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 to 10% during the same period of time.

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Field surveys of Ambient Dose Rates (ADRs)

Coordinated by the Japanese Nuclear Regulatory Authority / Atomic Energy Agency

**Airborne** (dec. 2012) along flying routes

**Carborne** (dec. 2012) along road network

**In situ** (dec. 2012) of undisturbed bare soils

Sanada et al., 2012; Sanada et al. 2014a,b; Tsuda and Tsusumi, 2012; Tsuda et al. 2014; Tanigaki et al., 2013; Kinase et al., 2014; Andoh et al., 2014; Mikami et al., 2014a; Mikami et al., 2014b; Onda et al., 2014; Saito et al., 2014a; Saito et al., 2014b; Matsuda et al., 2014
Aerial versus in situ (Oct. 2011)

Airborne < in situ in densely inhabited areas

⇒ natural wash-off, traffic erosion & decontamination

Airborne > 3× in situ in evergreen coniferous forests

⇒ dry atmospheric deposition

Gonze et al., ES&T 2014
Time decrease of ADRs (1m height)
... averaged within 80 km & normalized by its value in June 2011

- Faster than predicted by physical decay, in 2011-2012
- Decrease rate: carborne > airborne > in situ
Time decrease of ADRs (1m height) … averaged within 80 km & normalized by its value in June 2011

Carbone decrease rate: urban > agricultural > coniferous
Ongoing research projects

Open questions

- Which environmental processes could explain such a variability in ADRs?
- To what extent can forest vegetation modify ADRs inside/above forests?
- Can we gain further understanding from process-based & dynamic models?

AMORAD project (2013-2019)

Improvement of models for predicting radionuclide transfer in biosphere, with one focus put on forest systems

French National Research Agency

EDOFU project (2014-2016)

Improvement of models for predicting $\gamma$ ADRs in a multimedia and patchy environment

Electricité de France

Modeling Cs transfer …

Key processes or factors that are likely to influence ADRs:

- Dry/wet deposition
- Interception by vegetation
- Depuration of vegetation

**FOREST LAND**
(Bq m⁻²)
- Evergreen coniferous forests
- Deciduous broadleaf forests

**AGRICULTURAL LAND**
(Bq m⁻²)
- Grassland fields
- Cropland fields

**INHABITED LAND**
(Bq m⁻²)
- Urban surfaces
- Bare soil areas

**ATMO DEPOSITION**
(Bq m⁻² h⁻¹)
Onto forest, agricultural and inhabited lands

**IRSN’s modelling platform (SYMBIOSE)**
Modeling Cs transfer …

Key processes or factors that are likely to influence ADRs:

- Dry/wet deposition
- Interception by vegetation
- Depuration of vegetation
- Ploughing of cultivated soils
- Harvesting of crops
- Flooding of paddy fields
- Vertical migration within soils
- Depuration & decontamination of urban surfaces
- Influence of road & roadside on carborne DRs (not accounted for)
- Influence of snow cover (not accounted for)
... and ADRs

IRSN’s modelling platform (SYMBIOSE)
Use of:

- **ADR coefficients expressed in** \((\text{Gy/h})/\text{(Bq/m}^2\text{)}\)
- **Pre-calculated with** MCNP code
- **Depending on** detector altitude, depth of source and medium characteristics (e.g., geometry, density & elemental composition)

**Equivalent Medium assumption**

- Soil, vegetation & atmosphere layers with homogeneous properties
- Plane or volumetric radioactive source of homogeneous intensity
Regional simulations

- **Spatio-temporal domain**
  - 80 km from FDNPP
  - Computational regular grid
  - March 2011 to March 2014 (3 years)

- **Environmental parameters**
  - Mostly generic
  - A few site-specific
  - Land use map
  - Cs contamination maps (airborne & in situ)
  - Seasonal climatic data
  - Agricultural practices
  - Depuration/decontamination rates for urban surfaces
  - Depuration of forest vegetation
  - …
Tree depuration flux
at 21 evergreen coniferous sites

Observation

Model prediction (best estimate)

cypress, cedar, red pine

Mar-11 Sep-11 Mar-12 Sep-12 Mar-13 Sep-13 Mar-14

Forest sites (Fukushima prefecture)
... and inventory in soil at 21 evergreen coniferous sites

Model prediction (best estimate)

Observation

Tree depuration flux (1/d)

Model prediction (best estimate)

cypress, cedar, red pine

Mar-11 Sep-11 Mar-12 Sep-12 Mar-13 Sep-13 Mar-14

Stock in soil (n.d.)

- 10%
- 20%
- 40%
- 60%
- 80%
- 100%

1E-6 1E-5 1E-4 1E-3 1E-2 1E-1
Deciduous broadleaf forests (4 sites)
ADR coefficient in a coniferous forest

... for a **plane** source of $^{134}$Cs of increasing height

![Graph showing dose rate coefficient vs. height of $^{134}$Cs source](image)

- Detector height: 1 m
- Detector height: 15 m
- Detector height: 30 m
- Detector height: 100 m

30 m tree layer

30 cm soil layer
ADR coefficients in a coniferous forest for a **volumic** source of $^{134}$Cs in the **top 1 cm soil layer** or **30 m tree layer**.

 CONTEXT & OBJECTIVES

 MODELLING METHODOLOGY

 RESULTS & DISCUSSION

Predicted ADRs at ground level ($^{134+7}$Cs)...

Mean value within the 80 km region and normalized by its value in June 2011

CONTEXT & OBJECTIVES

MODELLING METHODOLOGY

RESULTS & DISCUSSION
Mean value within the 80 km region and normalized by its value in June 2011.

...versus in situ & carborne data

Theoretical versus in situ & carborne data

Mean value within the 80 km region and normalized by its value in June 2011.
Predicted ADRs at 200m versus airborne data

Mean value within the 80 km region and normalized by its value in June 2011

- Coniferous forests: -25% in 6 months (-20% due to tree depuration)
- Undisturbed soils: -10% in 6 months
- Urban surfaces: -50% in 6 months
- Physical decay
- Croplands

CONTEXT & OBJECTIVES
MODELLING METHODOLOGY
RESULTS & DISCUSSION

Further details in...

Compilation & analysis of monitoring observations in Japanese forests to be published shortly.
Japanese data highly valuable for improving our understanding of post-accidental consequences in terrestrial systems

Despite the lack of site-specific data & uncertainties on deposition characteristics, predicted ADRs globally consistent with field observations (thanks to some models improvement & calibration)

This study suggests that:

- Disagreement with carborne observations mostly attributed to road & roadside effects (not accounted for in our modelling study)
- Airborne observations above vegetation may not be representative of ground ADRs, due to tree depuration & shielding of gamma rays
- Influence of forest vegetation should be accounted for when converting counting rates (for especially low flying altitudes) => this requires assumptions on radionuclide distribution!
Predicted wet deposition ratio

Wet fraction > 0.8
Intense wet deposition might have occurred in the Abukuma valley & to the NW of FDNPP

Wet fraction < 0.4
Noticeable dry deposition might have occurred in S/SW regions = high forested areas of the Abukuma mountains