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Lagrangian simulation and tracking of the mesoscale eddies contaminated by Fukushima-derived radionuclides

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Abstract. A Lagrangian methodology is elaborated to simulate, track, document and analyze origin and history of water masses in ocean mesoscale features. It is aimed to distinguish water masses inside the mesoscale eddies originated from the main currents in the Kuroshio – Oyashio confluence zone. Computing trajectories for a large number of synthetic tracers advected by the AVISO velocity field after the Fukushima accident, we identify and track the mesoscale eddies which have been sampled in the cruises in 2011 and 2012 and estimate their risk to be contaminated by Fukushima-derived radionuclides. The simulated results are compared with *in situ* measurements to be in a good qualitative correspondence.

1 Introduction

High tsunami waves after the Tohoku earthquake on March 11, 2011 damaged the cooling system of the Fukushima Nuclear Power Plant (FNPP). Due to lack of electricity, it was not possible to cool nuclear reactors and the fuel storage pools that caused numerous explosions at the FNPP (for details see Povinec et al., 2013). The Fukushima accident was classified at the maximum level of 7, similar to the Chernobyl accident which happened in 1986 in the former Soviet Union. Radionuclides were released from the FNPP through two major pathways, direct discharges of radioactive water and atmospheric deposition onto the North Pacific Ocean. Indirect estimation of that deposition is in the range 6.4–35 PBq (Kumamoto et al., 2014). The total amount of ^{137}Cs isotope released into the ocean was estimated to be 3.6 ± 0.7 PBq by the end of May 2011 (Tsumune et al., 2013).

A few special research vessel (R/V) cruises have been conducted just after the accident and later to measure radioactivity in sea water, zooplankton, fish and in other marine organisms. ^{137}Cs and ^{134}Cs isotopes with 30.17 yr and 2.06 yr half-life, respectively, have been detected over a broad area in the western North Pacific in 2011 and 2012 (Honda et al., 2012; Buesseler et al., 2012; Inoue et al., 2012a, b; Tsumune et al., 2012, 2013; Kaeriyama et al., 2013; Oikawa et al., 2013; Aoyama et al., 2013; Kameník et al., 2013; Kumamoto et al., 2014; Kaeriyama et al., 2014; Budyansky et al., 2015). ^{137}Cs concentration levels off Japan before the accident were estimated at the background level to be 1–2 Bq m^{-3} or $\simeq$ 0.001–0.002 Bq kg^{-1}, while ^{134}Cs was not detectable. Because of a comparatively short half-life time, any measured concentrations of ^{134}Cs could only be Fukushima derived.

The studied area is shown in Fig. 1a. It is known as a Kuroshio – Oyashio confluence zone or a subarctic frontal area (Kawai, 1972). The Kuroshio Extension prolongs the Kuroshio Current which turns to the east at about $35\,^{\circ}$N and flows as a strong meandering jet constituting a front separating the warm subtropical and cold subarctic waters. It is a region with one of the most intense air-sea heat exchange and the highest eddy kinetic energy level. The Kuroshio–Oyashio confluence zone is populated with a plenty of mesoscale eddies that transfer heat, salt, nutrients, carbon, pollutants and other tracers across the ocean. They originate, besides from the Kuroshio Extension, from the Tsugaru Warm Current, flowing between the Honshu and Hokkaido islands, and from the cold Oyashio Current flowing out of the Arctic along the Kamchatka Peninsula and the Kuril Islands (Fig. 1a). The lifetime of those eddies ranges from a few weeks to a few years.

Lagrangian tools have been successfully used in simulating transport phenomena including propagation of oil after the explosion at the Blue Horizon mobile drilling rig in the Gulf of Mexico in April 2010 and propagation of radioactive isotopes after the accident at the FNPP. The standard approach is to run global or regional numerical models of circulation to simulate propagation of pollutants and try to forecast their trajectories. The outcomes provide "spaghetti-like" plots of individual trajectories which are hard to interpret. Moreover, majority of trajectories in a chaotic environment are very sensitive to small and inevitable variations in initial conditions. Those trajectories are practically unpredictable even over a comparatively short time.

The specific Lagrangian approach, based on dynamical systems theory, has been developed in the last decades with the aim to find more or less robust material structures in chaotic flows governing mixing and transport of tracers and creating transport barriers preventing diffusive-like propagation of a contaminant (for reviews see Samelson and Wiggins, 2006; Mancho et al., 2006; Koshel' and Prants, 2006; Haller, 2015). Identification of such structures in the ocean would help to predict for a short and medium time where a contaminant will move even without a precise solution of the Navier – Stokes equations.

The present authors have developed the appropriate Lagrangian tools for tracking origin, history and fate of water masses advected by analytic, altimetric and numerical velocity fields generated by eddy-resolved regional circulation models (Budyansky et al., 2009; Prants et al., 2011b, a; Prants, 2013; Prants et al., 2013; Prants, 2014; Budyansky et al., 2015). Each elementary volume of water can be attributed to physico-chemical properties (temperature, salinity, density, radioactivity, etc.) which characterize this volume as it moves. In addition, each water parcel can be attributed to more specific characteristics as trajectory's functions that carry key data but are not physico-chemical properties. We call them "Lagrangian indicators". They are, for example, distance passed by a fluid particle for some period of time; absolute, zonal, and meridional displacements of particles from their original positions; the number of their cyclonic and anticyclonic rotations; time of residence of fluid particles inside a given area and the exit time out off that area; the number of times particles visited different places in a studied region. The commonly used finite-time Lyapunov exponent is one of the Lagrangian indicators in our terminology.

The Lagrangian indicators contain information about the origin, history and fate of the corresponding water masses and allow to identify water masses moving coherently, either propagating together or rotating together. Even if adjacent waters are indistinguishable, say, by temperature, and the satellite SST images indicate no thermal front, the corresponding water masses can be distinguishable, for example, by their origin, travelling history and other factors. The Lagrangian indicators are computed by integrating advection equations (1) for a large number of synthetic tracers forward and backward in time. When integrating (1) forward in time one computes particle's trajectories to know the fate of the corresponding tracers and when integrating (1) backward in time one could know where the tracers came from and the history of their travel.

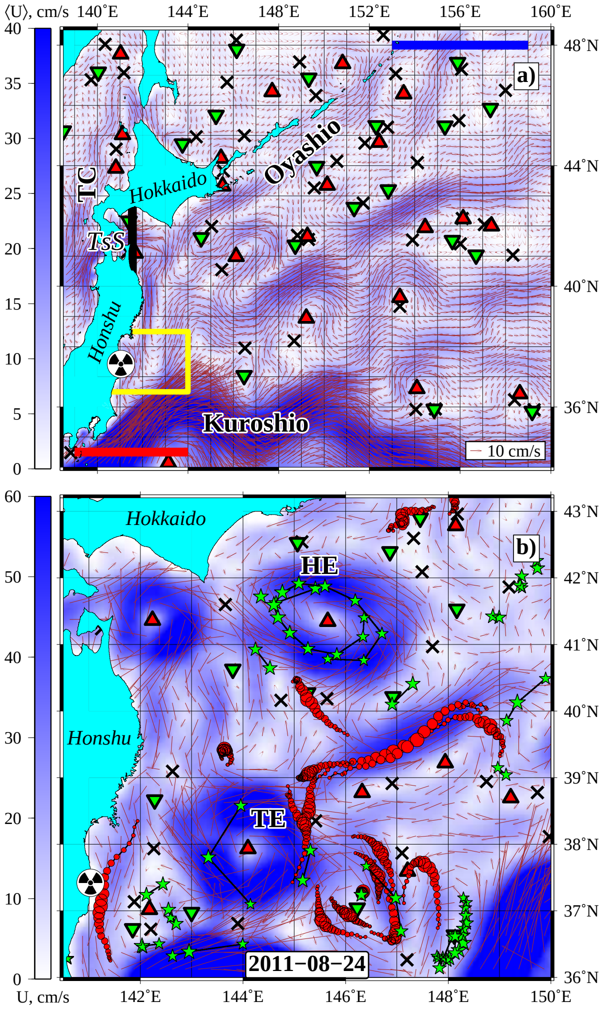

Figure 1. a) The AVISO velocity field in the Kuroshio – Oyashio confluence zone averaged from 1993 to 2016. TsS stands for the Tsugaru Strait. Elliptic and hyperbolic stagnation points with zero mean velocity are indicated by triangles and crosses, respectively, with up- and downward oriented triangles denoting anticyclones and cyclones, respectively. Location of the FNPP is shown by the radioactivity sign. The area just around the FNPP is shown by the yellow lines. b) The velocity field on August 24, 2011 with the Tohoku (TE) and Hokkaido (HE) eddies studied in the paper and with tracks of some available drifters (the red circles) and ARGO floats (the green stars) to be present in the area at that time.

The purpose of this paper is twofold. Firstly, we develop a Lagrangian methodology in order to track and document the origin and history of water masses constituting prominent mesoscale feature. It allows to distinguish water masses inside mesoscale eddies originated from the main currents in the Kuroshio – Oyashio confluence zone. Secondly, we apply that methodology in order to identify and track the mesoscale eddies, advected by the altimetric AVISO velocity field, with a risk to be contaminated by Fukushima-derived radionuclides. Finally, the simulation results are compared qualitatively with *in situ* sampling of those eddies in the R/V cruises. The location and form of the simulated eddies are verified, when possible, by tracks of surface drifters and diving Argo floats available at the sites www.argo.net and aoml.noaa.gov/phod/dac, respectively.

2 Data and methodology

Geostrophic velocities were obtained from the AVISO database (aviso.altimetry.fr) archived daily on a $1/4^\circ \times 1/4^\circ$ grid. We integrate equations for a large number of synthetic particles (tracers) advected by the interpolated AVISO velocity field

$$\frac{d\lambda}{dt} = u(\lambda,\varphi,t), \qquad \frac{d\varphi}{dt} = v(\lambda,\varphi,t), \tag{1}$$

where u and v are angular zonal and meridional velocities, φ and λ are latitude and longitude, respectively. Altimetry data provide the velocity field which is a geostrophical approximation to the real near-surface velocities. The results of our altimetry-based Lagrangian statistical analysis are expected to be valid on a mesoscale where the AVISO velocity field may be considered to be a good approximation.

In order to display the enormous amount of information, we compute Lagrangian maps which are plots of a specific Lagrangian indicator versus particle's initial positions. The region under study is seeded with a large number of tracers whose trajectories are computed for a given period of time. The results obtained are processed to get a data file with the field of a specific Lagrangian indicator in this area. Finally, its values are coded by color and represented as a map in geographic coordinates.

It is informative to impose "instantaneous" stagnation elliptic and hyperbolic points on the Lagrangian maps. We mark them by triangles and crosses, respectively. They are points with zero velocity which are computed daily with the AVISO velocity field. Up(down)ward orientation of one of the triangle's top means anticyclonic (cyclonic) rotations of water around them. The elliptic points, situated mainly in the centers of eddies, are those points around which the motion is stable and circular. The hyperbolic points, situated mainly between and around eddies, are unstable with the direction along which water parcels converge to such a point and another direction along which they diverge. The stagnation points are moving Eulerian features and may undergo bifurcations in the course of time. In spite of nonstationarity of the velocity field, some of them may exist for weeks and much more.

Being motivated by the problem of identification of Fukushima-contaminated waters in the core and at the periphery of persistent mesoscale eddies in the area, we develop in this paper a special Lagrangian technique oriented to distinguish water masses of a different origin inside the eddies with a risk to be contaminated. With this aim we specify, besides Fukushima-derived waters, water masses originated from the main currents in the Kuroshio – Oyashio confluence zone. The integration was performed backward in time for two years starting from a date indicated on the corresponding simulated Lagrangian map. In what follows we specify on the maps "yellow waters" as those which have a large risk to be contaminated because they came from the area just around the FNPP enclosed by the yellow lines in Fig. 1a for the period from the day of the accident, March 11, 2011, to May 18, 2011 when direct releases of radioactive isotopes to the ocean and atmosphere stopped. The "red waters" are salty and warm Kuroshio waters. To be more exact, they came from the red zonal line ($34.5\,^\circ$N, 139°E – 144°E) in Fig. 1a crossing the Kuroshio main jet. The "black waters" came from the warm Tsushima Current flowing via the Tsugaru Strait out off the Japan Sea and crossed that strait (the black line with 40° N – 43° N, 141.55° E). The "blue waters" are more fresh and cold waters originated from the Oyashio Current and crossed the blue zonal line (48° N, 153° E – 159° E) shown in Fig. 1a.

We are interested in advective transport for a comparatively long period of time, up to two years. It is hardly possible to simulate adequately motion of a specified passive particle in a chaotic flow, but it is possible to reproduce transport of statistically significant number of particles. Our results are based not on simulation of individual trajectories but on statistics for hundreds of thousands of tracers. We cannot, of course, guarantee that we compute "true" trajectories for individual tracers. The description of general pattern of transport for many thousands of tracers is much more robust. However, we do not try to simulate quantitatively concentration of radionuclides or estimate the content of water masses of different origin inside the studied eddies.

3 Results

A number of mesoscale eddies was present in the studied area to the day of the accident. The cyclonic eddies with the centers at downward-oriented triangles on the Lagrangian maps prevailed in the area to the north of the Subarctic Front, the boundary between subarctic ("blue") and subtropical ("red") waters in Fig. 2. The anticyclonic eddies with the centers at upward-oriented triangles prevailed to the south of the front. The large anticyclonic Tohoku eddy (TE) with the center at around 39° N, 144° E in March 2011 was sampled after the accident in the two R/V cruises in June (Buesseler et al., 2012) and July 2011 (Kaeriyama et al., 2013) to have large concentrations of ^{137}Cs, ^{134}Cs. The anticyclonic Hokkaido eddy (HE), genetically connected with the TE, was born in the middle of May 2011 with the center at around 40° N, 145° E and captured some Fukushima water from the TE. It was sampled partly in the end of July 2011 (Kaeriyama et al., 2013). The anticyclonic Tsugaru eddy (TsE) was genetically connected with the HE. It was born in the beginning of February 2012 with the center at around 41.9° N, 148° E and captured some Fukushima water from the HE. The TsE was sampled in the R/V "*Professor Gagarinskiy*" cruise on July 5, 2012 to have higher concentrations of ^{137}Cs and ^{134}Cs over the background level at the surface and in intermediate depths (Budyansky et al., 2015). All these eddies will be studied in this section from the Lagrangian point of view in order to simulate and document by which transport pathways they could gain water masses from the Fukushima area and water masses of other origin and to compare qualitatively the simulation results with the *in situ* measured ones.

3.1 The Tohoku eddy

We were able to track with daily computed Lagrangian maps the birth, metamorphoses and decay of the mesoscale anticyclonic TE. It was born in the middle of May 2010 with the elliptic point at around 38° N, 144° E at that time as the result of interaction between a warm anticyclonic Kuroshio ring and a cyclone with mixed Kuroshio and Oyashio core waters. It has interacted with another eddies almost for a year with multiple splittings and merging in the area to the east off the Honshu Island. Just after the accident, it begun to gain "yellow water" from the area around the FNPP. That eddy is clearly seen in earlier simulation

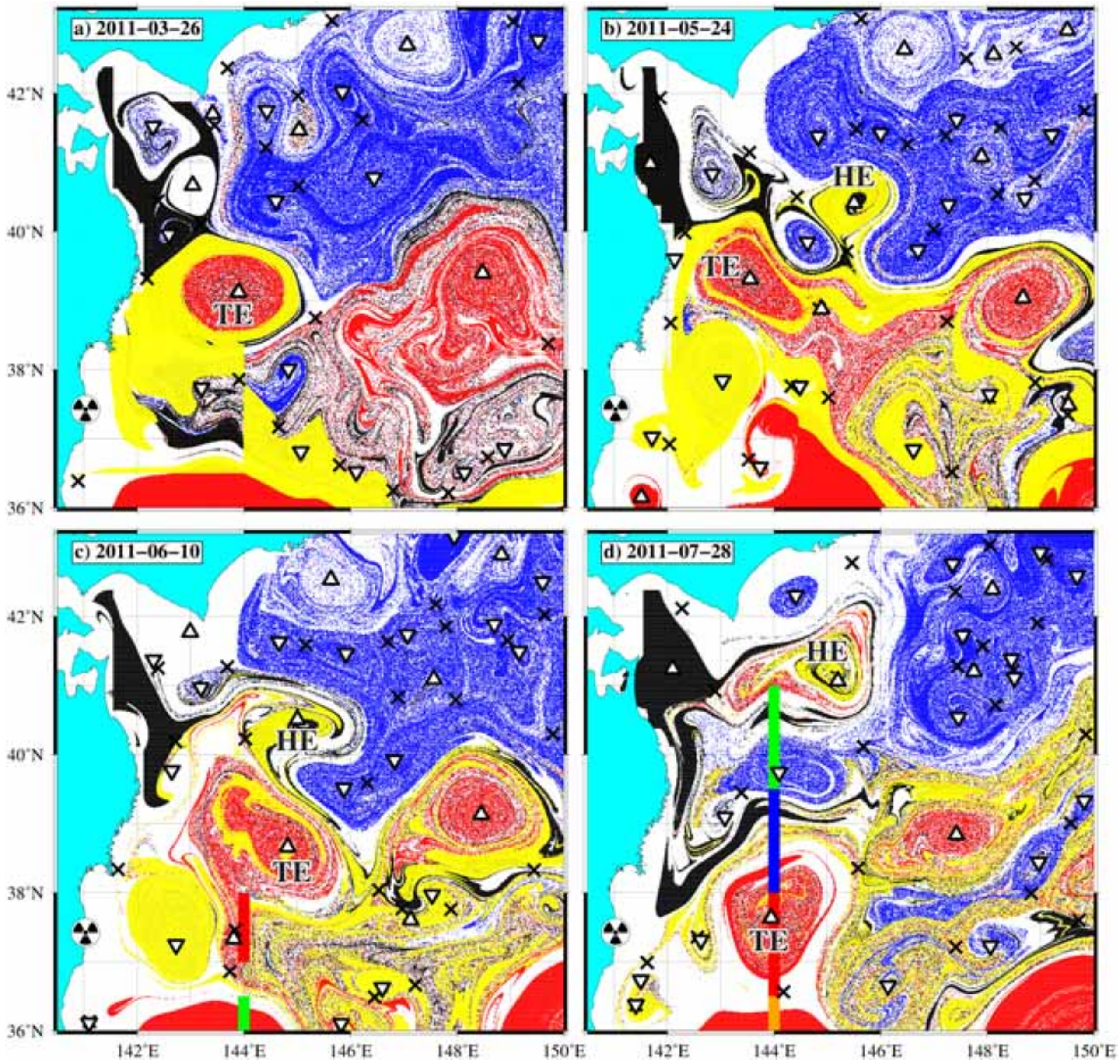

Figure 2. The Lagrangian maps show evolution of the Tohoku eddy (TE) after the FNPP accident to the days of its sampling and the origin of waters in its core and at the periphery. The red, black and blue colors specify waters which came for two years in the past to their places on the maps from the Kuroshio, Oyashio and Tsushima currents, respectively, more exactly, from the corresponding line segments shown in Fig. 1a. The TE has been sampled on June 10 and 11, 2011 (Buesseler et al., 2012) along the colored transect at 35.5° N – 38° N, 144° E shown in panel c) and in the end of July 2011 (Kaeriyama et al., 2013) along the colored transect 35° N – 41° N, 144° E shown in panel d).

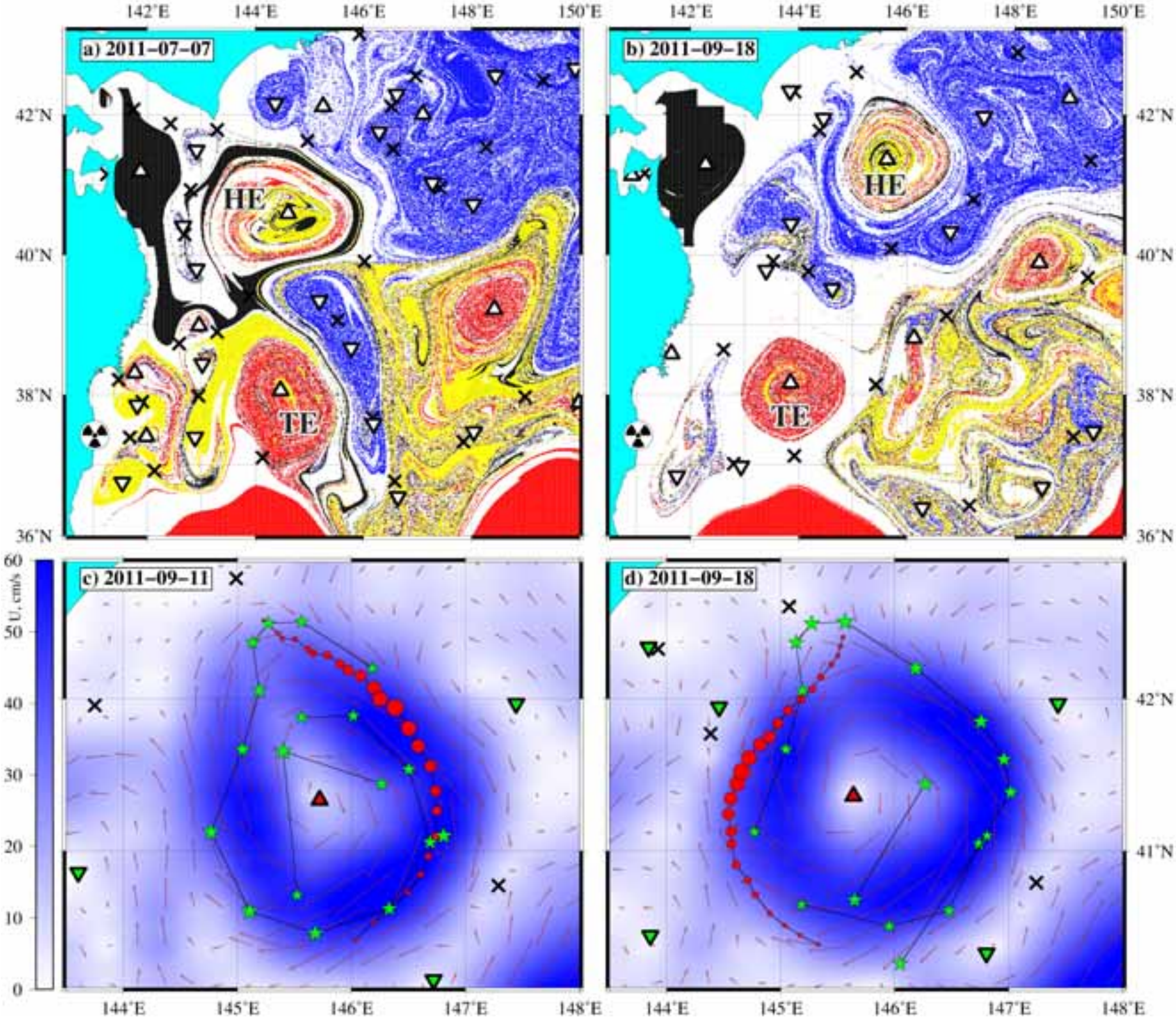

Figure 3. a) and b) The Lagrangian maps show evolution of the Hokkaido eddy (HE) after the FNPP accident to the days of its sampling and the origin of waters in its core and at the periphery. c) and d) A fragment of the track of the drifter no. 39123 is indicated by the full circles for two days before the day indicated with the size of circles increasing in time. Tracks of the three ARGO floats are shown by the stars. The largest star corresponds to the day indicated and the other ones show float's location each 5 days before and after that date.

just after the accident in Fig. 3b by Prants et al. (2011b) and on the Lagrangian map in Fig. 2a as a red patch with the center at 39° N, 144° E on March 26, 2011.

The maps in Fig. 2 and in the subsequent figures have been computed as it was explained in Sec. 2. The red color in the core of the TE means that its core water was of a Kuroshio origin. More exactly, the red tracers came for two years in the past to

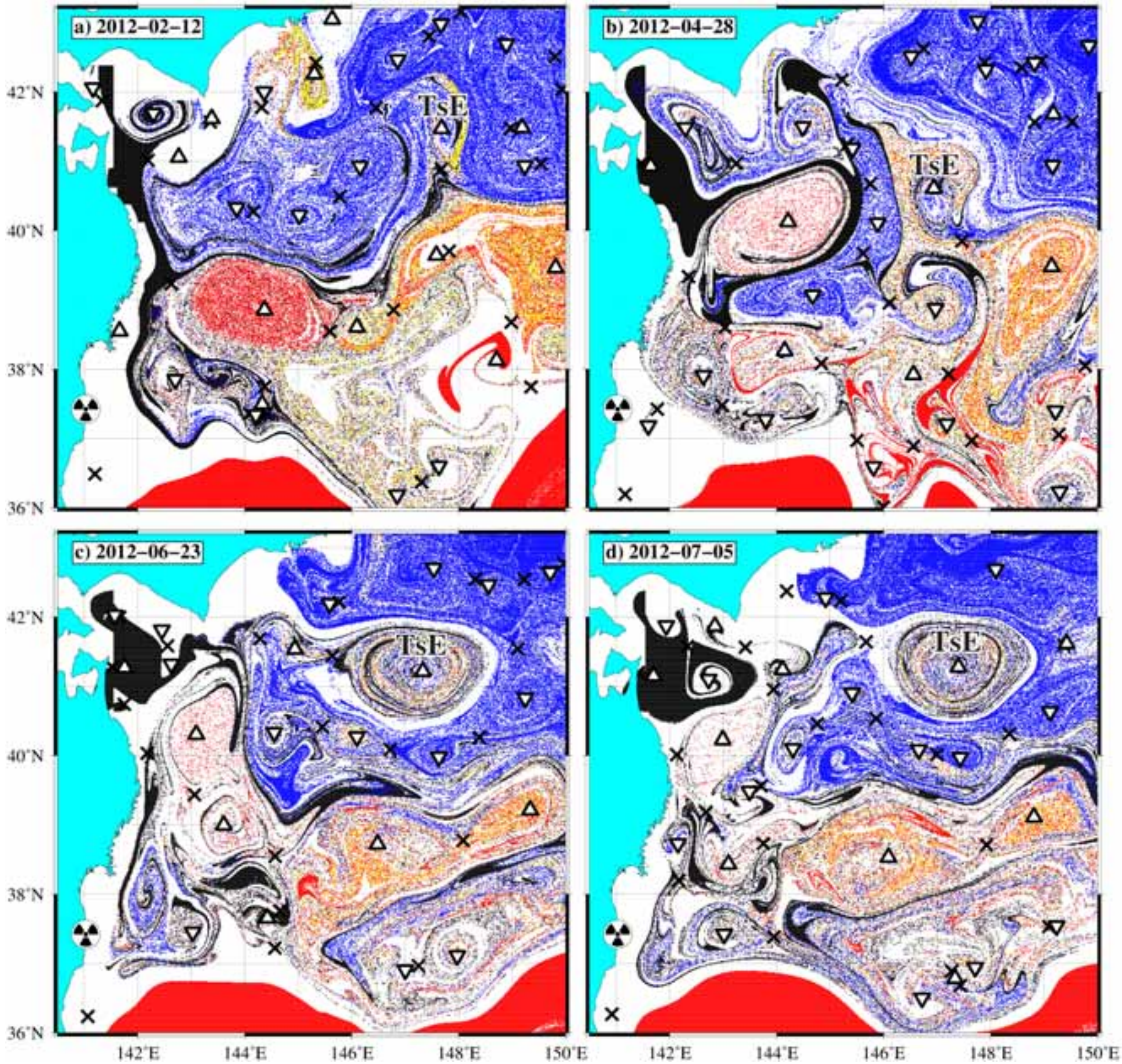

Figure 4. The Lagrangian maps show evolution of the Tsugaru eddy (TsE) in the first half of 2012 and the origin of waters in its core and at the periphery. That eddy was born on February 4, 2012 after splitting of the HE and sampled in the R/V "*Professor Gagarinskiy*" cruise on July 5, 2012 (Budyansky et al., 2015) to have higher concentrations of ^{137}Cs and ^{134}Cs over the background level at the surface and in intermediate depths.

their places on the map from the red line segment in Fig. 1a. In March 2011 "yellow water", coming from the area around the FNPP with a comparatively high risk to be contaminated, wrapped round the TE. A thin streamer of Tsugaru "black water", coming from the black line segment in Fig. 1a, wrapped a periphery of the TE to the end of March. “Yellow waters” propagated gradually to the east and south due to a current system sometimes wrapping round the eddies to be present in the area.

In April and May 2011 the TE had a sandwich-like structure with the red Kuroshio core belted with a narrow streamer of Fukushima “yellow waters” which, in turn, was encircled by a red streamer of Kuroshio water (Fig. 2b). A new eddy configuration appeared to the end of May in Fig. 2b with the TE interacting with a cyclone (the elliptic point at 39.9°N, 144.7°E) and a newborn anticyclone which we call the Hokkaido eddy (HE) with the center at 40.4°N, 145.5°E. The core of the cyclone consisted of a “blue” Oyashio water with low risk to be contaminated, but the HE core water came from the area around the FNPP with a high risk to be contaminated.

In the course of time the TE moved gradually to the south and was sampled in the beginning of June (Buesseler et al., 2012) and in the end of July 2011 (Kaeriyama et al., 2013). Fukushima-derived cesium isotopes have been measured on 10 and 11 June during the R/V “*Ka’imikai-o-Kanaloa*” cruise (Buesseler et al., 2012) along the 145°E meridional transect shown in Fig. 2c where ^{137}Cs concentrations have been found to be in the range from the background level, 1.4 ± 0.2 mBq/kg (station 13), to a high level of 173.6 ± 9.9 mBq/kg (station 10). The ratio ^{134}Cs/^{137}Cs was close to 1.

Prants et al. (2014) have simulated backward in time advection of the tracers placed on a material line along that transect. Computing how many times they visited each cell in the studied area from March 11 to April 10, 2011, they plotted so-called tracking maps. Traces of the particles, chosen at the green segment in Fig. 2c, have been found on the both sides of the Kuroshio Extension jet, whereas traces of particles at the red one have been found on the northern side of the jet only (see Fig. 6 by Prants et al. (2014)). The measured concentrations of ^{137}Cs along the green segment, were at the background level, in the range 1.4–3.6 mBq/kg (Buesseler et al., 2012), because the corresponding particles were advected by the Kuroshio jet. Density of traces of the “red” particles has been shown by Prants et al. (2014) to be comparatively high in the area around the FNPP. This finding correlates with the measurements along the red transect where the concentrations of Fukushima-derived radiocesium were in the range 21.9–173.6 mBq/kg. The red segment crosses only the very periphery of the TE visible in Fig. 2c as a deformed patch with the elliptic point at 38.7°N, 144.5°E with the “red” core and “yellow water” around.

A specific configuration of mesoscale eddies occurred in the area to the north of the FNPP to the end of July 2011, the days of sampling along the 144°E meridian from 35°N to 41°N in the R/V “*Kaiun maru*” cruise (Kaeriyama et al., 2013). That transect is shown in Fig. 2d. It crosses the TE and the cyclone with “blue” Oyashio water, which is genetically linked to the cyclone shown in Fig. 2b. The transect also crosses partly the periphery of the anticyclonic HE. The measured ^{137}Cs concentrations at the stations C43–C55 have been found to be in the range from the background level, 1.9 ± 0.4 mBq/kg, (station C52) to a much higher level 153 ± 6.8 mBq/kg (station C47). The tracking maps in Fig. 5 by Prants et al. (2014), colored as the corresponding segments in Fig. 2d, show where the tracers of that transect were walking from March 11 to April 10, 2011.

The risk of radioactive contamination of the orange markers was shown by Prants et al. (2014) to be small, because they were advected mainly by the Kuroshio Current from the southwest to the east (the corresponding concentrations have been measured to be 2–5 mBq/kg (Kaeriyama et al., 2013)). The red segment in Fig. 2d crosses the TE. The ^{137}Cs concentrations at the stations C49 and C50 of that segment were measured to be 36 ± 3.3 and 50 ± 3.6 mBq/kg (Kaeriyama et al., 2013). The highest concentration levels up to 153 ± 6.8 mBq/kg (Kaeriyama et al., 2013) have been measured at the stations C46, C47 and C48 situated at the blue segment and at C43, C44 and C45 on the green segment. The tracking maps in Figs. 5c and d by Prants et al. (2014) show clearly an increased density of traces of the corresponding markers in the area where the maximal leakage of radionuclides from the FNPP directly into the ocean and their atmospheric fallout on the ocean surface have been registered from March 11 to April 10, 2011. Thus, the TE has interacted for many months after the accident with a number of adjacent eddies and streamers providing transport of contaminated water to the north, south and east. Its influence to transport and mixing of the contaminated water in the area is evident as well on the tracking maps by Prants et al. (2014).

3.2 The Hokkaido eddy

Now we consider the anticyclonic HE. It was born in the end of May (see the yellow patch in Fig. 2b with the center at 40.3° N, 145.5° E) being genetically linked to the TE. During May, the TE gradually lost Fukushima "yellow water" from its periphery to form the core of the HE. Figure 3a shows the HE with a yellow core surrounded by modified subtropical "red water" which, in turn, is surrounded by Tsugaru "black water". The sampling of that eddy along the $144\,^\circ$ E meridian (the green segment in Fig. 2d) by Kaeriyama et al. (2013) in the end of July showed a high concentration of both the radiocesium isotopes. The location of the HE on August 24, 2011 is shown in the AVISO velocity field in Fig. 1b. To verify the simulated locations of the HE and its form, we plot in Figs. 3c and d fragments of the tracks of a drifter and three ARGO floats captured by that eddy in September 2011.

A fragment of the track of the drifter no. 39123 is shown by the red circles with the size increasing in time for two days before the dates indicated in Figs. 3c and d and decreasing for two days after those dates, i.e. the largest circle corresponds to the drifter's location at the indicated date. It was launched after the accident on July 18, 2011 at the point $45.588\,^\circ$ N, 151.583° E in the Oyashio Current, advected by the current to the south and eventually captured by the HE moving around clockwise. Fragments of the clockwise tracks of the three ARGO floats are shown in Figs. 3c and d by stars for seven days before and seven days after the indicated dates. The float no. 5902092 was released long before the accident on September 9, 2008 at the point 32.699° N, 145.668° E to the south off the Kuroshio Extension jet and was able to cross the jet and to get far north. The float no. 2901019 was released before the accident on April 19, 2010 at the point $41.723\,^\circ$ N, 146.606° E. The float no. 2901048 was released just after the accident on April 10, 2011 at the point $37.469\,^\circ$ N, 141.403° E nearby the FNPP.

Our simulation shows that the HE contained a large amount of a "yellow water" with the risk to be contaminated by the Fukushima-derived radionuclides. This conclusion is supported by an increased concentration of radiocesium measured by Kaeriyama et al. (2013) at its periphery in the end of July 2011. The HE persisted in the area around $42\,^\circ$ N, 148° E up to the end of January of the next year. It splitted eventually on January 31, 2012 into two anticyclones.

3.3 The Tsugaru eddy

The anticyclonic TsE was born on February 4, 2012 after splitting of the HE with the elliptic point at its center around $41.9\,^\circ$ N, 148° E. The core of that eddy consisted of an Oyashio "blue water" with a comparatively small amount of the Fukushima-derived "yellow water" at its periphery (Fig. 4a). Then it gained some modified subtropical "red water" (Fig. 4b) and Tsugaru “black water” (Fig. 4c). It was a comparatively large mesoscopic eddy around 150 km in diameter with the elliptic point at 41.3° N, 147.3° E to the day of sampling on July 5, 2012 in the cruise of the R/V “*Professor Gagarinskiy*” (Budyansky et al., 2015) (Fig. 4d).

Station 84 in that cruise was located near the elliptic point of that eddy (called as G by Budyansky et al. (2015)). The concentration of ^{137}Cs at the surface and at 100 m depth has been measured to be 11 ± 0.6 Bq m^{-3} and 18 ± 1.3 Bq m^{-3}, respectively, an order of magnitude larger than the background level. As to the ^{134}Cs concentration, it was measured to be smaller, 6.1 ± 0.4 Bq m^{-3} and 10.4 ± 0.7 Bq m^{-3} due to a shorter half-lifetime of that isotope. In fact, it was one of the highest cesium concentrations measured inside all the eddy features sampled in the cruise. The maximal concentration of radionuclides 15 months after the accident was observed, as expected, not at the surface but within subsurface and intermediate water layers (100–500 m) in the potential density range of 26.5–26.7 due to a convergence and subduction of surface water inside anticyclonic eddies. The corresponding tracking map in Fig. 10c by Budyansky et al. (2015) confirms its genetical link with the TE, and, therefore, a probability to detect increased cesium concentrations was expected to be comparatively large. We were able to track all the modification of the TsE up and its death on April 16, 2013 in the area around $40\,^\circ$ N, 147.5° E.

4 Conclusions

We elaborated a special Lagrangian methodology for simulating, tracking and documenting origin and history of water masses in ocean mesoscale features. Integrating advection equations for passive particles in the AVISO velocity field backward in time, we have computed Lagrangian maps demonstrating clearly by which waters the mesoscale eddies in the Kuroshio – Oyashio confluence zone were composed of. It allowed to simulate by which ways they gained and lost water with a risk to be contaminated by Fukushima-derived radionuclides. We have studied three genetically-linked persistent mesoscale anticyclonic eddies, TE, HE and TsE, which have been sampled in the R/V cruises in 2011 and 2012 to contain higher concentrations of radiocesium isotopes. The simulated Lagrangian maps allowed to document and analyze how they interact to pass radioactive water to each other. The simulated results have been shown to be in a good qualitative correspondence as compared with *in situ* measurements.

We hope that the proposed methodology could be applied to simulate propagation of pollutants after future possible accidents and identify and track contaminated persistent features in the ocean. The Lagrangian methodology seems to be useful, as well, to plan courses of the R/V cruises. It allows not only to track mesoscale eddies in the studied area but to identify the origin of water masses and to estimate *a priori* concentrations of radionuclides, pollutants or other Lagrangian tracers inside the eddies planned to be sampled.

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References

Aoyama, M., Uematsu, M., Tsumune, D., and Hamajima, Y.: Surface pathway of radioactive plume of TEPCO Fukushima NPP1 released ^{134}Cs and ^{137}Cs, Biogeosciences, 10, 3067–3078, doi:10.5194/bg-10-3067-2013, 2013.

Budyansky, M. V., Uleysky, M. Y., and Prants, S. V.: Detection of barriers to cross-jet Lagrangian transport and its destruction in a meandering flow, Physical Review E, 79, 056 215, doi:10.1103/physreve.79.056215, 2009.

Budyansky, M. V., Goryachev, V. A., Kaplunenko, D. D., Lobanov, V. B., Prants, S. V., Sergeev, A. F., Shlyk, N. V., and Uleysky, M. Y.: Role of mesoscale eddies in transport of Fukushima-derived cesium isotopes in the ocean, Deep Sea Research Part I: Oceanographic Research Papers, 96, 15–27, doi:10.1016/j.dsr.2014.09.007, 2015.

Buesseler, K. O., Jayne, S. R., Fisher, N. S., Rypina, I. I., Baumann, H., Baumann, Z., Breier, C. F., Douglass, E. M., George, J., Macdonald, A. M., Miyamoto, H., Nishikawa, J., Pike, S. M., and Yoshida, S.: Fukushima-derived radionuclides in the ocean and biota off Japan, Proceedings of the National Academy of Sciences, 109, 5984–5988, doi:10.1073/pnas.1120794109, 2012.

Haller, G.: Lagrangian Coherent Structures, Annual Review of Fluid Mechanics, 47, 137–162, doi:10.1146/annurev-fluid-010313-141322, 2015.

Honda, M. C., Aono, T., Aoyama, M., Hamajima, Y., Kawakami, H., Kitamura, M., Masumoto, Y., Miyazawa, Y., Takigawa, M., and Saino, T.: Dispersion of artificial caesium-134 and -137 in the western North Pacific one month after the Fukushima accident, Geochemical Journal, 46, e1–e9, 2012.

Inoue, M., Kofuji, H., Hamajima, Y., Nagao, S., Yoshida, K., and Yamamoto, M.: ^{134}Cs and ^{137}Cs activities in coastal seawater along Northern Sanriku and Tsugaru Strait, northeastern Japan, after Fukushima Dai-ichi Nuclear Power Plant accident, Journal of Environmental Radioactivity, 111, 116–119, doi:10.1016/j.jenvrad.2011.09.012, 2012a.

Inoue, M., Kofuji, H., Nagao, S., Yamamoto, M., Hamajima, Y., Yoshida, K., Fujimoto, K., Takada, T., and Isoda, Y.: Lateral variation of ^{134}Cs and ^{137}Cs concentrations in surface seawater in and around the Japan Sea after the Fukushima Dai-ichi Nuclear Power Plant accident, Journal of Environmental Radioactivity, 109, 45–51, doi:10.1016/j.jenvrad.2012.01.004, 2012b.

Kaeriyama, H., Ambe, D., Shimizu, Y., Fujimoto, K., Ono, T., Yonezaki, S., Kato, Y., Matsunaga, H., Minami, H., Nakatsuka, S., and Watanabe, T.: Direct observation of ^{134}Cs and ^{137}Cs in surface seawater in the western and central North Pacific after the Fukushima Dai-ichi nuclear power plant accident, Biogeosciences, 10, 4287–4295, doi:10.5194/bg-10-4287-2013, 2013.

Kaeriyama, H., Shimizu, Y., Ambe, D., Masujima, M., Shigenobu, Y., Fujimoto, K., Ono, T., Nishiuchi, K., Taneda, T., Kurogi, H., Setou, T., Sugisaki, H., Ichikawa, T., Hidaka, K., Hiroe, Y., Kusaka, A., Kodama, T., Kuriyama, M., Morita, H., Nakata, K., Morinaga, K., Morita, T., and Watanabe, T.: Southwest Intrusion of ^{134}Cs and ^{137}Cs Derived from the Fukushima Dai-ichi Nuclear Power Plant Accident in the Western North Pacific, Environmental Science and Technology, 48, 3120–3127, doi:10.1021/es403686v, 2014.

Kameník, J., Dulaiova, H., Buesseler, K. O., Pike, S. M., and Št'astná, K.: Cesium-134 and 137 activities in the central North Pacific Ocean after the Fukushima Dai-ichi Nuclear Power Plant accident, Biogeosciences, 10, 6045–6052, doi:10.5194/bg-10-6045-2013, 2013.

Kawai, H.: Hydrography of the Kuroshio Extension, in: Kuroshio: Physical Aspects of the Japan Current, edited by Stommel, H. M. and Yoshida, K., pp. 235–352, University of Washington Press, Seattle, 1972.

Koshel', K. V. and Prants, S. V.: Chaotic advection in the ocean, Physics-Uspekhi, 49, 1151–1178, doi:10.1070/PU2006v049n11ABEH006066, 2006.

Kumamoto, Y., Aoyama, M., Hamajima, Y., Aono, T., Kouketsu, S., Murata, A., and Kawano, T.: Southward spreading of the Fukushima-derived radiocesium across the Kuroshio Extension in the North Pacific, Scientific Reports, 4, 1–9, doi:10.1038/srep04276, 2014.

Mancho, A. M., Small, D., and Wiggins, S.: A tutorial on dynamical systems concepts applied to Lagrangian transport in oceanic flows defined as finite time data sets: Theoretical and computational issues, Physics Reports, 437, 55–124, doi:10.1016/j.physrep.2006.09.005, 2006.

Oikawa, S., Takata, H., Watabe, T., Misonoo, J., and Kusakabe, M.: Distribution of the Fukushima-derived radionuclides in seawater in the Pacific off the coast of Miyagi, Fukushima, and Ibaraki Prefectures, Japan, Biogeosciences, 10, 5031–5047, doi:10.5194/bg-10-5031-2013, 2013.

Povinec, P. P., Hirose, K., and Aoyama, M.: Fukushima Accident: Radioactivity Impact on the Environment, Elsevier, Amsterdam, doi:10.1016/B978-0-12-408132-1.01001-9, 2013.

Prants, S. V.: Dynamical systems theory methods to study mixing and transport in the ocean, Physica Scripta, 87, 038 115, doi:10.1088/0031-8949, 2013.

Prants, S. V.: Chaotic Lagrangian transport and mixing in the ocean, The European Physical Journal Special Topics, 223, 2723–2743, doi:10.1140/epjst/e2014-02288-5, 2014.

Prants, S. V., Budyansky, M. V., Ponomarev, V. I., and Uleysky, M. Y.: Lagrangian study of transport and mixing in a mesoscale eddy street, Ocean Modelling, 38, 114–125, doi:10.1016/j.ocemod.2011.02.008, 2011a.

Prants, S. V., Uleysky, M. Y., and Budyansky, M. V.: Numerical simulation of propagation of radioactive pollution in the ocean from the Fukushima Dai-ichi nuclear power plant, Doklady Earth Sciences, 439, 1179–1182, doi:10.1134/S1028334X11080277, 2011b.

Prants, S. V., Ponomarev, V. I., Budyansky, M. V., Uleysky, M. Y., and Fayman, P. A.: Lagrangian analysis of mixing and transport of water masses in the marine bays, Izvestiya, Atmospheric and Oceanic Physics, 49, 82–96, doi:10.1134/S0001433813010088, 2013.

Prants, S. V., Budyansky, M. V., and Uleysky, M. Y.: Lagrangian study of surface transport in the Kuroshio Extension area based on simulation of propagation of Fukushima-derived radionuclides, Nonlinear Processes in Geophysics, 21, 279–289, doi:10.5194/npg-21-279-2014, 2014.

Samelson, R. M. and Wiggins, S.: Lagrangian Transport in Geophysical Jets and Waves: The Dynamical Systems Approach, vol. 31 of *Interdisciplinary Applied Mathematics*, Springer Science+Business Media, LLC, doi:10.1007/978-0-387-46213-4, 2006.

Tsumune, D., Tsubono, T., Aoyama, M., and Hirose, K.: Distribution of oceanic ^{137}Cs from the Fukushima Dai-ichi Nuclear Power Plant simulated numerically by a regional ocean model, Journal of Environmental Radioactivity, 111, 100–108, doi:10.1016/j.jenvrad.2011.10.007, 2012.

Tsumune, D., Tsubono, T., Aoyama, M., Uematsu, M., Misumi, K., Maeda, Y., Yoshida, Y., and Hayami, H.: One-year, regional-scale simulation of ^{137}Cs radioactivity in the ocean following the Fukushima Dai-ichi Nuclear Power Plant accident, Biogeosciences, 10, 5601–5617, doi:10.5194/bg-10-5601-2013, 2013.