Spread of Fukushima-derived radiocesium over the coastal ocean in response to typhoon-induced flooding in September 2011

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Abstract

The Tohoku earthquake off the Pacific coast of Japan on 11 March 2011 and the resulting tsunami led to severe damage to the Fukushima Daiichi Nuclear Power Plant (FDNPP) in Japan. Therefore, a shipboard survey was conducted to elucidate spread processes of radioactive cesium over the coastal ocean in the Kuroshio–Oyashio transition zone (south of the FDNPP) from 07 to 12 September 2011, that is, within 8 d of a river flood event associated with Typhoon Talas (T1112). In the survey, broad distributions of radiocesium and low-salinity water extending nearly 100 km off the coast were successfully observed at the sea surface. Moreover, a significant negative correlation was detected between radiocesium and salinity in the coastal ocean. Just before the shipboard survey, the typhoon brought extremely heavy rainfall over the catchment areas of the Tone and Naka Rivers flowing into the survey region, resulting in discharges from the Tone and Naka Rivers reaching approximately 2800 and 700 m3 s−1, respectively, at their peaks (04 September). These discharges were the highest recorded since 2007. Satellite images corresponding to the high-radioactivity and low-salinity areas revealed that chlorophyll blooms also spread over a broad area during the survey. These results indicate that the broad distributions of radiocesium and low-salinity water over the coastal ocean were brought about by the high levels of river discharge associated with the typhoon.

The Tohoku earthquake off the Pacific coast of Japan on 11 March 2011, and the resulting tsunami led to severe damage to the Fukushima Daiichi Nuclear Power Plant (FDNPP). As a result, a significant amount of radioactive materials, such as radioactive cesium, was released into the ocean via four routes: (1) atmospheric fallout on the ocean surface, (2) direct discharge from the plant, (3) groundwater discharge, and (4) riverine discharge (Buesseler et al. 2017). The initial and greatest discharge was the atmospheric fallout on the ocean surface, and the subsequent and second greatest was the direct discharge from the plant, and they both reached their peaks within a month of the FDNPP accident. The groundwater and riverine discharges were estimated to be lesser than those of the former two discharges. However, the groundwater and riverine discharges should have reached their peaks a long time after the accident, and they may be ongoing to date (Evrard et al. 2015; Buesseler et al. 2017; Onda et al. 2020).

In this study, we focus on the riverine discharge of radioactive cesium originating from the FDNPP accident. The atmospheric fallout of radioactive cesium on the ground occurred over a broad region extending more than 200 km from the FDNPP (Morino et al. 2011; Evrard et al. 2013, 2014; Takata et al. 2014; Mikami et al. 2015; Laceby et al. 2016; Chartin et al. 2017; Kato et al. 2019; Onda et al. 2020). Rivers has subsequently gathered the fallout radioactive cesium in this region and has discharged it into the coastal ocean. River runoff in Japan is characterized by extreme temporal variability, and there are extraordinary differences in river water discharge under ordinary and flood conditions. This is because extremely heavy rainfall occurs frequently in Japan (Chartin et al. 2017);
this excess rainfall water flows rapidly down steep rivers on mountains near the ocean (Onda et al. 2020). River flood conditions increase the concentration of cesium radioactivity in river channels around the FDNPP (Nagao et al. 2013, 2015; Ueda et al. 2013; Yamashiki et al. 2014; Laceby et al. 2016). Therefore, it is necessary to clarify the influence of riverine radioactive cesium discharge under flood conditions, as well as under low-stage conditions, on the coastal ocean.

The transport of radioactive cesium in river channels around the FDNPP has been observed and investigated by many authors (Evrard et al. 2013, 2014, 2015; Nagao et al. 2013, 2015; Ueda et al. 2013; Yamashiki et al. 2014; Takata et al. 2015, 2020; Yoshimura et al. 2015; Kakehi et al. 2016; Laceby et al. 2016; Buesseler et al. 2017; Chartin et al. 2017; Taniguchi et al. 2019; Irisawa et al. 2020; Onda et al. 2020). In particular, Takata et al. (2020) found that the radioactivity of cesium was higher in nearshore waters than in river and offshore waters during the typhoon season (October 2019), indicating the desorption of radioactive cesium from riverine suspended particles in the nearshore waters. However, the typhoon-induced riverine discharge of radioactive cesium has not been thoroughly investigated, especially for further spread over the coastal ocean: in Takata et al. (2020), the oceanic study area was located within 20 km from the coast.

It is difficult for shipboard surveys to be conducted immediately after river flood events. Nevertheless, we were able to conduct a shipboard survey within 8 d of a river flood event associated with a typhoon, and thus were able to directly observe a broad spread of radioactive cesium over the coastal ocean in the Kuroshio–Oyashio transition zone (south of the FDNPP). It should be especially noted that in our study region, the typhoon resulted in the highest river discharge recorded since 2007, as will be discussed later (in the subsection of the Precipitation and river discharge section). Moreover, our observations were made in September 2011, that is, within 6 months of the FDNPP accident. According to Kaeriyama (2015) and Taniguchi et al. (2019), the coastal concentration and preceding riverine discharge of radioactive cesium declined over a year, after which they have remained at low levels (less than an order of magnitude from the initial values).

The objective of this study is to present the broad spread of a large amount of radioactive cesium that extended nearly 100 km offshore through typhoon-induced river runoff in September 2011. Moreover, we investigate paths that radioactive cesium and freshwater followed from the land to the ocean by linking precipitation over the ground, the subsequent river runoff, and their spread over the coastal ocean.

**Materials**

A shipboard survey (RV Tansei-Maru cruise KT-11-22) was conducted in the coastal ocean of the Kuroshio–Oyashio
transition zone from 07 to 12 September 2011 (Fig. 1a), using a conductivity-temperature-depth (CTD) profiler (SBE 9plus; Sea-Bird Electronics) and a ship-mounted acoustic Doppler current profiler (ADCP; 75 kHz Ocean Surveyor; Teledyne RD Instruments). CTD measurements were conducted at the stations marked by crosses on the four lines (I, H, O, and K).

Table 1. $^{134}$Cs and $^{137}$Cs activity of surface seawater collected during the shipboard survey (RV Tansei-Maru cruise KT-11-22; 07–12 Sep 2011). The activity was decay corrected to the sampling date. Detection limit of $^{134}$Cs and $^{137}$Cs is 0.2 mBq kg$^{-1}$ for 20 liter seawater.

| Station | Lat. (°N) | Lon. (°E) | Date         | Cs-134 (mBq kg$^{-1}$) | Mean  | SD  | Cs-137 (mBq kg$^{-1}$) | Mean  | SD  |
|---------|-----------|-----------|--------------|------------------------|-------|-----|------------------------|-------|-----|
| I-01    | 37.098    | 141.035   | 07 Oct 2011 12:11 | 41.62                  | 0.52  |     | 48.76                  | 0.70  |     |
| I-04    | 37.096    | 141.232   | 07 Oct 2011 14:57 | 9.31                   | 0.66  |     | 11.33                  | 0.84  |     |
| I-07    | 37.099    | 141.636   | 07 Oct 2011 18:36 | 31.21                  | 1.64  |     | 33.10                  | 2.24  |     |
| H-01    | 36.665    | 140.749   | 08 Oct 2011 08:22 | 64.42                  | 0.92  |     | 72.70                  | 1.06  |     |
| H-04    | 36.666    | 140.948   | 08 Oct 2011 06:13 | 27.25                  | 1.63  |     | 32.51                  | 1.90  |     |
| H-08    | 36.666    | 141.354   | 08 Oct 2011 17:26 | 7.03                   | 0.58  |     | 9.83                   | 0.69  |     |
| H-11    | 36.666    | 141.650   | 08 Oct 2011 21:45 | 35.84                  | 1.39  |     | 43.01                  | 2.02  |     |
| O-01    | 36.316    | 140.651   | 09 Oct 2011 05:22 | 70.34                  | 0.88  |     | 80.78                  | 1.18  |     |
| O-04    | 36.316    | 140.848   | 09 Oct 2011 05:34 | 14.69                  | 0.63  |     | 20.07                  | 0.84  |     |
| O-08    | 36.317    | 141.160   | 09 Oct 2011 20:48 | 54.00                  | 2.76  |     | 61.30                  | 3.89  |     |
| O-13    | 36.319    | 141.673   | 09 Oct 2011 11:57 | 63.57                  | 1.52  |     | 69.04                  | 1.76  |     |
| K-01    | 36.018    | 140.697   | 09 Oct 2011 07:16 | 77.41                  | 3.25  |     | 87.39                  | 3.79  |     |
| K-04    | 35.998    | 140.899   | 09 Oct 2011 09:28 | <D.L.                  |       |     | <D.L.                  |       |     |
| K-11    | 36.000    | 141.466   | 09 Oct 2011 17:45 |                      | 1.41  | 0.56|                      |       |     |

<D.L. indicates less than detection limit.

Fig. 2. Horizontal distribution of (a) surface radiocesium activity ($^{134}$Cs and $^{137}$Cs), and (b) surface salinity (superimposed onto the radiocesium activity) at a depth of 10 m. In (a, b), colored open circles indicate the radiocesium activity (mBq kg$^{-1}$), and crosses indicate the CTD stations (where water-sampling for radiocesium was not performed). In (a), the high-concentration areas in the inshore and offshore areas are enclosed by thick broken lines and labeled as “Hi” and “Ho,” respectively. In (b), lower salinity is denoted by darker shading.
in Fig. 1b, and water sampling for radioactive cesium measurements was conducted at a depth of 10 m at the stations marked by open circles. ADCP data were obtained at a depth of 24.7 m along the four lines and on nearby lines.

The radioactivity of cesium ($^{134}$Cs and $^{137}$Cs) was measured for an ammonium phosphomolybdate/Cs compound using gamma-ray spectrometry with low-background germanium detectors (GEM-251855 and other similar models; ORTEC) equipped with multichannel analyzers (Model 7700 and other similar models; SEIKO EG&G) at the Low-Level Radioactivity Laboratory and the Ogoya Underground Laboratory of Kanazawa University (Table 1). Gamma emission peaks were used to calculate the activity at 605 keV for $^{134}$Cs and at 661 keV for $^{137}$Cs. The cascade summing effect was corrected for $^{134}$Cs using a Fukushima-contaminated soil sample, and decay correction of the radioactivity of $^{134}$Cs and $^{137}$Cs was performed to the sampling date (Nagao et al. 2013, 2014). Therefore, the total radioactivity of $^{134}$Cs and $^{137}$Cs was obtained as the sum of dissolved and particulate forms, hereafter simply referred to as radiocesium.

The precipitation data used in this study were derived from Radar/Raingauge-Analyzed Precipitation data provided by the Japan Meteorological Agency (JMA), and data regarding the river discharge flowing into the study region were derived from the Water Information System provided by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) of Japan. The catchment areas of the rivers were designated based on the National Land Numerical Information from the MLIT. The deposition density of the initial $^{137}$Cs fallout was obtained from the Center for Research in Isotopes and Environmental Dynamics (CRiED), University of Tsukuba (Kato et al. 2019). Chlorophyll $a$ (Chl $a$) data measured by the Geostationary Ocean Color Imager (GOCI) onboard the COMS satellite were derived from the Korea Ocean Satellite Center. Surface current data were obtained from the JCOPE-T ocean circulation model (Varlamov et al. 2015) of the Japan Agency for Marine-Earth Science and Technology.

**Results**

**Distribution of surface radiocesium**

The observed distribution of surface radiocesium (at a depth of 10 m) is shown in Fig. 2. Higher radioactivity (> 100 mBq kg$^{-1}$) was not detected on the nearest line to the FDNPP (Line I), but was detected in two areas relatively far from the FDNPP. One of the higher-radioactivity areas was located inshore along the coastline (labeled “Hi” in Fig. 2a),

**Fig. 3.** Vertical profiles of temperature ($T$), salinity ($S$), and sigma-t ($\sigma$) at Sta. O-08. The profiles within (a) the upper 100 m and (b) over the entire depth. The shaded region in (b) is shown enlarged in (a).

**Fig. 4.** Scatterplot between surface salinity and radiocesium ($^{134}$Cs and $^{137}$Cs) activity. The four most inshore stations along the coastline (K-01, O-01, H-01, and I-01) are colored in gray, while the other offshore stations are denoted by solid black circles. The linear regression line for the solid black circles (offshore stations) is indicated by a solid line ($r = -0.68, p < 0.05$), and its 95% confidence intervals are indicated by dashed lines. The 95% prediction intervals for the solid black circles (offshore stations) are indicated by dash-dotted lines.
especially in the southern part, where radioactivity higher than 160 mBq kg\textsuperscript{-1} was observed. The other area of high radioactivity was located offshore in the southern area of the study region (labeled “H\textsubscript{o}” in Fig. 2a). These features of the surface radiocesium distribution in September 2011 were somewhat different from those observed in May and June 2011 (Kaeriyama 2015), where it appears that there was a tendency for the radioactivity to decrease as the distance from the FDNPP increased.

One possible explanation for the presence of H\textsubscript{i} (high inshore radioactivity) is that a southward coastal current could advect radiocesium that had been released directly from the FDNPP into the coastal ocean. The southward coastal current was found in June 2011 by surface drifter trajectory (Buesseler et al. 2012) and numerical simulations (Tsumune et al. 2012, 2013; Rypina et al. 2013). However, the southward coastal current does not explain why the observed radiocesium activity was higher in the southern part (Sta. K-01 and O-01) than in the northern part, near the FDNPP (Sta. H-01 and I-01). As seen in the referenced studies, the southward coastal current may be variable, sometimes being separated from the coast by a mesoscale eddy.

Another explanation for the presence of H\textsubscript{i} is that it was caused by discharge from the Tone, Naka, and Kuji Rivers, the mouths of which are located in the southern part of the study region (green triangles in Figs. 1, 2). These three rivers are the only ones in the region that are classified as first-class (very important large) rivers by the MLIT. As with many other first-class rivers in Japan (Tanaka et al. 2009; Yamashiki et al. 2014), they discharge abundant freshwater into the coastal ocean. Therefore, it is plausible that a large amount of radiocesium originating from the land was discharged near the river mouths through river runoff. The probability of this type of discharge will increase if a large runoff event occurs just before a water-sampling survey, which was the case in this study (as will be discussed in the subsection of the Precipitation and river discharge section). Moreover, it is plausible that the large amount of river runoff stirred up and resuspended radiocesium that had already accumulated on the shallow sea bottom near the river mouths; high levels of radiocesium had been deposited onto seabed sediments in coastal areas (Charette et al. 2013; Otosaka and Kobayashi 2013; Otosaka and Kato 2014; Buesseler et al. 2015; Sanial et al. 2017; Uchiyama et al. 2017; Takata et al. 2020).

The presence of H\textsubscript{o} (in the offshore southern area) may also be explained by two possibilities. One explanation is that it was caused by mesoscale eddies. Similar offshore distributions of high radiocesium activity were found in other observational (Buesseler et al. 2012) and numerical studies (Tsumune et al. 2012, 2013; Rypina et al. 2013), in which mesoscale eddies advected radiocesium that had been released directly from the FDNPP into the coastal ocean. However, it should be noted that the offshore locations of the high-radioactivity areas differ between this study and the four studies referenced above, and the high-radioactivity area in this study (mainly west of 141.5\degree E) was located well inshore of those of the referenced studies (mainly east of 141.5\degree E). In fact, the high-radioactive offshore area

![Fig. 5. Horizontal distribution of (a) the precipitation integrated over 8 d from 30 Aug to 06 Sep 2011, and (b) the deposition density of the initial $^{137}$Cs fallout around the FDNPP. In (a, b), the bold gray lines indicate the Tone, Naka, and Kuji Rivers with their tributary rivers, while the bold black lines indicate the outer boundaries of their catchment areas. The precipitation in (a) was derived from Radar/Raingauge-Analyzed Precipitation data (JMA), and the catchment areas of the rivers were designated based on National Land Numerical Information (MLIT). The deposition density in (b) was derived from the database reconstructed on the basis of airborne monitoring by CRIED (University of Tsukuba).](image-url)
observed in the referenced studies was formed in an offshore eddy, into which the southward coastal current from the FDNPP intruded.

Another explanation for Ho is that the large river runoff caused not only H2 but also Ho. The observations for this study were made in September during the typhoon season, while those for studies referenced above were made in June of 2011 (before the typhoon season). In other words, the distribution of surface radiocesium over the coastal ocean in this study was strongly affected by river runoff. Indeed, freshwater from Japanese first-class (very important large) rivers often extends more than 50 km offshore from the coast during flood events (Tanaka et al. 2009). In the following subsections, therefore, special attention is given to the influence of the high river runoff on the spread of radiocesium over the coastal ocean.

Surface salinity

Figure 2b shows the observed distribution of surface salinity (at a depth of 10 m), which is superimposed onto the surface activity of radiocesium. According to Kubo (1988), water with a salinity of less than 34 psu in this region is usually defined as coastal water, which is strongly influenced by river runoff. Vertical profiles of temperature, salinity, and sigma-t at Sta. O-08, where high radioactivity was observed, are shown in Fig. 3. These profiles indicate that low-salinity water was distributed only in the surface layer with a thickness of approximately 10 m. Moreover, little or almost no precipitation was recorded over the coastal area just before and during the observation, as will be shown later (in the subsection on the precipitation and river discharge). These results strongly suggest that the low salinity observed in this study was mainly due to river runoff.

Figure 2b suggests that in the offshore area, there may be a tendency for higher radiocesium activity to be detected in lower-salinity water. In contrast, in the inshore area, there was no such tendency, as the highest radioactivity was detected in high salinity water at Sta. K-01. To clarify this point, Fig. 4 shows the correlation between salinity and radiocesium. In this figure, the inshore stations along the coastline (K-01, O-01, H-01, and I-01) are colored in gray to distinguish them from the other offshore stations because the inclusion processes of radiocesium into seawater must have differed between the former (inshore) and latter (offshore) stations. That is, it is reasonable to expect that a considerable portion of the radiocesium was in particulate form at the inshore stations, whereas it was mainly in dissolved form at the offshore stations. The reason for the presence of particulate radiocesium at the inshore stations is that, as mentioned above, the large amount of river runoff stirred up and resuspended radiocesium that had already accumulated on the shallow sea bottom near the river mouths (Charette et al. 2013; Otosaka and Kobayashi 2013; Otosaka and Kato 2014; Buesseler et al. 2015; Sanial et al. 2017; Uchiyama et al. 2017; Takata et al. 2020).

In contrast, the resuspension of radiocesium is unlikely to have occurred in the offshore stations, where the strong pycnocline clearly separated the surface layer from the ocean interior (Fig. 3). Moreover, the majority of the particulate radiocesium must have sunk below the surface layer before reaching the offshore area, because it takes a few to several days for river water to be advected from river mouths to offshore regions. According to Honda and Kawakami (2014), the sinking velocity of most particulate radiocesium is approximately 50 m d⁻¹ in the northwestern Pacific (although this was estimated using open-ocean data).

Consequently, a significant negative correlation \( r = -0.68, p < 0.05 \) was observed between the salinity and radiocesium activity after excluding the most inshore stations (i.e., considering only the black points) in Fig. 4. Indeed, the confidence intervals (dashed lines) suggest that the regression is robust, although the samples (black points) have large variances with wide prediction intervals (dash-dotted lines). The significant negative correlation is as expected and strongly supports our inference that the high activity of radiocesium was caused by river runoff that transported a large amount of radiocesium from the land.
similar negative correlation between salinity and radio-
cesium activity was also observed in the Abukuma River
estuary area (38.03°N to the north of the FDNPP) in 2013
and 2014 (Kakehi et al. 2016).

Precipitation and river discharge

Typhoon Talas (T1112) crossed Japan’s main island in early
September of 2011. Although the center of the typhoon pas-
sed more than 500 km west of the FDNPP, the typhoon
brought heavy rainfall throughout the country. Figure 5a
shows the distribution of precipitation integrated over 8 d
(30 August to 06 September) in and around the study region.

Very heavy precipitation (> 500 mm) was observed at some
places in the catchment areas of the Tone and Naka Rivers. It
is also interesting to note that the locations with heavy precip-
itation were located more than 100 km away from the FDNPP,
but little precipitation was recorded near the FDNPP and over
the coastal ocean region.

What is important is that a large amount of radioesium
had already been deposited on the land surface around the
FDNPP, as mentioned in the introduction. Figure 5b shows
the deposition density of the initial $^{137}$Cs fallout around the
FDNPP. The high-density areas of the initial $^{137}$Cs fallout
around 36.5–37.0°N and 138.5–140.0°E correspond to the

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**Fig. 7.** Horizontal distribution of Chl $a$ derived from GOCI L2 satellite data (Korea Ocean Satellite Center). (a) 28 Aug (approximately 10 d before the
shipboard survey), (b) 10 Sep (during the survey), (c) 24 Sep (approximately 2 weeks after the survey), and (d) 07 May 2012 (3 d after another extreme
rainfall over the catchment areas of this study). In (b), colored open circles and thick dashed lines indicate the radioesium activity and the isopleths of
$S = 33.2$, respectively (Fig. 2b).
heavy precipitation areas in the catchment areas of the Tone and Naka Rivers (Fig. 5a).

Heavy precipitation from the typhoon resulted in the highest river discharge recorded since 2007. Figure 6 shows the daily water discharges from the three rivers over time, which indicated that the discharges were remarkably high in early September 2011. The discharges from the Tone and Naka Rivers reached approximately 2800 and 700 m³ s⁻¹, respectively, at their peaks (04 September). As mentioned earlier, it has been reported that in other areas near the FDNPP, large amounts of radiocesium have been transported from the land to the coastal ocean during flood events in rivers, many of which were caused by typhoons (Evrad et al. 2013, 2014, 2015; Nagao et al. 2013, 2015; Ueda et al. 2013; Yamashiki et al. 2014; Takata et al. 2015, 2020; Yoshimura et al. 2015; Kakehi et al. 2016; Lacey et al. 2016; Buesseler et al. 2017; Chartin et al. 2017; Taniguchi et al. 2019; Irasawa et al. 2020; Onda et al. 2020). Therefore, we can say that the same process occurred in this study region far from the FDNPP. In other words, a large amount of radiocesium, which had already been deposited on the land surface in the catchment areas of the Tone and Naka Rivers, was transported into the coastal ocean in the Kuroshio–Oyashio transition zone through typhoon-induced river discharge.

The strong impact of the typhoon-induced river discharge on the coastal ocean is also evident in Fig. 7; chlorophyll blooms also spread over a broad area during the shipboard survey (Fig. 7b), which corresponds to the high-radioactivity and low-salinity areas observed by the shipboard survey. In contrast, high chlorophyll concentrations were usually confined within a narrow inshore area along the coastline (Fig. 7a,c). Figure 7d shows another flood-induced blooming on 07 May 2012 just before discharges from the Tone and Naka Rivers reached 2500 and 1400 m³ s⁻¹, respectively (on 04 May 2012). These results support the importance of river flood events in the broad spread of radiocesium over the coastal ocean in the study region.

A summary of the results is presented in Fig. 8. The waters from the Naka and Kuji Rivers tended to be deflected to the right immediately after they were discharged into the coastal ocean, which is under the influence of the Coriolis force in the Northern Hemisphere (Minato 1983; Yankovsky and Chapman 1997; Tanaka et al. 2011), and then separated from the coastline. In contrast, water from the Tone River separated immediately after leaving the river mouth because topographic effect of Cape Inubo blocked its path. The offshore spread of the Tone River water may also be influenced by the Kuroshio current, along which it seems to have been stretched toward the northeast.

**Conclusions**

A shipboard survey was conducted to elucidate the spread processes of radioactive cesium over the coastal ocean in the Kuroshio–Oyashio transition zone (south of the FDNPP) from 07 to 12 September 2011, that is, within 8 d of a river flood event associated with Typhoon Talas (T1112). During the survey period, broad distributions of radiocesium and low-salinity water were observed at the sea surface extending nearly 100 km offshore. A significant negative correlation was detected between surface radiocesium and surface salinity over the coastal ocean (except for at inshore stations).

Just before the shipboard survey, Typhoon Talas (T1112) brought extremely heavy rainfall over the catchment areas of the Tone and Naka Rivers flowing into the survey region. The discharges from the Tone and Naka Rivers flowing into the survey region. The discharges from the Tone and Naka Rivers reached approximately 2800 and 700 m³ s⁻¹, respectively, at their peaks (04 September), which were the highest recorded since 2007. It was also shown by satellite images that corresponding to the high-radioactivity and low-salinity areas, chlorophyll blooms also spread over a broad area during the survey. Therefore, assuming that the sources of radiocesium, low-salinity

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**Fig. 8.** Summary illustration: Near-surface velocities (at a depth of 24.7 m) measured by a ship-mounted ADCP are indicated by thin black arrows. Observation was performed from 07 to 12 Sep 2011. The zone of strong surface currents >1.0 m s⁻¹ in the Kuroshio is colored yellow (average between 09 and 11 Sep), which were reproduced in the JCOPE-T ocean data-assimilation model having a horizontal resolution of 1/36° and 46 generalized sigma layers over the western North Pacific. Probable paths of river runoff during the observation are indicated by bold green arrows.
water, and nutrients that triggered the chlorophyll blooms were the same, we can conclude that they were brought about by high river discharge levels associated with the typhoon. The importance of this study is that making use of a variety of data (in situ ocean, precipitation, initial radiocesium fallout, river discharge, satellite, and numerical simulation), we firmly linked the rainfall on the ground, the subsequent river runoff, and the resultant spread of freshwater and associated radiocesium over the coastal ocean, which will be useful in the future to develop comprehensive water circulation models linking land–river–ocean processes.

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Conflict of Interest

None declared.

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