Journal of Environmental Radioactivity 148 (2015) 80–91

Contents lists available at ScienceDirect

Journal of Environmental Radioactivity

journal homepage: www.elsevier.com/locate/jenvrad

Modeling of long range transport pathways for radionuclides to Korea during the Fukushima Dai-ichi nuclear accident and their association with meteorological circulations

Kwan-Hee Lee [a, b, **], Ki-Hyun Kim [c], Jin-Hong Lee [b], Ju-Yong Yun [a], Cheol-Hee Kim [d, *]

[a] Korea Institute of Nuclear Safety, 62 Gwahak-ro, Yuseong-gu, Daejeon 305-338, Republic of Korea
[b] Chungnam National University, 99 Daehak-ro, Yuseong-gu, Daejeon 305-764, Republic of Korea
[c] Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 133-791, Republic of Korea
[d] Pusan National University, 2 Busandaehak-ro 63 Beon-gil, Geumjeong-gu, Busan 609-735, Republic of Korea

A R T I C L E I N F O

Article history:
Received 19 November 2014
Received in revised form
7 June 2015
Accepted 8 June 2015
Available online 3 July 2015

Keywords:
Fukushima accident
Long range transport
Radionuclide
FLEXPART

A B S T R A C T

The Lagrangian FLEXible PARTicle (FLEXPART) dispersion model and National Centers for Environmental Prediction/Global Forecast System (NCEP/GFS) meteorological data were used to simulate the long range transport pathways of three artificial radionuclides: ^{131}I, ^{137}Cs, and ^{133}Xe, coming into Korean Peninsula during the Fukushima Dai-ichi nuclear accident. Using emission rates of these radionuclides estimated from previous studies, three distinctive transport routes of these radionuclides toward the Korean Peninsula for a period from 10 March to 20 April 2011 were exploited by three spatial scales: 1) intercontinental scale – plume released since mid-March 2011 and transported to the North to arrive Korea on 23 March 2011, 2) global (hemispherical) scale – plume traveling over the whole northern hemisphere passing through the Pacific Ocean/Europe to reach the Korean Peninsula with relatively low concentrations in late March 2011 and, 3) regional scale – plume released on early April 2011 arrived at the Korean Peninsula via southwest sea of Japan influenced directly by veering mesoscale wind circulations. Our identification of these transport routes at three different scales of meteorological circulations suggests the feasibility of a multi-scale approach for more accurate prediction of radionuclide transport in the study area. In light of the fact that the observed arrival/duration time of peaks were explained well by the FLEXPART model coupled with NCEP/GFS input data, our approach can be used meaningfully as a decision support model for radiation emergency situations.

1. Introduction

On 11 March 2011, a strong earthquake occurred off the coast of Japan's main island Honshu and an accompanying large tsunami severely damaged the Fukushima Dai-ichi NPP (Nuclear Power Plant). Due to this accident, a large quantity of radioactive material was released into atmosphere over an extended period. Significant releases occurred on March 12 with its rate varying considerably over the following week. As such, there have been marked increases in occurrences of particular incidents each unit (e.g. hydrogen explosions, venting, and leakage from the reactors and their containment systems). After the first week, the rate of release gradually declined with a little fluctuation over limited periods (UNSCEAR, 2014).

As the Korea Institute of Nuclear Safety (KINS) was established to manage nationwide monitoring of environmental radiation in Korea, it immediately started monitoring upon recognizing the Fukushima accident. This monitoring program included measurements of ambient dose rate and concentrations of radionuclides from a number of environmental samples including air particle, deposition, and so on (Kim et al., 2012). After the KINS first detected the incident signal at one monitoring station on March 28, they reinforced the extent of monitoring program. Incident-related radionuclides were detected continuously until mid-April in many other monitoring stations and intermittently until the end of April.

* Corresponding author. Pusan National University, 2 Busandaehak-ro 63 beon-gil, Geumjeong-gu, Busan 609-735, Republic of Korea.
** Corresponding author. Korea Institute of Nuclear Safety (KINS), 62 Gwahak-ro, Yuseong-gu, Daejeon 305-764, Republic of Korea.
E-mail addresses: khlee@kins.re.kr (K.-H. Lee), chkim2@pusan.ac.kr (C.-H. Kim).

http://dx.doi.org/10.1016/j.jenvrad.2015.06.007
0265-931X/

A 3-dimensional numerical method was recommended as a prerequisite tool to quantitatively simulate the impact of accidents with emission source term provided. However, source terms were not well defined to numerically simulate and quantitatively estimate the concentrations in line with observations (Hong et al., 2012; Kim et al., 2012). Hence, numerous efforts had been put to quantify source terms in more meaningful ways (Stohl et al., 2012a, 2012b; Terada et al., 2012; Christoudias and Lelieveld, 2013; UNSCEAR, 2014).

In this study, we carried out the FLEXPART Lagrangian Particle Dispersion Model (LPDM) by employing recently published source term information (e.g., Stohl et al., 2012a, 2012b; Terada et al., 2012). By simulating atmospheric transport of radionuclides from the Fukushima Dai-ichi nuclear accident to Korea, we identified the main pathways of transport processes in this study. The model performance has been validated through direct comparison with the observation data over northeast Asia. In the course of this study, we analyzed the simulated horizontal distributions by tracking the trajectories of the radionuclides. The basic features of long range transport pathways to Korean Peninsula upon the Fukushima Dai-ichi nuclear accident were characterized on three different scales: 1) intercontinental, 2) global (or hemispherical), and 3) regional scales. Our simulation period was set to cover 10 March to 20 April 2011. Other modeling problems such as source uncertainties, meteorological parameters, and synoptic features during the transport of radionuclides were also investigated and described.

2. Methods

As the key simulation components, three artificial radionuclides were selected: ^{131}I, ^{137}Cs, and ^{133}Xe. The two radionuclides, ^{131}I and ^{137}Cs, were selected in light of their potential harmfulness on human health. Note that the ^{131}I is known to accumulate in the thyroid gland for a few weeks after the exposure, while ^{137}Cs can remain in the environment over many years following the release (UNSCEAR, 2014). In addition, noble gas, ^{133}Xe, has also been selected as a simulation component, as it exhibited the largest activity from the Fukushima. Source terms for ^{137}Cs and ^{133}Xe were used by referring to the study of Stohl et al. (2012a, 2012b), while those of ^{131}I from Terada et al. (2012). These source terms had been documented (Christoudias and Lelieveld, 2013; UNSCEAR, 2014) and used in many recent modeling studies.

2.1. Radionuclides measurement

The KINS has been continuously monitoring environmental radiation and the associated dose rates throughout Korea. Fig. 1 depicts the locations of 12 monitoring stations in Korea along with Fukushima Dai-ichi NPP which is located about 1000 km east from the Korean Peninsula. The KINS conducts routine monitoring of airborne particulates, fallout, and rainwater for early detection of radiation contamination to take timely response for urgent situations at 12 stations installed in densely populated major city areas across the Korean Peninsula. After the Fukushima accident, airborne samples were analyzed on a weekly basis. Since artificial radionuclides were first detected on 28 March 2011, the samples were analyzed every day. Radioactive xenon was analyzed at 12 h intervals at the monitoring station located on the east coast of Korean Peninsula. Airborne samples were collected from each of the 12 monitoring stations (Fig. 1) at 01 UTC every morning onto a glass fiber filter with a high volume air samplers with flow rate of 51 m^3/h for 24 h, during March 28 to May 31, 2011.

All samples prepared for gamma-spectrometry were analyzed by a high purity germanium detector for 24 h. For the quality control of measurement results in gamma spectrometric analysis, the samples were analyzed together with IAEA reference materials, and then analytical results were compared with values of the reference materials. The Minimum Detectable Concentration (MDC) of ^{137}Cs differed slightly over the monitoring stations, roughly falling between 0.02 and 0.1 mBq/m^3. In addition, that of ^{131}I was similar to ^{137}Cs, ranging approximately between 0.03 and 0.1 mBq/m^3. Detailed information of the airborne sampling and radioactivity measurement was described elsewhere (Kim et al., 2012). In addition, KINS built a collection and analysis system for radioactive xenon by the Swedish Automatic Unit for Noble Gas Acquisition II - International Monitoring System (SAUNA II-IMS). This detection system is located on the east coast of Korean Peninsula (not shown in Fig. 1) to collect air samples at every 12 h interval. The system is capable of detecting trace-level radioactive xenon in the atmosphere (http://www.saunasystems.se).

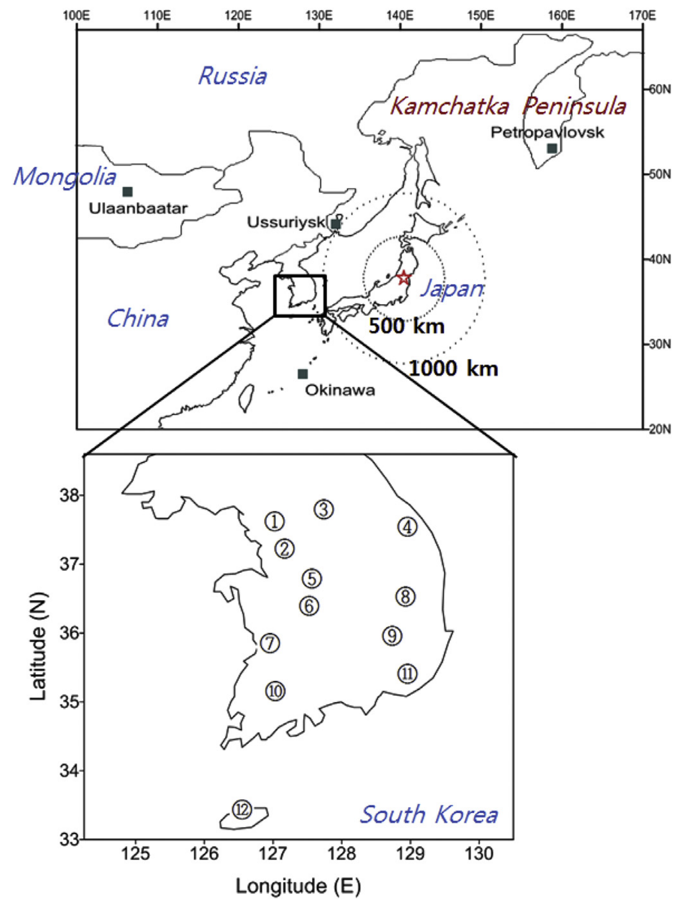

Fig. 1. Map of the location of 12 monitoring stations in Korea, Fukushima NPP, and CTBTO stations used in this study. ①–⑫ denote ① Seoul ② Suwon ③ Chuncheon ④ Gangneung ⑤ Cheongju ⑥ Daejeon ⑦ Gunsan ⑧ Andong ⑨ Daegu ⑩ Gwangju ⑪ Busan ⑫ Jeju, respectively, star (★) represents Fukushima NPP, and filled rectangles (■) denote CTBTO stations, respectively.

2.2. Atmospheric transport modeling

To simulate radionuclide dispersion in the atmosphere, the Lagrangian particle dispersion model FLEXPART version 9.0 (Stohl et al., 1998; Stohl and Thomson, 1999; Stohl et al., 2005) was used. In order to integrate the trajectory equation for radionuclide, Lagrangian transport process in FLEXPART uses simple first order scheme as follows: