Radioactive impact in South Korea from the damaged nuclear reactors in Fukushima: evidence of long and short range transport

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Abstract
Traces of long-lived fallout-derived radioisotopes ($^{134}$Cs and $^{137}$Cs) were found in wet and dry deposition samples collected from the west and east coasts of South Korea from March to May 2011 following the release of radionuclides from the damaged nuclear power plants in Fukushima, Japan. The analysis of air mass back trajectory and atmospheric pressure systems indicated that the Fukushima-derived radiocaesium had predominantly reached South Korea from the west by surface westerlies from 11 March to 5 April; however, after 6 April, air masses arrived from Japan directly due to a high pressure system that developed to the east of Japan. Spatial variation of deposition fluxes of radiocaesium in South Korea was partly attributed to the presence of local longitudinal orography.

(Some figures may appear in colour only in the online journal)

1. Introduction
On 11 March 2011 a severely damaging earthquake measuring 9.0 on the moment magnitude scale (numerically the same as the Richter scale) occurred 180 km off the coast of the...
first Fukushima nuclear power plant (NPP). The earthquake was the largest that Japan had experienced since AD 869 (Minoura et al. 2001). It caused all of the operating units (units 1, 2 and 3) to automatically scram on their seismic reactor protection system trips. The loss of primary and secondary containment integrity of the spent fuel resulted in ground-level releases of radioactive material. The Nuclear Safety Commission of Japan estimated that approximately 17 million curies \((6.3 \times 10^{17} \text{ Bq})\) of iodine-131 equivalent radioactive material was released into the air and 0.127 million curies \((4.7 \times 10^{15} \text{ Bq})\) into the sea between 11 March and 5 April (INPO 2011), although accurate information has yet be published.

The atmospheric radionuclide releases largely occurred between 12 and 16 March 2011 with smaller contributions on 20 March following pressure venting of the reactor containments, hydrogen explosions and fires in the first Fukushima NPP. The total atmospheric releases of \(^{134}\text{Cs}\) and \(^{137}\text{Cs}\) were estimated to be around 15.6 and 13 PBq, respectively (Nakano and Povinec 2012). The contribution of \(^{134}\text{Cs}\) was similar to \(^{137}\text{Cs}\) with a \(^{134}\text{Cs} / ^{137}\text{Cs}\) activity ratio of 1.2 at the source in the Fukushima reactors (Nakano and Povinec 2012), although a range of activity values have been reported from less than unity (0.85–0.93) in southern Europe to \(\sim 2.3\) in Fukuoka, Japan and \(\sim 1.8\) in Russia and Greece (Bolsunovsky and Dementyev 2011, Lozano et al. 2011, Momoshima et al. 2011, Manolopoulou et al. 2011, Povinec et al. 2012). Some 13% of the \(^{131}\text{I}\) and 22% of the \(^{137}\text{Cs}\) was deposited over the Japanese islands and the rest was transported to other regions and the sea (Morino et al. 2011).

Fukushima emission had reached the westernmost part of Europe (Iceland) on 19 March (IRSA 2011) and subsequently moved eastward and peaked between 28 March and 3 April in Krakow (Poland) and Mstislav (Belarus) (Pittauerova et al. 2011, Povinec et al. 2012, Masson et al. 2011), eventually arrived at the Korean Peninsula between 1 and 6 April with a peak on 6 April (Korea Institute of Nuclear Safety, www.kins.re.kr/, Hernandez-Ceballos et al. 2012). Lozano et al. (2011) traced the pathways of the radioactive air plume originating from Fukushima to the western coast of the Iberian Peninsula, where it was detected on 27 March. By day 15 after the first release in the air, traces of radionuclides from the Fukushima accident were detectable across the whole Northern Hemisphere. While the radioactive materials remained confined to the Northern Hemisphere for the first 4 weeks, they had spread to the Southern Hemisphere by 13 April. Radioactivity was detected at monitoring stations of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) at locations in Australia, Fiji, Malaysia and Papua New Guinea (CTBTO Preparatory Commission 2012). Artificial radionuclides released from Fukushima were spread across the entire Northern Hemisphere by surface westerlies (Hernandez-Ceballos et al. 2012). Nuclear power production is still an important option for energy generation. However, accidents like this do not create a positive image among the general public, despite energy production from fossil fuels resulting in increased atmospheric \(\text{CO}_2\) which in turn causes global climate change (Lee 2012). In addition, lessons learned from this disaster are likely to help to shape future emergency responses to multi-facetted disasters (Van Deventer et al. 2012).

In this paper, utilising the date of arrival of radioactivity coming from the Fukushima accident as observed at several sites over South Korea, and by using the hybrid single-particle Lagrangian integrated trajectory model along with direct fallout measurements on both the west and east coasts of the Korean Peninsula, we determined the path of the radioactive cloud from the Fukushima NPP to South Korea. The meteorological conditions affected the spatial and temporal variability of the atmospheric concentrations of radiocaesium in South Korea.
2. Materials and methods

2.1. Study area

Aerosol total deposition and rain samples were routinely collected at two sites in South Korea: one on the east coast at Uljin, facing Japan (37°04′32.02″N, 129°24′19″E) (collected since January 2011) and the other on the west coast at Ansan, facing China (37°17′8″N, 126°49′58″E) (collected since 1992 with some interruptions as a part of the study on the production, evolution and impacts of the land and ocean-derived aerosols in the region) (see figure 1). These sampling stations are located at approximately the same latitude as Fukushima (37°18′56″N, 141°1′33″E), Japan. The atmospheric boundary layer is generally separated between the western and eastern coasts of the Korean Peninsula due to the presence of a mountain range situated longitudinally and ranging in altitude from 200 m from the south to over 800 m in the north (Hong and Lee 2009). It was previously known that Seoul, located about 40 km northeast of Ansan, receives air parcels from four regions: the west (China, 79%), southeast (Japan, 13%), southwest (East China Sea, 6%) and northeast (2%) in any given year (Choi et al 2009). Therefore it is not unusual that the western part of South Korea receives air parcels directly from Japan. In Uljin, the wind generally blows from the northwest (January), west (March, April), south or southeast (from Japan) in July and northwest in October (Chu et al 2003).

2.2. Radionuclide determinations

Dry and wet deposition samples were collected over the roof top (about 12 m above the ground) of the KORDI campus at Ansan and Uljin using a plastic bucket (aspect ratio >3). The surface area of the deployed collector was 0.5–5 m². Rain samples were collected on an event basis. Prior to the rain event, the dust collector was manually removed and replaced by a rain collector. The KORDI campuses at Ansan and Uljin are both relatively isolated from the towns and located at the seashore. As we did not use an automatic rain gauge and dry deposition sampler, and the influence of turbulence around the samplers at the roof top was not assessed, our samples were only used here as an indication of the arrival of Fukushima fallout. After the
rainout event the rain collector was washed with 6 M HCl. The wash solution was combined with rainwater samples. Rainwater samples smaller than 6 l were evaporated to dryness and the residue was quantitatively transferred to a counting vial and was directly counted using a HPGe gamma spectrometer. Rainwater samples larger than 6 l were processed to separate caesium from the solution by precipitating with ammonium molybdophosphate (AMP) (Hong et al 2006). Dust samples were directly counted in the HPGe gamma spectrometer (Hong et al 1999) and counts per minute were converted to disintegrations per minute using standard sources of National Institute of Standards and Technology traceable $^{134}$Cs and $^{137}$Cs from Eckert and Ziegler and Isotope Products Laboratories. The detection limits for both $^{137}$Cs and $^{134}$Cs were 0.6 Bq kg$^{-1}$ for dust samples and 0.02 mBq kg$^{-1}$ for rainwater samples.

2.3. Meteorological modelling. The HYSPLIT model

The air mass analysis in the reference sites was based on the calculation of three-dimensional (3D) backward trajectories by using the hybrid single-particle Lagrangian integrated trajectory (HYSPLIT; version 4.9) model (Draxler and Hess 1998, Draxler et al 1997). Model-calculated vertical velocities were used to compute backward trajectories, which are more accurate than other operational methods contained in the model such as the isobaric or isoentropic ones (Stohl 1998). This method uses directly the vertical motion field contained in the global data assimilation system (GDAS) meteorological data set (reprocessed from NOAA’s National Centres for Environmental Prediction Final Analysis Data by the Air Resources Laboratory) that was used as meteorological input for the trajectory model. The GDAS’s meteorological files with a spatial resolution of $1^\circ \times 1^\circ$ in latitude were used to study the air mass movement and its impact on global and synoptic transport (Seinfeld and Pandis 2006), while the GDAS 0.5$^\circ$ (~55 km) daily meteorological files for every 3 h were used to calculate detailed and reliable air mass movement over a regional scale in South Korea. Furthermore, the hourly 3D backward trajectories were computed from 11 March to 30 April 2011 in order to avoid the large uncertainty and limited significance of a single back trajectory (Stohl 1998), and to achieve a more reliable representation of the synoptic airflow in the given region.

The level of 1000 m above the model topography was taken as reference to analyse the global transport, following the methodology applied in similar works (Lozano et al 2011, Hernadez-Ceballos et al 2012). This reference height has been considered to represent the synoptic and regional circulation over South Korea after taking into account the similar behaviour of air masses at 500 and 1000 m. In addition, it is necessary to consider that the transport of the emitted nuclides depends on the height of the source due to differences in the atmospheric conditions such as vertical wind shear and turbulence. During the initial release of these nuclides, they would be expected to reach heights <300 m, while during explosions (such as the explosion of unit 3 and to some extent that of unit 4), the plume could have reached up to 1000 m (Stohl et al 2011). Therefore, this level is appropriate and allows tracking of the emitted radionuclides in the planetary boundary layer.

As the Korean Peninsula is topographically rugged due to the presence of mountains about 1000 m high situated between Ansan and Uljin, the orographic effect was duly evaluated to enhance the validity of the application of the HYSPLIT model in the region. A model surface height contour map was generated to see how the model is able to ‘see’ these mountains by using a maximum height of 600–700 m in the surroundings of Uljin (figure 2). In addition, the higher spatial resolution used to resolve, with more accuracy, the spatial variation in the atmospheric activity concentration of radiocaesium over South Korea during its peak concentration yields more confidence in the results.
3. Results

3.1. Fukushima-derived radiocaesium over South Korea

The dust samples collected at ground level in Uljin appeared to be contaminated with Fukushima-derived radiocaesium from 1 April onwards (Hernadez-Ceballos et al. 2012). Several rain samples collected in episodic events suggest that wet deposition of Fukushima-derived radiocaesium varied between 290 and 649 $^{137}$Cs Bq m$^{-2}$ and 261 and 802 $^{134}$Cs Bq m$^{-2}$ from 7–28 April in Uljin and Ansan, respectively (figures 3(a) and (b)). The dry depositional fluxes in Uljin varied from below the detection limit to 151 mBq m$^{-2}$ d$^{-1}$ for $^{137}$Cs and below the detection limit to 90 mBq m$^{-2}$ d$^{-1}$ for $^{134}$Cs from 26 March to 31 May (table A.2). In Uljin, the wet depositional fluxes of $^{137}$Cs and $^{134}$C were less than 20% of the dry deposition flux for the period of 11 March to 27 April 2011 (see the appendix). It should be noted that our dry deposition may contain local resuspended soil particles, although the magnitude of their contribution was not estimated.

The activity ratios of $^{134}$Cs/$^{137}$Cs in rain varied from 0.2–2.4 in Ansan (west coast) and 0.8–0.9 in Uljin (east coast) during April 2011 (figure 3(c)). The activity ratio of dust collected at the coast in Uljin varied from 0.6 to 2.5 during April and the early part of June (figure 3(d)).

3.2. Air mass analysis in South Korea

A whole set of hourly backward trajectories at a final height of 1000 m at Uljin from 11 March to 30 April, covering a time period of 192 h (8 days), was reproduced from the time of the Fukushima NPP accident until activity concentrations at the Uljin monitoring site were minimal. Although we did not measure daily radiocaesium activity in aerosol samples, temporal variation of radiocaesium activity is available from the Korea Institute of Nuclear Safety (KINS) (Kim et al. 2011). From the measured data by KINS, the Fukushima-derived radiocaesium was detected on 24 March and later and peaked on about 6 April (1.2 mBq m$^{-3}$).
Figure 3. Wet deposition of $^{137}\text{Cs}$ (a) and $^{134}\text{Cs}$ (b) and the activity ratio of $^{134}\text{Cs}/^{137}\text{Cs}$ in wet (c) and dry (d) deposition in Uljin and Ansan, South Korea, along with the activity ratio of $^{134}\text{Cs}/^{137}\text{Cs}$ in the atmosphere in Fukuoka (dotted line), Japan (after Momoshima et al (2011)). Data for Uljin were imported from Hernandez-Ceballos et al (2012).

of both $^{134}\text{Cs}$ and $^{137}\text{Cs}$ in the air and then returned to the below detection limit by the end of April over much of South Korea (figure 4). The activity ratio of $^{134}\text{Cs}/^{137}\text{Cs}$ varied from 0.6 to 1.5 in general with an exceptional high value of 3.3 at Kunsan on 5 April.

Taking the temporal evolution of radionuclide activity in Busan (figure 4) as a reference, the whole period (11 March–30 April) was divided into four different stages, with the aim of tracing the origin of the air mass: (1) from the time of nuclear accident to the beginning of the peak of radioactivity in Busan (11 March–5 April); (2) during the period when the peak radioactivity concentration in the air was observed (6–7 April); (3) the period when the activity in the air decreased to the values prior to the peak values (8–18 April); and (4) from 19 April to the end of the month in which the minimum activity was measured. This analysis enabled us to identify the origin of radionuclide concentrations registered in eastern South Korea and the temporal relationship between these measurements and the emissions from Fukushima NPP.

During the first period (11 March–5 April; figure 5(a)), the backward trajectory analysis indicated dominance of westerly flows over South Korea, pointing out the homogeneous
movement of air masses, without large horizontal variations, from Europe to Asia. In addition, the hourly analysis displayed the non-existence of any air mass circulation with a pathway showing a displacement along Japan or in areas adjacent to the Fukushima NPP. Consequently South Korea received very little of the Fukushima radioactive plume during this period. These results are in agreement with the reported eastward movement of the plume from Fukushima after the explosions (RIU 2011, Takemura et al 2011).

After this period, South Korea was still influenced by strong westerly flows. However, in the second period (6–7 April) (figure 5(b)), distinct $^{134}$Cs and $^{137}$Cs peaks were detected at Busan and other areas (figure 4) as well as $^{131}$I (Kim et al 2011), and a different direction of movement of the air masses prior to their arrival over eastern South Korea was shown. During this period, the air masses underwent clockwise movement from the north to the south of Japan, sweeping the Fukushima area and resulting in the dispersion of the plume from Fukushima to South Korea. This displacement also resulted in the transport of the Fukushima radioactive plume to Fukuoka, western Japan (Momoshima et al 2011). Considering the predominance of westerly flows, this special advection could be attributed to regional meteorological conditions over the South Korea–Japan area. The same air mass moved southwest in the south of Japan and extended to Taiwan and the Philippines and transported a large amount of radiocaesium to Taiwan (Huh et al 2012).

During the third period (8–18 April; figure 5(c)), South Korea largely received westerlies with smaller contribution from southeast flows. The contribution of the southeasterly wind was much smaller than during the earlier period of 6–7 April. During the fourth period (19–30 April; figure 5(d)), ground air over South Korea was again separated from Japan as the westerly flows occupied the whole of South Korea, although with more variability and less horizontal displacement than in the previous period. The wind field over the Northern Hemisphere for each period is shown in figure 6.

**4. Discussion**

**4.1. The atmospheric pressure system during the sampling (11 March–30 April)**

The long- and short-term temporal and spatial variability of high and low pressure systems is closely related to the variability and pathway of the movement of radionuclide-containing aerosols. For this reason, an analysis of the synoptic configuration over this area was made to understand the temporal variability of radionuclide concentrations over the set of monitoring sites in South Korea.
Figure 5. 192h-backward trajectories at 1000 m over Busan (South Korea) during (a) 11 March–5 April, (b) 6–7 April, (c) 8–18 April and (d) 19–30 April.
Figure 6. Mean sea level pressure (hPa) and wind vectors on (a) 14 March (representative of 11–16 March: Fukushima release), (b) 27 March (representative of 11 March–5 April: before peak radiocaesium activity concentration), (c) 6 April (representative of 5–7 April: peak radiocaesium activity concentration), (d) 14 April (representative of 8–18 April: after the peak) and (d) 25 April (representative of 19–30 April: activity concentration below the detection limit of radiocaesium).
With this aim, the GDAS files have been used to show the changes in the synoptic configuration over this area. During the releases of radionuclides to the atmosphere between 12 and 16 March 2011, the synoptic atmospheric configuration over Korea and Japan was characterised by a west–east directional dipole-like surface pressure structure, with high pressure to the west and low pressure to the east (figure 6(a)), resulting in displacement of the air mass to the east of Japan and the arrival of westerly flows over South Korea. This resulted in an air mass disconnection between South Korea and Japan during this period. Following this period until 5 April this area was influenced by the arrival of westerly air masses from central Europe due to the large predominance of high pressure systems over Asia. As shown in figure 6(b), the pressure configuration on 27 March is an example of this, with dominance of high pressure values over the study area. As a consequence, the intact plume of Fukushima accident could not reach South Korea during this period (11 March–5 April) due to the random movement of the air mass.

The local meteorological conditions in the Korea–Japan area changed between 5 and 7 April and were governed by the west–east movement of a small high pressure system (figure 6(c)). This new configuration modified the air flow over South Korea to connect Japan and South Korea directly. Therefore, this special and local configuration was responsible for this air mass displacement (figure 4), sweeping the surroundings of the Fukushima NPP, and hence is the reason for the high radionuclide concentrations registered in South Korea during this short period (figure 4).

After this short period of high atmospheric radionuclide concentrations, prevalence of the synoptic configurations resulted in the continuous direct arrival of westerly air masses from Europe over South Korea until mid-April (18 April), as shown in figure 5. However, during this period, the synoptic configuration was characterised by a combination of high and low pressure systems over the region (figure 6(d)).

Finally, low pressure systems gradually displaced a large cyclonic pressure system from the west over Asia from mid-April until the end of the month, and consequently air moved to the east. Figure 6(e) displays a synoptic configuration in which the presence of a low pressure system to the north of South Korea allowed movement of the air mass from the north over South Korea. This change in the atmospheric pressure configuration resulted in predominantly northerly advection.

4.2. The radioactivity peaked around 6 April over South Korea

Upon assessing the dynamics of the air mass movement closely during the period of 6–7 April, described earlier in figure 5(b), it was found that the air masses over the east coast of Korea (Uljin) arrived from the Pacific Ocean south of Japan and the air masses over Korean west coast (Ansan) arrived from the Japanese islands (figure 7). The former were laden with a smaller amount of radioactivity than the latter. This difference in air masses could result in a higher activity concentration in Ansan than in Uljin (figure 3). In addition, the amount of rain could contribute to the spatial variability of radionuclide concentrations and depositional fluxes, as can be observed in table A.1. The activities of $^{134}$Cs and $^{137}$Cs in aerosols were also higher around 7 April in Busan, Jeju, Kunsan, Suwon, Chucheon and Seoul (all these sites being situated on the western side of the mountain range) than in Kangrung (east of the mountain range) according to observations KINS.

This air mass displacement was also observed and modelled independently in Fukuoka (Momoshima et al 2011) and in Taiwan (Huh et al 2012) and in CTBTO’s simulation (CTBTO website 2011). In Fukuoka (130°25’E, 32°27’N), $^{134}$Cs concentrations were found to be 0.01–4.04 mBq m$^{-3}$ with a peak on 6 April. The activity ratio (AR) of $^{134}$Cs/$^{137}$Cs varied
from 0.09 to 2.36 with a peak on 5 April. The peak in the amount and AR coincide well with those obtained in the Korean Peninsula, particularly in the western part of the peninsula (KINS data). Therefore, the 7 April peak was due to a change in the air mass displacement from Japan. And by comparing the activity concentration of this peak with the results shown in Stohl et al (2011), which indicate a significant amount of $^{137}\text{Cs}$ release up to 20 March 2011 from the NPP, the origin of this higher activity could come from resuspended or recirculated material polluted by NPP emissions. At the northern tip of Taiwan, $^{134}\text{Cs}$ concentrations were about 1.1 mBq m$^{-3}$ with a peak on 6–7 April (Huh et al 2012). The same air mass transported Fukushima-derived radioactive substances further southwest to Vietnam with much reduced activity (0.03 mBq m$^{-3}$) a few days later (Long et al 2012).

The $^{134}\text{Cs}/^{137}\text{Cs}$ activity ratios in aerosols can be used to delineate the sources of radiocaesium—from spent fuel pools and/or reactor cores—since releases from recently active fuel rods and spent fuel rods are expected to have different $^{134}\text{Cs}/^{137}\text{Cs}$ ratios due to the differences in their half-lives and the duration of storage of the spent fuel rods; thus this ratio can be used to quantify the sources of radiocaesium. Based on the $^{134}\text{Cs}/^{137}\text{Cs}$ activity ratios, Kirchner et al (2012) suggested those radionuclides were released from reactor cores.

Figure 7. Hourly backward trajectories at 500 and 1000 m computed at Ansan (western South Korea) and Uljin (eastern South Korea) corresponding to 5–6 April.
The time of occurrence of peak of $^{134}$Cs/$^{137}$Cs activity ratios in the ground air over South Korea on 5 April (KINS observation) coincided with that in Fukuoka (Momoshima et al. 2011) and later on 7 and 18 April (figure 2(c)) reflecting air mass displacement from Japan (figure 4(c)). Momoshima et al. (2011) reported a range of values, $0.53 \pm 0.23$ to $2.36 \pm 0.19$ (mean $1.02$, $n = 23$) in aerosol samples collected at Fukuoka, Japan (figure 3(c)). Our range of values of $0.2 \pm 0.6$ to $2.4 \pm 0.5$ falls within the published ones in Seattle, Washington ($0.55 \pm 0.12$ to $1.00 \pm 0.13$; (Diaz Leon et al. 2011)) as well as in Chernobyl (around 0.55; summarised in Baskaran et al. 1991, UNSCEAR 2008). The differences in the atmospheric aerosols could be due to different values in the three reactor cores and the spent fuel pools. In addition, it is interesting to note that the range of values reported in water samples near the NPP was relatively constant (Buresseler et al. 2011) while the values in aerosols varied widely.

5. Conclusions

From our study, we have traced the pathways of the radioactive plume from Fukushima which arrived at the Korean Peninsula shortly after the accident (11 March 2011) to 60 days. The long-lived radiocaesium arrived almost exclusively from the west on 11 March to 5 April; however, during 6–7 April, air moved directly from Japan to South Korea, resulting in activity concentration peaks in the ground air over South Korea, particularly to the west of the longitudinal mountain range. In the remaining days in April, the air once again disconnected from the east (Japan) and predominantly blew from the west. This temporal air mass displacement was well reflected in the deposition fluxes of $^{134}$Cs and $^{137}$Cs on both west and east coasts of South Korea.

This work clearly demonstrated how the surface air circulation is intimately connected over the entire Northern Hemisphere and little dissipation occurred during this time due to the particular global air circulation system. There are 94 active nuclear reactors in southeast Asia (54 in Japan, 21 in South Korea, 13 in China and 6 in Taiwan) and a few tens of reactors are planned by 2030 in northeast Asia. This region is inhabited by well over a billion people and populated densely along the coast. Therefore, special care should be taken to ensure the safety of the operating and planned reactors and managing nuclear waste in the region.

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Appendix

Wet and dry deposition of $^{134}$Cs and $^{137}$Cs over South Korea for the two months after Fukushima Daiichi NPP accident on 11 March 2011.
Table A.1. Wet deposition on the east (Uljin) and west (Ansan) coasts of South Korea (ND: not detected). Precipitation data for Ansan were taken from the Suwon observatory situated 13 km east of Ansan.

<table>
<thead>
<tr>
<th>Site</th>
<th>Start date</th>
<th>End date</th>
<th>Rainfall (mm)</th>
<th>Rainwater concentration</th>
<th>Depositional flux</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$^{137}$Cs (mBq kg$^{-1}$)</td>
<td>$^{134}$Cs (mBq kg$^{-1}$)</td>
</tr>
<tr>
<td>Uljin</td>
<td>17 March 2011</td>
<td>21 March 2011</td>
<td>15</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td></td>
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<td>1</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td></td>
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<td>ND</td>
</tr>
<tr>
<td></td>
<td>7 April 2011</td>
<td>8 April 2011</td>
<td>2</td>
<td>30 ± 0.5</td>
<td>25.2 ± 1.0</td>
</tr>
<tr>
<td></td>
<td>21 April 2011</td>
<td>25 April 2011</td>
<td>20.5</td>
<td>10.1 ± 0.3</td>
<td>9.2 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>25 April 2011</td>
<td>27 April 2011</td>
<td>10.5</td>
<td>2.15 ± 0.1</td>
<td>2.1 ± 0.3</td>
</tr>
<tr>
<td>Ansan</td>
<td>7 April 2011</td>
<td>8 April 2011</td>
<td>19.0</td>
<td>30 ± 1.0</td>
<td>39 ± 3.2</td>
</tr>
<tr>
<td></td>
<td>18 April 2011</td>
<td>19 April 2011</td>
<td>1.5</td>
<td>11.9 ± 1.6</td>
<td>28 ± 4.0</td>
</tr>
<tr>
<td></td>
<td>25 April 2011</td>
<td>26 April 2011</td>
<td>5.0</td>
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<tr>
<td></td>
<td>27 April 2011</td>
<td>28 April 2011</td>
<td>3.5</td>
<td>13.4 ± 0.5</td>
<td>2.4 ± 0.8</td>
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<tr>
<td></td>
<td>30 April 2011</td>
<td>1 May 2011</td>
<td>136</td>
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<td>1.24 ± 0.13</td>
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<tr>
<td></td>
<td>12 May 2011</td>
<td>13 May 2011</td>
<td>35.5</td>
<td>0.9 ± 0.2</td>
<td>ND</td>
</tr>
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</table>
**Table A.2.** Dry deposition on the east (Uljin) coast of South Korea (ND: not detected).

<table>
<thead>
<tr>
<th>Start date</th>
<th>End date</th>
<th>Flux $({\text{mBq m}^{-2} \text{day}^{-1}})$</th>
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<tr>
<td></td>
<td></td>
<td>$^{137}\text{Cs}$</td>
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<tr>
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</tr>
<tr>
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</tr>
<tr>
<td>8 April 2011</td>
<td>11 April 2011</td>
<td>$30 \pm 3$</td>
</tr>
<tr>
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</tr>
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</tr>
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<td>$9 \pm 3$</td>
</tr>
<tr>
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<td>14 April 2011</td>
<td>ND</td>
</tr>
<tr>
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<td>$0.51 \pm 0.18$</td>
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