Chapter 4
Late Atmospheric Effects of a Nuclear Accident: Comparison Between the Fukushima Daiichi NPP and Chernobyl Accidents

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Abstract Nuclear disasters such as the Chernobyl nuclear power plant (NPP) and Fukushima Daiichi NPP (FDNPP) accidents have contaminated global atmosphere, terrestrial and marine environments by radioactive materials. The environmental impacts of the nuclear accidents continued over more than 10 years. In this chapter, we focus on long-term atmospheric effects of the nuclear accidents by comparing impacts of the FDNPP and Chernobyl for better understanding of their long-term atmospheric effects. For both accidents, the atmospheric concentrations of ^{137}Cs, which is a major radionuclide released from damaged reactors, decreased rapidly with an apparent atmospheric half-life of 1 and 2 weeks at the initial stage, and after that decreased gradually with an apparent atmospheric half-life of about 1 year. The areas affected by the late atmospheric effects correspond to a slow decrease rate of airborne ^{137}Cs, depending on the total release of radioactivity. The late atmospheric effects have been related to radionuclide resuspension and additional emissions from the damaged reactors. However, the current understanding of resupension is more complicated, as it depends on the wind blow of soil particles, human activity in fields as well as on roads and construction sites, forest fires, ecosystem activities of forests, and others. It is noteworthy that a significant fraction of radioactively contaminated areas for both major accidents was forested. These findings suggest that long-term atmospheric radioactivity monitoring is necessary to assess the environmental effects of the nuclear accidents.

Keywords Chernobyl · Fukushima · ^{137}Cs · Late effect · Resuspension · Atmosphere

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4.1 Introduction

Two serious nuclear power plant (NPP) accidents, i.e., Chernobyl and Fukushima Daiichi NPP (FDNPP) accidents, have occurred during the past six decades of peaceful use of nuclear energy for electricity production. As a result, huge amounts of radioactivity were released in the environment and spread all over the globe. Radioactivity emitted into the environment has seriously affected human society with potential impacts on human health. The Chernobyl and FDNPP accidents, which have been rated on the International Atomic Energy Agency (IAEA) International Nuclear and Radiological Event Scale (INES) as a "Major Accident" (INES scale 7), were one of the biggest environmental disasters in the recent five decades [1, 2]. In order to implement adequate protective actions for the nuclear disaster and to assess the environmental impact of the Chernobyl/FDNPP radioactivity, a lot of environmental monitoring had been conducted by the national and local governments, research institutes and universities in Russia/Japan and in the world, including the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) network. The major influence of radioactivity released by the NPP accidents appeared for the first 1 month; however, it continued for a long time. In order to predict the impact and fate of possible new NPP accidents to environment, it is important to assess what happened in the past NPP accidents. Therefore, comparison of environmental impacts between the Chernobyl and the FDNPP accidents, which has been recently reviewed [3], is important. In this chapter, we describe the difference in environmental impacts between the Chernobyl and FDNPP accidents, and discuss about similar long-term atmospheric effects, including factors controlling the atmospheric levels of anthropogenic radionuclides.

4.2 Characteristics of Chernobyl and FDNPP Accidents

4.2.1 Overview of the Accidents and Total Releases of Radionuclides

The Chernobyl accident occurred on April 26, 1986, in the course of a technical test in Unit 4 at the Chernobyl NPP, located in Ukraine about 20 km south of the border with Belarus. An initial high atmospheric emission rate of radionuclides on the first day was caused by the explosion of the RBMK-type reactor. There followed a 5-day period of declining releases, which was associated with the hot air and fumes from the burning reactor graphite core materials, after that, the atmospheric release rates of radionuclides increased until tenth day from the initial explosion, and finally the releases stopped sharply. As a result, the radionuclide releases from the damaged reactor occurred mainly over a 10-day period. Major radionuclides released from the Chernobyl accident were due to ^{131}I and ^{137}Cs, taking into account radiological effects and their half-lives. For ^{137}Cs, inventory of the reactor core at the time of accident was estimated to be 260–290 PBq (1 PBq = 10^{15} Bq). The corresponding

inventory of ^{131}I was 3200 PBq. The environmental release of ^{137}Cs is estimated to be 85 PBq, corresponding to about 30% of the core inventory. From average deposition densities of ^{137}Cs and the areas of land and ocean regions, the total ^{137}Cs deposition in the northern hemisphere was estimated to be 70 PBq, which is in good agreement with the estimate from the reactor core [1]. For ^{131}I, the release was estimated to be 1760 PBq [1], about 50% of the core inventory. In this case, this value is about five times higher than predictions of the early UNSCEAR (1988) Report [4]. To prevent release of radioactivity in the environment, construction of a sarcophagus covering Unit 4 began in August 1986 and was completed in November 1986.

On March 11, 2011, a 9.0-magnitude earthquake occurred near northeast Honshu, Japan, creating a devastating tsunami. As a result of the earthquake and the subsequent tsunami, the loss of off-site and on-site electrical power (station blackout) and compromised safety systems at the Fukushima Daiichi Nuclear Power Plant (FDNPP) mainly due to flooded diesel electricity generators led to severe core damage to three of the six nuclear reactors on the site [5, 6]. The atmospheric release of radioactivity started in Reactor 1 (BWR MARK I) at night, March 11, 2011, due to melt of nuclear fuel. On March 12, 2011, a hydrogen explosion occurred in the Reactor 1. Large amounts of radioactivity were released in the environment from the FDNPP. On March 14, a hydrogen explosion occurred in the Reactor 3. On March 15, Reactor 2 was seriously damaged. The greatest amounts of radioactivity were released into the atmosphere from March 15 to 16. High emission rates of radioactivity continued until March 23, 2011 [7]. After March 24, emission rates decreased with time.

Major radionuclides released from the FDNPP accident were ^{131}I and ^{137}Cs, as did the Chernobyl accident. For ^{137}Cs, the core inventory of the three reactors at the time of accident was estimated to be 700 PBq. Corresponding core inventory of ^{131}I was 6010 PBq [6]. The atmospheric release of ^{137}Cs was estimated to be 9–36 PBq from reverse and inverse methodologies using monitoring results [2, 7–11]. Aoyama et al. [12] evaluated more accurate total release of ^{137}Cs comparing between model-simulated results including atmosphere and ocean, which was 15–20 PBq, corresponding to about 2% of the core inventory. For ^{131}I, the release is estimated to be 160 PBq, about 3% of the core inventory [6].

For the Chernobyl and FDNPP accidents, major atmospheric emission of radioactivity continued for about 10 days, although the history of radionuclide emission rates differed between the Chernobyl and FDNPP accidents. The total atmospheric release of ^{137}Cs, the most concerned radionuclide from all emissions due to its radiological significance was for the Chernobyl accident by about five times greater than for the FDNPP accident.

4.2.2 Physical and Chemical Properties of Released Radionuclides

The atmospheric behaviors of the radionuclides emitted from the NPP depended on the physical and chemical properties of the radionuclide-bearing particles. For the Chernobyl accident, there were only a few measurements of the aerodynamic

diameter of radionuclide-bearing particles released in early days after the accident. A crude analysis of air samples, collected at 400–600 m above the ground in the vicinity of the Chernobyl power plant on April 27, 1987, implied that large radioactive particles, varying the size from several to tens of micrometers, were observed, together with an abundance of smaller particles [13]. The aerosol samples were collected on May 14 and 16, 1986, above the damaged reactor, in which radionuclide-bearing particles showed the superposition of two lognormal distributions: one having an activity median aerodynamic diameter (AMAD) with a range from 0.3 to 1.5 μm, and the other one of more than 10 μm [14]. According to the results of aerosol sampling in remote sites, the AMADs of ^{131}I-, ^{103}Ru-, ^{137}Cs-, and ^{134}Cs-bearing particles were in sub-micrometer range [15–19], whereas the ^{90}Sr and plutonium isotopes were found in larger micrometer particles [20, 21]. The AMADs of Chernobyl-derived radionuclides varied temporally due to the difference in the emission processes at the damaged reactor and/or the fractionation in the transport processes of the Chernobyl radioactivity.

For the FDNPP accident, Doi et al. [22] determined AMADs of particles carrying Fukushima-derived ^{131}I, ^{134}Cs, and ^{137}Cs. The AMAD of ^{131}I-bearing particles was 0.7 μm for both April 4–11 and April 14–21, 2011, events; the AMAD of ^{134}Cs-bearing particles was 1.8 and 1.0 μm in the first and the second period, respectively, while for ^{137}Cs-bearing particles it was 1.5 and 1.0 μm in the first and the second period, respectively. The mass size distribution of the total aerosol was bimodal with peaks in particle diameters at about 0.5 μm and 5–10 μm, which correspond to sulfate and soil particles, respectively. Thus the ^{134}Cs- and ^{137}Cs-bearing particles observed in April differed in diameter from both sulfate and soil particles. The difference in particle size distributions between ^{131}I and radiocesium implies that the process of formation of ^{134}Cs- and ^{137}Cs-bearing particles differed from that of ^{131}I. In another report on the size distribution of Fukushima radiocesium-bearing particles at Tsukuba in the two periods April 28–May 12 and May 12–26, Kaneyasu et al. [23] revealed that ^{134}Cs and ^{137}Cs, having AMAD values around 0.5–0.6 μm, were attached to sub-micrometer sulfate particles. Both findings suggest that the AMAD of the observed radiocesium-bearing particles changed with time. The particle size of radiocesium observed in April may reflect hot particles transported directly from the NPP because the radiocesium concentrations in surface air were more than one order of magnitude greater in April than they were in May. Adachi et al. [24] by using a scanning electron microscope equipped with an energy dispersive X-ray spectrometer revealed that FDNPP-derived radionuclides emitted during the period of March 15–16 were contained in spherical radiocesium-bearing particles (diameter: 2.6 μm), which were water less soluble than sulfate particles. Masson et al. [25] determined size distributions of the FDNPP-derived radionuclide-bearing particles at several places in Europe; the AMAD ranged from 0.25 to 0.71 μm for ^{137}Cs, from 0.19 to 0.69 μm for ^{134}Cs, and from 0.30 to 0.53 μm for ^{131}I, thus in the accumulation mode of the ambient aerosols (0.1–1 μm).

Although the reactor types of the Chernobyl (RBMK) and FDNPP (BWR) differed from each other, most of the ^{137}Cs-bearing aerosols existed as sub-micrometer particles in both cases [15, 23]. At an early stage of the both accidents, significant amounts of radiocesium were emitted into the atmosphere as hot particles, easily

removed from the atmosphere by dry and wet deposition processes, unlike the submicrometer particles emitted from Chernobyl [15, 20, 26]. The hot particles derived from the Chernobyl accident were classified into two broad categories: (1) fuel fragments with a mixture of fission products bound to a matrix of uranium oxide, similar to the composition of the fuel in the core, so including plutonium isotopes and other actinides, but sometimes strongly depleted in volatile fission products such as radiocesium, radioiodine, and radioruthenium, and (2) particles consisting of one dominant element (ruthenium and barium) but sometimes also having traces of other elements [27–31]. These monoelemental particles may have derived from embedments of these elements produced in the fuel during the operation and released during the fragmentation of the fuel [28]. For the FDNPP accident, hot particles with spherical shape and amorphous structure contained high amounts of radiocesium, which was embedded into silicate [24, 32]. There is no clear evidence of presence of hot particles consisting of fuel materials. The difference in hot particles between the Chernobyl and FDNPP accidents may be due to the difference in the formation processes of hot particles in the reactor and/or particle formation in release processes [33].

4.2.3 Radioactively Contaminated Areas

In order to effectively conduct radiation protective actions for the FDNPP-derived radionuclide distribution for NPP accidents, it is essential to construct detailed radioactivity contamination (deposition density) maps. After the Chernobyl accident, radioactive contamination of the ground surface was found to some extent in practically every country of the northern hemisphere. The detailed contamination patterns had been established from extensive monitoring of the affected areas. The high contamination area of ^{137}Cs (>37 kBq m^{-2}), which is greater than that of maximum deposition density due to global fallout (~10 kBq m^{-2}) [34], was estimated to be 1.82×10^5 km^2, in which about 75% of the total highly contaminated area are present in the territories of Belarus, the Russian Federation, and Ukraine, where about 25% exists in north and east Europe [1]. The highly ^{137}Cs contaminated areas spread in Belarus (B), the Russian Federation (RF), and Ukraine (U) and were classified as four classes: the class 1 area (>1.48 MBq m^{-2}) was estimated to be 3100 km^2 (RF: 300, B: 2200, U: 600 km^2), the class 2 area (0.555–1.48 MBq m^{-2}) was 7200 km^2 (RF: 2100, B: 4200, U: 900 km^2), the class 3 area (0.185–0.555 MBq m^{-2}) was 19,100 km^2 (RF: 5700, B: 10,200, U: 3200 km^2), and the class 4 area (37–185 kBq m^{-2}) was 116,900 km^2 (RF: 49,800, B: 29,900, U: 37,200 km^2) [1]. The contaminated areas (>185 kBq m^{-2}) in Belarus are 43% agricultural areas, 39% forested, and 2% rivers and lakes.

The highly contaminated area of the FDNPP-derived radionuclides was limited in Japanese territory. The size of the contamination area in Japan with levels >185 kBq m^{-2} after the FDNPP accident, in comparison, is measured by an area of approximately 1700 km^2 [3], which is <6% of corresponding contaminated area for the Chernobyl accident (29,400 km^2). This result is consistent with the findings that

about 20–30% of the total atmospheric ^{137}Cs release from the FDNPP was deposited on land [12] and that the total amount of FDNPP-derived ^{137}Cs is about 20% of that of the Chernobyl. In Japan, more than 75% of the contaminated area is forested, <10% rice paddy fields, <10% other agricultural areas, and <5% urban areas.

4.2.4 Atmospheric Effects

Radioactivity measurement in surface air is one of the most important issues in emergency environmental monitoring. After the Chernobyl accident, high levels of radioactivity in surface air and deposition (wet and dry) were observed in early May 1986 at many air monitoring stations in the northern hemisphere. The high activities of Chernobyl radionuclides, typically ^{131}I, ^{137}Cs, ^{134}Cs, and ^{103}Ru, were found in air samples, in which a maximum occurred in early May and after that rapidly decreased with time, although second and third peaks were observed at some sampling stations [35]. An apparent atmospheric half-life of the Chernobyl radionuclides was estimated to be 6 days for observation at remote sites [36]. However, the decrease rate of the Chernobyl radionuclides in air and deposition was slow down. Atmospheric effects of the Chernobyl radioactivity continued for a long time [6].

For the FDNPP accident, various air monitoring campaigns of radionuclides released from the FDNPP had been conducted to elucidate the emission history, which is closely related to sequence of the FDNPP accident, although we had incomplete information on the environmental contamination at the early stage of the accident due to destruction of monitoring systems as a result of the great earthquake and the resulting tsunami [6]. The high level of radionuclides, typically ^{131}I, ^{137}Cs, and ^{134}Cs, was observed in surface air until late March 2011. Although some high peaks of air radionuclides, accompanied with the arrival of the radioactive plume from the FDNPP, occurred during the period of March to April, the level of air radionuclides decreased rapidly, which is corresponding to the decrease of radioactivity emission rates in the FDNPP. An apparent atmospheric half-life of the FDNPP-derived ^{137}Cs during the period of March to June 2011 was calculated to be about 12 days from monthly deposition data [37]. After July 2011, the decrease rates of the surface air concentration and deposition of FDNPP-derived ^{137}Cs declined. In Austria, atmospheric ^{131}I exhibited an apparent half-life between 4 and 6 days and was detectable until May 16, 2011 [38].

4.3 Late Atmospheric Effects of NPP Accidents

4.3.1 Trends of Atmospheric Radionuclides

After the NPP accidents, the terrestrial environment suffered major contaminations, dominantly including forest and agricultural areas. Radioactivity contaminated area is a potential source of radioactive aerosols due to resuspension. On the other hand,

sporadic and/or continuous emission of radionuclides from the damaged nuclear reactors may occur in isolation and remediation processes. Therefore, long-term monitoring of anthropogenic radionuclides in air and deposition samples has been required to assess the environmental effects of post-accident.

Since the mid-1950s, radioactivity monitoring sites in Europe, USA, and Japan have been constructed to measure anthropogenic radionuclides, especially ^{137}Cs, ^{90}Sr, and ^{239,240}Pu in surface air and deposition to elucidate the effects of nuclear events such as atmospheric nuclear testing, NPP accident, and others. The monitoring results revealed that the ^{137}Cs in surface air and deposition does not return to pre-Chernobyl level at 1 year after the accident. Figure 4.1 shows the temporal variations of annual ^{137}Cs, ^{90}Sr, and ^{239,240}Pu deposition in Germany and Greece during the period of 1987–1997 [39–41], in which Tsukuba (Japan) is selected as a reference site [42–44]. In pre-Chernobyl era, the surface air concentrations of anthropogenic radionuclides were controlled by stratospheric–tropospheric fallout due to the atmospheric nuclear testing; in the mid-latitude region, similar level of anthropogenic radionuclides was observed at monitoring stations [45]. In the post-

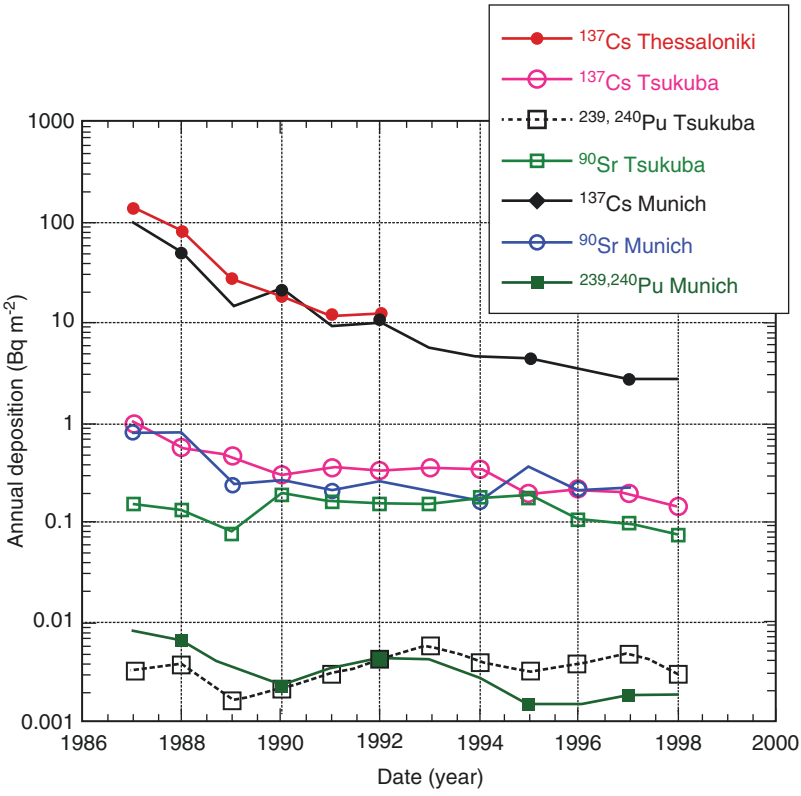

Fig. 4.1 Temporal variations of annual ^{137}Cs deposition observed in Europe and Japan during the period of 1987–1998. The figure was synthesized form papers [39–41]

Chernobyl era, the level of ^{137}Cs deposition in Europe (Germany and Greece) was more than two orders of magnitude larger than that in the Fareast Asia (Japan). The annual depositions of ^{90}Sr and ^{239,240}Pu in Munich were affected by the Chernobyl fallout in the late 1980s, although impacts of the Chernobyl-derived ^{90}Sr and ^{239,240}Pu are weaker than those of ^{137}Cs. The annual ^{137}Cs deposition in European sites decreased with apparent atmospheric half-life (AAHL) of 1 y; AAHLs at Neuherberg, Germany [46], Mappenberg, Germany [47], and Thessaloniki, Greece [48] were 0.77 y (Aug. 1986–Dec. 1988), 1.07 y (1988–1989), and 1.33 y (1987–1992), respectively. After 1992, the decrease rate of annual ^{137}Cs deposition at Neuherberg was declined. These sites are located at a distance of about 1500 km from Chernobyl. The similar time scale of the AAHL (0.47–2.2 years) was determined for over 20 European sites [49]. The surface ^{137}Cs concentrations in Bratislava were decreasing with the AAHL of 1.9 years during the period of 2003–2010 [50]. On the other hand, irrespective of the long distance of about 8000 km from Chernobyl, small amounts of Chernobyl-derived ^{134}Cs were detected in deposition collected in 1987 at Tsukuba, which may be explained by fallout of the Chernobyl radiocesium partly transported into the lower stratosphere [51–53]. Radiocesium from Chernobyl even significantly elevated the contamination levels in Japanese wheat in 1986 [54]. Although the AAHL of the Chernobyl ^{137}Cs observed in Europe is similar to the time scale of the stratospheric fallout, it is considered that high ^{137}Cs levels in surface air and its deposition should be supported by resuspension of Chernobyl ^{137}Cs deposited on land [41, 49].

FDNPP-derived ^{137}Cs in monthly deposition samples was detected after 2012 at most of the monitoring stations within about 300 km of the FDNPP, as shown in Fig. 4.2. Although the ^{137}Cs deposition gradually decreased with time during the period of 2012–2016 [56, 57], at the end of 2016, the ^{137}Cs levels at these stations were more than one order of magnitude higher than the pre-Fukushima level. The annual ^{137}Cs deposition decreased with the AAHLs of 1.0–1.6 years during the period of 2012–2016. However, the annual ^{137}Cs deposition in 2017 increased at many monitoring sites within about 300 km from the FDNPP; especially, it was 15.3 kBq m^{-2} at Futaba near the FDNPP, which was about twice higher than that in 2016 (7.68 kBq m^{-2}) [55]. This finding suggests that the trend of the annual ^{137}Cs deposition in the vicinity of the FDNPP is governed by the additional release of ^{137}Cs from the FDNPP, although its influence decreases with distance from the FDNPP.

4.3.2 Seasonal Change

Seasonal change of anthropogenic radionuclides in surface air and deposition has been considered to be important information to elucidate sources and transport processes of anthropogenic radionuclides. In the pre-Chernobyl period until 1985, seasonal change of ^{137}Cs in air and deposition, whose peaks occur in May–June, is

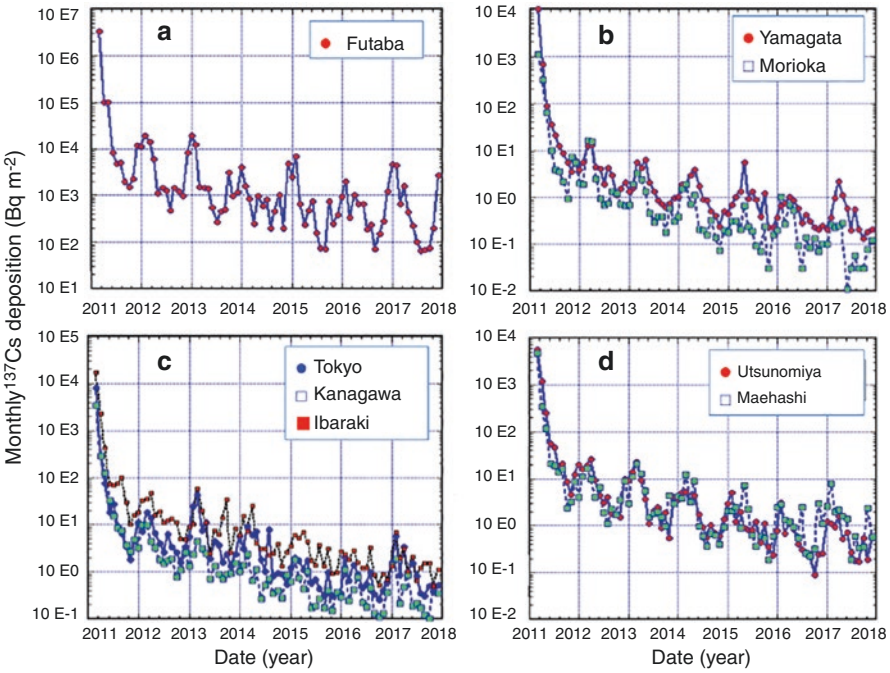

Fig. 4.2 Temporal variations of monthly ^{137}Cs deposition observed in east central Japan. The figure was depicted by using data of NRA [55]. (**a**) Futaba-Okuma near the FDNPP (37.40°N 149.99°E), (**b**) northwest inland sites, Yamagata (38.25°N 140.33°E) and Morioka (39.68°N 141.13°E), (**c**) southwest sites near Pacific coast, Ibaraki-Hitachinaka (36.40°N 140.58°E), Tokyo (35.71°N 139.70°E), and Kanagawa-Chigasaki (35.33°N 139.38°E), (**d**): southwest inland sites, Utsunomiya (36.60°N 139.94°E) and Maehashi (36.40°N 139.10°E)

strongly related to stratospheric fallout due to the atmospheric nuclear testing [58, 59]. According to measurements of ^{137}Cs activity in surface air in Europe, for the post-Chernobyl era, the seasonal pattern of ^{137}Cs exhibits two peaks with enhanced activity in spring (April) and second peak in fall (October). These peaks were explained by advection through the atmosphere boundary layer from Chernobyl. Although seasonal change pattern of surface air ^{137}Cs activity varied between sampling locations (44.5°N–68°N), seasonal change is governed by atmospheric transport from the Chernobyl [59]. On the other hand, the monthly deposition of anthropogenic radionuclides (^{137}Cs, ^{90}Sr, and ^{239,240}Pu) in the 1990s and 2000s exhibited clear seasonal pattern with a spring peak (March–May) in Japan, which is concluded the long-range transport of Asian dust, including global fallout radionuclides without those from Chernobyl, blown up in the east Asian deserts and arid area, based on the knowledge about their level, activity ratios between anthropogenic radionuclides, isotope ratios of plutonium, major element composition of dust including anthropogenic radionuclides, seasonal and inter-annual variations of frequency of dust events and model simulation [43, 44, 60, 61].

After the FDNPP accident, the seasonal pattern of monthly ^{137}Cs depositions within about 300 km from the FDNPP exhibited a peak in February–May and minimum in fall as shown in Fig. 4.2, whereas the seasonal change of ^{137}Cs near the FDNPP showed a marked peak in winter (December–February) and minimum in summer (August). It is likely that the monthly ^{137}Cs deposition near the FDNPP is affected by additional radioactivity emission from the reactor buildings of the FDNPP. The seasonal pattern of the monthly ^{137}Cs depositions within about 300 km from the FDNPP slightly varied spatially and temporally, which implies that a simple process does not control the seasonal pattern of the enhanced ^{137}Cs deposition due to a post-accident emission. The ^{137}Cs activities in fine particles (<1.1 μm) at Fukushima site about 60 km from the FDNPP showed a seasonal pattern in spring (March) maximum, whereas the ^{137}Cs in coarse (>1.1 μm) particles exhibited two peaks in February and August [62]. On the other hand, ^{137}Cs concentrations in surface air of evacuated area showed a clear seasonal change with a peak during summer and fall in 2013 [63]. It is noteworthy that sporadic emission from the FDNPP occurred in August 2013 [64]. These results suggest that it is difficult to recognize their sources and transport from only seasonal pattern of anthropogenic radionuclides, although seasonal pattern is one of the most important knowledge.

4.3.3 Factors Controlling Late Atmospheric Effect

Resuspension is an important process to sustain a level of anthropogenic radioactive aerosols in the surface air. The radionuclides deposited onto ground and/or vegetation are adsorbed onto fine organic or mineral particles. Some meteorological conditions such as aridness and strong wind may blow off fragments of dried soil and vegetation [65]. The resuspension of ^{137}Cs deposited on land surface has been discussed as a significant process supporting the post-accident ^{137}Cs levels in surface air and deposition [66]. Garger et al. [66] summarized the resuspension sources following the Chernobyl accident as (1) dust emission (2) human activity in fields as well as on roads and construction sites, (3) forest fires, and (4) emissions from the power plant (i.e., opening of the Chernobyl sarcophagus). As other resuspension sources, burning of contaminated wastes including biomass and bioaerosols (pollen, spores, bacteria and others) [67, 68] is speculated as the process to support air concentrations and deposition of the FDNPP-derived ^{137}Cs since 2012. Although emission of soil dust is a possible process supporting ^{137}Cs in atmosphere, levels of FDNPP-derived ^{137}Cs deposition observed in Kanto area, central Japan, were hardly supported by dispersion of local soil particles, although its seasonal pattern with high in spring was similar to local dust emission [69]. As a cause of the late atmospheric effects of FDNPP-derived radionuclides, continuous additional atmospheric emission of radiocesium from the FDNPP may be contributed significantly [56].

Model simulation has been developed to assess long-term changes of atmospheric radiocesium after the FDNPP accident, in which includes resuspension from bare soil and forest ecosystem [67, 68], in which a resuspension scheme for

^{137}Cs from bare soil was formulated based on the observation of schoolyard [70] and a forest ecosystem scheme contained term of the green area fraction using normalized difference vegetation index. In this model, resuspension rate from forest was used a constant value of 10^{-7} h. The model simulation reproduced the seasonal pattern of surface atmospheric ^{137}Cs in 2013. However, model simulation of interannual trend remains an issue [5].

4.3.4 Effect of Sporadic Emission

The radionuclides derived from the Chernobyl accident, as did global fallout, had contaminated wide areas of Eurasia [1] and remain a potential source of radioactive aerosols. Forest fires have frequently happened in Eurasia causing the emission of aerosols. Radiocesium, radioiodine, and chlorine were found in the smoke of biomass fires [71]. The high ^{137}Cs concentrations in surface air sporadically occurred in Lithuania. This was due to the transport of the biomass burning plumes including anthropogenic radionuclides, especially volatile radionuclides such as ^{137}Cs, which led to lower ^{239,240}Pu/^{137}Cs ratios than that of global fallout [72]. The radiological risk due to wildfires in Chernobyl contaminated forests was evaluated by model simulation [73]. For the FDNPP accident, there is no clear evidence that biomass burning had a significant impact on atmospheric ^{137}Cs [68].

Sporadic peak events of radioactive emission occurred in August 2013, associated with the debris removal operation in the damaged reactors. High ^{137}Cs concentration in surface air was observed at Namie [67]. Steinhauser et al. [64] estimated the gross release amount of 0.28 TBq to this event using measurements of weekly air filter sampling and monthly deposition and a model simulation.

4.4 Conclusion

The nuclear disasters such as the Chernobyl and FDNPP accidents have caused serious radioactivity contamination of the environment. The environmental impacts of radioactivity released from the nuclear accidents depend on the scale of the total emission from the damaged reactors. After the NPP accidents, atmospheric levels of radionuclides rapidly decreased due to the initial action to cease large emission of radionuclides from the damaged reactors, resulting in apparent atmospheric half-life of 1–2 weeks. A major radionuclide affecting at long time-scale impacts of NPP accidents is ^{137}Cs, although ^{90}Sr and fissile materials such as plutonium are locally important pollutants as well. High atmospheric levels of ^{137}Cs derived from the NPP accident continued over time scale of 1 year, resulting in the apparent atmospheric half-life of about 1 year. However, areas, where late atmospheric effects are observed, depend on spreading of heavily contaminated material, thus ultimately depending on the total radioactivity release. The late atmospheric effect of

radioactivity is governed by resuspension of radionuclides initially deposited on land surface, including forests, grass land, agricultural fields, and artificial construction, although additional emission of radioactivity from the damaged reactors occurs continuously and sporadically accompanied with remediation. The current implication of resuspension is complicated because of forests, which is the dominant type of vegetation in the heavily radioactively contaminated areas for both Chernobyl and FDNPP. In order to assess the late atmospheric effects of the NPP accident, it is important to gain better understanding of mechanisms and controlling factors of resuspension, especially host aerosols containing radionuclides.

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