A Numerical Simulation of Global Transport of Atmospheric Particles Emitted from the Fukushima Daiichi Nuclear Power Plant

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Abstract

The powerful tsunami generated by the massive earthquake that occurred east of Japan on March 11, 2011 caused serious damages of the Fukushima Daiichi Nuclear Power Plant on its cooling facilities for nuclear reactors. Hydrogen and vapor blasts that occurred until March 15 outside of the reactors led to the emission of radioactive materials into the air. Here we show a numerical simulation for the long-range transport from the plant to the U.S. and even Europe with a global aerosol transport model SPRINTARS. Large-scale updraft organized by a low-pressure system traveling across Japan from March 14 to 15 was found effective in lifting the particles from the surface layer to the level of a westerly jet stream that could carry the particles across the Pacific within 3 to 4 days. Their simulated concentration rapidly decreases to the order of $10^{-8}$ of its initial level, consistent with the level detected in California on March 18. The simulation also reproduces the subsequent trans-Atlantic transport of those particles by a poleward-deflected jet stream, first toward Iceland and then southward to continental Europe as actually observed.

1. Introduction

A massive earthquake, which was 9.0 on the Richter scale according to the Japan Meteorological Agency, occurred on March 11, 2011 off the Pacific coast of northeastern Japan. The devastating tsunami generated by the earthquake swept dozens of coastal cities and towns, causing the loss of more than 15,000 lives and leaving at least 7,000 people still missing. Located on the Pacific coast, the Fukushima Daiichi Nuclear Power Plant operated by the Tokyo Electric Power Company also suffered seriously from the powerful tsunami. Although the nuclear reactors stopped their operation automatically on the occurrence of the earthquake, the cooling system for nuclear fuel almost broke down due mainly to the loss of power supply. The hydrogen and vapor blasts that had subsequently occurred until March 15 destroyed the buildings that had contained the reactors, resulting in the release of radioactive materials (e.g., iodine 131, cesium 137) into the atmospheric boundary layer (Nuclear and Industrial Agency, Japanese Ministry of Economy, Trade and Industry 2011). Leaving the soil and water polluted, those airborne materials rapidly spread into the vicinity of the plant where evacuation was forced.

Though extremely low in their concentration, radioactive materials that were quite likely to originate from the Fukushima Daiichi Nuclear Power Plant have also been detected at such distant locations as North America and Europe. The long-range transport of radioactive materials from the power plant was simulated by the Institut de Radioprotection et de Sûreté Nucléaire (IRSN)/Météo France, and the simulated result is opened via website (Institut de Radioprotection et de Sûreté Nucléaire (IRSN) 2011). In this study, we attempt to simulate this long-range atmospheric transport with a global aerosol transport model SPRINTARS (Takemura et al. 2000; Takemura et al. 2002; Takemura et al. 2005), by releasing a number of particles from a model grid point that is closest to the Fukushima Plant (37.4°N, 141.0°E), and to analyze the meteorological condition for the long-range transport.

2. Model description

SPRINTARS (Takemura et al. 2000; Takemura et al. 2002; Takemura et al. 2005) is normally used for simulating global distributions and climate effects of main tropospheric aerosols, including black carbon, organic matter, sulfate, soil dust and sea salt, and for weekly prediction of global aerosol distributions (SPRINTARS Developer Team 2007). It calculates physical processes involved in the transport of particles, including their emission, molecular and turbulent diffusion, advection by air motions on grid and larger scales and their deposition down to the surface by gravity, turbulence, and precipitation. SPRINTARS by itself can simulate the time-evolving global atmospheric state, such as air motion, temperature, moisture, clouds and precipitation, through its dynamical core, which is based on the atmospheric component of a global climate model, MIROC (Watanabe et al. 2010), developed by the Atmosphere and Ocean Research Institute (AORI)/University of Tokyo, National Institute for Environmental Studies (NIES), and Japan Agency for Marine-Earth Science and Technology (JAMSTEC). The horizontal resolution of the model is approximately 0.56° by 0.56° in latitude and longitude (T213 spectral truncation in the dynamical core), and the model has 20 vertical levels including 4 levels below the altitude of 1 km (approximately at the 50, 200, 500 and 1000-m levels). For raising accuracy of our simulation, however, atmospheric state internally generated by the dynamical core was nudged in this study to 6-hourly data based on the observations.

In our experiment particles were released from a particular grid point at the lowest layer that is closest to the Fukushima Daiichi Nuclear Power Plant. The radius of the particles, 10 μm, released in the particular simulation has been determined by comparing the quantitative spread of the radioactive materials measured in eastern Japan and its counterpart based on pre-simulations carried out with several different-order particle sizes. After release from the power plant, particles are treated as dust aerosol in the simulation for dry and wet depositions and gravitational settling according to Takemura et al. (2000). The in-cloud coefficient defined in equation (A8) of Takemura et al. (2000) is 0.1. Particles were kept released from 1200 UTC, March 14, when
observed radiation dose at the power plant rapidly increased (Japan Atomic Energy Agency (JAEA) 2011). Since the time-varying emission of the materials, even their total amount, is unknown, constant emission of a unit mass of particles had to be assumed in our simulation. Under this hypothetical setting, the simulated result presented below thus merely indicates the ratio in particle concentration between the domain within a few tens of kilometers from the power plant and a given distant location. The analysis in this study is, however, basically on the initial arrival of particles to the North America and Europe, therefore it is not critical to treat the emission as constant. Furthermore, any particle in this simulation is treated as a general passive tracer but not as a specific radioactive material.

3. Results and discussion

Figure 1a (also see Supplement 1) indicates that some of the particles emitted from the Fukushima Daiichi Nuclear Power Plant are simulated to reach the west coast of North America.
within 4 days from the initial date of the emission. Their simulated mass concentration is about $10^{-4}$ relative to that around the power plant. The Comprehensive Nuclear Test Ban Treaty Organization (CTBTO) stated that radioactive materials detected in California (CA) on March 18 were likely to originate from the Fukushima Power Plant (U.S. Environmental Protection Agency (EPA) 2011; CNN 2011). The amount of radiation dose measured in CA was on the order of $10^{-3}$ relative to that naturally received from rocks and solar radiation in daily life. Considering the fact that measured radiation dose at a few tens of kilometers away from the power plant was about $10^3$ times larger (around 10 µSv hour$^{-1}$) than usual (less than 0.1 µSv hour$^{-1}$), we therefore conclude that the simulated result is consistent with the measurement in CA. Our simulation also successfully reproduce the subsequent trans-Atlantic transport of the radioactive particles with the power-plant origin. As actually observed (Reuters 2011), some of the particles released from the Fukushima area reach Iceland on March 20 (local time) (Fig. 1b; also see Supplement 1) before arriving at Switzerland (Fig. 1c; also see Supplement 1). In the model, the particle concentration near the surface around Iceland estimated to be on the order of $10^{-3}$ relative to that simulated in CA, and the trans-Atlantic transport occurred mainly along the jet stream.

The long-range atmospheric transport over ~10,000 km within 3 to 4 days as actually observed and also simulated for the particles that were emitted from the Fukushima Daiichi Nuclear Power Plant is attributable to a strong westerly jet stream. In the period from March 17 to 21, the jet stream flew over Japan, CA and Iceland across the Pacific, continental U.S. and Atlantic (Fig. 2). In fact, along this jet stream, radioactive materials were detected in that period over the east and west coasts of the U.S. (U.S. Environmental Protection Agency (EPA) 2011; CNN 2011) In order for the particles to be transported with the jet stream, they must be lifted up from the surface boundary layer to the mid- or upper troposphere. Large-scale updraft was indeed observed around eastern Japan with a traveling low-pressure system on March 14 through 15 (Figs. 2 and 3), when the water vapor and hydrogen blasts occurred at the nuclear power plant. Once lifted up to the altitude of 5 km or so, the particles could be carried for ~3,000 km a day by the westerlies and therefore transported across the North Pacific within 3 to 4 days, as confirmed in our simulation (Fig. 1a). Stronger than in the climatological-mean state (Fig. 4a), the westerlies in mid-March were thus particularly effective in the trans-Pacific transport of the radioactive materials. Over the North Atlantic, the westerly jet stream was deflected poleward in mid-March due to an abnormally developed pressure ridge over Europe (Fig. 4a). As confirmed in our simulation (Fig. 1; also see Supplement 1), the particles that had been transported across the Atlantic thus reached Iceland first and then continental Europe following the meandered westerlies and associated downdraft just east of the pressure ridge (Fig. 4b). In the course of this hemispheric-scale transport, however, the particle concentration had been rapidly decreasing, as simulated and actually observed (U.S. Environmental Protection Agency (EPA) 2011; CNN 2011; Reuters 2011).

The particular low-pressure system that organized large-scale updraft in traveling across eastern Japan from March 14 to 15 accompanied light precipitation and near-surface (south-) easterly wind (Fig. 3). This onshore wind aded radioactive materials from the nuclear power plant on the coast toward inland, contributing to the particularly high radiation dose observed after March 15 along the Ukedo River basin (Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) 2011), which extends northwestward from just north of the plant. The radioactive materials transported inland and then deposited on the ground have been (and will possibly keep) emitting radiation. Owing to their rather coarse spatial resolution, global transport models, including SPRINTARS, are not suited for realistic simulation of regional transport of radioactive materials over eastern Japan. For this purpose it is therefore essential to utilize regional transport models with much higher spatial resolution by incorporating detailed and continuous measurements of radioactive materials. The authors' research group is simulating and discussing the transport and deposition of radioactive materials from the Fukushima

![Fig. 2. Speed (color) and direction (arrows) of mid-tropospheric (500 hPa) wind averaged from March 17 to 21 analyzed by the Climate Data Assimilation System (JCDAS), Japan Meteorological Agency (JMA) (Onogi et al. 2007). Fukushima, CA, and Iceland are indicated with blue, red and black circles, respectively. Heavy block lines indicate areas of updraft that was stronger than 3 cm s$^{-1}$ at around the top of the boundary layer (850 hPa) at 1200UTC, March 14.](image)

![Fig. 3. Surface weather map around Japan for 0900UTC, March 15 analyzed by JMA. The Fukushima Daiichi Power Plant is indicated with a red dot.](image)

Daiichi Nuclear Power Plant with regional models considering temporal variation of the emission and detailed deposition processes for radioactive materials, which will be reported in next papers.

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Supplement

SPRINTARS simulation of near-surface mass concentration of particles emitted continuously from the Fukushima Daiichi Nuclear Power Plant since March 14 in the Supplement 1. The concentration indicated is relative to that within a few tens kilometers around the power plant. Each range of color contours corresponds to one order of magnitude.

References


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SOLA: http://www.jstage.jst.go.jp/browse/sola