



HAL
open science

Global and local cancer risks after the Fukushima Nuclear Power Plant accident as seen from Chernobyl: A modeling study for radiocaesium (^{134}Cs & ^{137}Cs)

Nikolaos Evangeliou, Yves Balkanski, Anne Cozic, Anders Pape Møller

► To cite this version:

Nikolaos Evangeliou, Yves Balkanski, Anne Cozic, Anders Pape Møller. Global and local cancer risks after the Fukushima Nuclear Power Plant accident as seen from Chernobyl: A modeling study for radiocaesium (^{134}Cs & ^{137}Cs). *Environment International*, 2014, pp.17-27. 10.1016/j.envint.2013.11.020 . hal-02874061

HAL Id: hal-02874061

<https://hal.science/hal-02874061>

Submitted on 24 Jun 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Global and local cancer risks after the Fukushima Nuclear Power Plant accident as seen from Chernobyl: A modeling study for radiocaesium (^{134}Cs & ^{137}Cs)



Nikolaos Evangeliou^{a,*}, Yves Balkanski^a, Anne Cozic^a, Anders Pape Møller^b

^a Laboratoire des Sciences du Climat et de l'Environnement (LSCE), CEA-UVSQ-CNRS UMR 8212, Institut Pierre et Simon Laplace, L'Orme des Merisiers, F-91191 Gif sur Yvette Cedex, France

^b Laboratoire d'Ecologie, Systématique et Evolution, CNRS UMR 8079, Université Paris-Sud, Bâtiment 362, F-91405 Orsay Cedex, France

ARTICLE INFO

Article history:

Received 10 September 2013

Accepted 29 November 2013

Available online 20 December 2013

Keywords:

Cancer
Caesium-137
Fukushima
LNT-model
Death risks

ABSTRACT

The accident at the Fukushima Daiichi Nuclear Power Plant (NPP) in Japan resulted in the release of a large number of fission products that were transported worldwide. We study the effects of two of the most dangerous radionuclides emitted, ^{137}Cs (half-life: 30.2 years) and ^{134}Cs (half-life: 2.06 years), which were transported across the world constituting the global fallout (together with iodine isotopes and noble gases) after nuclear releases. The main purpose is to provide preliminary cancer risk estimates after the Fukushima NPP accident, in terms of excess lifetime incident and death risks, prior to epidemiology, and compare them with those occurred after the Chernobyl accident. Moreover, cancer risks are presented for the local population in the form of high-resolution risk maps for 3 population classes and for both sexes. The atmospheric transport model LMDZORINCA was used to simulate the global dispersion of radiocaesium after the accident. Air and ground activity concentrations have been incorporated with monitoring data as input to the LNT-model (Linear Non-Threshold) frequently used in risk assessments of all solid cancers. Cancer risks were estimated to be small for the global population in regions outside Japan. Women are more sensitive to radiation than men, although the largest risks were recorded for infants; the risk is not depended on the sex at the age-at-exposure. Radiation risks from Fukushima were more enhanced near the plant, while the evacuation measures were crucial for its reduction. According to our estimations, 730–1700 excess cancer incidents are expected of which around 65% may be fatal, which are very close to what has been already published (see references therein). Finally, we applied the same calculations using the DDREF (Dose and Dose Rate Effectiveness Factor), which is recommended by the ICRP, UNSCEAR and EPA as an alternative reduction factor instead of using a threshold value (which is still unknown). Excess lifetime cancer incidents were estimated to be between 360 and 850, whereas 220–520 of them will be fatal. Nevertheless, these numbers are expected to be even smaller, as the response of the Japanese official authorities to the accident was rapid. The projected cancer incidents are much lower than the casualties occurred from the earthquake itself (>20,000) and also smaller than the accident of Chernobyl.

© 2013 Elsevier Ltd. All rights reserved.

1. Introduction

Accidental releases of radioactive material have occurred several times at NPP with Chernobyl and, recently, Fukushima to be the most severe events (Fesenko et al., 2004; Terada et al., 2012). Modeling tools may prove very efficient in assisting the authorities in decision-making and preventing extended radiological exposure of the population (WHO, 2012). However, environmental contamination cannot be prevented and may affect the public indirectly. High doses have deleterious consequences for humans, including, but not exclusively, enhanced cancer occurrences. At doses greater than 50–100 mSv

(protracted exposure) or 10–50 mSv (acute exposure), direct epidemiological evidence demonstrates increased risk for some cancers. Nevertheless, the situation is much less clear for very low radiation doses, although the risks of low-dose radiation are of societal importance due to medical tests, occupational exposure, radiological terrorism etc. (e.g. Brenner et al., 2003). Once radionuclides are released, they may enter the body directly by ingestion and inhalation causing DNA and cell damage, and cancers known to have a mutational basis. Another irradiation factor is external exposure, which might be chronic or acute. The first includes irradiation from radionuclides deposited at the ground's surface, whereas the second during fallout transport.

The tsunami that struck the Fukushima Daiichi NPP in northeastern Japan in 2011 caused significant fuel meltdown along with hydrogen explosions after the cooling system failed. Several radionuclides were released into the atmosphere and dispersed over long distances. The emissions lasted for about 40 days (whereas additional discharges of

* Corresponding author at: Laboratoire des Sciences du Climat et de l'Environnement (LSCE), CEA-CNRS-UVSQ, Institut Pierre et Simon Laplace, L'Orme des Merisiers, F-91191 Gif sur Yvette Cedex, France. Tel.: +33 1 6908 1278; fax: +33 1 6908 3073.

E-mail address: Nikolaos.Evangeliou@lsce.ipsl.fr (N. Evangeliou).

cooling water to the Pacific Ocean are still ongoing) and traces of radionuclides were detected worldwide (Diaz Leon et al., 2011; Hong et al., 2012; Masson et al., 2011). Two years after the accident, the cancer risk to the population remains unknown, as no epidemiological studies are available yet. In fact, the effects of radiation to humans can be assessed several years later through the cancer registration system of Japan, when death certificates are available and a statistic analysis is possible.

The present study provides estimates of the worldwide health effects from the Fukushima NPP accident, in terms of excess lifetime cancer incident and death risks prior to epidemiology. We have used the LNT-model, also used by the World Health Organization (WHO, 2013), to quantify the health impact with respect to radiogenic cancer diseases. The main goal is to evaluate our model's response by addressing the global health risks from the accident in Japan and comparing them with the findings of the WHO (based on measurements). This is very important if one takes into account that a large number of NPPs already exists (437) presenting an increasing trend in the future (see Fig. S1, Supplementary Information—SI). A sensitivity analysis is also attempted by assessing how the different model resolutions affect the results (presenting risks after Chernobyl). In addition, we provide high-resolution maps of excess lifetime cancer incident and death risks to the local population of 2010, in contrast to the region-specific estimates reported by Ten Hoeve and Jacobson (2012). However, because many researchers argue on the use of the LNT-model for such calculations, we present the same excess lifetime risks using a DDREF of 2 as a reduction factor instead of a threshold (still uncertain), below which no visible effects on humans can be observed. In addition, we present age- and sex-specific LAR (Lifetime Attributable Risk) and LFR (Lifetime Fractional Risk) maps for the local population of Japan. Deaths from Fukushima are expected to be fewer than from Chernobyl by more than an order of magnitude due to lower total emissions, lower deposition rates over populated land and more precautionary measures taken immediately after the accident (Ten Hoeve and Jacobson, 2012).

2. Methodology

2.1. Source emission and model general characteristics

The aerosol module INCA (INteractions between Chemistry and Aerosols) is coupled to the general circulation model (GCM), LMDz, developed at the Laboratoire de Météorologie Dynamique in Paris, and the global vegetation model ORCHIDEE (ORganizing Carbon and Hydrology In Dynamic Ecosystems Environment) (LMDZORINCA) (see also Szopa et al., 2012). The gas phase chemistry part in the model is described by Hauglustaine et al. (2004). Aerosols and gasses are treated in the same code to ensure coherence between gas phase chemistry and aerosol dynamics as well as possible interactions between gasses and aerosol particles. The model was used in the simulations for the Chernobyl and Fukushima accidents achieving a maximum horizontal resolution of 2.5° in longitude and 1.27° in latitude (regular grid). However, the GCM also offers the possibility to zoom over specific regions by stretching the grid with the same number of grid-boxes. In the present study the zoom version was used for Europe (Chernobyl runs) and Asia (Fukushima runs for the local health assessment) achieving a resolution of 0.45° × 0.51°. On the vertical plane, the model uses sigma-p coordinates with 19 levels extending from the surface up to about 3.8 hPa corresponding to a vertical resolution of about 300–500 m in the planetary boundary layer (first level at 70 m height) and to a resolution of about 2 km at the tropopause (with 7–9 levels located in the stratosphere). Each simulation lasted until the end of the year, which is a sufficient period for the 99.5% of ¹³⁷Cs to be deposited (Brandt et al., 2002; Paatero et al., 2012). As regards to the emissions of ¹³⁷Cs, the inventories (36.7 PBq) reported by Stohl et al. (2012) were adopted estimated by inverse modeling using the CTBTO (Comprehensive Nuclear Test Ban Treaty Organization) global measurement network. For the

Chernobyl accident, the emissions reported by De Cort et al. (1998) were used.

LMDZORINCA accounts for emissions, transport (resolved and sub-grid scales), photochemical transformations, and scavenging (dry deposition and washout) of chemical species and aerosols interactively in the GCM. Several versions of the model are currently available depending on the envisaged applications with the chemistry–climate model. The model runs in a nudged mode (using the ERA40 Re-analysis data – 6 h wind fields – by the European Centre for Medium-Range Weather Forecasts, ECMWF, 2002) with a relaxation time of 10 days for the regular grid, whereas for the zoom version relaxing to 4.8 days in the center of the zoom and to 10 days outside (Hourdin and Issartel, 2000).

The radioactive tracer ¹³⁷Cs (half-life = 30.2 years) was inserted as an inert tracer within the model. The behavior of ¹³⁷Cs in the atmosphere is strongly related to its chemical form as it may be released in the atmosphere in gaseous form or adsorbed onto particles. Here, it is assumed that mostly ¹³⁷Cs behaves as an aerosol and as such it is treated in the model. In fact, this is true, as it has been reported that over 80% of the ¹³⁷Cs emitted in the atmosphere during accidental releases is in the form of particulates (Potiriadis et al., 2011; Ritchie and McHenry, 1990; Sportisse, 2007; Yoschenko et al., 2006). The partitioning between gaseous form and particles and the size distribution of aerosols strongly affects dry deposition and scavenging, which is presented in detail in the SI (p. 3–6). We examine radiocaesium isotopes (¹³⁴Cs and ¹³⁷Cs) because, together with ¹³¹I and ¹³³Xe (half-lives: 8.02 and 5.24 days), they have been found to be the most abundant in the global fallout after Fukushima (Christoudias and Lelieveld, 2013; Kristiansen et al., 2012; Stohl et al., 2012). Moreover, they emit gamma rays and can substitute potassium in living organisms; hence, they are among the most dangerous.

2.2. Risk calculations to humans

The LNT-model of human exposure (SI, p. 6) was used to calculate radiological health effects, similar to the Chernobyl accident (EPA, 1999; ICRP, 2005). The model assumes that each radionuclide's disintegration has the same probability of causing cell transformation, and that each transformed cell has the same probability of developing a cancer tumor. Although the LNT-model has been employed extensively in radiation safety (NRC, 2006; UNSCEAR, 2010), several arguments about its validity and response at low doses still remain unresolved. For example, Cuttler (2010) stated that low doses of radiation might improve health in living organisms including humans, whereas Tubiana et al. (2009) argued for its use based on radiation biological and experimental data. This is mainly because epidemiological studies have only considered doses above 100 mSv showing a statistically significant increase in stochastic cancer risk, although at doses below 100 mSv significance or lack thereof has not been observed. On the other hand, supporters of the LNT-model claim that the difficulty in detecting and attributing a small number of cancers to low doses does not necessarily indicate that there is an absence of risk at these doses (Hoffman et al., 2012). Nevertheless, given that the NRC (Nuclear Regulatory Commission) and the WHO accept the LNT hypothesis for health assessments, we adopted it in the study. The main purpose for that was mainly to compare our results to what the WHO has already published (WHO, 2013).

A radiogenic cancer risk model defines the relationship between radiation dose and the subsequent force of death (or incident) attributable to that dose. Death risk is defined as an estimate of the risk to an average member of the population of dying from cancer over its lifetime. Incident risk is the risk of experiencing radiogenic cancer during a person's lifetime, whether or not the cancer is fatal. Inhalation exposure, ground-level external exposure, and atmospheric external exposure pathways were considered for ¹³⁴Cs, ¹³⁷Cs, and their decay products ¹³⁴Ba and ^{137m}Ba, respectively (ICRP, 1995). Health effects from

radionuclide ingestion pathways were only calculated for the Japanese population based on monitoring data reported by the WHO (2012). In these calculations, it is assumed that the local population exclusively consumes food produced in areas where food monitoring was implemented and the deposition of ¹³⁷Cs decreases only by radioactive decay. The respective contribution of ¹³⁴Cs deposition rates in each grid cell and time step was also included assuming a ¹³⁴Cs/¹³⁷Cs isotopic ratio of 0.92, based on CTBTO observations following the Fukushima NPP accident (Christoudias and Lelieveld, 2013). However, considering that a full range monitoring system has been established in Japan after the radioactive releases, it is expected that this pathway might be overestimated here as all the foodstuffs are measured for radioactive substances and are handled according to international and national standards. On the other hand, in coastal regions of Japan located far from the large population centers it is expected that fishermen might consume food products without prior radioactivity monitoring. Taking into account that cooling water from the damaged reactor is still discharged to the ocean, several inhabitants may consume contaminated foodstuffs. This practically means that the model may underestimate the risk coming from food ingestion.

LAR was calculated, which specifies the probability of a premature incident of a cancer attributable to radiation exposure in a representative member of the population (Kellerer et al., 2001; Thomas et al., 1992; Vaeth and Pierce, 1990). For a given dose, LAR is the additional cumulated probability of having a specific cancer up to the age of 89 years (89 years is the average death age of the Japanese population, WHO, 2013). It relies on the use of a risk model derived from the epidemiological literature and is a classical risk indicator in the field of radiation protection. LAR specifies for a person exposed to a low dose the radiation-related excess probability for a fatal cancer. If, as is usual, the concept is applied to an exposed population, it specifies the expected number of fatalities, and such numbers – when they are not linked to the number of spontaneous cases – can be misleading. It is then more conducive for a realistic perception of risk to refer to a relative number. Such a number is obtained if LAR is scaled to the lifetime spontaneous cancer death (or incident) in the reference population leading to the LFR. All the relative functions used to calculate the LAR and LFR probabilities can be seen in SI (pages 6–11). They have been calculated for both sexes (males and females) and ages of 1 year (infants), 10 years (children) and 20 years (young adults) in different locations of Japan and for all solid cancers.

Moreover, the excess lifetime cancer death and incident risk from each exposure pathway (below for inhalation and ingestion) was calculated by the following equation (Ten Hoeve and Jacobson, 2012):

$$R_s = \sum_i \sum_j \left\{ P_{ij} \left[1 - \exp \left[-r_s \sum_t \left(I_r (A_{i,j,t,s} - A_{th,d}, 0) \right) \right] \right] \right\} \quad (1)$$

where

- R_s is the total number of lifetime cancer deaths or incidents due to species s over all times t and grid cells ij ,
- P_{ij} is the 2010 population (or 1990 population for the estimates of Chernobyl) in each grid cell ij (NASA, 2013),
- r_s is the relative cancer death or incident risk coefficient for species s expressed in units of Bq^{-1} (or $m^2 Bq^{-1}$ and $m^3 Bq^{-1}$ for ground-level and external atmospheric exposure) from EPA (1994),
- I_r is the inhalation or ingestion rate ($17.8 m^3 day^{-1}$, EPA, 1999 and $0.75 kg day^{-1}$, Table S1 (SI)),
- $A_{i,j,t,s}$ is the species concentrations in each grid cell ij at time t , and
- $A_{th,d}$ is the threshold concentration below which no health effect occurs (for the LNT-model is zero by default). For the calculation of the risks from food ingestion, monitoring data for the foodstuffs cereals, green vegetables, root vegetables, orchard

fruits, soft fruits, milk, beef, lamp, fish and mushrooms were taken from the WHO (2012).

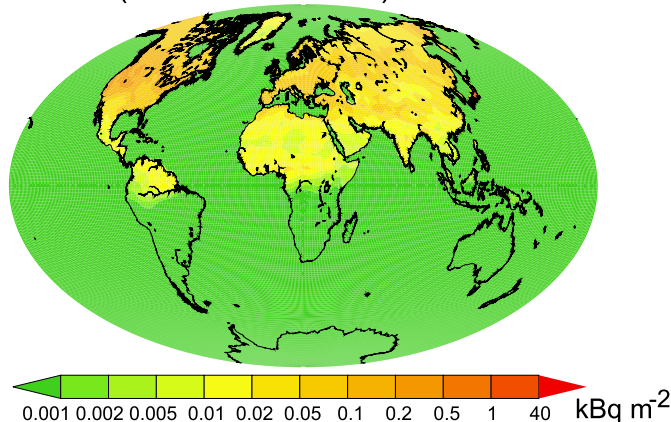
External ground deposition and external atmospheric exposure were calculated using the same equation without the respective internal rates (I_r). The respective incident risks for ¹³⁴Cs (ground deposition, atmospheric exposure) were adopted from EPA (1994). The shielding effect inside structures was also taken into account by assuming a 30% reduction in exposure from particulate ¹³⁴Cs, ¹³⁷Cs and their decay products for 12 h each day when people are assumed to be indoors (Price and Jayaraman, 2006). However, the effect of the vertical migration of radiocaesium (in ground based exposure pathway) was not taken into consideration and the only temporal reduction of the radionuclides occurred via radioactive decay. It has been found that radiocaesium resided in the atmosphere for 2–3 months after the accident (Long et al., 2012; Masson et al., 2011; McMullin et al., 2012; Paatero et al., 2012); therefore, external atmospheric and internal inhalation exposures were negligible after 3 months and only ground-level exposure was significant the following years.

3. Results

3.1. Deposition, annual doses from radiocaesium and comparison with measurements

The global deposition of radiocaesium from Fukushima is shown in Fig. 1 for 2011. The maximum value at the relevant scale is $40 kBq m^{-2}$

Cumulative deposition of radiocaesium (Cs-134 & Cs-137) in 2011



Effective dose from radiocaesium (Cs-134 & Cs-137) in 2011

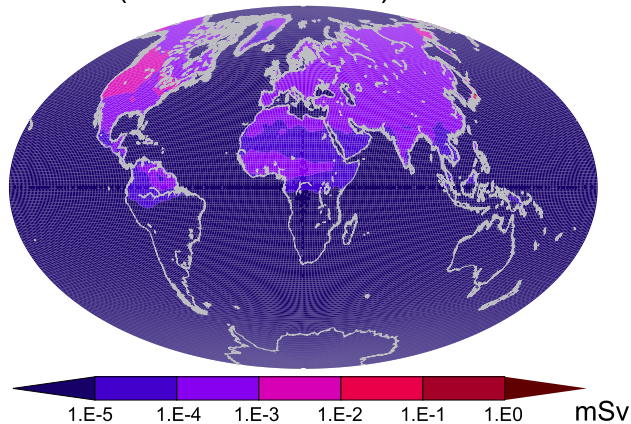


Fig. 1. Global cumulative deposition of radiocaesium (¹³⁴Cs and ¹³⁷Cs) after the Fukushima NPP accident at the end of 2011. Annual effective dose from radiocaesium exposure due to inhalation, surface deposition and fallout transport.

as it is the threshold value of radioactive contamination (IAEA, 2009). The highest deposition was found in the pixel of Fukushima (in the range of MBq m^{-2}), where deposition exceeded the contamination limit affecting an area with more than 9 million inhabitants. In the West USA the deposition was found between 100 and 500 Bq m^{-2} decreasing to the East. For the South-west USA, Wetherbee et al. (2012) reported that the deposition of ^{137}Cs was $30\text{--}240 \text{ Bq m}^{-2}$ and $2\text{--}46 \text{ Bq m}^{-2}$ for ^{134}Cs , which is in the same order as in our calculations (Fig. 1). The same investigators reported a deposition of ^{137}Cs in Alaska to be $16\text{--}27 \text{ Bq m}^{-2}$ and around 55 Bq m^{-2} for ^{134}Cs similar to those presented here ($50\text{--}100 \text{ Bq m}^{-2}$). In the rest of the US they measured ^{137}Cs between 1 and 45 Bq m^{-2} and ^{134}Cs between 1 and 3 Bq m^{-2} , which are close to ours ($50\text{--}200 \text{ Bq m}^{-2}$), although we slightly overestimate. Low deposition of radiocaesium was observed in Europe with the respective values to be $20\text{--}100 \text{ Bq m}^{-2}$, which are slightly overestimated comparing to what has been recorded. For example, Povinec et al. (2012) measured a deposition between 2 and 114 Bq m^{-2} for ^{137}Cs and up to 100 Bq m^{-2} for ^{134}Cs in Slovakia, Barsanti et al. (2012) reported a radiocaesium deposition of 0.3 Bq m^{-2} in La Spezia (Italy), Carvalho et al. (2012) reported 1 Bq m^{-2} of radiocaesium in Portugal, Evrard et al. (2012) found ^{134}Cs deposition near Paris (France) to be around 2 Bq m^{-2} , Kritidis et al. (2012) observed ^{137}Cs deposition in Athens (Greece) around 10 Bq m^{-2} , and Pham et al. (2012) assessed that the deposition of radiocaesium in Monaco is few Bq m^{-2} . The model also predicted identically low depositions over Asia ($0.5\text{--}50 \text{ Bq m}^{-2}$), which are comparable to observations (e.g. 3 Bq m^{-2} in Korea, Kim et al., 2012). Further comparison of ambient ^{137}Cs concentrations from the model and the CTBTO network can be found in the SI (Fig. S4).

Regarding dosimetric calculations, there were assumptions about the implementation of protective measures and food consumption based on options that are more likely to overestimate than to underestimate the radiation exposure. For example, the assumption that all foodstuffs were obtained from the market where monitoring occurs (given that this is a rural prefecture, a lot – perhaps most – of the foodstuffs may derive from gardens and farms); also, the assumption that all people in Fukushima prefecture consumed only food produced in Japan. Therefore, some possible dose overestimation may have occurred. In the present study, dosimetric calculations were applied using environmental modeling and food monitoring data, rather than direct human measurements. The experience from Chernobyl has shown that when whole-body counting was used to determine human exposure, the resulting doses were much lower (IAEA, 2006). Monitoring data of internal and external exposures at Fukushima during the last 2 years show that, in some cases, the doses reported here might be slightly higher (Akahane et al., 2012; Kamada et al., 2012; Monzen et al., 2011; Tsubokura et al., 2012). Applying the gridded data of the 2010 global population in the excess lifetime risk calculations, we estimate that more than 90% of the Japanese residents received an annual effective dose from radiocaesium of less than 0.5 mSv , whereas the rest received up to 5 mSv . However, it is expected that this percentage exposure to the highest levels is even smaller when taking into account the interventions that can reduce radiation exposure (e.g. evacuation) including more stringent standards and remedial actions (e.g. cleanup of buildings, remediation of soils and vegetation, treatment of agricultural fields, waste management) that cannot be accounted for in the model.

3.2. Global health risks of low-level radiation exposure

Radiation exposure can be acute over short time-scales (accidents) or chronic (occupational exposure). In general, protracted exposures are associated with lower risks than acute ones for the same total dose, both for cancer and other endpoints (Little et al., 2009). Good evidence of an increase in cancer risk is shown for acute doses of greater than 50 mSv . As expected from basic radiobiology, the doses above, where statistically significant risks are seen, are somewhat higher

for protracted exposures than for acute ones (Boice, 2012). The dose–response relations used in the present study are depicted in Fig. S3 (SI). The linear relation is a possible descriptor of low-dose radiation oncogenesis, although different endpoints may well exhibit differently shaped dose–response relations. About one fifth of people worldwide and one third of people in industrialized regions are diagnosed with cancer during their lifetime (IARC, 2008). Radiation can induce cancers that are indistinguishable from cancers resulting from other causes. Most population-based cancer risk estimates come primarily from the Japanese atomic bomb survivors. In addition, there are several other sources of radiation exposure of which useful epidemiological data are available (e.g. past accidents, medical and environmental exposures). Increased radiation-related risks have been observed for leukemia (Tsushima et al., 2012), and for a large number of solid cancer sites (Douple et al., 2011).

The global excess lifetime death risks from radiocaesium for the Fukushima accident (applying zero threshold in Eq. (1)) are depicted in Fig. 2 for the gridded population of 2010, together with the respective ones just after the Chernobyl accident in 1986 (for the population of 1990). Finally, an estimation of the contribution of both accidents is shown for the global population of 2010 for an average life expectancy of 69 years assuming physical decay and indoor occupancy to be the reducing factor after Chernobyl. The pathways of deposition, air-submersion and inhalation were taken into consideration, whereas food ingestion was assumed to be negligible in these global estimates. Caesium-134 was included in radiocaesium estimations for the Chernobyl accident using the respective isotopic ratio $^{134}\text{Cs}/^{137}\text{Cs}$ equal to 0.5 certified by measurements (De Cort et al., 1998). The accident in Japan presents a negligible radiological risk, both in terms of cancer incidents and deaths, with a peak in the adjacent regions of the NPP (Fig. 2) as approximately 80% of the released radionuclides were deposited in the ocean and only 20% across populated regions (Christoudias and Lelieveld, 2013).

The number of projected deaths, however, is still considerably smaller than the estimated ones after Chernobyl (Fig. 2), due to the larger emissions after Chernobyl (139 PBq of radiocaesium after Chernobyl, 69.7 PBq after Fukushima) and also because most of them were deposited over continental regions (90%). Definitely, the most dangerous exposure pathways remain inhalation and ingestion as internal factors, although deposition may play an important role as a chronic parameter. An example of chronic exposure is given in Fig. 2, where health risks from radiocaesium were estimated from both accidents. Although we account for radioactive decay and indoor occupancy, there is still enhanced excess lifetime cancer incident and death risk for the global population of 2010 for the areas around the nuclear site of Chernobyl.

4. Discussion

4.1. Importance of model resolution

Fig. 3 depicts excess lifetime risks from radiocaesium (applying zero threshold) after the Chernobyl accident from air-submersion, inhalation and deposition exposures. The vast majority of the incident and death risks were estimated in the nearby countries of the NPP, although significant ones were observed in Sweden and Finland and Greece and Turkey following the fallout transport and the prevailing precipitation patterns (Brandt et al., 2002; Evangelioi et al., 2013). However, when a better-resolved version of our model was used ($0.45^\circ \times 0.51^\circ$) much lower levels of danger were recorded limited to the restricted exclusion zone. In fact, this is very accurate since the dose rates observed in this area just after the accident were such that no human would be able to survive for many days without taking a lethal dose of radiation. For example, the radiation levels near the reactor building have been estimated to be $5.6 \text{ Roentgens per second}$ (R s^{-1}), equivalent to more than $20,000 \text{ Roentgens per hour}$ (lethal dose: $500 \text{ Roentgens over } 5 \text{ h}$) (Medvedev, 1990). Approximately 50% of the lifetime risk was due to inhalation, whereas the rest was caused by air-submersion and

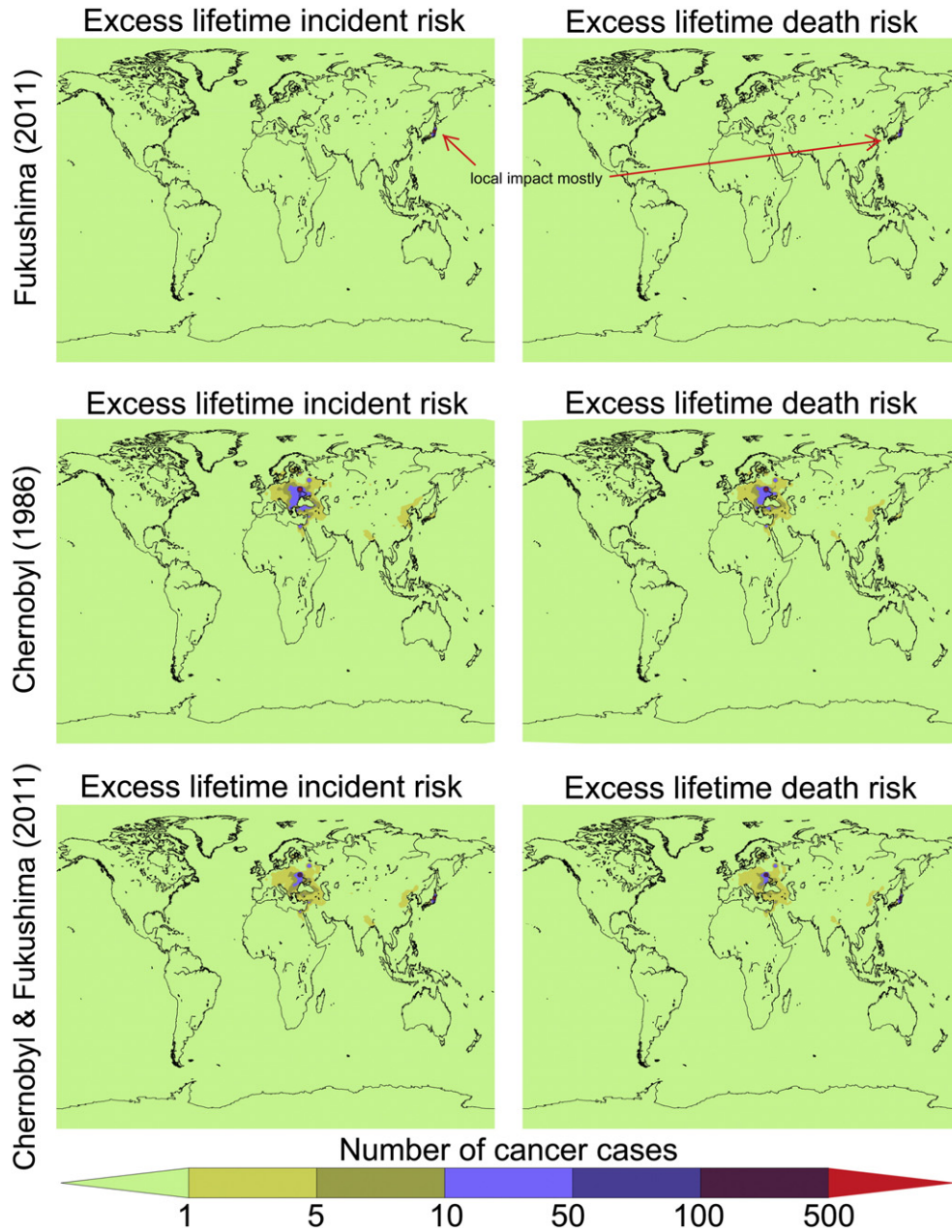


Fig. 2. Global excess lifetime cancer incident and death risks from radiocaesium (^{134}Cs and ^{137}Cs) after the Fukushima accident applied to the global population of 2010. In contrast, the same excess lifetime risks have been estimated after the Chernobyl accident for the global population of 1990. Also, the impact of both accidents is presented for the population of 2010 assuming that the only reducing parameters after Chernobyl are the physical decay of the radionuclides and the indoor-human occupancy.

deposition. Ingestion was not taken into consideration due to the lack of statistical data. In total, excess lifetime risks obtained using both model resolutions for the Chernobyl accident differ by about 25%, with the lowest observed using the highest resolution. Therefore, a possibility of overestimation should be considered in such studies increasing the total uncertainty of the calculations.

4.2. Health risks of the Japanese population

In order to be more accurate and efficient in this preliminary metrics of radiation risk without causing panic to the population, the resolution of $0.45^\circ \times 0.51^\circ$ was used over Asia. LAR and LFR for all solid cancers were estimated for infants (1 year old), children (10 years old) and young adults (20 years old) of both sexes and are illustrated in Fig. 4 and Fig. S5 (SI). LAR expresses the probability of a premature incident of a

radiation-related cancer. The concept of LAR has an implicit “cumulative” nature derived from the way LAR values are calculated: as an integration of the risk that could be attributed to radiation exposure, arising on a year-per-year basis (excluding the latency period). In this context, LAR is an “extra” lifetime risk that is added to an already existing Lifetime Baseline Risk (LBR) (SI, page 9). The LFR reflects the relative increase in cancer risk that could be attributed to radiation exposure.

LAR in Japan is higher in female infants (>14 in 10,000), and lower for 10-year-old male children (<4 in 10,000) for the areas of approximately 100 km northeast of the Fukushima NPP, and in general higher for females as shown in Fig. 4. Inhalation exposure contributed to LAR for approximately 46%, whereas 29% was due to deposition, 22% was due to ingestion, and 3% was due to the external air submersion (Fig. 5). These results are in good agreement with reported values by the WHO (2013). If the inhalation exposure pathway is excluded, risks

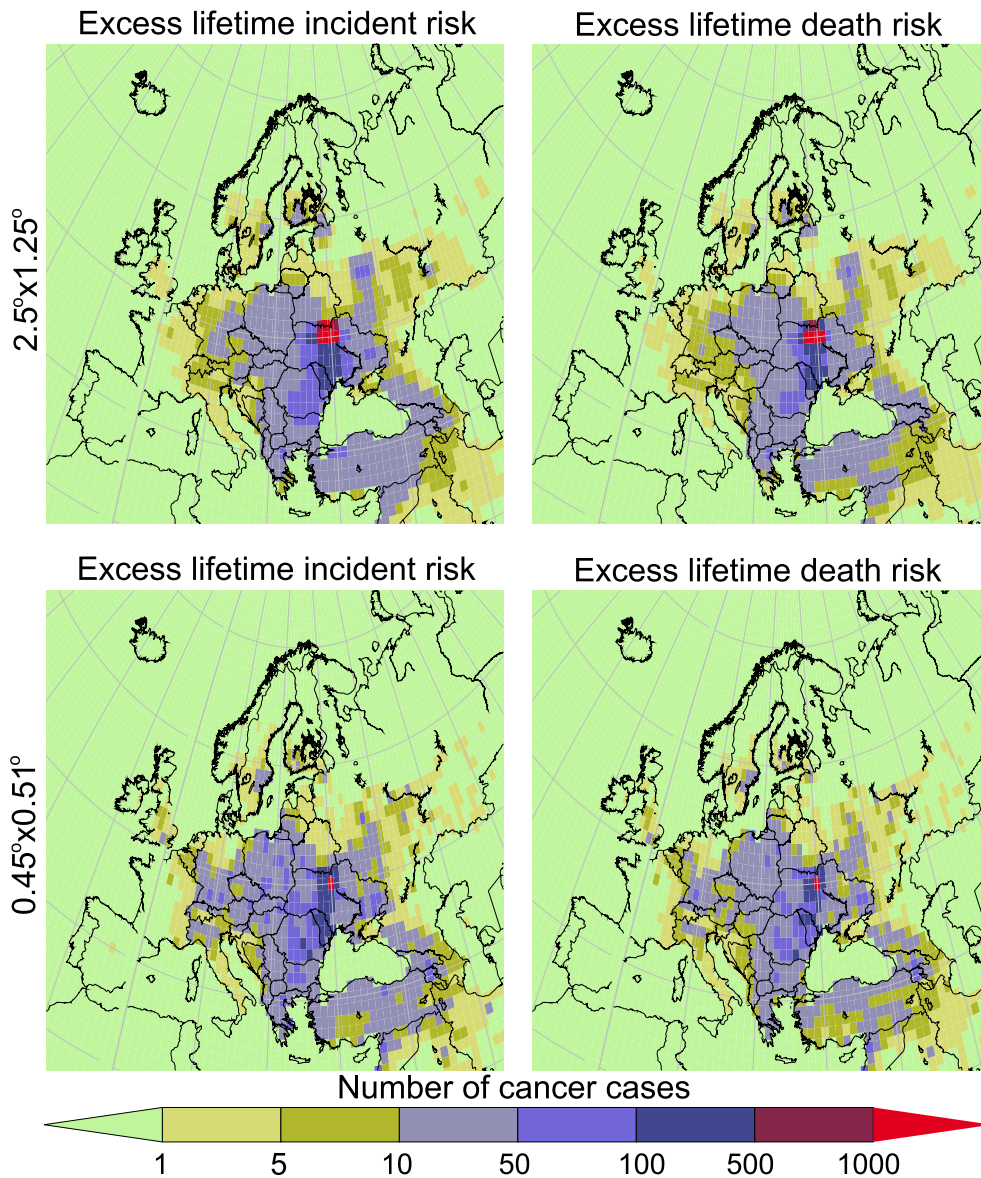


Fig. 3. Excess lifetime cancer incident and death risks from radiocaesium (^{134}Cs and ^{137}Cs) after the Chernobyl NPP accident in Ukraine (1986) using 2 different resolutions in the model. Using the highest resolution more than 25% lower risks are obtained.

are higher for 1-year-old infants and 10-year-old children than for 20-year-old adults. However, given that the inhalation rate for infants and children is much smaller ($5.2 \text{ m}^3 \text{ day}^{-1}$ for infants, 15.28 for children and 22.18 for adults), LAR was calculated to be higher for adults.

LFR follows the same patterns (Fig. S5) and is highest for adult and infant females in the restricted area of the NPP (1.1%), whereas it falls below 0.2% (minimum) in the nearby Tokyo metropolitan areas (and in the rest of Japan) with these values being lower than those reported by the WHO (2013). Very small LFR for all solid cancers indicates that the actual number of “extra” cancer cases is likely to be small; therefore, the impact in terms of public health would be limited. The exposures that contribute more to the risk are again the internal ones (43% for inhalation and 28% for food ingestion) (Fig. 5).

No acute effects of radiation exposure such as acute syndrome or skin burns have been recorded in Japan, since they are usually observed after exposure to high doses. Given the range of prevailing doses, no increase in the frequency of cataracts, circulatory diseases or any other tissue reactions is expected for the general population. In general, cancer

incident and death rates increase with age. Even a modest absolute excess reflects a large relative risk in children, as seen by the LAR and LFR. Women tend to be at a greater risk of cancer from a given unit dose of radiation than men and the sex difference is largely independent on the age-at-exposure (Figs. 4 and S4).

4.3. Excess lifetime incidents and deaths with and without a threshold

Fig. 6 (upper panels) and Figs. S6–S7 (SI) depict the excess lifetime cancer incident and death risks, from all types of exposure in radiocaesium in Japan. They have been estimated for the Japanese population of 2010, which was the last available dataset of population density. We estimate 730–1700 excess cancer incidents, of which 450–1040 might be fatal worldwide similar to those reported by Ten Hoeve and Jacobson (2012) (15–1100 incidents and 24–1800 deaths from exposure to ^{134}Cs , ^{137}Cs and ^{131}I) with more than 90% to occur in Japan (a relevant comparison can be found at SI, Table S2). It is apparent in Fig. 6 (two upper panels) that the fatal incidents are accumulated

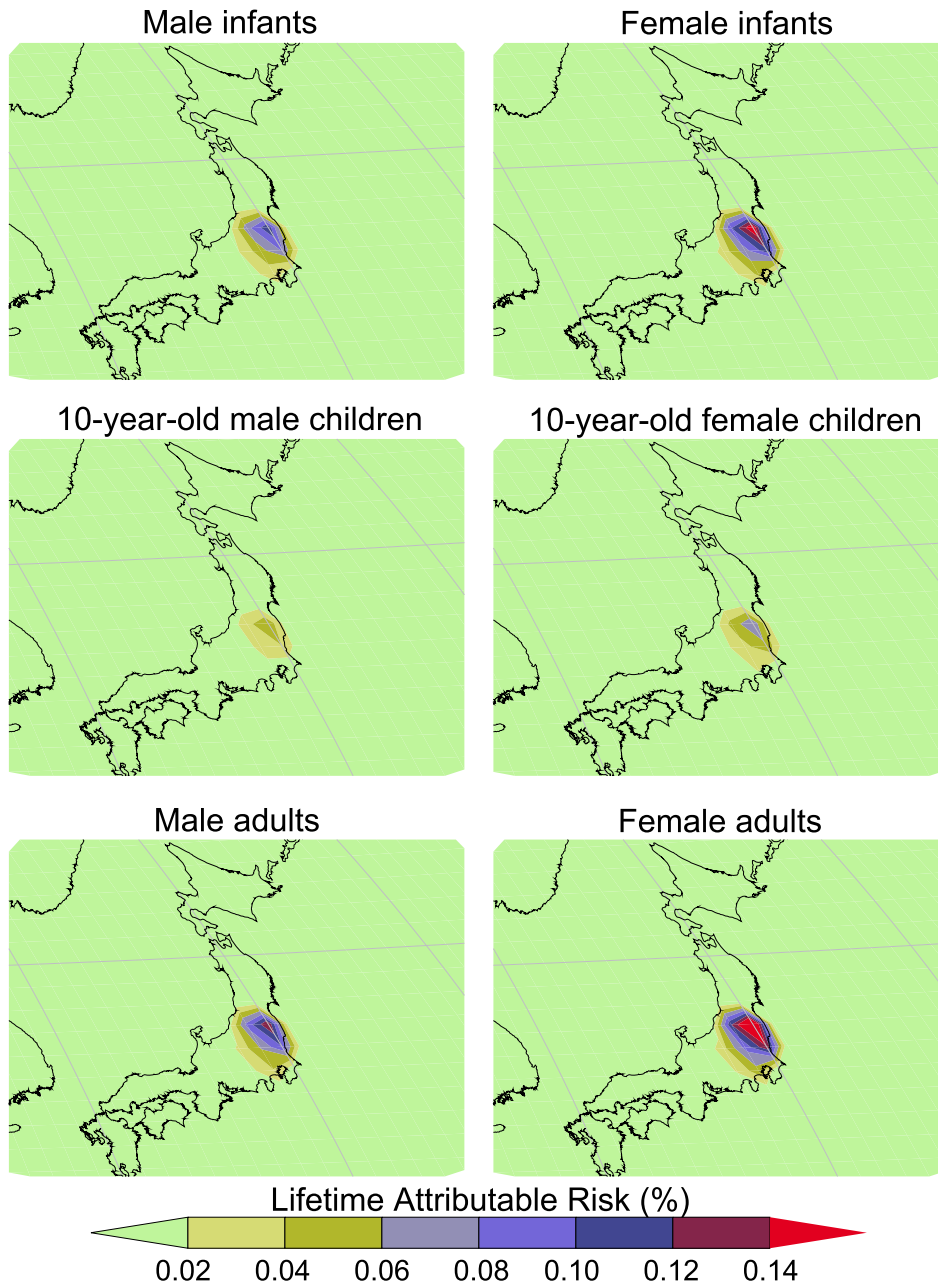


Fig. 4. LAR for both sexes (males and females) of 1 year (infants), 10 years (children) and 20 years (young adults) in different locations of Japan for all solid cancers.

where the exclusion zone has been set up, which shows very well the validity of the modeling results. However, we expect these values to be much lower, because of the evacuation measures, because these

changes were not taken into account in the population data of 2010. A rough estimation made by setting population to zero in the pixels of the exclusion zone and spreading it to the westerly-adjoined pixels

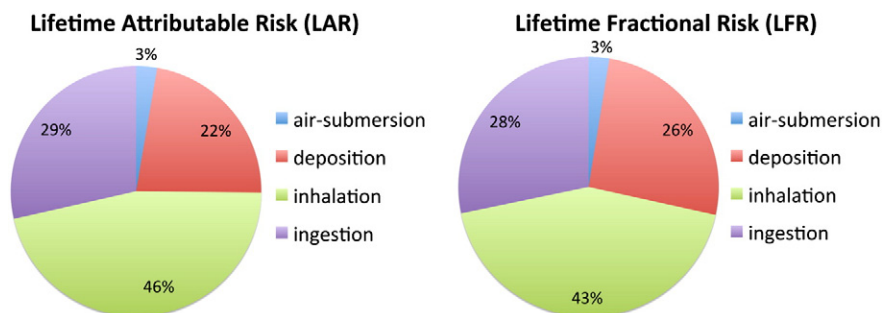


Fig. 5. Relevant exposure contribution to the calculated risk for the Japanese population. Internal exposure pathways contribute more (inhalation: 46% in LAR, 43% in LFR—food ingestion: 29% in LAR, 28% in LFR) together with the cumulative deposition of radiocaesium (22% in LAR, 26% in LFR).

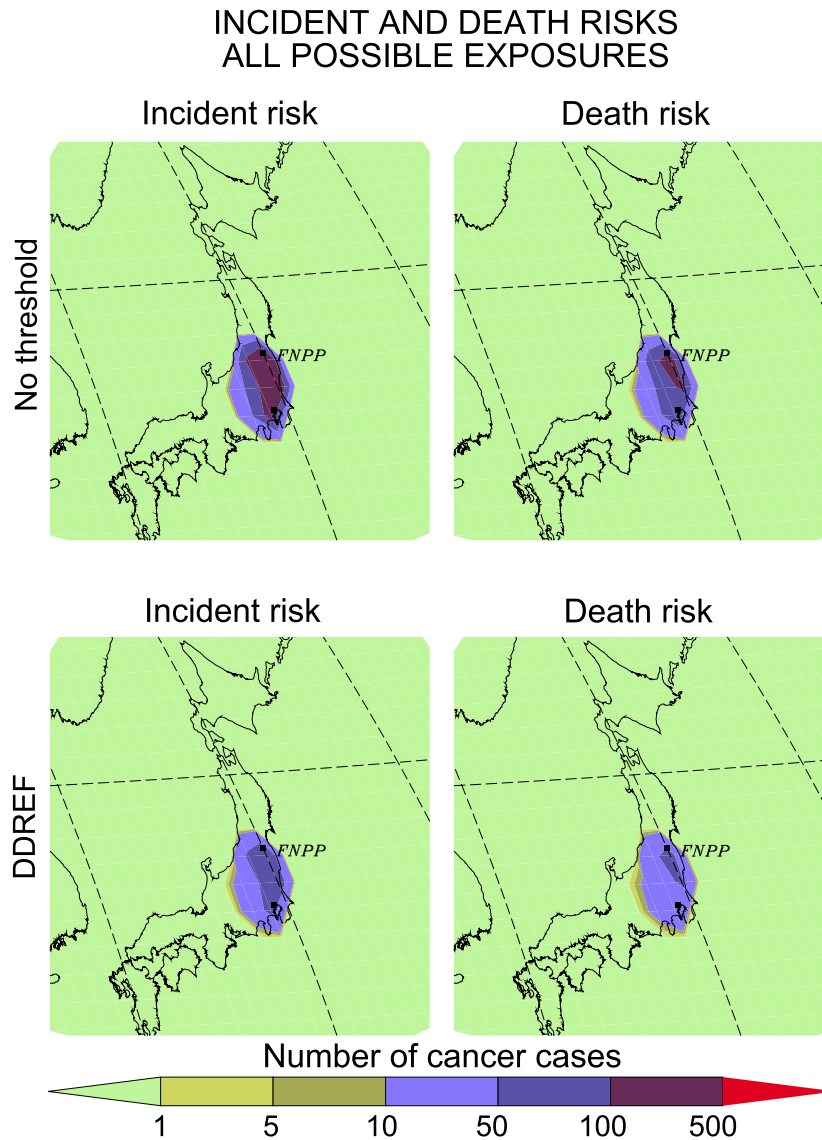


Fig. 6. Excess lifetime cancer incidents and deaths from radiocaesium exposure (air-submersion, deposition, inhalation, food-ingestion) in Japan. The upper two panels depict the incidents without any threshold in Eq. (1), whereas in the bottom two panels the DDREF recommended by the ICRP, UNSCEAR and EPA has been applied to our estimates.

showed that the lifetime deaths and incidents would be decreased by 45%. Nevertheless, this is only a scenario as it is unknown where the population moved after evacuation and also how many people remained near the plant and for how long (e.g. plant workers, firemen etc.).

Given that many researchers do not accept the LNT-hypothesis for risk calculations believing that there must be a threshold dose (see Subsection 2.2), below which no visible effects can be observed, we perform some additional estimations for the excess lifetime risk calculations applying the DDREF. In general, epidemiological estimates of overall and site-specific cancer risks (except for leukemia) related to radiation exposure are statistically consistent with a linear dose–response relationship (ICRP, 2005). For the same reasons that data restricted to low doses tend to be uninformative about radiation-related excess risk, this apparent linearity does not rule out, on statistical grounds, the possibility of increased, decreased, or even absent excess risk per unit dose at very low doses. For those reasons the linear-model estimated excess risks are often divided by a DDREF at low doses and low dose rates as a method to substitute the uncertain threshold. Specifically, the ICRP notes in Publication 103 (ICRP, 2007) that “the Commission considers that the adoption of the LNT-model combined with a judged value of a dose and dose rate effectiveness factor (DDREF) provides a prudent basis for the practical purposes of

radiological protection, i.e., the management of risks from low-dose radiation exposure”. Although a threshold has been identified to be somewhere between 5 and 25 mGy (ICRP, 2005), the exact dose still remains unknown. Therefore, a DDREF of 2 should be applied for radiation protection purposes, whereas the UNSCEAR (UNSCEAR, 1993) recommended that the chosen DDREF should be applied to chronic exposures at dose rates less than 6 mGy h^{-1} averaged over the first few hours, and to acute exposures at total doses less than 0.2 Gy. This recommendation was also adopted by the EPA (EPA, 1999). The resulting excess lifetime incidents and deaths from radiocaesium exposure in Japan after applying the DDREF to our calculations can be seen in Fig. 6 (two bottom panels) and also in the SI (Figs. S8–S9). The total incidents are now calculated to be between 360 and 850 (incidents) and between 220 and 520 (deaths), which are in the lowest level if compared with the range that Ten Hoeve and Jacobson (2012) have reported. However, as discussed previously, these amounts are expected to be even lower due to the evacuation measures taken immediately after the accident.

The highly contaminated zone close to the NPP is of the order of two pixels in our simulations and only few grid-cells represent the whole of Japan. The spatial resolution of our simulations may not be sufficient to allow detailed analysis of the consequences in the immediate vicinity of Fukushima (perhaps, a local/regional model would be more appropriate).

However, basic preliminary insights can be gained about what has happened in Japan and how the local population might be affected by this accident, although epidemiological studies are mandatory for more detailed discussions. Another point is the associated uncertainty of the results, which is definitely high. This is mainly because of the uncertainty in the source term (still researchers and Japanese authorities argue on the exact amounts released), the prevailing depositional fields (European Centre for Medium-Range Weather Forecasts, ERA40 Re-analysis data—6 h wind fields were used), the LNT-model (see Subsection 2.2) and also the DDREF used to perform a more realistic assessment (EPA, 2011). Given that epidemiological studies will be published in several decades from now (when death certificates will be available), such model assessments present an overview of the current and future situation.

5. Conclusions

The atmospheric transport model LMDZORINCA was used to record the impact of radiocaesium (^{134}Cs and ^{137}Cs) on the global and Japanese population from the recent accident in Fukushima Daiichi NPP (Japan) that occurred after a large earthquake (off the coast) and the subsequent tsunamis that attacked the east coast. Most of the released radiocaesium was deposited in the nearby areas of the NPP and the Pacific Ocean, whereas low impact was recorded in North America and even lower in Eurasia. Nevertheless, the model is definitely very close to the measurements reported elsewhere.

In order to evaluate the magnitude of the accident, the impact on the global population was estimated using the LNT-model and specifically the excess lifetime cancer incident and death risks after Chernobyl and Fukushima (for the relevant population density). The accident in Japan presents a negligible radiological risk, both in terms of cancer incidents and deaths, with a peak in the adjacent regions of the NPP much lower in comparison to the Chernobyl accident. This is due to the different emissions (almost double in Chernobyl) and also because most of the radiocaesium released from Fukushima was deposited in the World Ocean.

The impact on the local population was assessed using the LAR and LFR variables estimated from the LNT-model. The risk was higher for female infants, and lower for 10-year-old male children for the nearby areas of the NPP. In general, women are more sensitive to radiation exposure, while the sex is completely independent from the age-at-exposure. Moreover, the relevant lifetime cancer death and incident risks were calculated for the Japanese population of 2010 showing approximately 730 to 1700 cancer incidents and 450 to 1040 deaths from exposure to radiocaesium. However, many researchers have addressed their doubts about the extrapolation of the risk into low doses using the LNT-hypothesis. For that reason we performed the same computations of excess lifetime cancer risks applying the DDREF on our results. Cancer incidents were estimated to be between 360 and 850, of which 220–520 might be fatal, although these numbers are expected to be lower due to the evacuation decided by the official authorities. According to the French Institute of Radioprotection and Nuclear Safety (IRSN, 2012) approximately 73 radionuclides were released after Fukushima. Therefore, one might argue on the low impact concluded in our study claiming that only radiocaesium has been studied instead of the 73 radionuclides emitted. However, this is not expected to affect very much the present results, as (i) most of the radionuclides emitted constitute the local fallout (they are more refractory and heavier); hence, they were deposited where population was moved (WNA, 2013), and (ii) it has been found that the worldwide fallout consists mainly of Cs and I isotopes (short-lived) and noble gasses (short-lived) (e.g. Masson et al., 2011). A study for thyroid cancer in Fukushima has showed that the average risks of cancer incident and death due to ^{131}I for infants were estimated to be 3×10^{-5} and 0.2×10^{-5} , respectively, lower than the annual risks of traffic accidents, naturally occurring radioactive material, and environmental pollutants such as diesel exhaust particles (Murakami and Oki, 2012). In contrast, another study (Yasumura

et al., 2013) showed that the overall (total radioactivity) death rate has been found to be 2.4 times higher in 2011 than in 2010 suggesting that the impact of a disaster on the excess death of institutionalized elderly is most significant in the immediate aftermath, but has a lasting impact due to continuing changes in nutritional, hygienic, medical and general care conditions.

Since Chernobyl, long-term psychological effects including depression, anxiety, fear, and unexplained physical symptoms have been found to increase (Bromet, 2012; Bromet et al., 2011). Similar effects are likely to occur in evacuees after Fukushima together with widespread mistrust of the Japanese government. In addition the accident also resulted in economic losses of billions of dollars due to cleanup costs and reduced economic activity in areas affected by radioactivity (Brumfiel and Fuyuno, 2012). The Chernobyl accident had a cost through May 1990 of \$ 450 billion (Hopkins, 2002) and is likely to exceed \$ 1 trillion by 2013. It is a fact that the preventive actions by the Japanese authorities after Fukushima have reduced radiological health impact substantially, as stable iodine was provided to evacuees, and the government prohibited cultivation of all vegetables, and the use of local milk and other food products, whereas all children from the evacuation zone were measured for radioactivity by the end of March. In contrast, millions of children ingested contaminated milk and food products in ex-USSR after Chernobyl due to the lack of available information. Although the resulting deaths from Fukushima are smaller than those of the earthquake itself (>20,000) and also than those from Chernobyl, epidemiological studies should be conducted to re-assess the estimates presented here.

Funding sources

This study was funded by the GIS Climat-Environnement-Société, (<http://www.gisclimat.fr/projet/radioclimfire>). It was also granted access to the HPC resources of [CCRT/TGCC/CINES/IDRIS] under the allocation 2012-t2012012201 made by GENCI (Grand Equipement National de Calcul Intensif).

Conflict of interest statement

The authors declare that there are no conflicts of interest.

Acknowledgments

We appreciate Dr. Evaggelos Kritsikis (LSCE) and Dr. Olivier Evrard (LSCE) for the valuable discussions.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.envint.2013.11.020>.

References

- Akahane K, Yonai S, Fukuda S, Miyahara N, Yasuda H, Iwaoka K, et al. The Fukushima Nuclear Power Plant accident and exposures in the environment. *Environmentalist* 2012;32(2):136–43.
- Barsanti M, Conte F, Delbono I, Iurlaro G, Battisti P, Bortoluzzi S, et al. Environmental radioactivity analyses in Italy following the Fukushima Dai-ichi nuclear accident. *J Environ Radioact* 2012;114:126–30.
- Boice Jr JD. Radiation epidemiology: a perspective on Fukushima. *J Radiol Prot* 2012;32: N33–40.
- Brandt J, Christensen JH, Frohn LM. Modelling transport and deposition of caesium and iodine from the Chernobyl accident using the DREAM model. *Atmos Chem Phys* 2002;2:397–417.
- Brenner DJ, Doll R, Goodhead DT, Hall EJ, Land CE, Little JB, et al. Cancer risks attributable to low doses of ionizing radiation: assessing what we really know. *Proc Natl Acad Sci U S A* 2003;100(24):13761–6.
- Bromet EJ. Mental health consequences of the Chernobyl disaster. *J Radiol Prot* 2012;32: N71–5.
- Bromet EJ, Havenaar JM, Guey LT. A 25 year retrospective review of the psychological consequences of the Chernobyl accident. *Clin Oncol* 2011;23:297–305.

- Brumfiel G, Fuyuno I. Japan's nuclear crisis: Fukushima's legacy of fear. *Nature* 2012;483:138–40.
- Carvalho FP, Reis MC, Oliveira JM, Malta M, Silva L. Radioactivity from Fukushima nuclear accident detected in Lisbon, Portugal. *J Environ Radioact* 2012;114:152–6.
- Christoudias T, Lelieveld J. Modelling the global atmospheric transport and deposition of radionuclides from the Fukushima Dai-ichi nuclear accident. *Atmos Chem Phys* 2013;13:1425–38.
- Cuttler JM. Commentary on using LNT for radiation protection and risk assessment. *Dose-response* 2010;8:378–83.
- De Cort M, Dubois G, Fridman SD, Germenchuk MG, Izrael YA, Janssens A, et al. Atlas of caesium deposition on Europe after the Chernobyl accident. Luxembourg: Office for Official Publications of the European Communities 92-828-3140-X; 1998 [Catalogue number CG-NA-16-733-29-C. EUR 16733].
- Diaz Leon J, Jaffe DA, Kaspar J, Knecht A, Miller ML, Robertson RGH, et al. Arrival time and magnitude of airborne fission products from the Fukushima, Japan, reactor incident as measured in Seattle, WA, USA. *J Environ Radioact* 2011;102:1032–8.
- Double EB, Mabuchi K, Cullings HM, Preston DL, Kodama K, Shimizu Y, et al. Long-term radiation-related health effects in a unique human population: lessons learned from the atomic bomb survivors of Hiroshima and Nagasaki. *Disaster Med Public Health Prep* 2011;5:S122–33.
- ECMWF. ERA-40, forty-year European re-analysis of the global atmosphere. Available at: <http://www.ecmwf.int/products/data/archive/descriptions/e4.2002>, 2002.
- EPA. Review of ecological assessment case studies from a risk assessment perspective volume II. EPA 630-R-94-003 Risk Assessment Forum. Washington, DC: United States Environmental Protection Agency; 1994. [Available: <http://www.epa.gov/raf/publications/pdfs/ECORISK.PDF> [accessed 10 February 2013]].
- EPA. Cancer risk coefficients for environmental exposure to radionuclides. EPA 402-R-99-001 United States Environmental Protection Agency; 1999 [Available: <http://www.epa.gov/radiation/docs/federal/402-r-99-001.pdf> [accessed 10 February 2013]].
- EPA. EPA radiogenic cancer risk models and projections for the U.S. population. EPA 402-R-11-001 United States Environmental Protection Agency; 2011 [Available: <http://www.epa.gov/radiation/docs/bluebook/bbfinalversion.pdf> [accessed: 4 September 2013]].
- Evangelidou N, Balkanski Y, Cozic A, Møller AP. Simulations of the transport and deposition of ¹³⁷Cs over Europe after the Chernobyl NPP accident: influence of varying emission-altitude and model horizontal and vertical resolution. *Atmos Chem Phys* 2013;13:7183–98.
- Evrard O, Van Beek P, Gateuille D, Pont V, Lefèvre I, Lansard B, et al. Evidence of the radioactive fallout in France due to the Fukushima nuclear accident. *J Environ Radioact* 2012;114:54–60.
- Fesenko SV, Alexakhin RM, Balonov MI, Bogdevitch IM, Howard BJ, Kashparov VA, et al. An extended critical review of 20 years of countermeasures used in agriculture after the Chernobyl accident. *Sci Total Environ* 2004;383(1–3):1–24.
- Hauglustaine DA, Hourdin F, Walters S, Jourdain L, Filiberti M-A, Larmarque J-F, et al. Interactive chemistry in the Laboratoire de Météorologie Dynamique general circulation model: description and background tropospheric chemistry evaluation. *J Geophys Res* 2004. <http://dx.doi.org/10.1029/2003JD003957>.
- Hoffman FO, Kocher DC, Apostoaiei AI. Beyond dose assessment: using risk with full disclosure of uncertainty in public and scientific communication. *Health Phys* 2012;102:591–2.
- Hong GH, Hernández-Ceballos MA, Lozano RL, Kim YI, Lee HM, Kim SH, et al. Radioactive impact in South Korea from the damaged nuclear reactors in Fukushima: and evidence of the long and short transports. *J Radiol Prot* 2012;32(4):397–411.
- Hopkins AT. *Unchained reactions: Chernobyl, glasnost, and nuclear deterrence*. Honolulu, Hawaii: University Press of the Pacific; 2002.
- Hourdin F, Issartel JP. Sub-surface nuclear tests monitoring through the CTBT xenon network. *Geophys Res Lett* 2000;27:2245–8.
- IAEA. Environmental consequences of the Chernobyl accident and their remediation: twenty years of experience. Report of the Chernobyl Forum Expert Group "Environment-2". International Atomic Energy Agency; 2006 [Available: http://www-pub.iaea.org/mtcd/publications/pdf/pub1239_web.pdf [accessed 10 October 2013]].
- IAEA. Regulations for the safe transport of radioactive material. Safety requirements no. TS-R-1. International Atomic Energy Agency; 2009 [Available: http://www-pub.iaea.org/MTCD/publications/PDF/Pub1384_web.pdf [accessed 29 January 2013]].
- IARC. Estimated cancer incidence, mortality, prevalence and disability-adjusted life years (DALYs) worldwide in 2008. GLOBOCAN 2008 database, version 3.0. International Agency for Research on Cancer; 2008 [Available: <http://globocan.iarc.fr/> [accessed 16 November 2012]].
- ICRP. Age-dependent doses to members of the public from intake of radionuclides. International Commission on Radiation Protection, Part 4 ICRP Publication, 71. Oxford: Pergamon Press; 1995.
- ICRP. Low-dose extrapolation of radiation-related cancer risk: International Commission on Radiation Protection, Publication 99. *Ann ICRP* 2005;35(4). [Available: <http://www.icrp.org/publication.asp?id=ICRP%20Publication%2099> [accessed 14 January 2013]].
- ICRP. The 2007 recommendations of the International Commission on Radiological Protection. Publication 2007;103. [Available: http://ac.els-cdn.com/S0146645307000322/1-s2.0-S0146645307000322-main.pdf?_tid=db497cae-14b1-11e3-9942-00000aacb362&acdnat=1378224167_208939b2be48f8a71d6e866c6bdc3782 [accessed 3 September 2013]].
- IRSN. Fukushima, one year later –initial analyses of the accident and its consequences. Report IRSN/DG/2012-0032012. Institut de Radioprotection et de Sureté Nucleaire; 2012 [Available: http://www.irsn.fr/EN/publications/technical-publications/Documents/IRSN_Fukushima-1-year-later_2012-003.pdf [accessed 3 September 2013]].
- Kamada N, Saito O, Endo S, Kimura A, Shizuma K. Radiation doses among residents living 37 km northwest of the Fukushima Daiichi Nuclear Power Plant. *J Environ Radioact* 2012;110:84–9.
- Kellerer AM, Nekolla EA, Walsh L. On the conversion of solid cancer excess relative risk into lifetime attributable risk. *Radiat Environ Biophys* 2001;40(4):249–57.
- Kim C-K, Byun J-I, Chae J-S, Choi H-Y, Choi S-W, Kim D-J, et al. Radiological impact in Korea following the Fukushima nuclear accident. *J Environ Radioact* 2012;111:70–82.
- Kristiansen NI, Stohl A, Wotawa G. Atmospheric removal times of the aerosol-bound radionuclides ¹³⁷Cs and ¹³¹I measured after the Fukushima Dai-ichi nuclear accident—a constraint for air quality and climate models. *Atmos Chem Phys* 2012;12:10759–69.
- Kritidis P, Florou H, Eleftheriadis K, Evangelidou N, Gini M, Sotiropoulou M, et al. Radioactive pollution in Athens, Greece due to the Fukushima nuclear accident. *J Environ Radioact* 2012;114:100–4.
- Little MP, Wakeford R, Janet Tawn E, Bouffler SD. Risks associated with low doses and low dose rates of ionizing radiation: why linearity may be (almost) the best we can do. *Radiology* 2009;251:6–12.
- Long NQ, Truong Y, Hien PD, Binh NT, Sieu LN, Giap TV, et al. Atmospheric radionuclides from the Fukushima Dai-ichi nuclear reactor accident observed in Vietnam. *J Environ Radioact* 2012;111:53–8.
- Masson O, Baeza A, Bieringer J, Brudecki K, Bucci S, Cappai M, et al. Tracking of airborne radionuclides from the damaged Fukushima Dai-ichi nuclear reactors by European networks. *Environ Sci Technol* 2011;45:7670–7.
- McMullin S, Giovanetti GK, Green MP, Henning R, Holmes R, Vorren K, et al. Measurement of airborne fission products in Chapel Hill, NC, USA from the Fukushima Dai-ichi reactor accident. *J Environ Radioact* 2012;112:165–70.
- Medvedev ZA. The legacy of Chernobyl. In: Paperback, editor. W. W. Norton & Company 978-0-393-30814-3; 1990.
- Monzen S, Hosoda M, Tokonami S, Osanai M, Yoshino H, Hosokawa Y, et al. Individual radiation exposure dose due to support activities at safe shelters in Fukushima prefecture. *PLoS One* 2011;6(11):1–4.
- Murakami M, Oki T. Estimation of thyroid doses and health risks resulting from the intake of radioactive iodine in foods and drinking water by the citizens of Tokyo after the Fukushima nuclear accident. *Chemosphere* 2012;87(11):1355–60.
- NASA. Gridded population of the world. National Aeronautical Space Agency; 2013 [Available: <http://sedac.ciesin.columbia.edu/data/collection/gpw-v3> [accessed 22 March 2013]].
- NRC. Health risks from exposure to low levels of ionizing radiation. BEIR VII Phase 2 Report. United States National Research Council 978-0-309-09156-5; 2006.
- Paatero J, Vira J, Siitari-Kauppi M, Hatakka J, Holmén K, Viisanen Y. Airborne fission products in the high Arctic after the Fukushima nuclear accident. *J Environ Radioact* 2012;114:41–7.
- Pham MK, Eriksson M, Levy I, Nies H, Osvald I, Betti M. Detection of Fukushima Daiichi nuclear power plant accident radioactive traces in Monaco. *J Environ Radioact* 2012;114:131–7.
- Potiriadis C, Kolovou M, Clouvas A, Xanthos S. Environmental radioactivity measurements in Greece following the Fukushima Daiichi nuclear accident. *Radiat Prot Dosim* 2011;150:441–7.
- Povinec PP, Šykora I, Holý K, Gera M, Kováčik A, Brestáková L. Aerosol radioactivity record in Bratislava/Slovakia following the Fukushima accident: a comparison with global fallout and the Chernobyl accident. *J Environ Radioact* 2012;114:81–8.
- Price BN, Jayaraman B. Indoor exposure to radiation in the case of an outdoor release. Report LBNL-60662. Lawrence Livermore National Laboratory; 2006 [Available: <http://e-reports-ext.llnl.gov/pdf/335508.pdf> [accessed 10 December 2012]].
- Ritchie JC, McHenry JR. Application of radioactive fallout cesium-137 for measuring soil erosion and sediment accumulation rates and patterns: a review. *J Environ Qual* 1990;19:215–33.
- Sportisse B. A review of parameterizations for modelling dry deposition and scavenging of radionuclides. *Atmos Environ* 2007;41:2683–98.
- Stohl A, Seibert P, Wotawa G, Arnold D, Burkhardt JF, Eckhardt S, et al. Xenon-133 and caesium-137 releases into the atmosphere from the Fukushima Dai-ichi nuclear power plant: determination of the source term, atmospheric dispersion, and deposition. *Atmos Chem Phys* 2012;12:2313–43.
- Szopa S, Balkanski Y, Cozic A, Deandreis C, Dufresne J-L, Hauglustaine D, et al. Aerosol and ozone changes as forcing for climate evolution between 1850 and 2100. *Clim Dyn* 2012. <http://dx.doi.org/10.1007/s00382-012-1408-y>.
- Ten Hoeve JE, Jacobson MZ. Worldwide health effects of the Fukushima Daiichi nuclear accident. *Energy Environ Sci* 2012;5:8743–57.
- Terada H, Katata G, Chino M, Nagai H. Atmospheric discharge and dispersion of radionuclides during the Fukushima Dai-ichi Nuclear Power Plant accident. Part II: verification of the source term and analysis of regional-scale atmospheric dispersion. *J Environ Radioact* 2012;112:141–54.
- Thomas D, Darby S, Fagnani F, Hubert P, Vaeth M, Weiss K. Definition and estimation of lifetime detriment from radiation exposures: principles and methods. *Health Phys* 1992;63(3):259–72.
- Tsubokura M, Gilmour S, Takahashi K, Oikawa T, Kanazawa Y. Internal radiation exposure after the Fukushima nuclear power plant disaster. *J Am Med Assoc* 2012;308(7):669–70.
- Tsushima H, Iwanaga M, Miyazaki Y. Late effect of atomic bomb radiation on myeloid disorders: leukemia and myelodysplastic syndromes. *Int J Hematol* 2012;95(3):232–8.
- Tubiana M, Feinendegen LE, Yang CC, Kaminski JM. The Linear No-Threshold relationship is inconsistent with radiation biologic and experimental data. *Radiology* 2009;251:13–22.
- UNSCEAR. Sources, effects and risks of ionizing radiation. United Nations Scientific Committee on the Effects of Atomic Radiation Report to the General Assembly, with Scientific Annexes. New York, NY: United Nations; 1993 [E.94.IX.2].
- UNSCEAR. Summary of low-dose radiation effects on health. United Nations Scientific Committee on the Effects of Atomic Radiation Report 978-92-1-642010-9; 2010

- [Available: http://www.unece.org/docs/reports/2010/UNSCEAR_2010_Report_M.pdf [accessed 10 October 2013]].
- Vaeth M, Pierce D. Calculating excess lifetime risk in relative risk models. *Environ Health Perspect* 1990;87:83–94.
- Wetherbee GA, Debey TM, Nilles MA, Lehmann CMB, Gay DA. Fission products in National Atmospheric Deposition Program—wet deposition samples prior to and following the Fukushima Dai-ichi Nuclear Power Plant incident, March 8–April 5, 2011. U.S. Geological Survey Open-File Report 2011, 27; 2012 [Available: <http://pubs.usgs.gov/of/2011/1277/report/OF11-1277.pdf> [accessed 5 February 2013]].
- WHO. Preliminary dose estimation from the nuclear accident after the 2011 Great East Japan earthquake and tsunami. World Health Organisation 978 92 4 150366 2; 2012 [Available: http://whqlibdoc.who.int/publications/2012/9789241503662_eng.pdf [accessed 8 October 2013]].
- WHO. Health risk assessment from the nuclear accident after the 2011 Great East Japan Earthquake and Tsunami based on a preliminary dose estimation. World Health Organisation 978 92 4 150513 0; 2013 [Available: http://apps.who.int/iris/bitstream/10665/78218/1/9789241505130_eng.pdf [accessed 12 October 2013]].
- WNA. Fukushima accident 2011. Available: <http://world-nuclear.org/info/Safety-and-Security/Safety-of-Plants/Fukushima-Accident-2011/#.UiXxBZw3A4>, 2013. [accessed 3 September 2013].
- Yasumura S, Goto A, Yamazaki S, Reich MR. Excess mortality among relocated institutionalized elderly after the Fukushima nuclear disaster. *Public Health* 2013;127(2):186–8.
- Yoschenko VI, Kashparov VA, Protsak VP, Lundin SM, Levchuk SE, Kadygrib AM, et al. Resuspension and redistribution of radionuclides during grassland and forest fires in the Chernobyl exclusion zone: part I. Fire experiments. *J Environ Radioact* 2006;86: 143–63.