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A multiscale Bayesian data integration approach for mapping air dose rates around the Fukushima Daiichi Nuclear Power Plant

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ABSTRACT

This paper presents a multiscale data integration method to estimate the spatial distribution of air dose rates in the regional scale around the Fukushima Daiichi Nuclear Power Plant. We integrate various types of datasets, such as ground-based walk and car surveys, and airborne surveys, all of which have different scales, resolutions, spatial coverage, and accuracy. This method is based on geostatistics to represent spatial heterogeneous structures, and also on Bayesian hierarchical models to integrate multiscale, multi-type datasets in a consistent manner. The Bayesian method allows us to quantify the uncertainty in the estimates, and to provide the confidence intervals that are critical for robust decision-making. Although this approach is primarily data-driven, it has great flexibility to include mechanistic models for representing radiation transport or other complex correlations. We demonstrate our approach using three types of datasets collected at the same time over Fukushima City in Japan: (1) coarse-resolution airborne surveys covering the entire area, (2) car surveys along major roads, and (3) walk surveys in multiple neighborhoods. Results show that the method can successfully integrate three types of datasets and create an integrated map (including the confidence intervals) of air dose rates over the domain in high resolution. Moreover, this study provides us with various insights into the characteristics of each dataset, as well as radiocaesium distribution. In particular, the urban areas show high heterogeneity in the contaminant distribution due to human activities as well as large discrepancy among different surveys due to such heterogeneity.

1. Introduction

The accident at the Fukushima Daiichi Nuclear Power Plant (NPP) after the Great East Japan Earthquake resulted in the release of radioactive contaminants to the atmosphere and environment in March 2011. The radioactive contaminants were subsequently deposited on soil and plants via wet and dry precipitation (Tanaka, 2012). The soils in Fukushima and neighboring prefectures are contaminated with deposition of multiple radionuclides, such as ^{131}I, ^{129m}Te, ^{110m}Ag, ^{134}Cs and ^{137}Cs. The radiocaesium contamination is currently considered to be the most serious long-term health hazard due to its activity released and half-life.

Measurements and monitoring of air dose rates (i.e., ambient dose equivalent rates) in the region around the Fukushima Daiichi NPP have been performed continuously since the accident (e.g., Saito and Onda, 2015; Mikami et al., 2015). The measurements have been conducted using various techniques such as walk surveys using portable monitoring systems, car surveys, and airborne surveys. Soil samples also have been collected to assess the extent of contamination in the terrestrial environment (Saito et al., 2015). Such mapping efforts are essential to protect the public, to guide decontamination efforts, and to plan the return of evacuated residents.

In addition to traditional fixed-location monitoring posts or handheld monitors, advanced measurement techniques have been developed, and are currently used routinely in the area. Among them, airborne monitoring or surveys have been extensively used to map the air dose rates in the regional scale (e.g., 100 km radius) with resolution of several hundred meters. In the airborne surveys, a radiation detector is mounted on helicopters, which then fly over the target area (Torii et al., 2012). Calibration methods have been

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developed to compute air dose rates at 1 m above the ground surface by considering attenuation in the air and various factors. Airborne data have provided vital information to identify the extent of large-scale contaminant distribution as well as to make policy decisions for radiation protection purposes. In addition, a GPS-aided mobile radiation monitoring system mounted on a car or motorcycle—the Kyoto University RAdiation MApping system (KURAMA, Tanigaki et al., 2015) —has been used extensively to characterize the distribution of air dose rates along roads in real time (Andoh et al., 2015). The KURAMA system has a significant advantage for real-time monitoring, with the help of online data streaming and cloud storage system (Tsuda et al., 2015). The KURAMA system has been rigorously tested and verified to be acceptable for mass monitoring of air dose rates (Tsuda et al., 2015).

With many data survey types available, it has become clear that there are discrepancies among them in terms of measured air dose rates, even collected at around the same time and same locations. This is mainly because each type of data has a different level of accuracy and a different support scale (i.e., support volume, resolution). For example, airborne surveys measure average air dose rates over a much larger area (typically a radius of several hundred meters) than ground-based measurements (~several tens of meters). Such averaging becomes particularly problematic, because soil contamination and air dose rates are both highly heterogeneous, having many hotspots (JAEA, 2012). Physics-based radiation transport modeling by Malins et al. (2016) also showed that uncertainty in the above-ground air dose rates is associated with the horizontal heterogeneity of radio-caesium distribution in soil rather than the vertical distribution.

In addition to the resolution and support volumes, the different data types also have different spatial sampling density and different spatial coverage. Car survey data are, for example, limited to the locations along roads, even though their data provide relatively high-density data points along the roads (Tsuda et al., 2015). Walk surveys are further limited in spatial coverage and often clustered in several neighborhoods, since it takes time and physical labor for a person to walk around with a device. The airborne survey has the large spatial coverage at the regional scale, although the resolution is low due to the averaging, missing many hotspots and detailed heterogeneity.

To reconcile such discrepancies, there is a need to develop an approach to integrate different types of measurements, and to provide an integrated map of air dose rates by taking into account the characteristics and uncertainty of each type of measurement. In environmental science, monitoring and spatiotemporal mapping of various properties—such as CO_2 concentration, wind velocity or reactive transport properties in subsurface—have been the focus of extensive research in the past decades. Although many traditional datasets are point-scale and sparse in time and space, recent advanced datasets can cover large areas, such as remote sensing in atmospheric/terrestrial sciences and geophysical techniques in subsurface sciences. Such datasets, however, are known to have some discrepancy with traditional point measurements, because they tend to have a larger support volume (or lower resolution), such that each pixel represents the average of heterogeneous properties in the vicinity. Various approaches have been proposed to integrate remote sensing or geophysical datasets with traditional point measurements (e.g., Wikle et al., 2001; Zhou and Michalak, 2009; Wainwright et al., 2014, 2015).

Particularly, the Bayesian hierarchical approach has been proposed as a flexible and expandable framework to integrate multiscale datasets (Wikle et al., 2001; Wainwright et al., 2014, 2015). A Bayesian hierarchical model typically consists of a series of statistical sub-models mainly in two categories: data models and process models. The process models—in this context—describe the spatial pattern (or map) of air dose rates within the domain, representing the spatial trend and heterogeneity of contamination. The data models connect this pattern with actual data, given measurement errors. These data models can represent, for example, a direct ground-based measurement or a function of the pattern such as spatial averaging over a certain area for a low-resolution airborne dataset. The overall model— a series of statistical sub-models—is flexible and expandable so that it can include complex correlations or various types of observations. Once all the sub-models are developed, we can estimate the map of air dose rates and its confidence interval, using sampling-based or optimization-based methods. One of the main advantages is that this method can quantify the possible estimation errors and provide confidence intervals of the estimated air dose rates at any given location.

In addition, geostatistics have been developed to characterize the spatial heterogeneity of environmental properties and to interpolate those properties based on sparse measurements (Deutsch and Journel, 1998; Diggle and Ribeiro, 2007). Geostatistics are based on the spatial autocorrelation that determines the heterogeneity structure based on available datasets; i.e., how the property value changes over space. Diggle et al. (1998) has applied a model-based geostatistical approach to characterize the radionuclide concentrations (^{137}Cs) and to estimate the environmental decay rate on the Rongelap Island. In addition, geostatistical models are often used as process models within Bayesian approaches or Bayesian hierarchical models to integrate multiscale multi-type datasets (e.g., geophysics and core data, or remote sensing and ground-based measurements), and to estimate spatially heterogeneous properties (e.g., Chen et al., 2001, 2006; Sassen et al., 2012; Wainwright et al., 2014, 2015).

In this study, we develop a Bayesian geostatistical approach to integrate multiscale datasets (i.e., car, walk and airborne surveys) and to estimate the spatial distribution of air dose rates at 1 m above the ground surface in high resolution across the regional scale. Since we consider that the walk surveys represent the exposure dose of average individuals walking on the streets, we estimate the distribution of air dose rates equivalent to the walk survey data. In addition, we aim to gain a significant insight into the characteristics of each survey, as well as the spatial heterogeneity and trend of air dose rates. We demonstrate our approach using the datasets collected in Fukushima Prefecture, Japan, in November 2013 by Japan Atomic Energy Agency (JAEA).

2. Data description

In this paper, we integrated three types of datasets of air dose rates collected in Fukushima prefecture of Japan, including walk, car and airborne surveys. Although JAEA accumulated a vast amount of datasets of air dose rates since the accident, we used a subset of datasets to demonstrate our approach. Fig. 1 shows the domain of interest in this study, which is the northwestern region of the Fukushima Daiichi NPP approximately within the 80-km radius. We used the datasets collected around the same time in November 2013. We assumed that the effect of radiocaesium decay was negligible among these three surveys. All the datasets were publically available and downloaded from the data management system developed by JAEA (Seki et al., 2016).

We used the processed and converted airborne data equivalent to air dose rates at 1 m above the ground surface. The detailed procedures of data acquisition and calibration can be found in Torii et al. (2012). The actual flight altitude was approximately 300 m above the ground. The publicly available airborne data are interpolated on the 250 m-resolution grid. As shown in Fig. 1a, the airborne data capture the variability of air dose rates at the regional scale, and show the highly contaminated area extending in the