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How "lucky" we are that the Fukushima disaster occurred in early spring Predictions on the contamination levels from various fission products released from the accident and updates on the risk assessment for solid and thyroid cancers

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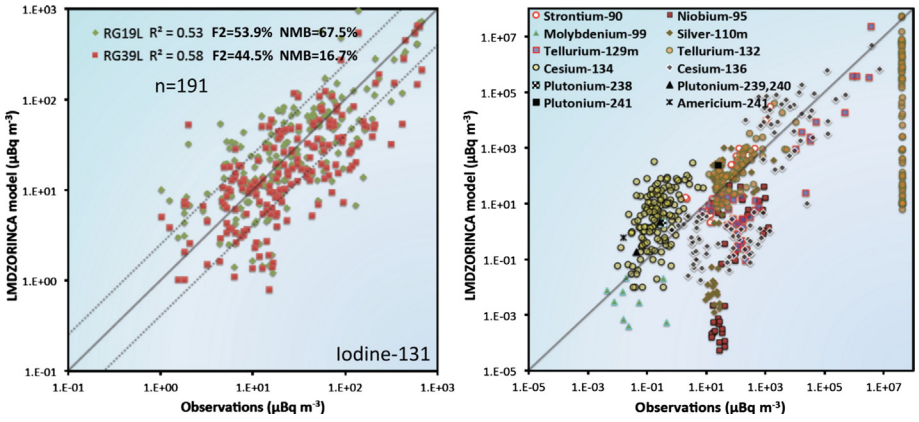
HIGHLIGHTS

- A GCM was used to assess impacts of FND during different seasons.
- Transport and deposition of multiple radionuclides were compared.
- 110 to 640 individuals are expected to die from solid cancers attributed to FND.
- Expected fatalities would be 5 to 32% higher if the FND occurred another season.
- Mortalities will be less than 5% of those who died from the tsunami (~20,000).

GRAPHICAL ABSTRACT



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ABSTRACT

The present paper studies how a random event (earthquake) and the subsequent disaster in Japan affect transport and deposition of fallout and the resulting health consequences. Therefore, except for the original accident in March 2011, three additional scenarios are assessed assuming that the same releases took place in winter 2010, summer 2011 and autumn 2011 in order to cover a full range of annual seasonality. This is also the first study where a large number of fission products released from the accident are used to assess health risks with the maximum possible efficiency. Xenon-133 and ^{137}Cs are directly estimated within the model, whereas 15 other radionuclides are calculated indirectly using reported isotopic ratios. As much as 85% of the released ^{137}Cs would be deposited in continental regions worldwide if the accident occurred in winter 2010, 22% in spring 2011 (when it actually happened), 55% in summer 2011 and 48% if it occurred during autumn 2011. Solid cancer incidents and mortalities from Fukushima are estimated to be between 160 and 880 and from 110 to 640 close to previous estimations. By adding thyroid cancers, the total number rises from 230 to 850 for incidents and from 120 to 650 for mortalities. Fatalities due to worker exposure and mandatory evacuation have been reported to be around 610 increasing total estimated mortalities to 730–1260. These estimates are 2.8 times higher than previously reported ones for radiocaesium and ^{131}I and 16% higher than those reported based on radiocaesium only.

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Total expected fatalities from Fukushima are 32% lower than in the winter scenario, 5% that in the summer scenario and 30% lower than in the autumn scenario. Nevertheless, cancer fatalities are expected to be less than 5% of those from the tsunami (~20,000).

1. Introduction

The accident at the nuclear complex of Fukushima (Japan) on March 11, 2011 resulted in a severe release of around 73 radionuclides (135, counting their radioactive progeny) (IRSN, 2012). It was a direct consequence of a high-magnitude earthquake (~9.0), which occurred in the Pacific Ocean near Japan's east coast creating two massive tsunamis, which in turn struck Japan almost 1 h later (Akahane et al., 2012). Seawater caused power loss and the cooling systems of the four nuclear reactors were disrupted increasing pressure levels due to extreme heating of the cooling water. The following days hydrogen explosions took place releasing large amounts of radioactivity in the atmosphere, whereas the responsible authorities ordered seawater to be used as a cooling medium fearing more severe damage of the reactors' cores (IRSN, 2012).

Since then several studies have been carried out in order to address global transport and deposition of the most important fallout radionuclides (e.g. Kristiansen et al., 2012; Christoudias and Lelieveld, 2013; Evangeliou et al., 2013), and the impact on the human population (e.g. Evangeliou et al., 2014; Ten Hoeve and Jacobson, 2012; WHO, 2013) and on animals and plants (e.g. Garnier-Laplace et al., 2011; Hiyama et al., 2012; Møller et al., 2012, 2013). At the same time many experimental research groups started monitoring Fukushima fallout to assess potential local consequences in Europe, Asia, USA and Japan (e.g. Evrard et al., 2012; Kim et al., 2012; Kinoshita et al., 2011; Kritidis et al., 2012; Long et al., 2012; McMullin et al., 2012; Paatero et al., 2012; Pham et al., 2012; Povinec et al., 2012).

According to the aforementioned groups, the majority of the released radioactivity had as a final receptor the ocean and the Arctic. Here we assess the consequences of the Fukushima releases on the global human population (and especially on the Japanese population) and address if a random phenomenon (such as an earthquake) could have resulted in different radiation effects depending on the season when it occurred. For this reason, we have applied three additional release scenarios for Fukushima (except for the original in spring 2011), assuming their starting season in early winter 2010, summer 2011 and in autumn 2011, respectively. Prior to the selection of the beginning date of each scenario, analyses of precipitation and advection took place in order to assure that 42 days of emissions after the accident would fall within a representative season. Fig. S1 (Supplementary Information—SI) depicts examples of anomalies of precipitation and surface temperature to assure that 2011 was a regular year in terms of climatology variations. This seems to be true, as precipitation and surface temperature remain relatively stable throughout 2006–2013. Given that the releases lasted for 42 days, meteorological conditions reflect seasonal patterns and cannot be considered random. We estimate deposition densities of cesium radioisotopes (^{134}Cs, ^{136}Cs and ^{137}Cs), ^{131}I, ^{133}Xe, ^{129m}Te, ^{132}Te, ^{95}Nb, ^{90}Sr, ^{110m}Ag, ^{99}Mo, ^{241}Am, ^{238}Pu, $^{239–240}$Pu, ^{241}Pu, ^{242}Cm and $^{243–244}$Cm and update excess lifetime risks for humans from the contribution of the radionuclides and all possible exposure pathways.

2. Methodology

2.1. The global model LMDZORINCA

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) (Szopa et al., 2012). The gas phase chemistry part in the model is described in Hauglustaine et al. (2004). Aerosols and gases were treated in the same code to ensure coherence between gas phase chemistry and aerosol dynamics, as well as possible interactions between gases and aerosol particles. The same releases were simulated for winter 2010 (starting in December), spring 2011 (March 2011, the timing of the actual accident), summer 2011 (starting in June) and autumn (starting in September) using a maximum horizontal resolution of 2.50° 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 keeping the same number of grid-boxes. In the present study the zoom version was used for East Asia (Cordex East Asia, http://cordex-ea.climate.go.kr) to assess local consequences of the accident achieving a resolution of 0.45° × 0.51°. On the vertical plane, the model uses sigma-p coordinates with 39 levels extending to the stratosphere. Each simulation lasted until the end of 2011, which is a sufficient period for aerosols (such as cesium radioisotopes) to be removed by scavenging processes (Kristiansen et al., 2012).

LMDZORINCA accounts for emissions, transport (resolved and subgrid scale), and scavenging (dry deposition and washout) of chemical species and aerosols interactively in the GCM. The detailed schemes can be found in Szopa et al. (2012). The model runs in a nudged mode (using the ERA-Interim – 6 h wind fields – by the European Centre for Medium-Range Weather Forecasts, ECMWF, 2014) with a relaxation time of 10 days for the regular grid, whereas for the zoom version relaxes to 4.8 days in the center of the zoom and to 10 days outside (Hourdin and Issartel, 2000).

The radioactive tracer ^{137}Cs was treated as a sub-micronic aerosol (radius 0.2–0.4 μm) in the model. Xenon-133 is a noble gas and is treated as a passive tracer in the model. Iodine-131, ^{134}Cs, ^{136}Cs, ^{129m}Te, ^{132}Te, ^{95}Nb, ^{90}Sr, ^{110m}Ag, ^{99}Mo, ^{241}Am, ^{238}Pu, $^{239–240}$Pu, ^{241}Pu, ^{242}Cm and $^{243–244}$Cm were estimated using the isotopic ratios presented in Table 1, whereas the respective half-lives are presented in Table S1. Radiocaesium isotopes together with ^{131}I and ^{133}Xe were found to be the most abundant in the global fallout after Fukushima (Christoudias and Lelieveld, 2013; Kristiansen et al., 2012; Stohl et al., 2012).

2.2. Source emissions following the accident

The emission source is still a subject of debate within the scientific community, due to the lack of reliable source emission information, including elevations of source, time variations of mass release rates, and chemical and physical compositions. Uncertainties in model-predicted concentrations and depositions are directly related to uncertainties in source emission release rates. Chino et al. (2011) and recently Terada et al. (2012) reported the total release of ^{137}Cs to be approximately 13 PBq (×10^{15} Bq), based on an inverse estimation of the source-term by coupling Japanese environmental monitoring data with regional atmospheric dispersion simulations. They estimated emissions using data from Japanese stations only and a regional simulation domain and assumed constant radioactivity ratios for the different radionuclides based on iodine and caesium concentrations in rain, snow and vegetation. They mentioned that the calculated emissions are associated with an uncertainty of at least a factor of five. The French Institute of Radioprotection and Nuclear Safety (IRSN) reported releases of ^{137}Cs