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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)

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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 gasses) 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.

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

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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 $0.45° \times 0.51°$. 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 ^{137}Cs to be deposited (Brandt et al., 2002; Paatero et al., 2012). As regards to the emissions of ^{137}Cs, 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 subgrid 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 ^{137}Cs (half-life = 30.2 years) was inserted as an inert tracer within the model. The behavior of ^{137}Cs 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 ^{137}Cs 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 ^{137}Cs 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 (^{134}Cs and ^{137}Cs) because, together with ^{131}I and ^{133}Xe (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 there-of 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 ^{134}Cs, ^{137}Cs, and their decay products ^{134}Ba 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 ^{137}Cs decreases only by radioactive decay. The respective contribution of ^{134}Cs deposition rates in each grid cell and time step was also included assuming a $^{134}Cs/^{137}Cs$ 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):

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

where

R_s is the total number of lifetime cancer deaths or incidents due to species s over all times t and grid cells i,j,

$P_{i,j}$ is the 2010 population (or 1990 population for the estimates of Chernobyl) in each grid cell i,j (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 i,j 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 ^{134}Cs (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 ^{134}Cs, ^{137}Cs 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}

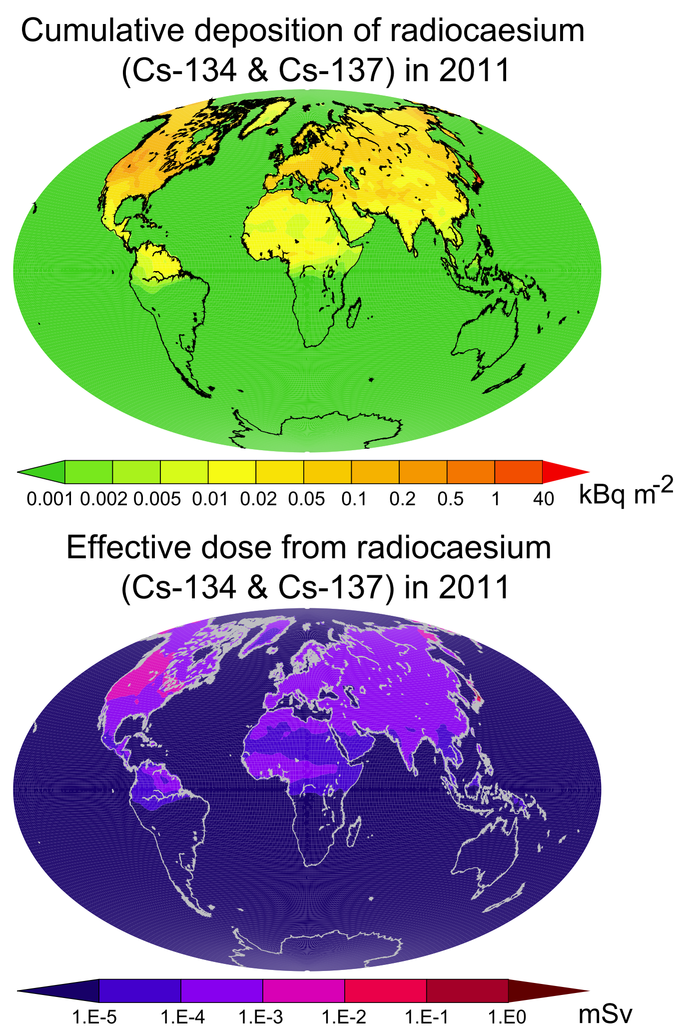

Fig. 1. Global cumulative deposition of radiocaesium (^{134}Cs and ^{137}Cs) after the Fukushima NPP accident at the end of 2011. Annual effective dose from radiocaesium exposure due to inhalation, surface deposition and fallout transport.

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 30–240 Bq m^{-2} and 2–46 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 16–27 Bq m^{-2} and around 55 Bq m^{-2} for ^{134}Cs similar to those presented here (50–100 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 (50–200 Bq m^{-2}), although we slightly overestimate. Low deposition of radiocaesium was observed in Europe with the respective values to be 20–100 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 (0.5–50 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}Cs/^{137}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; Evangeliou et al., 2013). However, when a better-resolved version of our model was used (0.45° × 0.51°) 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 Roentgens per second (R s^{-1}), equivalent to more than 20,000 Roentgens per hour (lethal dose: 500 Roentgens over 5 h) (Medvedev, 1990). Approximately 50% of the lifetime risk was due to inhalation, whereas the rest was caused by air-submersion and

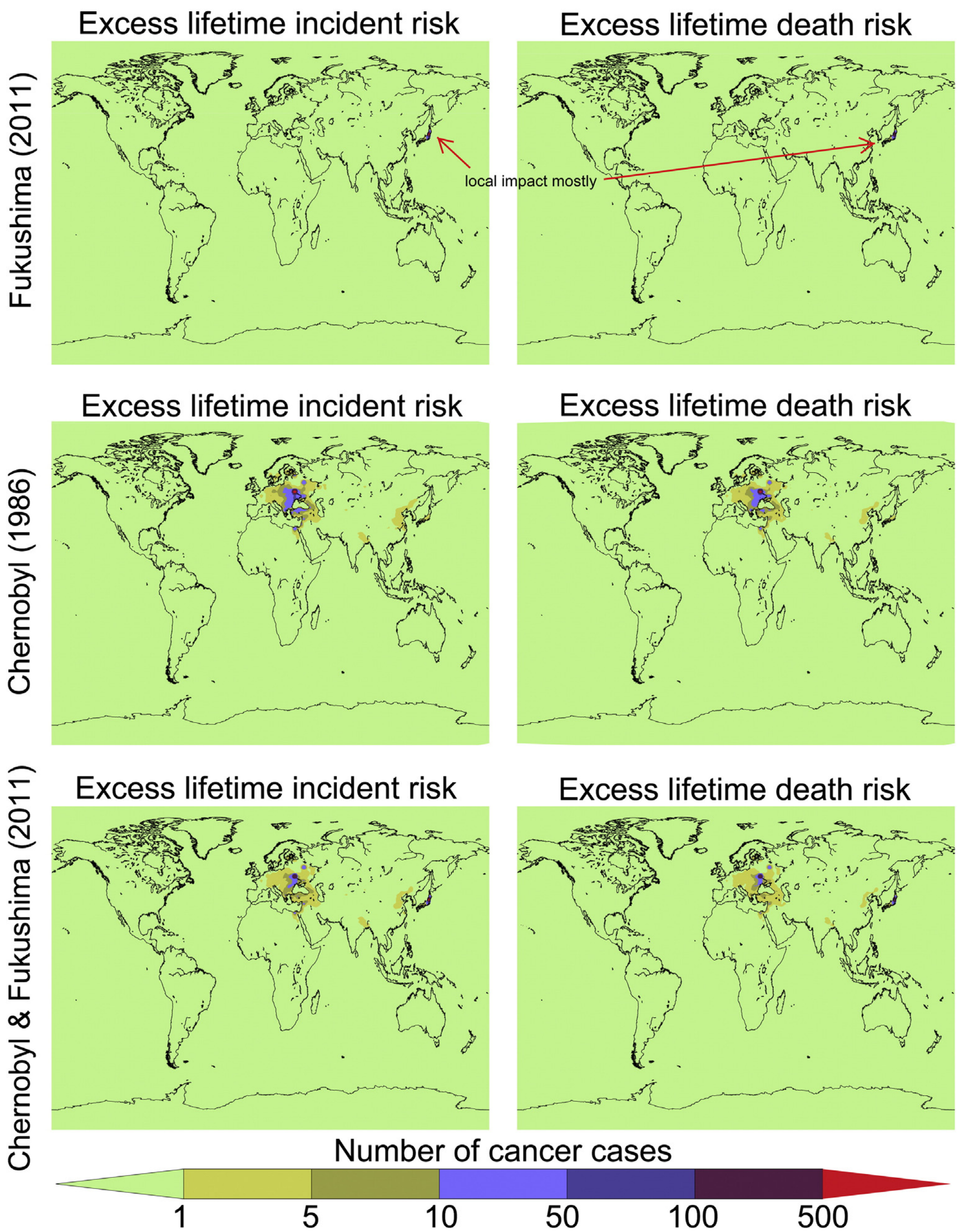

Fig. 2. Global excess lifetime cancer incident and death risks from radiocaesium (^{134}Cs and ^{137}Cs) after the Fukushima accident applied to the global population of 2010. In contrast, the same excess lifetime risks have been estimated after the Chernobyl accident for the global population of 1990. 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° × 0.51° 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

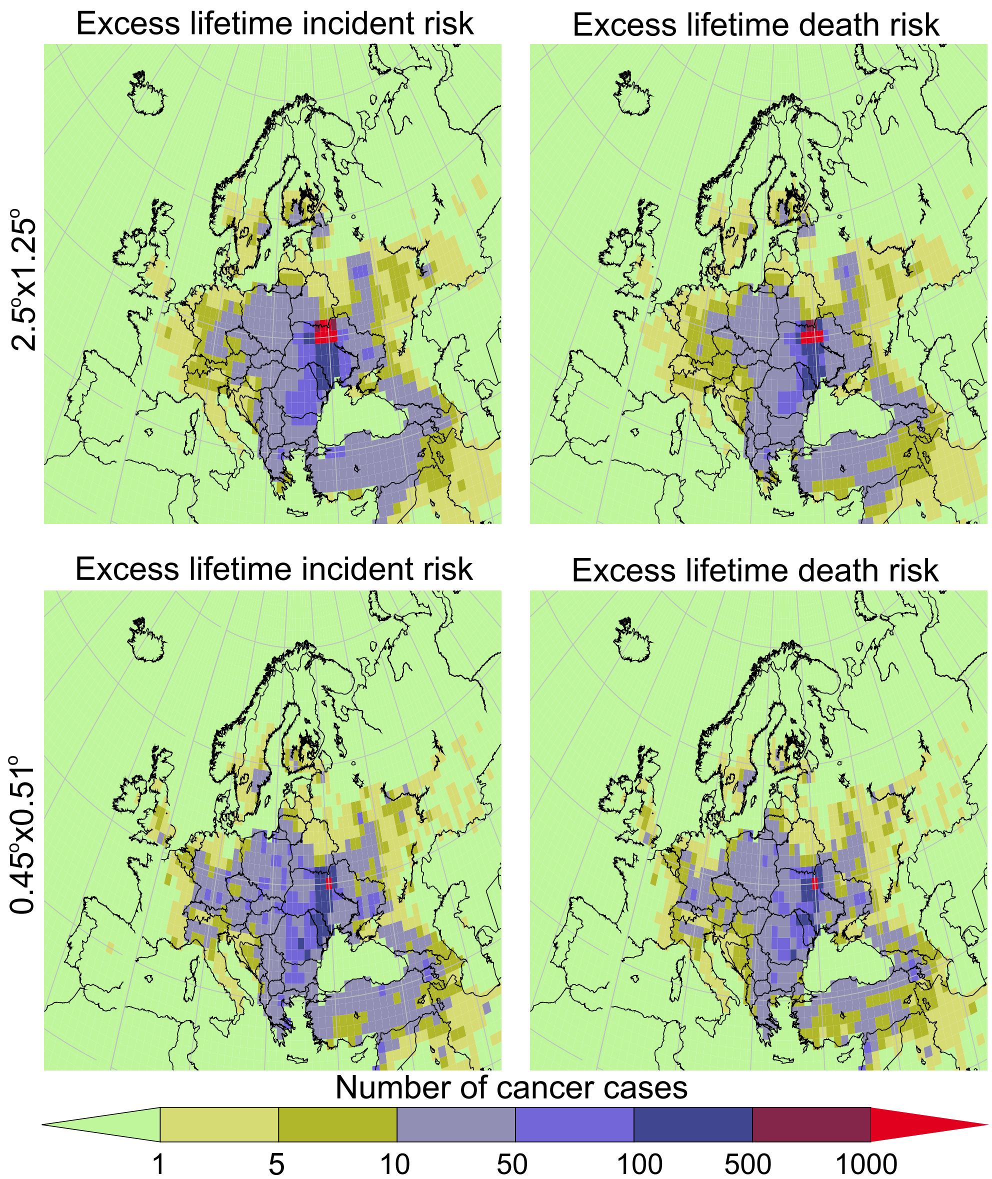

Fig. 3. Excess lifetime cancer incident and death risks from radiocaesium (^{134}Cs and ^{137}Cs) after the Chernobyl NPP accident in Ukraine (1986) using 2 different resolutions in the model. Using the highest resolution more than 25% lower risks are obtained.

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 m^3 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

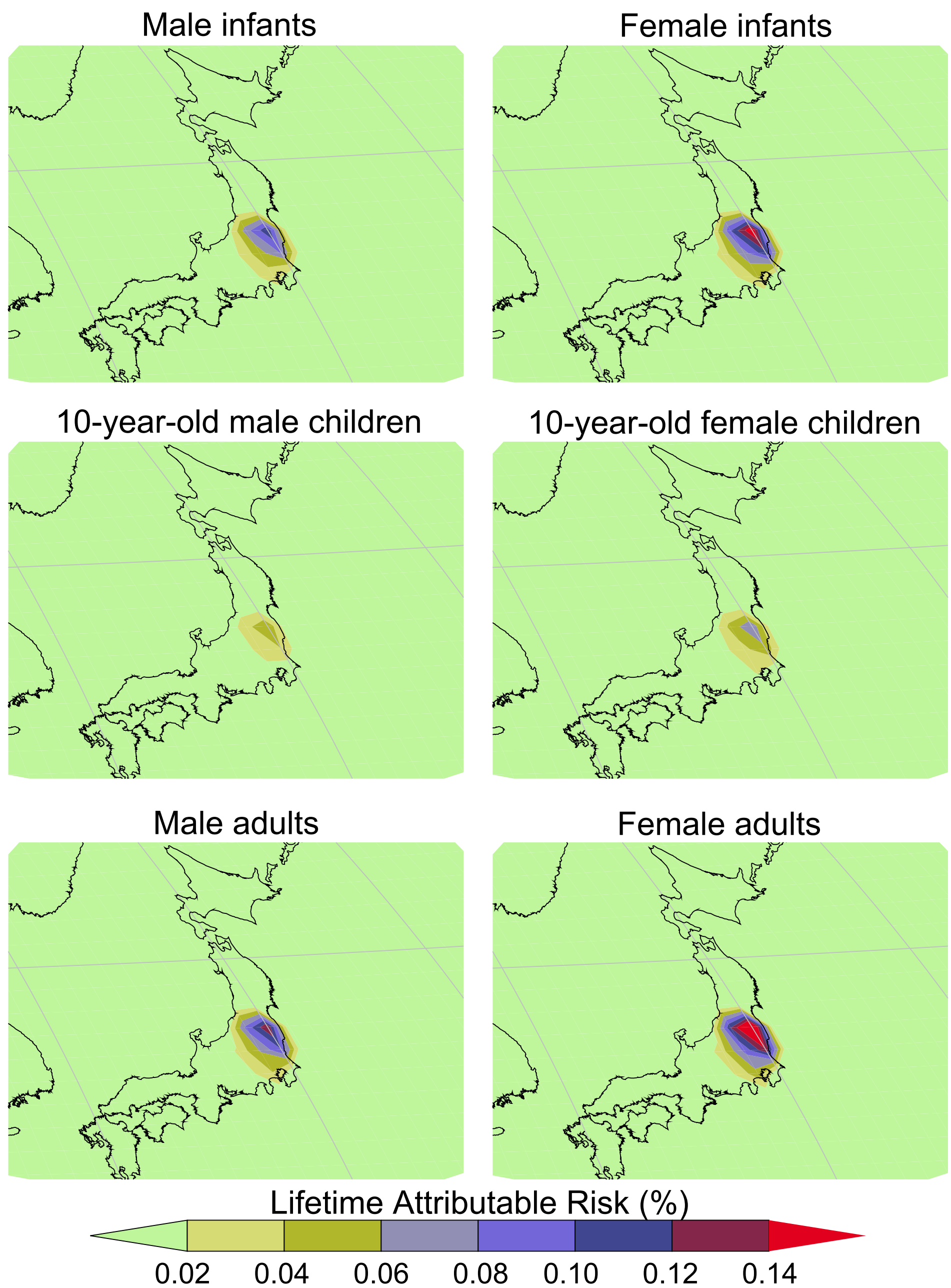

Fig. 4. LAR for both sexes (males and females) of 1 year (infants), 10 years (children) and 20 years (young adults) in different locations of Japan for all solid cancers.

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

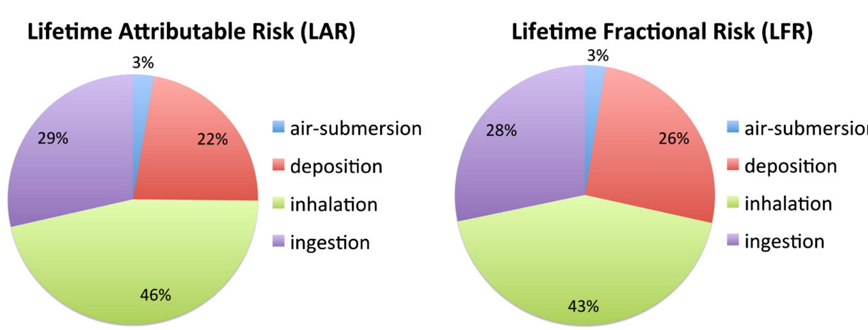

Fig. 5. Relevant exposure contribution to the calculated risk for the Japanese population. Internal exposure pathways contribute more (inhalation: 46% in LAR, 43% in LFR—food ingestion: 29% in LAR, 28% in LFR) together with the cumulative deposition of radiocaesium (22% in LAR, 26% in LFR).

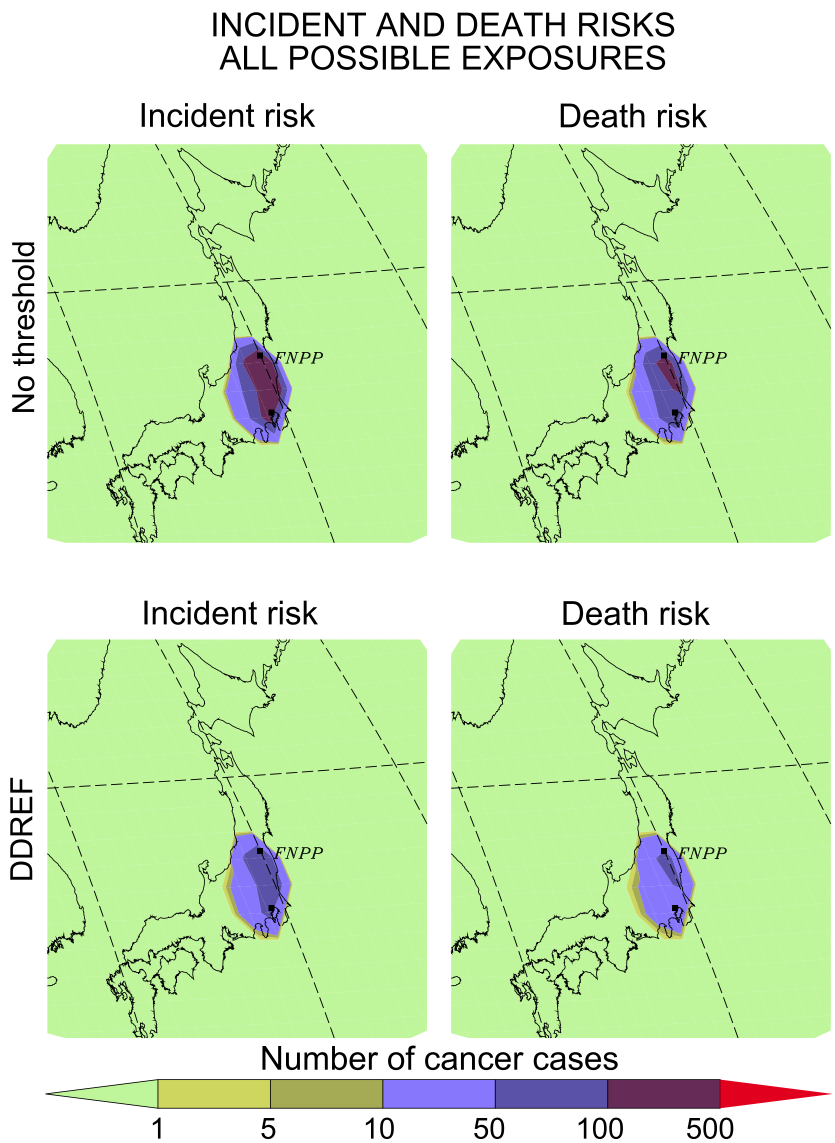

Fig. 6. Excess lifetime cancer incidents and deaths from radiocaesium exposure (air-submersion, deposition, inhalation, food-ingestion) in Japan. The upper two panels depict the incidents without any threshold in Eq. (1), whereas in the bottom two panels the DDREF recommended by the ICRP, UNSCEAR and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

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Conflict of interest statement

The authors declare that there are no conflicts of interest.

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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.

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