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Estimation of the radionuclides emission region using trajectory and atmospheric dispersion models

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ABSTRACT

A three-dimensional trajectory model has been developed to estimate the emission area of radioisotopes measured at the international monitoring stations of the Comprehensive Nuclear-Ban Treaty Organization (CTBTO). Calculated backward trajectories were compared with measurements of the European Tracer Experiment (ETEX). These trajectories generally moved toward the original release point and detected within the release duration of the tracer experiment. However, the comparative results had uncertainties with regard to starting time and the height of the tracer in the backward trajectory model. An atmospheric dispersion model based on the Fields of Regards (FOR) technique was used to reduce the uncertainties of trajectory model and to improve the accuracy of detective technology. The simulated results generated by the trajectory and atmospheric dispersion models together were agreed better with the measurements compared to those obtained from the trajectory model alone.

1. Introduction

There are many nuclear facilities such as nuclear power plants, research reactors, and reprocessing plants in Northeast Asia. Radioactive materials may be released into the air by an unexpected accident or covert nuclear activity from these facilities. Especially noble gases are released due to the nuclear activity from the reprocessing facility or underground nuclear test as well as the accident. Nowadays the Comprehensive Nuclear-Ban Treaty Organization (CTBTO) and the Korea Institute of Nuclear Safety (KINS) operate monitoring stations to measure radioisotopes released into the air by the nuclear activities such as the reprocessing plant and underground nuclear test (Ringbom et al., 2014; Lee, 2012).

If the radionuclide concentrations at the monitoring stations are measured to be high compared to normal conditions, this may infer that radioactive materials are released from the nuclear facilities of neighboring countries in Northeast Asia like North Korea, Japan, China, Taiwan, and South Korea. Therefore, it is important to estimate from which nuclear facilities the radioactive materials are originated, or to identify the covert nuclear activities or unexpected small nuclear accidents. North Korea conducted three nuclear tests in 2006, 2009, and 2013, and the radioxenon isotopes were detected at some stations of the International Monitoring Systems (IMS) operated by the CTBTO (Ringbom et al., 2014; Saey et al., 2007; Medalia, 2010). Underground nuclear tests can be confirmed primarily by seismic signal detection. However, the seismic system is unable to detect, if North Korea may perform covert activity for the downsizing and improvement of nuclear weapon.

Geer (2012) estimated that North Korea conducted low-yield nuclear tests on 11 May 2010 at the Mount Mantap site where the underground nuclear tests were previously carried out, even though no seismic signals from which tests were detected. This estimation was supported by detecting xenon and its daughter radionuclides at four atmospheric radionuclide surveillance stations in South Korea, Japan, and the Russian Federation between the 13th and 23rd of May 2010. Mount Mantap was estimated release region of the radioactive materials by using backward trajectory and atmospheric dispersion models, as well as monitoring data (Geer, 2012; Wright, 2013). The Web connected Graphics Engine (WebGrape; Saey, 2009) and the HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT; Draxler and Hess, 1997) models were used to estimate the emission area of radioisotopes released into the atmosphere at the time of the event in May 2010.

Small-unexpected nuclear accidents or covert nuclear activities may have occurred in Northeast Asia, especially in North Korea. It is important to identify the release origin of radioactive materials when detected radionuclides have concentrations of high values at the monitoring stations. In this study, a three-dimensional trajectory model has been developed to estimate the source origin

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of radionuclides released due to covert nuclear activities. The trajectory model was validated by the European Tracer Experiment (ETEX) measurements performed in 1994 in Europe (Dop et al., 1998). In addition, we applied an atmospheric dispersion model (Suh et al., 2006) to enhance the accuracy of the detective technology for estimating the emission region of the radioactive materials in conjunction with the trajectory model.

2. Trajectory model

A trajectory model, which describes the paths of air parcels, has been used to track the movement of pollutants in the atmospheric environment. A trajectory can be defined as the individual air parcels moving through time and space by time-varying wind fields. It is defined by the differential trajectory equation (Stohl, 1998),

$$\frac{dX}{dt} = V[X(t)]. \tag{1}$$

where, X is the position vector, t is the time, and V is the wind velocity vector. A forward formulation can be obtained from expansion of $X(t)$ in Eq. (1), by using a Taylor series at $t_1 = t_0 + \Delta t$

$$X(t_1) = X(t_0) + \Delta t \frac{dX}{dt}\bigg| t_0 + \frac{1}{2}(\Delta t)^2 \frac{d^2X}{dt^2}\bigg| t_0 + \ldots. \tag{2}$$

Similarly, one can obtain a backward formulation by applying a Taylor expansion at $t_0 = t_1 - \Delta t$ in Eq. (1).

$$X(t_0) = X(t_1) - \Delta t \frac{dX}{dt}\bigg| t_1 + \frac{1}{2}(\Delta t)^2 \frac{d^2X}{dt^2}\bigg| t_1 - \ldots. \tag{3}$$

Combining Eqs. (2), (3), we can obtain the trajectory equation at any time t_1. Considering only first two terms on the right-hand side (RHS) of Eqs. (2), (3), we get a constant acceleration solution for Eq. (1) (Stohl, 1998).

$$X(t_1) \cong X(t_0) + \frac{1}{2}\Delta t[V(t_0) + V(t_1)]. \tag{4}$$

If the trajectory of particle in Eq. (4) is obtained at $t = t_1$, it is a forward trajectory. On the other hand, if the solution of Eq. (1) is found at $t = t_0$, it is a backward trajectory. Eq. (4) should be solved by the iterative method, since $V(t_1)$ is not known a priori (Stohl, 1998; Seibert, 1993).

3. Validation of trajectory model

Measured data in ETEX (Dop et al., 1998) were used to validate the trajectory model. In this study, the data collected from the first experiment performed on 23rd October 1994, were used to compare the calculated results of the trajectory model. The first release started at 16:00 UTC on 23rd October, 1994 and lasted 11 h and 50 min. A total of 340 kg perfluoromethylcyclohexane (PMCH) was released in Montefil (2°W, 48°03′N) at an average flow rate of 8.0 g/s. The sampling network consisted of 168 ground-level sampling stations in Western and Eastern Europe. The locations of sampling stations are displayed in Fig. 1.

During the release, the wind blew from the direction between 240 and 290 degrees, i.e. between west-southwest and west-northwest. The wind was westerly at the start of the release with a tendency to be from west-northwest until midnight and from a west-southwest direction at the end of the release. The wind direction changed between south and west during the rest of the period. The wind speed during the release ranged between 4 and 7 m/s. The plume initially moved toward northeasterly direction. After 12 h, the tracer was detected at a few sites in France and Germany. Then the plume moved eastward and traversed Germany, 36 h after the release, it stretched from the west coast of Sweden to Hungary. About 60 h after the release, owing to the wind convergence line evaluated by most of the flow models, the eastwardly

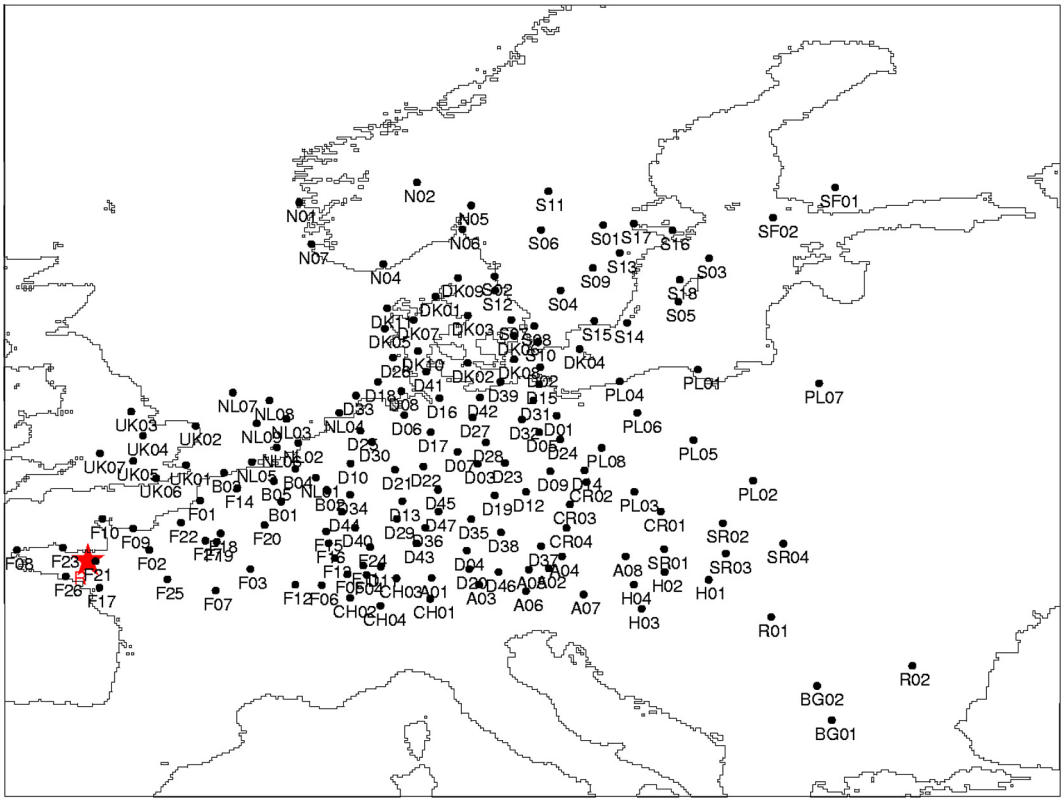

Fig. 1. Positions of the sampling network. (Red star means release point located at Montefil of France). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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