Annex IV of Technical Volume 4
RADIOACTIVITY IN THE MARINE ENVIRONMENT ARISING FROM RELEASES FOLLOWING THE FUKUSHIMA DAIICHI ACCIDENT

The bathymetry and surface currents averaged over April 2011 is presented in Fig. IV–1.

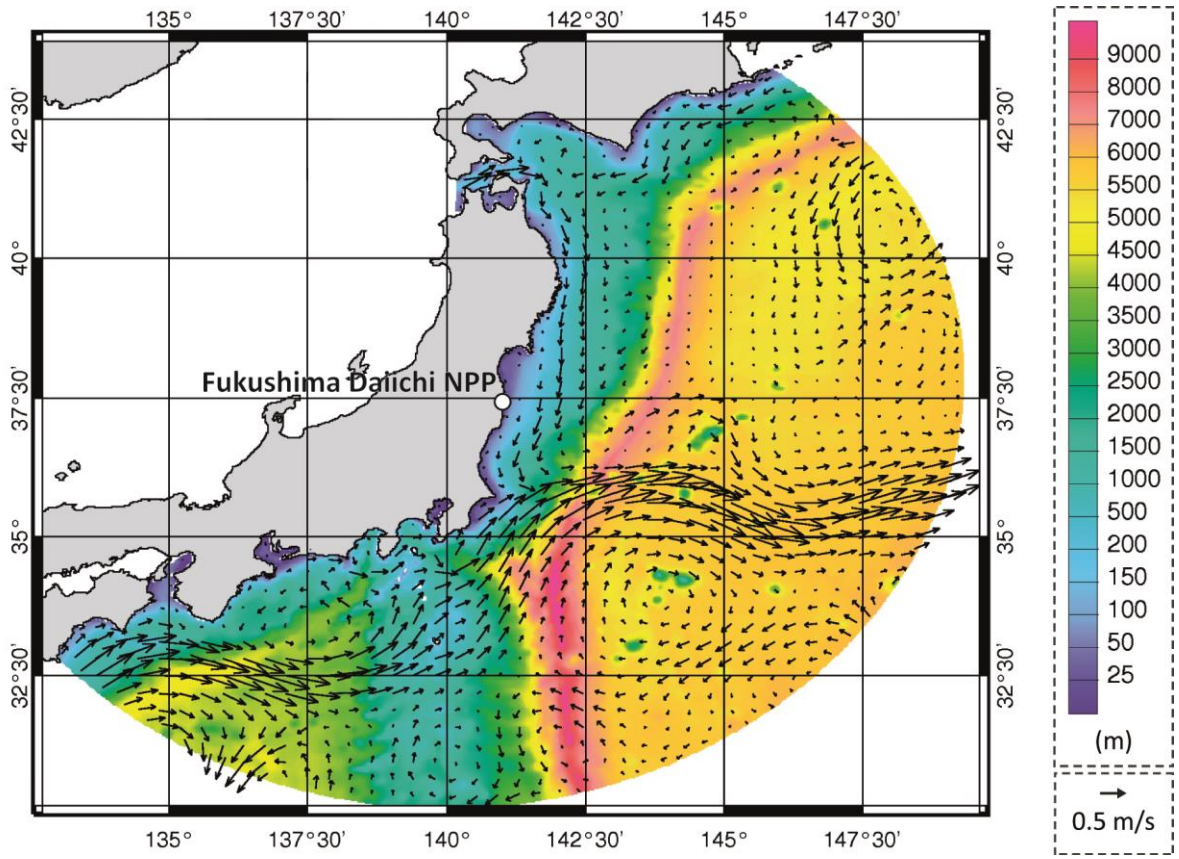


FIG. IV–1. Bathymetry (colour scale to the right of the map, in metres) and surface currents averaged over April 2011 (represented by arrows indicating speed and direction of current). The red circle indicates the position of the Fukushima Daiichi NPP. (Illustration courtesy of Sirocco group, University of Toulouse) [IV–1].

IV–1. ASSESSMENT OF RELEASES

IV–1.1. Deposition from atmospheric releases

The amount of ^{137}Cs released to the atmosphere from the Fukushima Daiichi NPP was estimated from 7 to 50 PBq (or 7–20 PBq if early estimates are excluded), as described in Section 4.1.2.1 of Technical Volume 4 and indicated in the range of references of which the following are a section: [IV–2 to IV–5]. Atmospheric depositions of ^{137}Cs on land and ocean have been estimated with large area scale atmospheric transference models in the intercomparison exercise (see Table IV–1). The amount of ^{137}Cs released in atmosphere is estimated to have been in the range 17.8 ± 8.2 PBq during the period from 11 March to 19 April 2011, and the ratio of ^{137}Cs deposition activity into the ocean in the atmospheric released activity of ^{137}Cs might be estimated to have been 73 ± 10% [IV–6].

TABLE IV–1. SUMMARY OF DIFFERENT ESTIMATES OF RADIONUCLIDES DEPOSITED ON THE LAND AND OCEAN SURFACE FROM ATMOSPHERIC RELEASE AND TRANSPORT (IN PBq) [IV–6]

	Over the land		Over the sea		Total deposition over the target region	Total emission
	Total deposition	Percentage of wet deposition	Total deposition	Percentage of wet deposition		
MEXT aircraft	2.65		—	—	—	—
CEREA	3.35 (17%)	68%	2.62 (14%)	85%	5.97 (31%)	19.3
CRIEPI	2.37 (27%)	79%	0.90 (10%)	54%	3.27 (37%)	8.8
IRSN	3.14 (15%)	46%	5.52 (27%)	71%	8.66 (42%)	20.6
JAEA	3.79 (43%)	67%	1.22 (14%)	65%	5.01 (57%)	8.8
JAMSTEC	1.95 (22%)	67%	1.45 (16%)	67%	3.40 (39%)	8.8
JMA	2.65 (30%)	50%	1.18 (13%)	36%	3.83 (44%)	8.8
MRI	3.31 (38%)	92%	1.72 (20%)	97%	5.03 (57%)	8.8
NIES	2.90 (33%)	98%	1.06 (12%)	96%	3.96 (45%)	8.8
SNU	1.29 (15%)	32%	1.76 (20%)	36%	3.05 (35%)	8.8
Ensemble mean	2.75 (27%)	67%	1.94 (16%)	67%	4.69 (43%)	11.3
Standard deviation	0.73 (10%)	20%	1.36 (5%)	22%	1.68 (9%)	4.6

Note: MEXT — Ministry of Education, Culture, Sports, Science and Technology, CEREA — Centre d'Enseignement et de Recherche en Environment Atmosphérique, CRIEPI — Central Research Institute of the Electric Power Industry, IRSN — Institute for Radiological Protection and Nuclear Safety, JAEA — Japan Atomic Energy Agency, JAMSTEC — Japan Agency for Marine-Earth Science and Technology, JMA — Japan Meteorology Agency, MRI — Meteorological Research Institute, NIES — National Institute for Environment Studies, SNU — Seoul National University.

TABLE IV–2. FURTHER SPECIFICATIONS RELATED TO TABLE IV–1 [IV–6].

Organizations	Model	Horizontal resolution	Number of grids	Layers	Trace models
CEREA	WRF/Polyphemus	Approximately 4 km	270x260	15	Eulerian
CRIEPI	WRF/CAMx	5 km	190x180	30	Eulerian
IRSN	JMA/1dX	Approximately 10 km	301x201	11	Eulerian
JAEA	MM5/GEARN	3 km	227x317	28	Lagrangian
JAMSTEC	WRF-Chem	3 km	249x249	34	Eulerian
JMA-MRI	NHM-LETKF-Chem	3 km	213x257	19	Eulerian
JMA	NHM/RATM	Approximately 5 km	601x401	50	Langrangian
NIES	WRF/CMAQ	3 km	237x237	34	Eulerian
SNU	ETM	27 km	164x119	25	Eulerian

Note: CEREA — Centre d'Enseignement et de Recherche en Environment Atmosphérique, CRIEPI — Central Research Institute of the Electric Power Industry, IRSN — Institute for Radiological Protection and Nuclear Safety, JAEA — Japan Atomic Energy Agency, JAMSTEC — Japan Agency for Marine-Earth Science and Technology, JMA-MRI — Japan Meteorology Agency, Meteorological Research Institute, JMA — Japan Meteorology Agency, NIES — National Institute for Environment Studies, SNU — Seoul National University, WRF — Weather Research and Forcasting, CAMx — Comprehensive Air Quality Model with Extensions, MM5 — fifth-generation mesoscale model, NHM-LETKF — non-hydrostatic meteorological model, RATM — Regional Atmospheric Transport Model, CMAQ — Community Multiscale Air Quality, ETM — Eulerian transport model.

Example model results are illustrated in Fig. IV–2. Further model results, including the estimated activity concentrations of ^{137}Cs in sea water, are presented in Section 4.1.3 (e.g. Fig. 4.1–18).

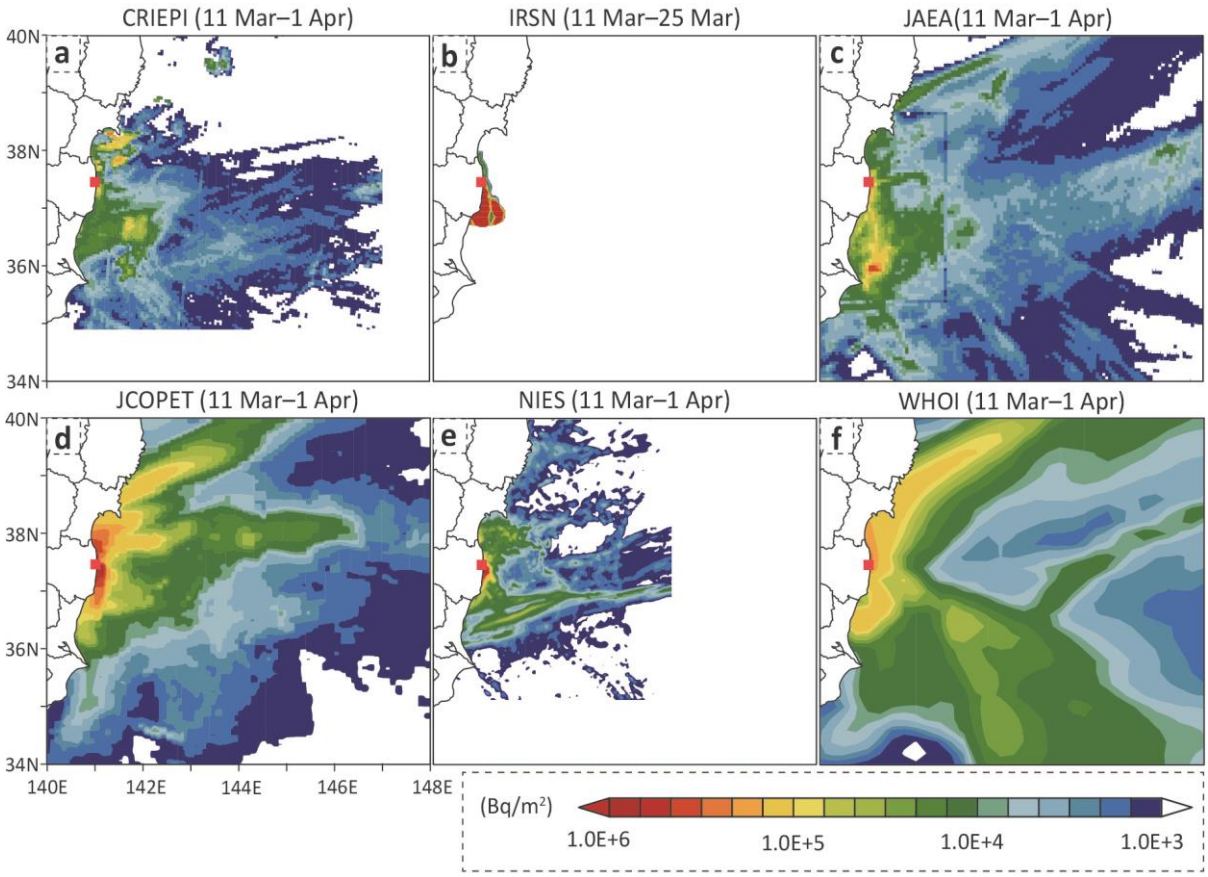


FIG. IV–2. Cumulated atmospheric deposition of ^{137}Cs from 11 March to 1 April 2011 for the (a) CRIEPI, (b) IRSN, (c) JAEA, (d) JCOPET, (e) NIES, and (f) WHOI models. Only the deposition over the ocean is shown. Note that, for the IRSN model, the period of accumulation is from 11 to 25 March. The WHOI-2D and WHOI-3D models use the same atmospheric deposition as shown in (f) [IV–6].

IV–1.2. Direct releases to the marine environment

There were no observations of the concentration of radionuclides in seawater until 21 March 2011, near the southern outlet site, and 23 March 2011, near the northern outlet of the Fukushima Daiichi NPP. Therefore, it is difficult to evaluate the direct release from the site to the ocean over the first few weeks of the accident. Estournel et al. [IV–1] have studied the impact of this lack of information on the total release by assuming two options: a nil release and a release rate equal to the first measured value. The difference between these two alternative scenarios has demonstrated that the amount of ^{137}Cs released to the ocean before 21 March was only 8% of the total liquid release. Most authors consider that the major direct release occurred in the period between 23 March and 8 April 2011. These results [IV–1] show a strong increase in direct release rate (>0.1 PBq/L) on 25 March. Another study [IV–7] concluded, from the analysis of the ^{131}I/^{137}Cs activity ratio, that the contribution of direct release to the measured ^{137}Cs concentration became larger than atmospheric deposition only after 26 March 2011. The evaluated values of ^{137}Cs directly released into the ocean ranged from 2.3 to 26.9 PBq [IV–1, IV–7 to IV–9].

The specifications and further information of used oceanic distribution models and the calculated regions are shown in Table IV–3 [IV–6].

TABLE IV–3. OCEANIC DISTRIBUTION SIMULATION MODELS: THE SPECIFICATIONS OF NUMERICAL MODELS IN THE INTERCOMPARISON EXPERIMENTS.

Model	Resolution (degrees)	Grids	Dispersion model type	Atmospheric fallout	Direct discharge	Note
CRIEPI	1/120 x 1/120	855 x 615	Euler	CRIEPI	CRIEPI type (3.5 PBq)	—
GEOMR	1/8 x 1/10	480 x 284	Euler	N/A	Instant release (26.9 PBq)	Using 1993 ECMWF forcing, which yields similar oceanic conditions as 2011 [IV–10]
IRSN	1/48 x 1/60	623 x 743	Euler	IRSN pX	IRSN (26.9 PBq)	Wind-turned case
JAEA	1/54 x 1/72	191 x 218	Lagrangian	JAEA	JAEA type (3.5 PBq)	—
JCOPET	1/36 x 1/36	830 x 578	Euler	JAMSTEC	CRIEPI type (6.0 PBq)	—
KIOST	1/60 x 1/60	601 x 661	Euler	N/A	JAE type (3.8 PBq)	Original grid is n unstructured system
Kobe U	1 km x 1 km	512 x 512	Euler	N/A	CRIEPI type (6.9 PBq)	Model domain is rotated horizontally to align with the Fukushima coastline
MSSG	1/55.6 x 1.55.6	168 x 239	Lagrangian	N/A	CRIEPI type (5.7 PBq)	—
NIES	1/20 x 1/20	91 x 97	Euler	NIES	CRIEPI type (3.6 PBq)	—
WHOI-2D	1/10 x 1/10	351 x 111	Lagrangian	Stohl et al. (2012) [IV–3]	JAEA type (16.2 PBq)	Geostrophic flow with satellite sea-surface height data
WHOI-3D	1/10 x 1/10	170 x 101	Lagrangian	N/A	JAEA type (16.2 PBq)	NCOM output

Note: CRIEPI — Central Research Institute of the Electric Power Industry, GEOMR — Research Center for Marine Geosciences, IRSN — Institute for Radiological Protection and Nuclear Safety, JAEA — Japan Atomic Energy Agency, KIOST — Korean Institute of Ocean Science and Technology, Kobe U — Kobe University, NIES — National Institute for Environment Studies.

The variation in the direct release source term is generally not large and in most analyses covers the range from 1 to 5.5 PBq for ^{137}Cs[1], except for the most conservative integral estimation given by IRSN (27 PBq, with an uncertainty interval of 12–41 PBq) [IV–6, IV–9]. However, in 2013 new studies of the Woods Hole Oceanographic Institution partly confirmed the value by IRSN [IV–11, IV–12], thus making the uncertainty range broader. The lower bound of release range corresponds to estimates by TEPCO and is based on the calculation of the leakage flow rate and concentration readings (0.94 PBq in case of the leakage near the water intake of Unit 2, other leakages being much smaller).

[1] See Technical Volume 1, Section 1.4 for more information.

The variation in the assessed levels of total direct ocean discharges of ^{137}Cs is due to large uncertainties in the different oceanic circulation and radionuclide dispersion models and inversion processes used by each study and the lack of spatially distributed observations in the surrounding region. This also leads to differences in the assessed values for the relative contribution of direct release and atmospheric deposition to levels of radionuclides in the ocean during the period of 12 March 2011 to May 2011. The ratio of the corresponding values of the source term (Bq released directly vs Bq deposited) varies from 0.13 [IV–13] to 300 [IV–9]. Several other analyses also demonstrate similar contributions [IV–1, IV–8].

Most analyses estimate the source term for direct release based on numerical modelling of ^{137}Cs dispersion in the ocean and using the measurement data as validation. the observations of ^{137}Cs concentrations near the outlets of the power plant were used in an inverse method to calculate the amounts of radionuclides released after the accident [IV–1]. The IRSN interpolated the individual measurement made in the period from 11 April to 12 July 2011. TEPCO used photos, rough calculations of the flow rate and concentration readings of the leaking water to directly estimate the released activity. A recent review of a model comparison indicates a range in estimated direct discharges of 3.5–15 PBq [IV–6].

Some analyses of levels of radionuclides in the ocean provide not only the integral value of the source term but also its variation with time, so that the relative contribution of atmospheric releases and direct discharges to the radioactivity input rate into the ocean can be compared (see some examples in Figs IV–3 and IV–4).

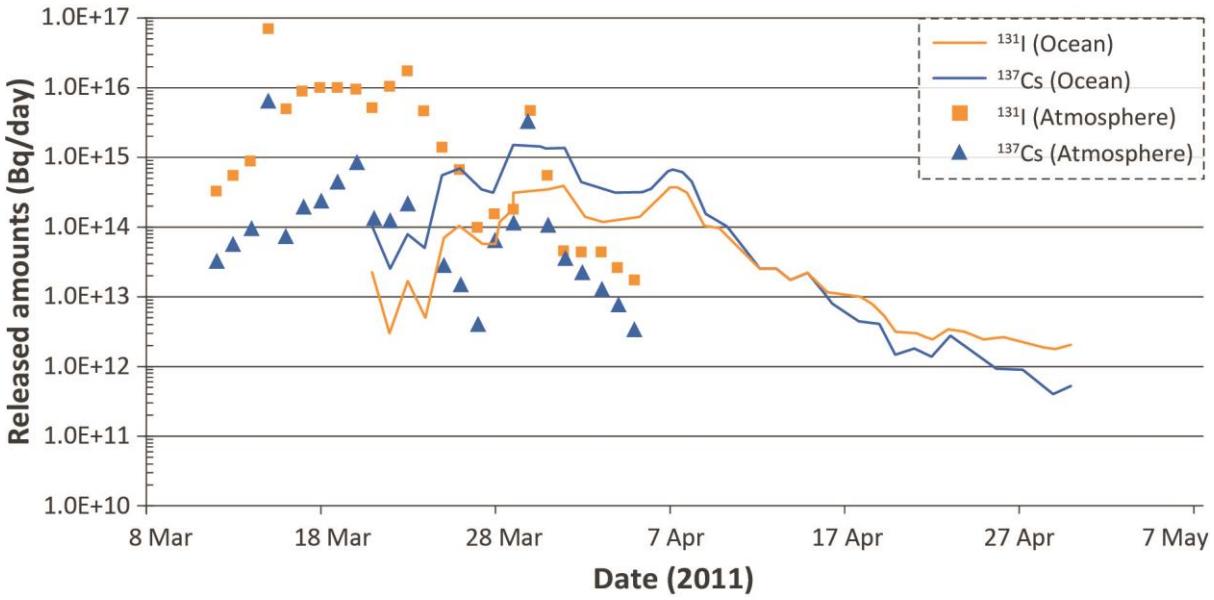
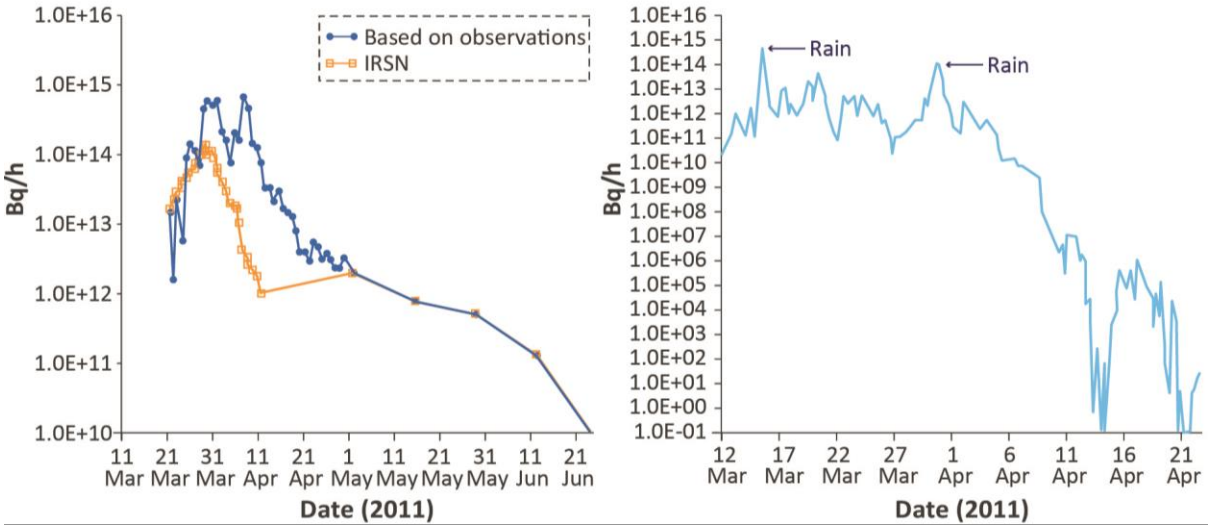


FIG. IV–3. Estimated amounts of ^{131}I and ^{137}Cs released into the ocean and atmosphere from the Fukushima Daiichi NPP from March to April 2011 [IV–8].



(a) (b)

FIG. IV–4. Time series of (a) direct release of ^{137}Cs estimated by IRSN and from interpolation from measurements near the plant performed by TEPCO and (b) atmospheric deposition rate of ^{137}Cs estimated on a regional scale using the Long-range Accident Dose Assessment System. (Figure adapted from [IV–14]).

IV–1.3. Seawater monitoring

The variation in activity concentrations of ^{131}I, ^{134}Cs and ^{137}Cs measured in surface water close to the Fukushima Daiichi NPP in the period March–May 2011 is illustrated in Fig. IV–5. This figure indicates that the highest releases into the marine environment occurred from the end of March to the beginning of April 2011, resulting in concentrations of ^{137}Cs, ^{134}Cs and ^{131}I of up to 10^3 to 10^5 Bq/L in seawater near to the reactors. It shows the temporal trend of the measured concentrations of these three radionuclides in the surface water from the end of March until the end of May 2011. It is clear that the initial high levels were rapidly diluted to significantly lower concentrations in the ocean by the current systems and turbulences outlined above.

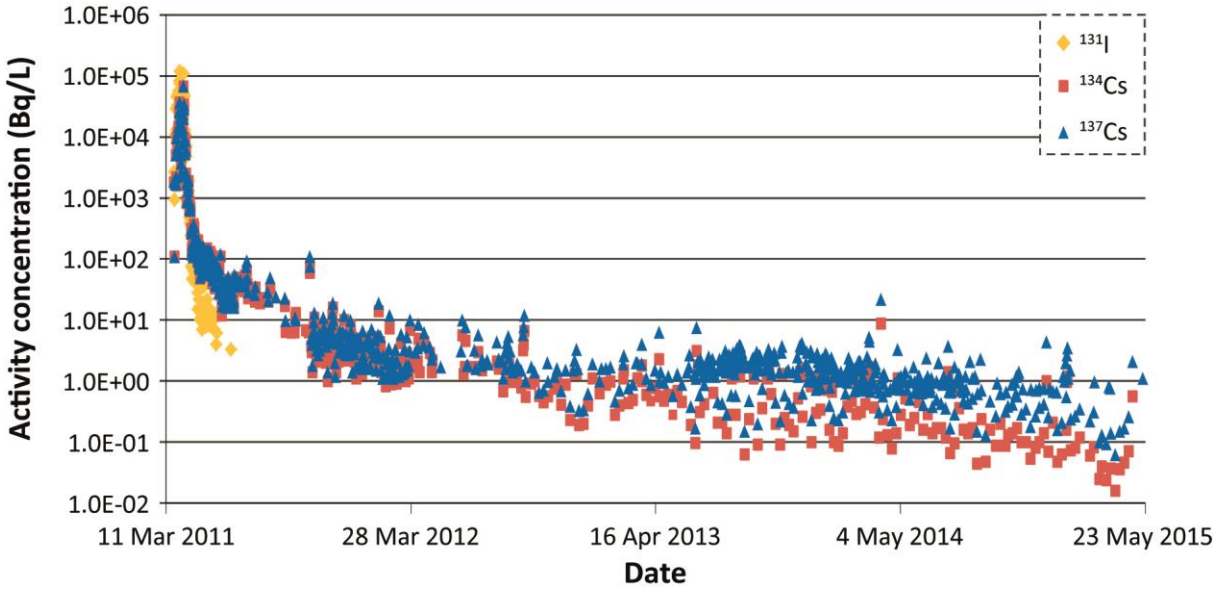


FIG. IV–5. Temporal trend of the activity concentrations in surface sea water at monitoring location T-1 near the discharge point (north of the port of the Fukushima Daiichi NPP) [IV–15].

In June 2011, a research group from the United States, with international participation, embarked on a research cruise to follow the evolution of the concentration over a wider off-shore area. The cruise covered the main area of the Kuroshio extension as well the influence of the cold Oyashio current from the north in the Pacific Ocean. The results of the cruise showed the expected effect of rapid dilution resulting in significantly lower concentrations, whereas relatively higher levels were still detected within about 600 km south-east of the release points. The measured activity concentrations for ^{137}Cs were generally very low (below 1 Bq/L, with a few exceptions of up to 2 Bq/L). The majority of the radionuclides were found in the surface layer of the ocean to a depth of 50 m. No activity associated with the accident was detected below a depth of 200 m. The distribution of ^{134}Cs in surface water measured during June 2011 is illustration in Fig. IV–6.

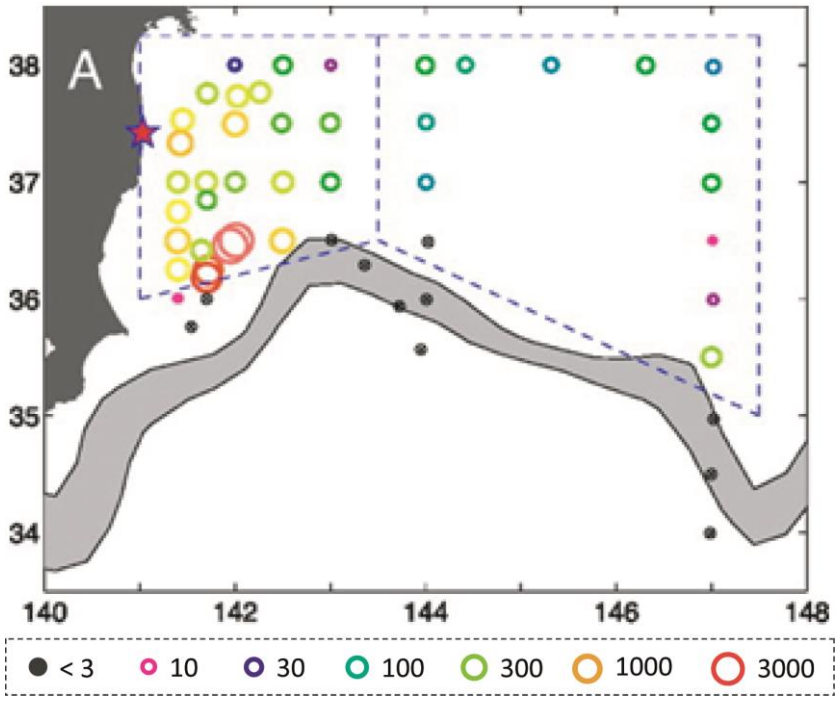


FIG. IV–6. Distribution of ^{134}Cs measured in surface water during the cruise of the research vessel KOK in June 2011 [IV–16].

Another investigation on a wider range of the ocean was undertaken about four weeks after the accident by Honda et al. [IV–17]. Most of measurements for ^{137}Cs were below 1 Bq/L, even at the closest stations to the Fukushima coast. Some of the slightly elevated levels above the expected background at the northern area of the investigation triangle may have been due to the atmospheric deposition or washout associated with the accident. These levels could not be from the direct discharge from the Fukushima Daiichi NPP source point due to the lateral transport and dispersion by ocean currents of such discharges.

Two Russian research expeditions collected a total of 88 seawater samples in April-May 2011 and August–September 2011 near the Kuril Islands (Oyashio current region) and the Kuroshio-Oyashio transition area in the Western Pacific Ocean [IV–18]. The lowest ^{134}Cs and ^{137}Cs activities were determined near the Russian coast (at pre-accident levels), while the highest levels (i.e. 0.029 Bq/L for ^{134}Cs and 0.034 Bq/L for ^{137}Cs) were observed in the open Pacific Ocean some 500–800 km offshore the Fukushima Daiichi NPP.

A number of further studies have been carried out on a wider range of the Pacific Ocean. One study by Aoyama et al. [IV–19] measured sea water samples from the Northern Pacific Ocean in 2011 to

2012. The results show that, in the surface layer of the eastern Pacific, activity concentrations of radiocaesium were only slightly above the pre-accident background levels of about 1–2 Bq/m³ for ^{137}Cs, with most values below 10 Bq/m³ in the central northern Pacific in March 2012. The results of this survey are shown in Fig. III–7.

The horizontal distribution of ^{137}Cs over the period from 9 May 2011 to 4–21 February 2012 is illustrated in Fig. IV–8.

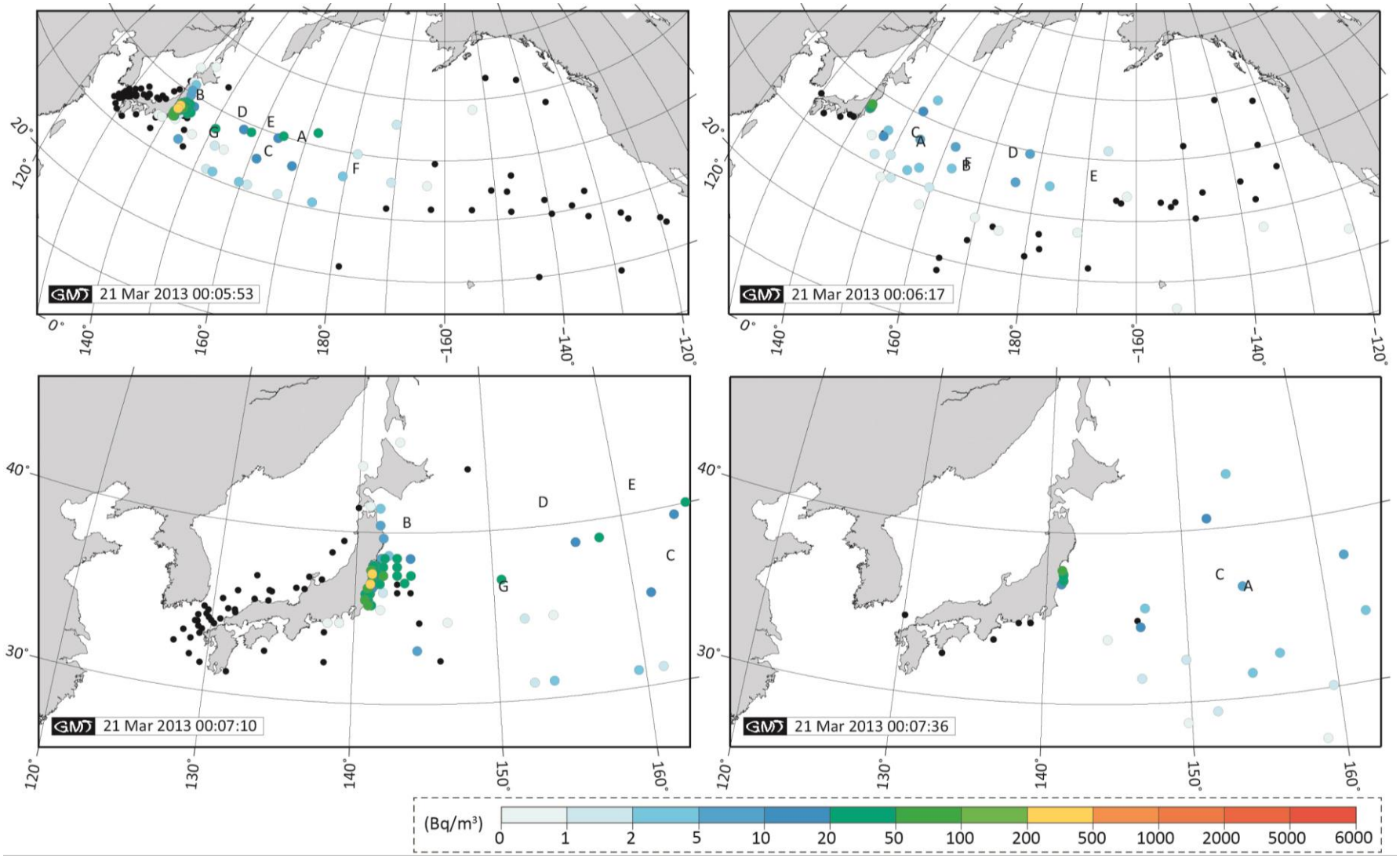


FIG. IV–7. ^{134}Cs activity in the surface water during the period from (a) October 2011 to December 2011 and (b) January to March 2012 for the North Pacific Ocean (top) and close to Japan (bottom). Positions of Argo floats on (a) 15 November 2011 and (b) 15 February are marked "A–G" [IV–15].

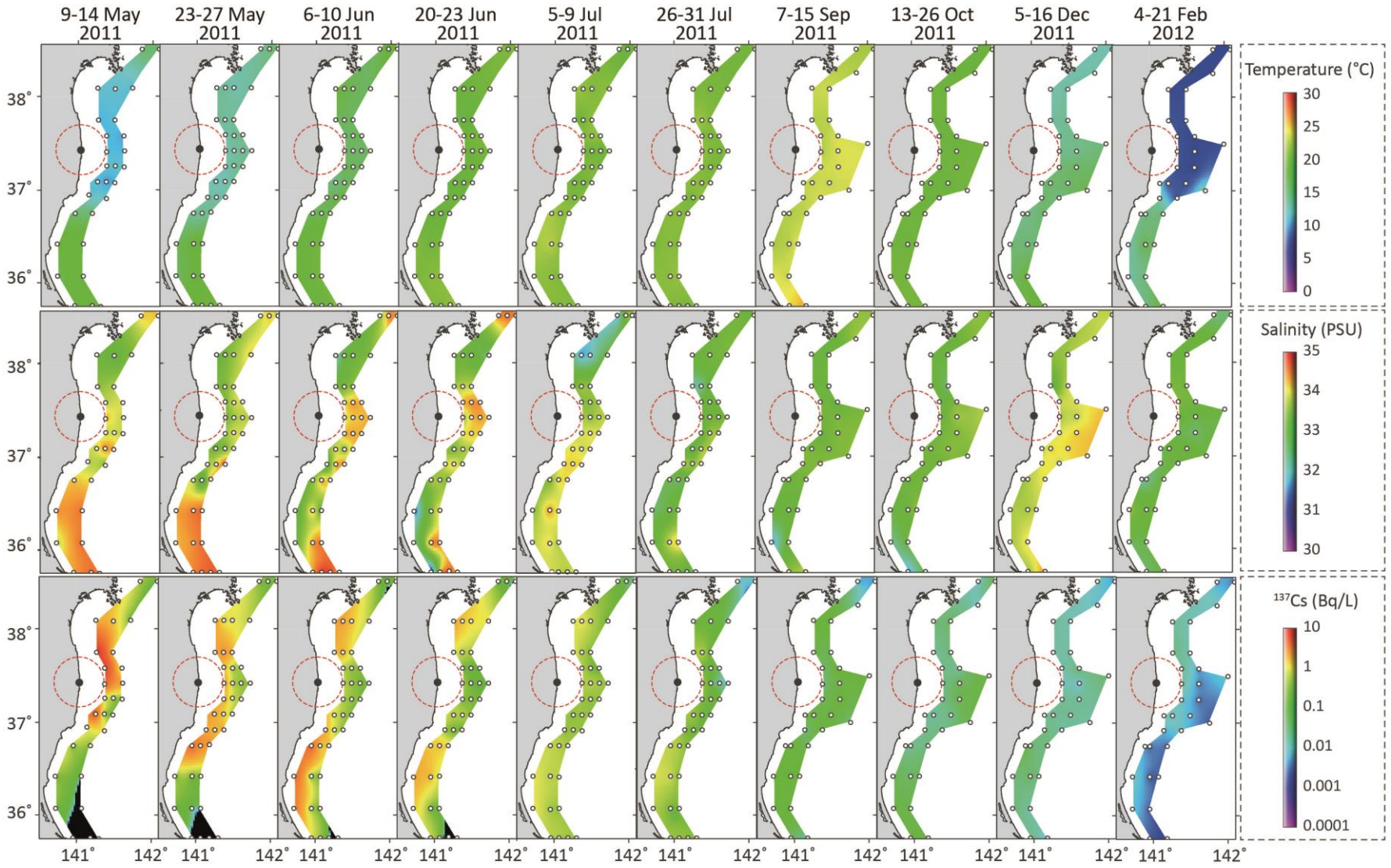


FIG. IV–8. Horizontal distributions of temperature, salinity and ^{137}Cs activity in surface water over the period from 9 May 2011 to 4–21 February 2012 [IV–20].

Three years after the accident, the concentrations of ^{137}Cs were found to be relatively stable. In January 2014, the activity concentration of ^{137}Cs was around 1 or 2 Bq/L in the area close to the Fukushima Daiichi NPP. In most of the sampling points along the coastal areas, the values for ^{137}Cs are less than 0.1 Bq/L. In remote offshore areas, the levels are closer to those existing prior to the accident (of the order of 0.001–0.003 Bq/L) [IV–21]. The variation in ^{137}Cs activity concentrations measured at monitoring stations located close to and at distance from the Fukushima Daiichi NPP is illustrated in Fig. IV–9.

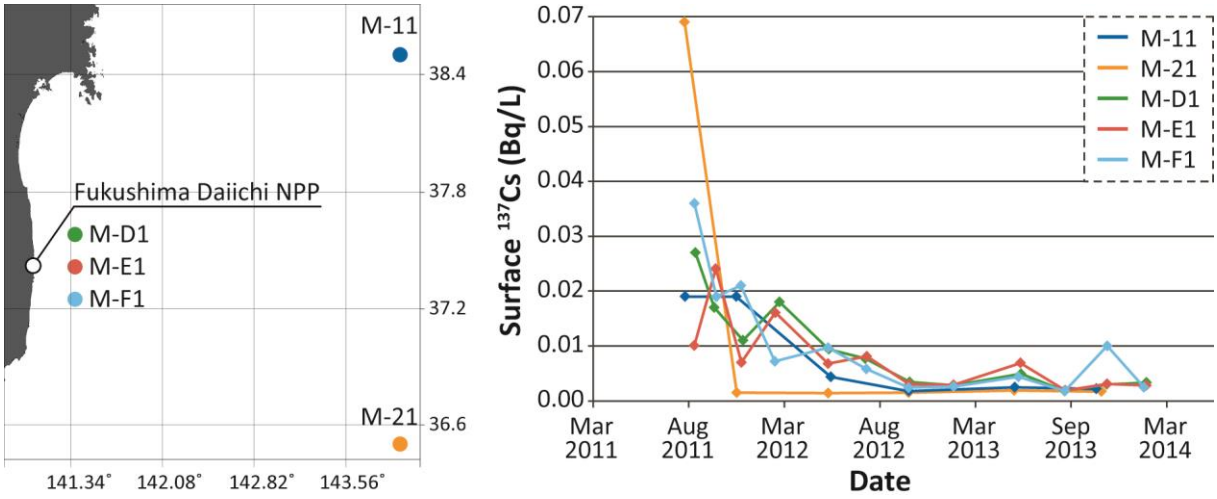


FIG. IV–9.Time-series of activity concentrations of ^{137}Cs (Bq/L) in surface water at near and far field stations.

The data are taken from the online resource: Environment Monitoring Database for the Distribution of Radioactive Substances Released by the TEPCO Fukushima Daiichi NPP Accident, which is hosted by the Japan Nuclear Regulation Authority (NRA) [IV–22]. The data are an amalgamation of measurements reported by TEPCO, MEXT and the NRA.

Some other radionuclides were observed but these were mostly the result of global fallout from atmospheric nuclear weapon tests in the 1960s and not necessarily attributed to the Fukushima Daiichi accident, as determined by the differences in isotopic ratios between weapons tests and reactor releases. Generally, the concentrations of isotopes of plutonium, strontium or tritium in sea water were found to be extremely low [IV–23]. Continuous monitoring data demonstrate that the levels of ^{90}Sr are negligible beyond the port area of the Fukushima Daiichi NPP [IV–24].

The data obtained can be compared to background levels originating from the global fallout from atmospheric nuclear weapon tests during the 1950s and 1960s, which are the major source for marine radioactivity in the ocean. The radionuclides tritium, ^{137}Cs, ^{90}Sr and ^{238}Pu, ^{239}Pu, ^{240}Pu and ^{241}Pu (^{241}Pu decaying to ^{241}Am) are the main remaining longer lived products in the environment from weapons fallout. There have also been other sources of these radionuclides such as authorized discharges from nuclear reprocessing plants in Europe, Japan, Russia and the United States of America and from nuclear wastes disposed of in the deep sea. The levels in surface ocean water near the coast of Japan, before the Fukushima Daiichi NPP accident, were of the order of 1.5–2 Bq/m³ for ^{137}Cs and about 1 Bq/m³ for ^{90}Sr. The latter value is based on the well known activity ratio between these two radionuclides in the global fallout.

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