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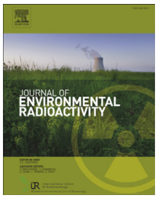

# Modelling the dynamics of ambient dose rates induced by radiocaesium in the Fukushima terrestrial environment

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## ABSTRACT

Since the Fukushima accident, Japanese scientists have been intensively monitoring ambient radiations in the highly contaminated territories situated within 80 km of the nuclear site. The surveys that were conducted through mainly carborne, airborne and *in situ* gamma-ray measurement devices, enabled to efficiently characterize the spatial distribution and temporal evolution of air dose rates induced by Caesium-134 and Caesium-137 in the terrestrial systems. These measurements revealed that radiation levels decreased at rates greater than expected from physical decay in 2011–2012 (up to a factor of 2), and dependent on the type of environment (i.e. urban, agricultural or forest). Unlike carborne measurements that may have been strongly influenced by the depuration of road surfaces, no obvious reason can be invoked for airborne measurements, especially above forests that are known to efficiently retain and recycle radiocaesium. The purpose of our research project is to develop a comprehensive understanding of the data acquired by Japanese, and identify the environmental mechanisms or factors that may explain such decays. The methodology relies on the use of a process-based and spatially-distributed dynamic model that predicts radiocaesium transfer and associated air dose rates inside/above a terrestrial environment (*e.g.*, forests, croplands, meadows, bare soils and urban areas). Despite the lack of site-specific data, our numerical study predicts decrease rates that are globally consistent with both aerial and *in situ* observations. The simulation at a flying altitude of 200 m indicated that ambient radiation levels decreased over the first 12 months by about 45% over dense urban areas, 15% above evergreen coniferous forests and between 2 and 12% above agricultural lands, owing to environmental processes that are identified and discussed. In particular, we demonstrate that the decrease over evergreen coniferous regions might be due the combined effects of canopy depuration (through biological and physical mechanisms) and the shielding of gamma rays emitted from the forest floor by vegetation. Our study finally suggests that airborne surveys might have not reflected dose rates at ground level in forest systems, which were predicted to slightly increase by 5–10% during the same period of time.

## 1. Introduction

The Fukushima nuclear accident led to high atmospheric releases and deposition of volatile fission products in north-eastern Japan. In order to assess the impact of the radioactive fallouts and take appropriate countermeasures, the Ministry of Education, Sports, Science and Technology (MEXT) commissioned the

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Japanese Atomic Energy Agency (JAEA) to conduct extensive radiation monitoring surveys. A special effort was made on the most contaminated areas located within 80 km from the damaged Fukushima Dai-ichi Nuclear Power Plant (FDNPP). This nearly 10,000 $km^2$ territory comprises forests (~80%), agricultural lands (~15%) and inhabited areas (~5%). The Fukushima forests are mainly populated by either evergreen coniferous species (~30%) or deciduous broadleaf species (~50%), while cultivated lands are dominated by paddy fields. These surveys that were conducted mainly with carborne, airborne and *in situ* gamma-ray measurement devices, enabled efficient characterization of the spatial distribution and the time evolution of air dose rates (ADRs) in the contaminated territories. The ADRs were measured both in terms of air kerma rate (in $\mu Gy\ h^{-1}$) and dose equivalent rate ($\mu Sv\ h^{-1}$). Quite detailed information regarding technologies, monitoring procedure and data can be found on the website of the Japanese Nuclear Regulatory Authority (NRA, 2015a,b,c) as well as in recent publications by Japanese scientists (Sanada et al., 2012, 2014; Sanada and Torii, 2014; Tsuda and Tsusumi, 2012; Tsuda et al. 2014; Tanigaki et al., 2013; Kinase et al., 2014; Andoh et al., 2014; Mikami et al., 2014a, 2014b; Onda et al., 2014; Saito et al., 2014a, 2014b; Matsuda et al., 2014).

Both carborne and airborne surveys revealed that ADRs decreased at rates significantly greater than predicted from the physical half-lives of radiocaesium isotopes (up to a factor of 2), although variable in space. A recent analysis by Gonze et al. (2014) indicated that radiation levels measured by aerial monitoring above dense urban regions decreased much faster than in soil environments, at least during the first few months after the accident. Carborne measurements further revealed that, in contrast to what was observed in inhabited or cultivated areas, ADRs in/above semi-natural environments, such as forests, could be significantly higher (up to 50% more) than in surrounding areas because the decrease was slower there (Kinase et al., 2014; Andoh et al., 2014). Finally, *in situ* measurements at ground level in bare soil plots of inhabited areas (*e.g.*, gardens, schoolyards …) tend to show that the decrease was also very limited in this type of environment, at least in places which remained undisturbed since the accident.

Despite this abundant literature, we are forced to recognize that the processes effectively involved in the decrease of air dose rates and the factors responsible for such contrasted observations have not been clearly identified yet. The main purpose of this paper is to bring new insights into the understanding of ambient radiations dynamics in a terrestrial environment contaminated by atmospheric fallouts. More specifically, we intend to simulate the behaviour of ADRs with the use of a dynamic, spatially-distributed and process-based modelling approach. The modelling methodology is first discussed and then applied to Caesium-134 ($^{134}Cs$) and Caesium-137 ($^{137}Cs$) within 80 km of the FDNPP site. The calculated air dose rates at ground level and a flying altitude of 200 m are then discussed and compared to Japanese monitoring data.

## 2. Materials and methods

### 2.1. Air dose rate data

Since April 2011, the MEXT regularly operated aerial radiation monitoring (ARM) surveys in collaboration with the U.S. Department of Energy, the JAEA and Japanese Prefectures (Lyons and Colton, 2012; Sanada et al., 2012, 2014; Sanada and Torii, 2014; NRA, 2015a,b,c). Gamma measurements by NaI scintillators were conducted from airplanes or helicopters flying at altitudes from 150 to 300 m above ground and along routes separated from each other by about 1.8 km or even less in the 7th ARM survey (NRA, 2015c). As stated in the survey reports, the flux of photons measured by the detector included contributions of deposited gamma-emitting radionuclides within a ground circle with a radius approximately equal to the flying altitude. The count rates (in cps) at flying altitude were extrapolated into ADRs at ground level (*i.e.* 1 m height) through an altitude correction function and a dose rate conversion coefficient (Sanada et al., 2014). Relatively accurate coefficients were first estimated after summer 2011 and used to convert the 4th ARM readings (October 2011). However, they did not take into account the influence of vegetation and orography. Intensive surveys of ambient radiation levels in undisturbed soil areas of inhabited environments, such as gardens, school yards or other undisturbed flat fields with little vegetation, were carried out (Saito et al., 2014a,b; Mikami et al., 2014a,b): three campaigns were conducted between June 2011 and December 2012, with measurements being made twice in the third: from August to September 2012 and from November to December 2012. In the first campaign, soil samples were collected at several thousand stations and then analysed by gamma-ray spectrometry using Ge detectors. While portable gamma-ray spectrometers were utilized in the 2nd and 3rd surveys, measurements of dose rates at 1 m above ground were made with NaI(Tl) scintillation survey meters during the 1st campaign. A series of seven carborne surveys were conducted from June 2011 to December 2013, using vehicles equipped with gamma-ray spectrometers (Tanigaki et al., 2013; Tsuda et al., 2014; Saito et al., 2014a; Kinase et al., 2014; Andoh et al., 2014; NRA, 2015b). They enabled the evaluation of the distribution of ADRs on roads covering the same large region. The dose rates measured inside the car were converted to those outside the cars using conversion factors.

The time evolution of the (regional) mean ADRs, normalized by its initial value in June 2011 is displayed in Fig. 1. Dose rates estimated at 1 m height from aerial measurements were normalized by the value measured in the 2nd ARM survey (end of May 2011), although this value was somewhat imprecise (due to the lack of calibrated conversion coefficients at that time). Based on the land-cover map from the Advanced Land Observing Satellite (ALOS, 2005), Kinase et al. (2014) classified carborne data within an 80 km radius according to land use categories. Their results which were derived for carborne surveys 1 to 3 are displayed in Fig. 1 for: urban areas, agricultural environments (*e.g.*, paddy fields, other crop fields and meadows), deciduous forests and evergreen forests. Unfortunately, equivalent results for airborne surveys were not published. Field measurements can be compared with the theoretical curve corresponding to the sole physical decay of $^{134}Cs$ (half-life of 2.1 years) and $^{137}Cs$ (30.2 years) with the same amount of deposit in March 2011. As stated in the above-mentioned publications, the carborne monitoring surveys demonstrated that ADRs along the road networks (at typically 1 m above road) decreased much faster than expected by physical decay between June 2011 and December 2012 (*i.e.* about 60% decrease against 30% predicted by physical decay). As shown in Fig. 1, the decrease was also much more pronounced there than in undisturbed bare soil environments. The Japanese scientists hypothesized that this could be due radiocaesium weathering by precipitation and traffic erosion (Andoh et al., 2014; Saito et al., 2014a). These results also indicated that the dose rate reduction along roads was rather sensitive to the land-use, the decrease being a little bit faster in urban areas than in environments dominated by evergreen forests. As shown in Fig. 1, ADRs estimated from aerial radiation monitoring also decreased faster than theoretically predicted between June 2011 and June 2012 (*i.e.* about 35% against 25% by physical decay over this period).

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