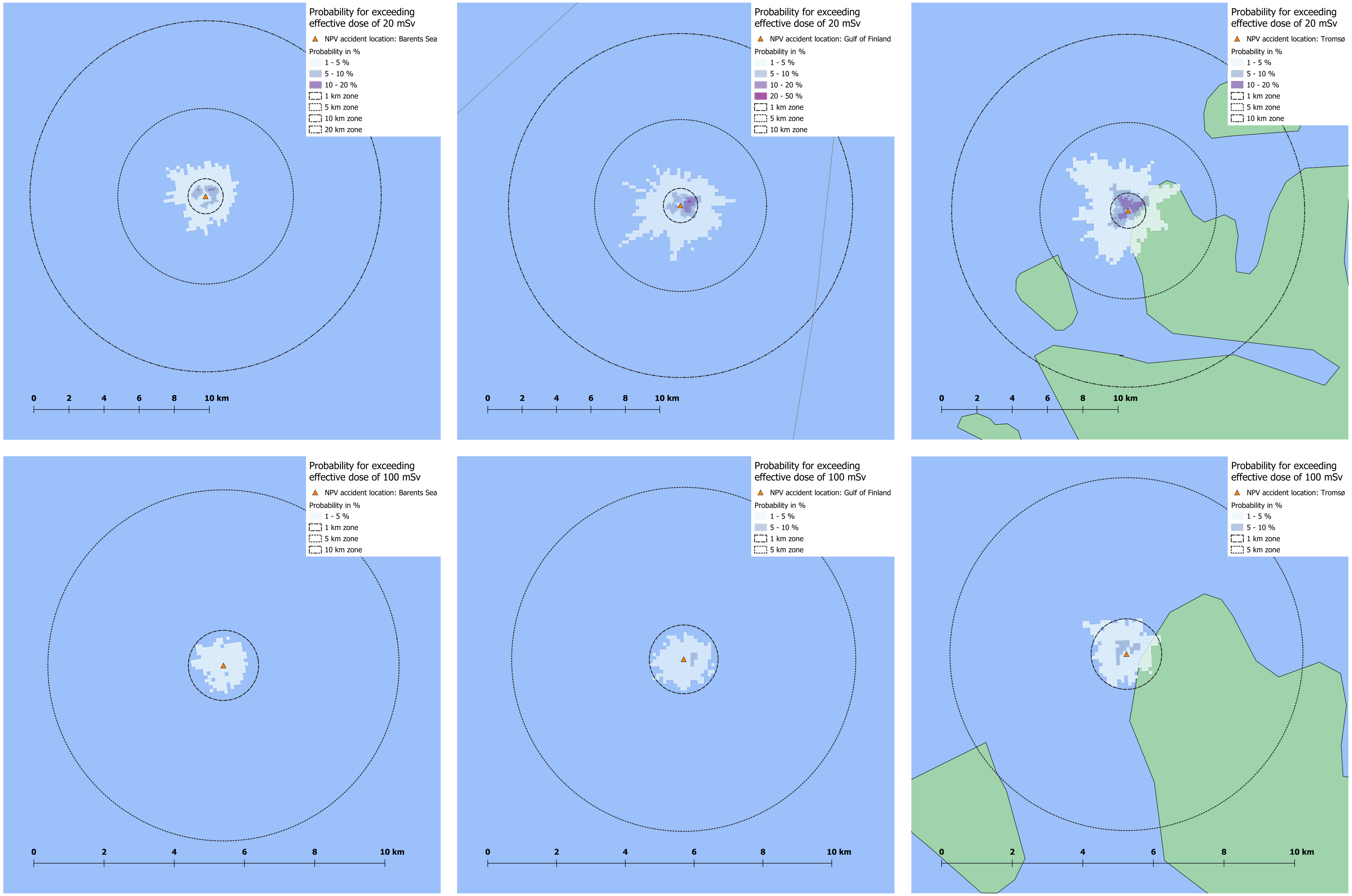

FIGURE 9B. The probabilities for effective dose exceeding 20 (upper) and 100 (4. lower) mSv due to releases from NPV accidents at Barents Sea (left column), the Gulf of Finland (middle column), and the coast of Tromsø (right column).

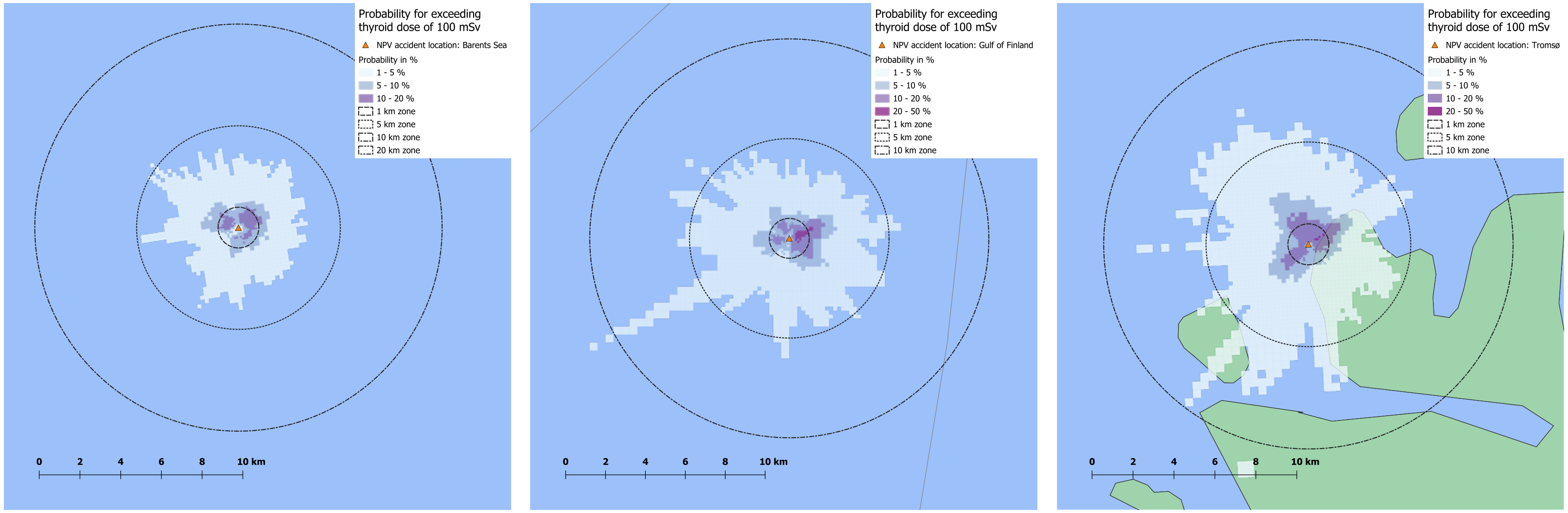

FIGURE 10. The probabilities for thyroid dose exceeding 100 mSv due to releases from NPV accidents at the Barents Sea (left), the Gulf of Finland (middle), and the coast of Tromsø (right).

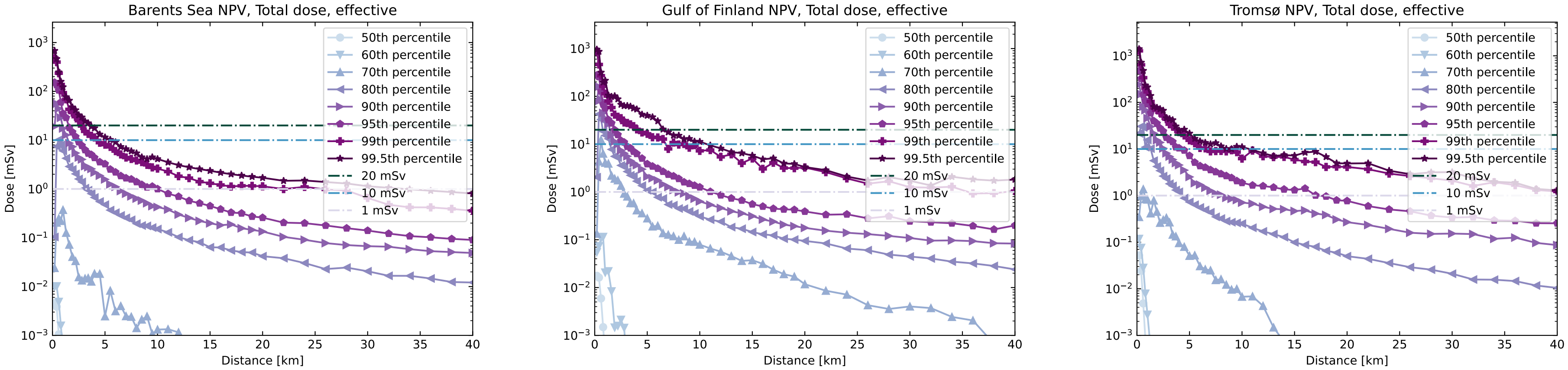

FIGURE 11. Total effective dose as function of distance for different percentiles of data due to releases from NPV accidents at the Barents Sea (left), the Gulf of Finland (middle), and the coast of Tromsø (right). The data from 50th to 99.5th percentile are shown for data points above 1 μSv. Horizontal lines show the dose limits of 1, 10 and 20 mSv.

In general, the cloud of radioactive substances remains fairly narrow when single release scenarios are considered (see Figure 4). When the wind direction varies during the year, the probabilities of exceeding any of the dose criteria remains well below 50%. Due to the same reason, the dose criteria are exceeded with more than 5 percent probability only in the vicinity of the accident location. Based on the analyses it can be concluded that exceeding effective dose of 10 mSv, 20 mSv and 100 mSv beyond 5 km, 3 km, and 1 km, respectively, from the accident location is highly unlikely. Furthermore, it is highly unlikely that thyroid equivalent dose exceeds 100 mSv beyond 7 km from the accident location.

5.2 Consequences of floating nuclear power plant transit accidents

The external dose rate of 1 μSv/h was not exceeded in any of the analyzed release scenarios for FNPP transit accident. Thus, the similar visualizations as in Figure 5 are not meaningful and it can be noted that any of the dose criteria or OILs are not exceeded in the considered FNPP transit accidents. In conclusion, it is highly unlikely that any of the protective actions would not be needed for the people or emergency workers due to considered releases from FNPP transit accident.

The effective and thyroid equivalent doses during first 2 days after the release from FNPP were estimated for marine locations in the Barents Sea and the Kara Strait (see Figures 12 and 13).

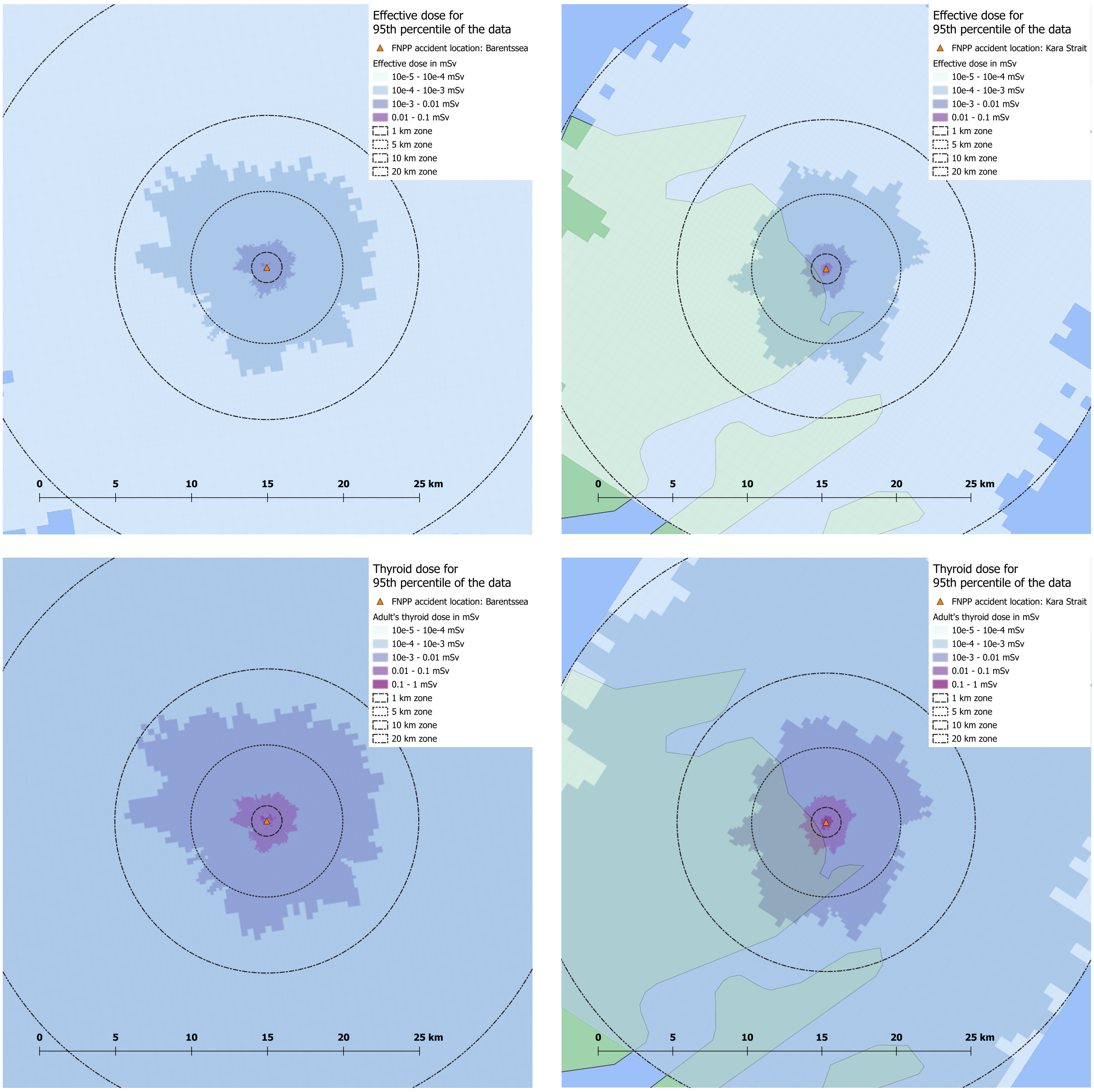

FIGURE 12. Effective dose for 95th percentile of the data for releases from FNPP transit accidents at Barents Sea (left) and Kara Strait (right).

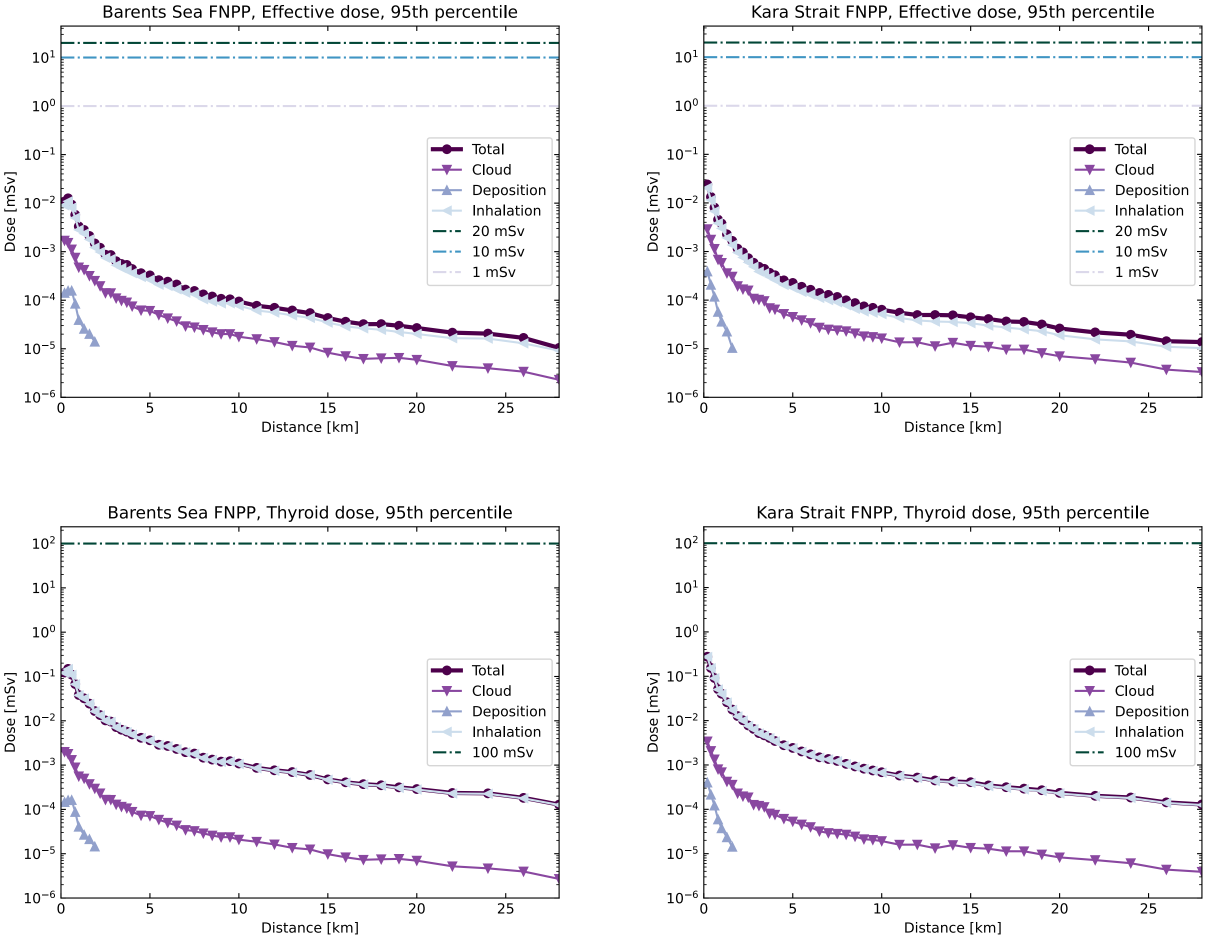

FIGURE 13. Maximum effective dose (upper row) and maximum thyroid dose (lower row) as function of distance for the 95th percentile of data due to releases from FNPP transit accidents at Barents Sea (left) and Kara Strait (right). The doses (●) are built up from components formed by cloud dose (▼), deposition dose (▲), and inhalation dose (◀). Horizontal lines show the dose limits of 1, 10, 20 and 100 mSv.

The effective and thyroid equivalent doses remain below 0.1 mSv and 1 mSv in all considered FNPP transit accidents and the dose criteria are not exceeded due to atmospheric release. Note that the doses on the FNPP are not considered in this work and the dose criteria may still be exceeded in it. World average for external dose rate from natural background is 0,059 μSv/h (UNSCEAR 2010). This leads to an estimate that the normal background causes effective dose of 0,0028 mSv in two days and that at 2 km distance downwind from accident location the external dose rate caused by the release is below the level of natural background.

The graphs in Figure 13 show that the majority of the effective dose is accumulated via inhalation (80.0%). In the considered accidents, the radionuclides in deposition and cloud form about 0.2% and 19.8%, respectively, of the effective dose. Inhaled radionuclides form even bigger part of thyroid equivalent dose (97.8%) as inhaled iodine isotopes accumulate into thyroid. The radionuclides in deposition and cloud form only about 0.02% and 2.2%, respectively, of the thyroid equivalent dose. In NPV accident, radionuclides in deposition formed larger part of total dose than the nuclides in the cloud. This is due to differences in inventories and release fractions. In the FNPP transit accident: 1. the radioactive iodine isotopes (are deposited) form smaller part of the total amount of radionuclides released than in NPV accidents 2. Kr-85 (is not deposited) form a higher part of the total amount of radionuclides released than in the NPV accidents. The same reason applies for cloud exposure causing higher fraction of total effective dose.

The effective was divided to components from different nuclide groups of iodine, cesium, and noble gases (see Figure 14). In the considered FNPP transit accidents, iodine isotopes form the majority of the total effective dose (53%) while cesium isotopes and noble gasses form about 25% and 20%, respectively. Note that also here the noble gases form higher part of the effective dose and in the NPV accident. This finding is in line with differences in inventory and release fractions mentioned above. The fractions of different nuclides are given with more detail in Appendix D.

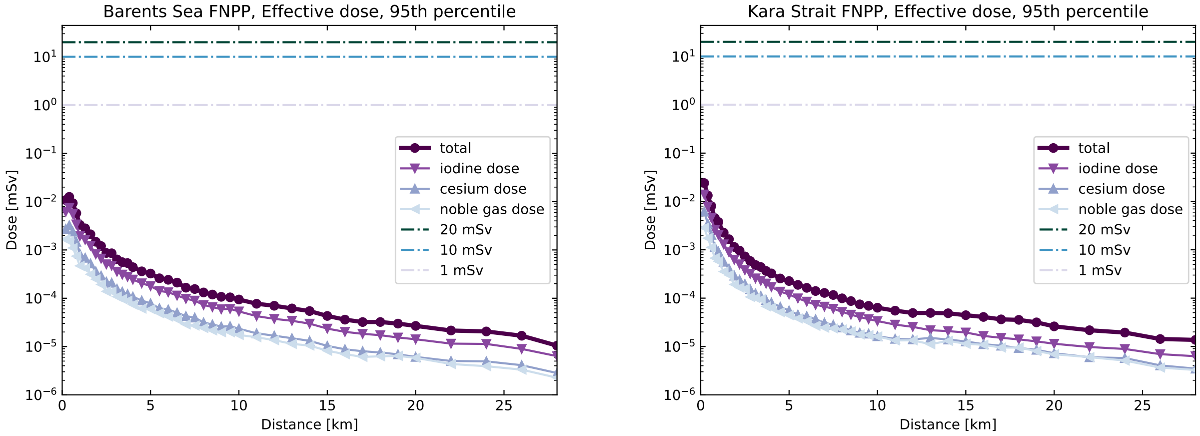

FIGURE 14. Maximum effective dose as a function of distance for the 95th percentile of data due to releases from FNPP accidents at Barents Sea (left) and Kara Strait (right). The total effective dose (●) is built up from components formed by iodine dose (▼), cesium dose (▲), and noble gas dose (◀). Horizontal lines show the dose limits of 1, 10 and 20 mSv.

The effective dose data of FNPP transit accidents in the Barents Sea and the Kara strait are presented in Figure 15 using different percentiles of the data. It can be seen that for data below 80th percentile remains below the dose caused by the natural background (0,0028 mSv in 2 d). Furthermore, the highest effective doses for 99.5th percentile of the data close to the accident locations are only about 30 times larger than the dose caused by the natural background.

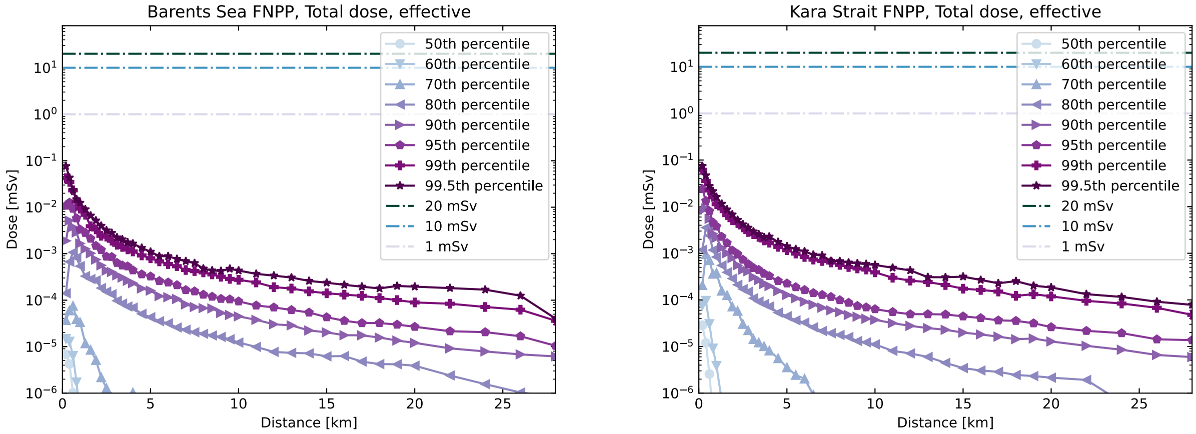

FIGURE 15. Total effective dose as function of distance for different percentiles of data due to releases from FNPP transit accidents at the Barents Sea (left) and the Kara Strait (right). The data from 50th to 99.5th percentile are shown for data points above 1 nSv. Horizontal lines show the dose limits of 1, 10 and 20 mSv.

6 Impact on search and rescue operations

The performed analyses offer estimates of potential consequences due to radioactive releases from an NPV accident and an FNPP transit accident. The results of this study support the preparedness planning for such events and give estimates of distances under which different protective actions might be needed. In case of an accident, the situation assessment must be performed using the available information of the accident and radiation situation. Radiation experts should be used to evaluate and define risks on-scene, define restriction areas, define direction of safe approach, and perform dispersion and dose calculations.

In the early phase of the accident, detailed information may not be available. The results of this type of study may be useful when estimating the potentially affected area. However, the emergency workers should be aware of the uncertainty of the estimates. The actual radiation situation and expert assessments should be confirmed with measurements if suitable equipment is available. When approaching the accident location from the safest direction, external dose rate measurements are essential. Firstly, the measurements guarantee the safety of the emergency workers. Secondly, the measurements can be used to improve the situation assessment, state of the reactors, magnitude of the atmospheric release, dispersion calculations and potential dose estimates. Communication with the accident vessel or with evacuated personnel helps with assessing the situation.

The dispersion model and dose calculation routines used in this study do not take properly into account the shape of the NPV or FNPP or external dose from upper layers of atmosphere. The dispersion model does not consider vortices and recirculation areas born due to the shape of an NPV or FNPP. The formed areas can gather the part of released radioactive substances and delay their dispersion. In the dose estimation, dose conversion factors, that assume half infinite homogeneous cloud, were used. In reality, the assumption of infinity does not describe completely the reality in the vicinity of accident location where concentration gradients may be significant. Together these phenomena cause slight underestimation of the dose in the vicinity of accident location. These factors increase the importance of measurement especially when approaching the scene.

The effective and thyroid doses were estimated for unprotected people. However, the PPE used by the emergency workers protect well, especially against the inhalation dose which was shown to cause the majority of the doses. A worker using an FFP3 mask, half-face mask with P3 filter, or full-face mask with P3 filter would get only 10%, 9%, or 6%, respectively, of the effective doses in NPV accident, and 24%, 23%, or 20%, respectively, of the effective doses in FNPP transit accident. Correspondingly, wearing these masks would lower the thyroid doses to 5%, 4% and 0.6% in an NPV accident, and to 7%, 6% and 2% in an FNPP accident. Here, it is assumed that the PPE does not protect from external radiation and that effective dose from inhaled radioactive particles is reduced according to the APF of the mask (see Section 3.1.). Note, however, that these APFs apply only for particulates and are not fully applicable for, e.g., molecular and organic forms of iodine. Furthermore, the overalls of emergency workers protect against external beta and alpha doses and the skin dose that were not considered in the assessment. Overalls also prevent the spreading of contamination when they are removed at a certain decontamination point on the border of contaminated and uncontaminated areas.

7 Conclusions

The aim of this assessment was to estimate the potential consequences of NPV accidents in the Gulf of Finland, in the Barents Sea, and on the coast nearby the city of Tromsø, and FNPP transit accidents in the Barents Sea and the Kara Strait. The consequences were assessed using probabilistic approach for atmospheric releases using NOMADS weather forecast data from year 2021 and the decision support system JRODOS. In the assessment, the probability and areas of different protective actions needed were estimated. The assessment was performed using external dose rate, effective dose, and thyroid equivalent dose. The basis of the assessment was the OILs and dose criteria defined for people and emergency workers in Finland (STUK 2022).

It was shown that in an NPV accident, the recommendation to limit being outside, sheltering indoors, and evacuation are needed as protective action for people up to 10 km, 3 km, and 2 km, respectively. Furthermore, the thyroid equivalent dose estimates revealed that the iodine prophylaxis for adults may be needed up to 5 km. In an NPV accident, the OIL of 10 µSv/h was exceeded at about 5 km downwind from the scene. The emergency workers should wear PPE in these areas and take other protective action as listed in Table 3, due to the elevated external dose rate. It was estimated that, depending on the type of worn face mask, a worker wearing PPE would receive only 6–10% of the effective dose and 0.6–4% of the thyroid dose of unprotected person in the considered NPV accidents. A correctly worn face mask considerably decreases the radiation doses via inhalation and forms the basis of radioprotection during the emergency. Wearing overalls does not protect emergency workers from external gamma radiation but their proper use prevents spreading of contamination to clean areas.

It was also shown that it is highly unlikely that any of the dose criteria or OILs would be exceeded in the FNPP transit accident due to low release fractions. It needs to be noted, however, that only dose due to atmospheric release was considered. Depending on the release route, the situation onboard or inside the FNPP may be different.

The results of the assessment can be used in the preparedness planning and as rough estimates of the potential consequences and protective actions needed for emergency workers and public. In a real accident, the importance of external dose rate measurements and personal dosimeters are essential. The measurement data provide information about the situation, and they can be used for verification of the results of dispersion and dose models.

Only the direct consequences of the accidents were considered in this assessment and the long-term consequences or consequences to marine or terrestrial environment were not studied. The results of the assessment can, however, be used as an input of such study. Modelled deposition maps can be used as a starting point for dispersion of radionuclides in the environment, radioecological models for uptake of radionuclides by different organisms in Arctic and, finally, potential dose to arctic communities via ingestion.

Acknowledgements

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Appendix A: Inventories of radioactive isotopes

TABLE A1. The inventory of selected radionuclides for civilian marine reactor 0.1 d, 100 d, 3 y, 6 y and 9 y after the end of power production (Reistad et al. 2006a). Note that values for decay time of 3, 6 and 9 years are derived from the values given by (Reistad et al. 2006a).

Decay time	**0.1 d**	**100 d**	**3 y**	**6 y**	**9 y**
Kr-85	1.01E+15	9.92E+14	8.32E+14	6.74E+14	4.50E+14
Xe-133	1.05E+17	2.27E+11	0.00E+00	0.00E+00	0.00E+00
Xe-135	3.78E+16	0.00E+00	0.00E+00	0.00E+00	0.00E+00
I-131	4.54E+16	8.26E+12	0.00E+00	0.00E+00	0.00E+00
I-132	6.76E+16	4.04E+07	0.00E+00	0.00E+00	0.00E+00
I-133	9.02E+16	0.00E+00	0.00E+00	0.00E+00	0.00E+00
I-135	7.70E+16	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cs-134	7.16E+15	6.53E+15	2.61E+15	8.74E+14	1.07E+14
Cs-136	2.13E+15	1.10E+13	0.00E+00	0.00E+00	0.00E+00
Cs-137	8.83E+15	8.77E+15	8.24E+15	7.64E+15	6.62E+15
Sr-89	6.62E+16	1.68E+16	2.00E+10	1.65E+03	0.00E+00
Sr-90	8.68E+15	8.63E+15	8.07E+15	7.46E+15	6.42E+15
Te-132	6.65E+16	3.92E+07	0.00E+00	0.00E+00	0.00E+00
Ba-140	9.72E+16	4.26E+14	0.00E+00	0.00E+00	0.00E+00

Appendix B: Release fractions

TABLE B1. Release fractions of a Nuclear powered vessel (NPV) accident (Reistad et al. 2006a) and transit of a Floating nuclear power plant (FNPP) accident (Compton et al. 2003).

Chemical family	Elements	Release fraction in NPV accident	Release fraction in FNNP accident
Noble gases	Kr, Xe	0.1	0.4
Halogens	I	0.01	3×10^{-3}
Alkali metals	Cs	0.01	1×10^{-6} – 1×10^{-8}
Alkali earth metals	Sr	0.002	1×10^{-8}
Chalcogens	Te	0.01	1×10^{-5} – 1×10^{-7}

Appendix C: Deposition of Cs-137 and I-131 in NPV accident

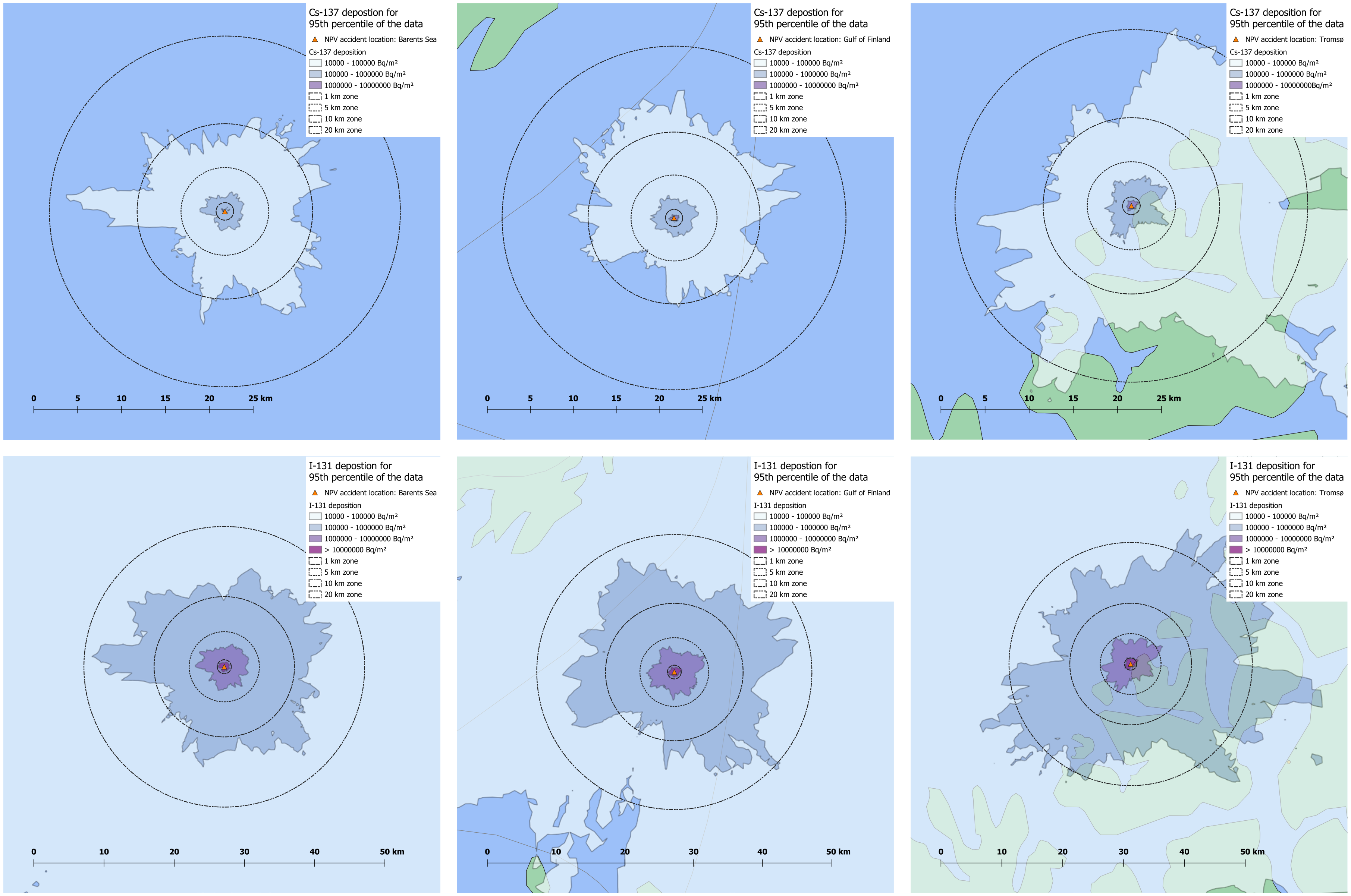

FIGURE C1. Depostion of Cs-137 (upper) and I-131 (lower) for 95th percentile of the data for releases from NPV accidents at the Barents Sea (left), the Gulf of Finland (middle), and the coast of Tromsø (right).

Appendix D:
Effective doses by different nuclides

TABLE D1. The fraction of effective dose formed by the considered radionuclides in NPV accident and FNPP transit accident.

	NPV accident (-)	FNPP transit accident (-)
Kr-85	7.3e-7	1.9e-1
Xe-133	1.6e-3	3.0e-4
Xe-135	3.2e-3	-
I-131	5.0e-1	5.3e-1
I-132	2.1e-2	-
I-133	1.7e-1	-
I-135	2.7e-2	-
Cs-134	2.9e-2	8.2e-2
Cs-136	2.3e-2	1.2e-6
Cs-137	2.4e-3	1.7e-1
Sr-89	4.6e-2	1.1e-3
Sr-90	3.6e-2	1.5e-2
Te-132	7.3e-2	-
Ba-140	6.0e-2	1.9e-3

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