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Measurement, simulation, and meteorological interpretation of medium-range transport of radionuclides to Korea during the Fukushima Dai-ichi nuclear accident

Hyo-Jung Lee [a], Hyun-Young Jo [a], Ki-Pyo Nam [b], Kwan-Hee Lee [c], Cheol-Hee Kim [a,*]

[a] Department of Atmospheric Sciences, Pusan National University, Busan 46241, Republic of Korea
[b] Air Quality Forecasting Center, National Institute of Environmental Research, Incheon 22689, Republic of Korea
[c] Department of Radiation Protection and Radioactive Waste, Korea Institute of Nuclear Safety, Daejeon 34142, Republic of Korea

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ABSTRACT

Two radionuclides (^{131}I and ^{137}Cs) were measured and simulated over the Korean Peninsula during the Fukushima Dai-ichi nuclear accident, and the resulting meso-scale meteorological characteristics were explored in order to interpret the medium-range transport of radionuclides from the site of the Fukushima Dai-ichi nuclear accident to the Korean Peninsula. Peak concentrations of radionuclides were detected across all sites in Korea for a period of April 2–8, 2011, with maximum concentrations of ^{131}I and ^{137}Cs at 3.12 mBq/m^3 (on April 6), and 1.25 mBq/m^3 (on April 7), respectively; the highest levels on record in Korea since measurements began. The multi-particle Lagrangian model, the FLEXPART simulation based on the National Centers for Environmental Prediction/Global Forecast System (NCEP/GFS), successfully explored these high radionuclide peaks resulting from long- and medium-range transport processes from the accident site.

The meteorological feature of the medium-range transport exploited in this study is the veering meso-scale circulation, in association with the presence of a blocking anticyclone, and its subsequent evolution with propagation eastwards over northeast Asia, which was one of the important factors in explaining the advection and redirection of radionuclides from the accident site to the Korean Peninsula. The blocking situation of the anticyclone, centered on the Korean Peninsula, lasted for two days (on April 4–5, 2011), and the northwesterlies and subsequent northerlies advected the radionuclides from the accident site to the southern Sea of Japan. They were then redirected towards Korea due to the veering circulations produced by the blocking anticyclone. The position-evolution of the anticyclone was concurrent with the timing of the transport of the highest level of ^{137}Cs concentrations recorded in Korea. The vertical meteorological structure of the blocking anticyclone was also well featured to maintain its position due to the persistent compensation provided by being aloft a convergence zone, which is in good accordance with the location of the ridge on the 500 hPa level.

1. Introduction

The Fukushima Dai-ichi nuclear accident, which occurred on March 11, 2011, is one of the largest nuclear disasters since the Chernobyl disaster of 1986, and the second disaster (after Chernobyl) to be given the Level 7 event classification of the International NuclearEvent Scale. During and after the Fukushima Dai-ichi nuclear accident occurred, numerous measurements and numerical studies have been carried out in order to understand the harmfulness and damages, along with how the radionuclides have been transported from the accident area since the accident (Mathieu et al., 2012; Park et al., 2013; Estournel et al., 2012; Momoshima et al., 2012; Long et al., 2012; Christoudias and Lelieveld, 2013). In Korea, the Korea Institute of Nuclear Safety (KINS) has been operating a monitoring program, and peak concentrations of ^{131}I and ^{137}Cs were detected across almost all sites in Korea during the period of April 2–8, 2011. These peaks are believed to be directly transported from the accident site through medium-range transport processes. Continuously, incident-related

* Corresponding author at: Department of Atmospheric Sciences, Pusan National University, 2, Busandaehak-ro 63beon-gil, Geumjeong-gu, Busan 46241, Republic of Korea.

E-mail address: chkim2@pusan.ac.kr (C.-H. Kim).

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radionuclides were detected until mid-April in many other monitoring sites and intermittently until the end of April.

In East Asia, the most frequent direction of atmospheric movement is from west to east, following the predominant upper air stream over mid-latitudes. Therefore, westerly winds are prevalent and can transport emitted radionuclides from East or Central Asia to North America with their seasonal variations of strength. The westerly winds are stronger in winter than summer and, therefore, radionuclides are transported at greater speeds and over greater distances during the winter months. In summer, the easterlies extend their influence northward so that the North American and Asian summer monsoons develop and drive surface emissions of radionuclides northward (UNECE, 2010). Therefore, the location and the time of the year in which the accident took place have a strong influence on the transport pathways and strength of transport events. With this in mind, westward medium-range transport, such as from Japan to Korea, occur much more rarely than eastward process over East Asia.

Lee et al. (2015) showed in their numerical studies that the basic features of long-range transport pathways to the Korean Peninsula, through the Fukushima Dai-ichi nuclear accident, were characterized on three different scales: (1) intercontinental, (2) global (or hemispherical), and (3) regional scales. This study, however, focused on the regional scale transport process of the radionuclides that were released on early April, 2011, arriving at the Korean Peninsula via the southwest Sea of Japan, and influenced by meteorological circulations. Lee et al. (2015) addressed the simulated arrival/duration time of peaks by employing the Lagrangian multi-particle model, FLEXPART (e.g. Stohl et al., 2012; Terada et al., 2012), coupled with NCEP/GFS input data. However, they did not demonstrate the details of the meteorological features that can explain the medium-range transport process from the accident site to the upstream region occurred particularly during early April, 2011.

In this study, we explored the features of medium-range transport process with spatiotemporal results of the measurements of ^{131}I and ^{137}Cs during April 2–8, 2011, and compared with the results produced by FLEXPART. The measured radionuclide data in South Korea were collected by and made available from the Korea Institute of Nuclear Safety (KINS). In addition, we attempted to explain that the direct medium-range transport process from the accident site to the Korean Peninsula should be meteorologically possible due to the features of wind fields around the flank of the quasi-persistent anticyclone. Since this transport pathway is associated with the presence of a quasi-persistent location, it was able to be identified by simply inspecting the weather maps; two synoptic weather maps of both the lower (850 hPa level) and upper atmosphere (500 hPa height fields) were employed for the identification of meteorological features that have been favored by the relevant transport process. Other information, such as streamline patterns and meso-scale meteorological dynamics, that were present during April 2–8, 2011, has also been discussed. By illustrating this sequence, we will point out the dominant role of the anticyclone in predicting the transport pathways by providing the proper interpretation of the meso-scale meteorological features over northeast Asia.

2. Measurements and modeling study

2.1. Measurement

In Korea, the KINS has been continuously monitoring both environmental radiation and the associated dose rates throughout Korea. When KINS first detected the incident signal at one monitoring station on March 28, 2011, it reinforced the extent of the monitoring program, and has monitored during and after the Fukushima accident.

Fig. 1 depicts the locations of the 12 Korean monitoring stations used in this study. The monitored data has also been used in the previous study (Lee et al., 2015). The radionuclide samples were collected at 01:00 UTC every morning and were analyzed every day during the study period. All samples were analyzed by a high purity germanium detector for 24 h, and prepared for gamma spectrometry. The samples were analyzed together with IAEA reference materials, and then analytical results were compared with values of the reference materials for the quality control of measurement results in gamma spectrometric analysis. The Minimum Detectable Concentration of ^{137}Cs and ^{131}I were ranging from 0.02 to 0.1 mBq/m^3, and 0.03 to 0.1 mBq/m^3, respectively (Lee et al., 2015). Other information on the radionuclide sampling is described by Lee et al. (2015) and Kim et al. (2012).

2.2. Model simulations

As the key simulation components, the two radionuclides (^{131}I and ^{137}Cs), were selected in light of their potential harmfulness to human health (UNSCEAR, 2014). The FLEXPART model was used to simulate the transport and dispersion processes in this study. FLEXPART was driven by the National Centers for Environmental Prediction/Global Forecast System (NCEP/GFS) wind fields with a

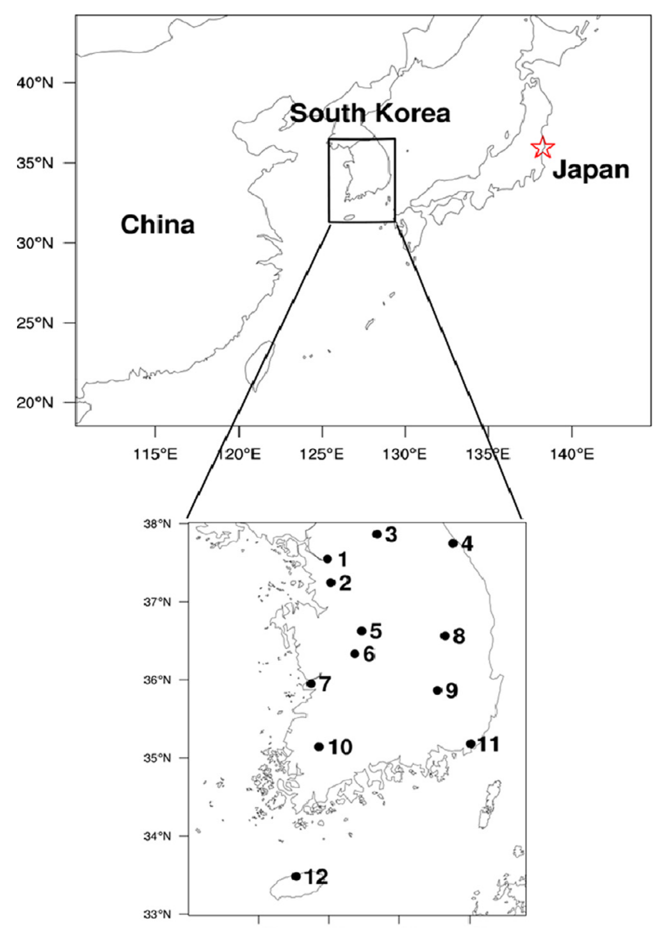

Fig. 1. Map of the locations of 12 monitoring stations in Korea and Fukushima nuclear accident site. The star (☆) denotes Fukushima nuclear accident site, and filled circles (●) denote the stations used in this study: (1) Seoul, (2) Suwon, (3) Chuncheon, (4) Gangneung, (5) Cheongju, (6) Daejeon, (7) Gunsan, (8) Andong, (9) Daegu, (10) Gwangju, (11) Busan, and (12) Jeju.