Lagrangian analysis of mesoscale eddies in the Kuroshio-Oyashio frontal zone

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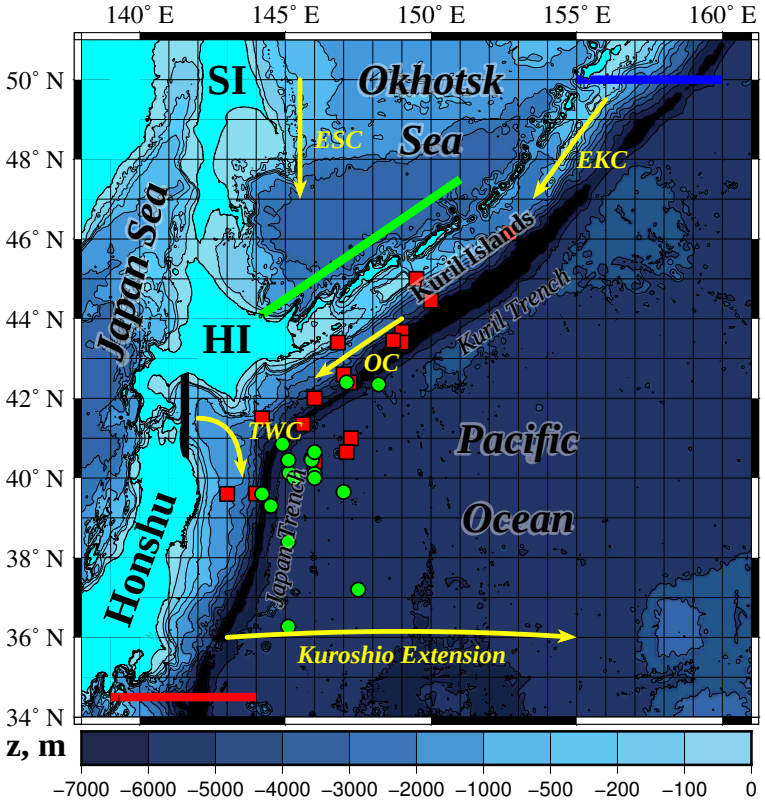
The Kuroshio-Oyashio frontal zone is a vast area where subtropical and subarctic waters converge to produce a variety of eddies composed of the waters originating from the Kuroshio Extension (KE), Oyashio Current (OC), Tsugaru Warm Current (TWC) and Okhotsk Sea (OS). The Oyashio has two major sources: cold and fresh OS waters and comparatively warm and saline waters of the East Kamchatka Current (EKC).

The Kuroshio rings and other mesoscale eddies in the area have a great impact on living organisms and on fishing ground formation [Saitoh 1986, Sugimoto 1992, SP 2014]. They may live for years and are able to reach high latitudes [Bogdanov 1985, Lobanov 1991, Sugimoto 1992]. In spite of winter cooling and freshening of the upper core water while travelling north, the positive heat and salinity anomalies of the Kuroshio rings, compared to the surrounding subarctic water, may be maintained for several years.

Warm-core eddies, originating from the TWC, may also propagate approximately following the Japan and Kuril trenches [Itoh 2010, SP 2014]. The Kuril eddies with cold and fresh core water originate from the EKC and OC and form near the Bussol' Strait. They may propagate to the southwest along the Kuril Trench [Yasuda 2000, Rogachev 2000, SP 2016].

The long standing problem: tracking of eddies in the real ocean, documenting their deformation and interaction with currents and other eddies and quantifying their properties.

We develop a Lagrangian methodology to track concrete mesoscale eddies in the real time and to document how they gain, retain and release water during their evolution.



The Kuroshio-Oyashio frontal zone with a scheme of the main currents. The red, black, blue and green line segments cross the Kuroshio Extension (KE), Tsugaru Warm Current (TWC), East Kamchatka Current (EKC) and the deep Kuril Basin in the Okhotsk Sea, resp. The places of birth and decay of the Hokkaido eddies with the KE core water from 1 Jan 1993 to 10 Dec 2016 are shown by green circles and red squares, resp.

Lagrangian biography of a Hokkaido eddy

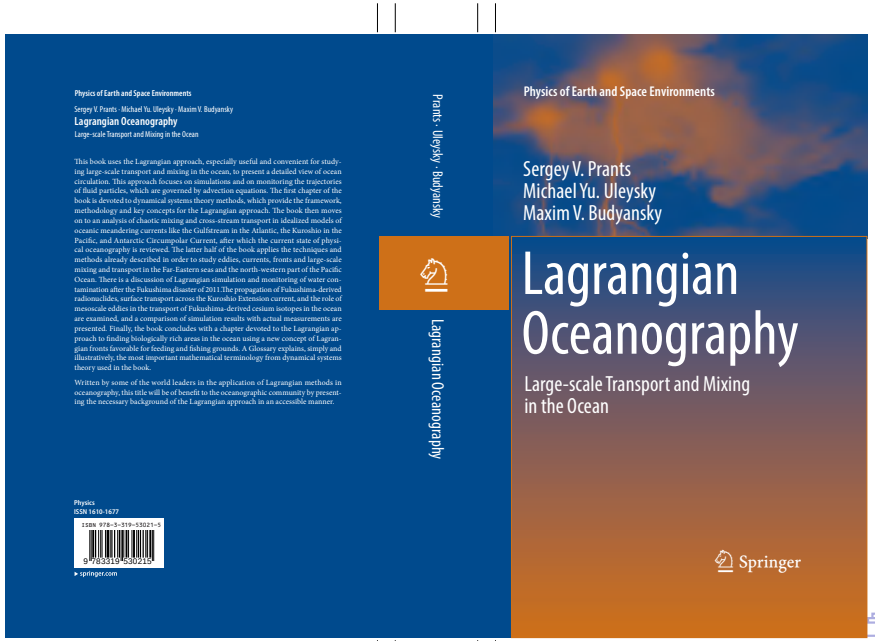
We focus at the mesoscale eddies propagating along the Japan and Kuril–Kamchatka trenches which have been observed from 1 January 1993 to the end of 2017 in the AVISO velocity field near the eastern coast of Hokkaido. We elaborate a Lagrangian methodology to track the origin of water masses in the core and at periphery of those eddies, to document directly the processes by which they gain, retain and release water and to record histories of their life. Here we focus at the case study of a Hokkaido eddy which has been carefully sampled in 2003 and 2004 by Itoh et al. J. Ocean. 2011.

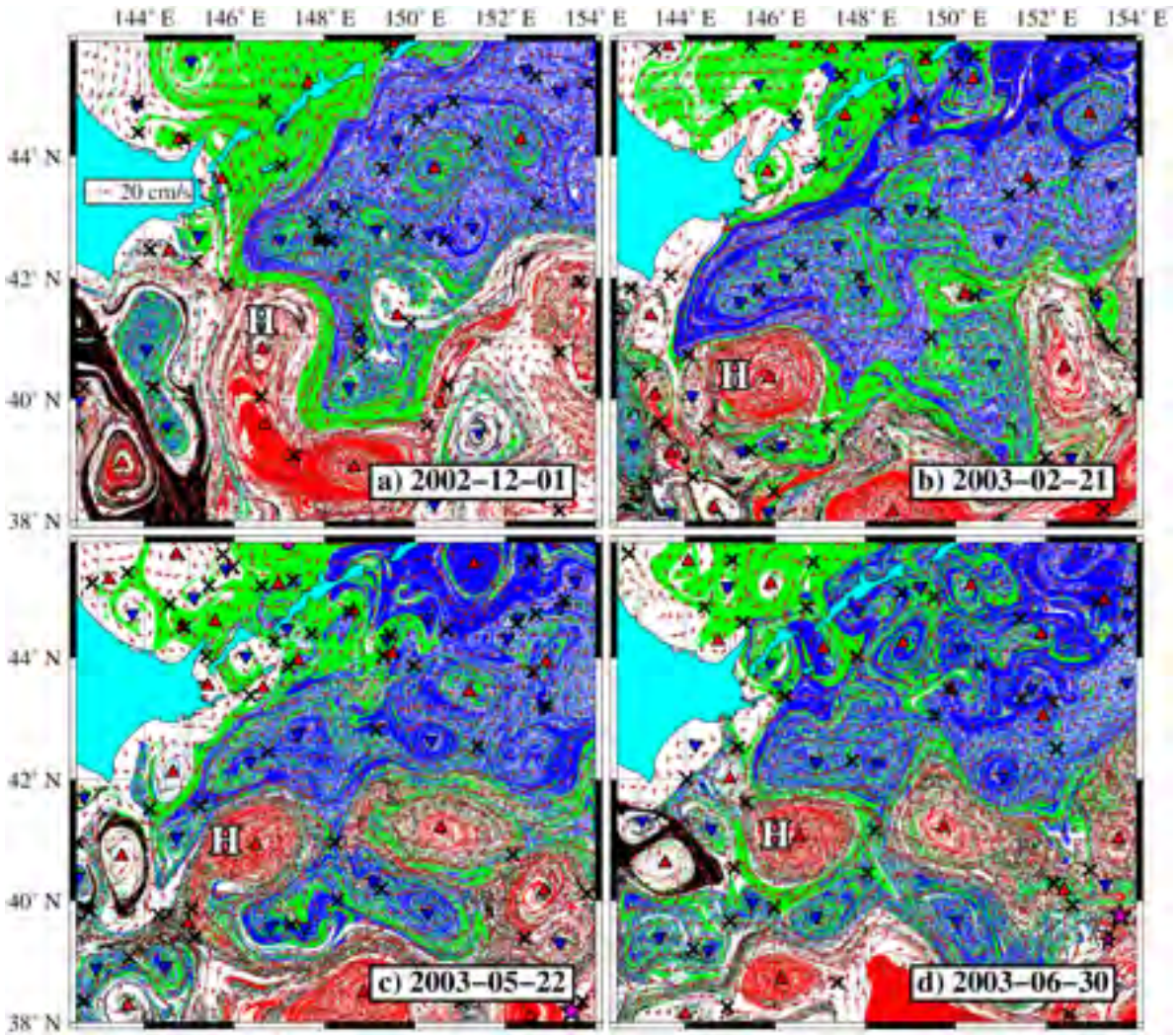
S.V. Prants, M.V. Budyansky, and M.Yu. Uleysky. How eddies gain, retain and release water: the case study of a Hokkaido anticyclone. Journal Geophysical Research. Oceans. DOI: 10.1002/2017JC013610.

Name	Birth date	Lat	Lon	Decay date	Lat	Lon	Lifetime
TE94	1994-03-30	42° N	146° E	1996-05-22	45° N	149.5° E	784
TE96	1996-04-25	40.1° N	146° E	1997-01-26	42.4° N	147.2° E	276
TE96'	1996-08-08	38.4° N	145.1° E	1998-11-18	44.4° N	150° E	832
TE98	1998-07-13	40.5° N	145.9° E	1999-11-10	42° N	146° E	485
KR	1998-10-19	36.3° N	145.1° E	2000-09-16	43.6° N	149° E	698
TE01	2001-01-07	40.1° N	145.1° E	2002-09-08	39.6° N	144° E	609
H	2002-10-11	40.4° N	145.9° E	2004-12-24	43.4° N	149° E	805
TE04	2004-09-19	37.2° N	147.5° E	2007-12-13	46.1° N	152.7° E	1180
TE06	2006-08-11	40.4° N	145.1° E	2008-08-11	41.5° N	144.2° E	731
HE08	2008-04-25	42.4° N	147.1° E	2008-12-30	43.4° N	146.8° E	249
TE08	2008-02-13	39.6° N	144.2° E	2011-04-26	42.6° N	147° E	1168
HE08'	2008-12-08	42.3° N	148.2° E	2009-03-24	43.4° N	148.7° E	106
TE10	2010-07-04	39.3° N	144.5° E	2011-04-20	41.3° N	145.6° E	290
TE11	2011-05-17	40° N	145.3° E	2013-04-11	41° N	147.3° E	695
TE13	2013-03-27	39.6° N	147° E	2015-04-29	40.6° N	147.1° E	763
TE15	2015-05-08	40.6° N	146° E	2016-01-24	40.4° N	146° E	261
TE16	2016-03-27	40° N	146° E	2017-03-19	43.2° N	148° E	357

The dates of the birth and decay of the Hokkaido eddies and their lifetime (in days) during the altimetric era from January 1, 1993. The eddies with the core water originating from the Kuroshio are named by the place and year of their birth as Tohoku eddies (TE), Kuroshio rings (KR) and eddies near Hokkaido (HE).

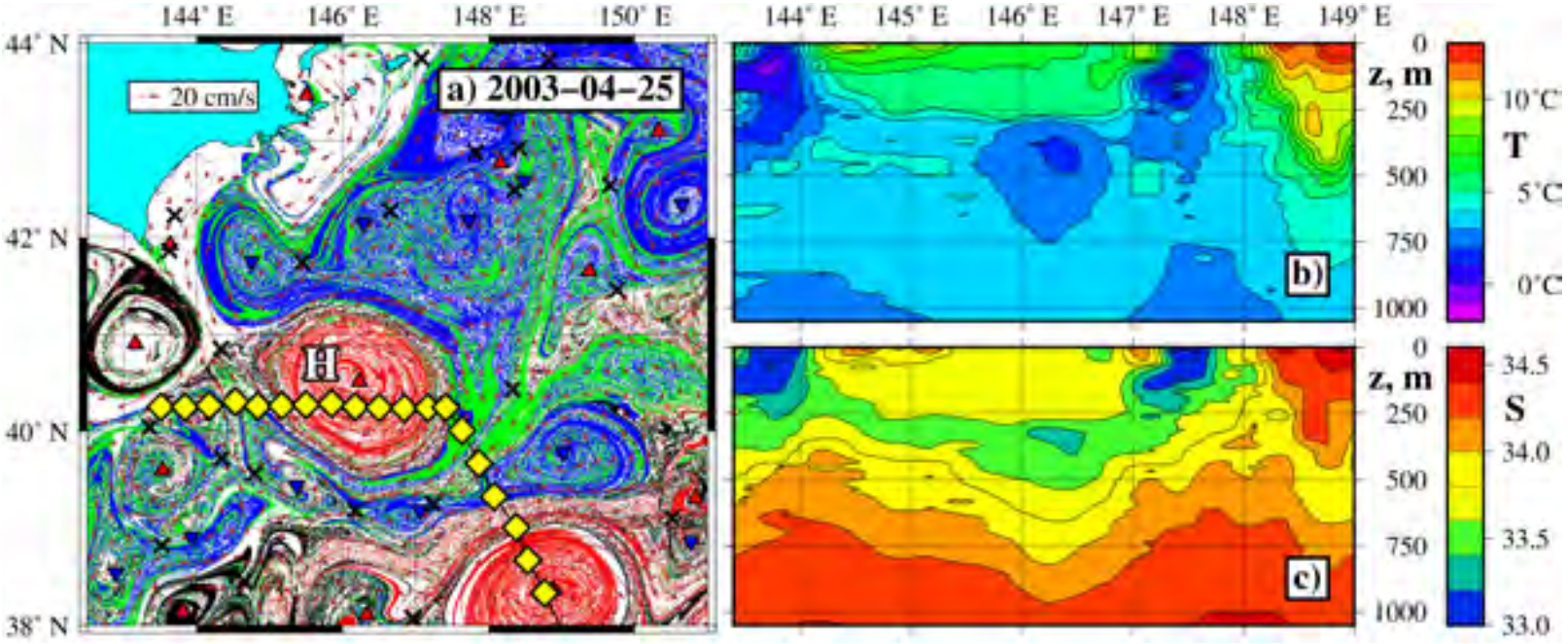
The methodology is based on solving advection equations forward and backward in time for millions of virtual particles and on computing a number of Lagrangian indicators which are functions of particle's trajectory. Lagrangian indicators provide information on the origin, history and fate of fluid particles. In order to display the enormous amount of information, we compute Lagrangian maps which are plots of Lagrangian indicators versus particle's initial positions. See the book now issued by Springer at http://www.springer.com/gp/book/9783319530215





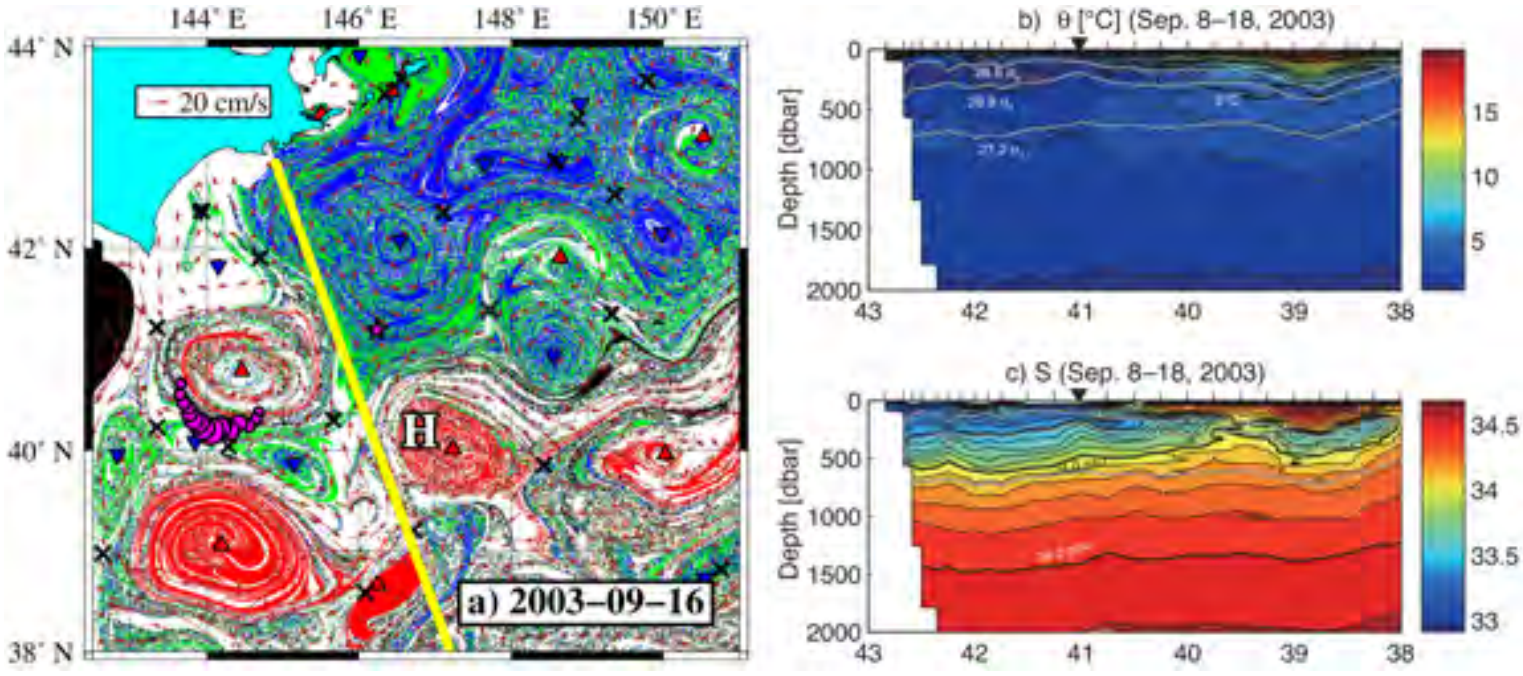
The Hokkaido eddy H in 2002 and 2003 on the origin maps. a) Beginning of formation in Dec 2002. b) Eventual formation in Feb 2003. c) Detrainment of red Kuroshio water from periphery in May 2003. d) Entrainment of green OS water in Jun 2003.

Sampling of the Hokkaido eddy in April 2003

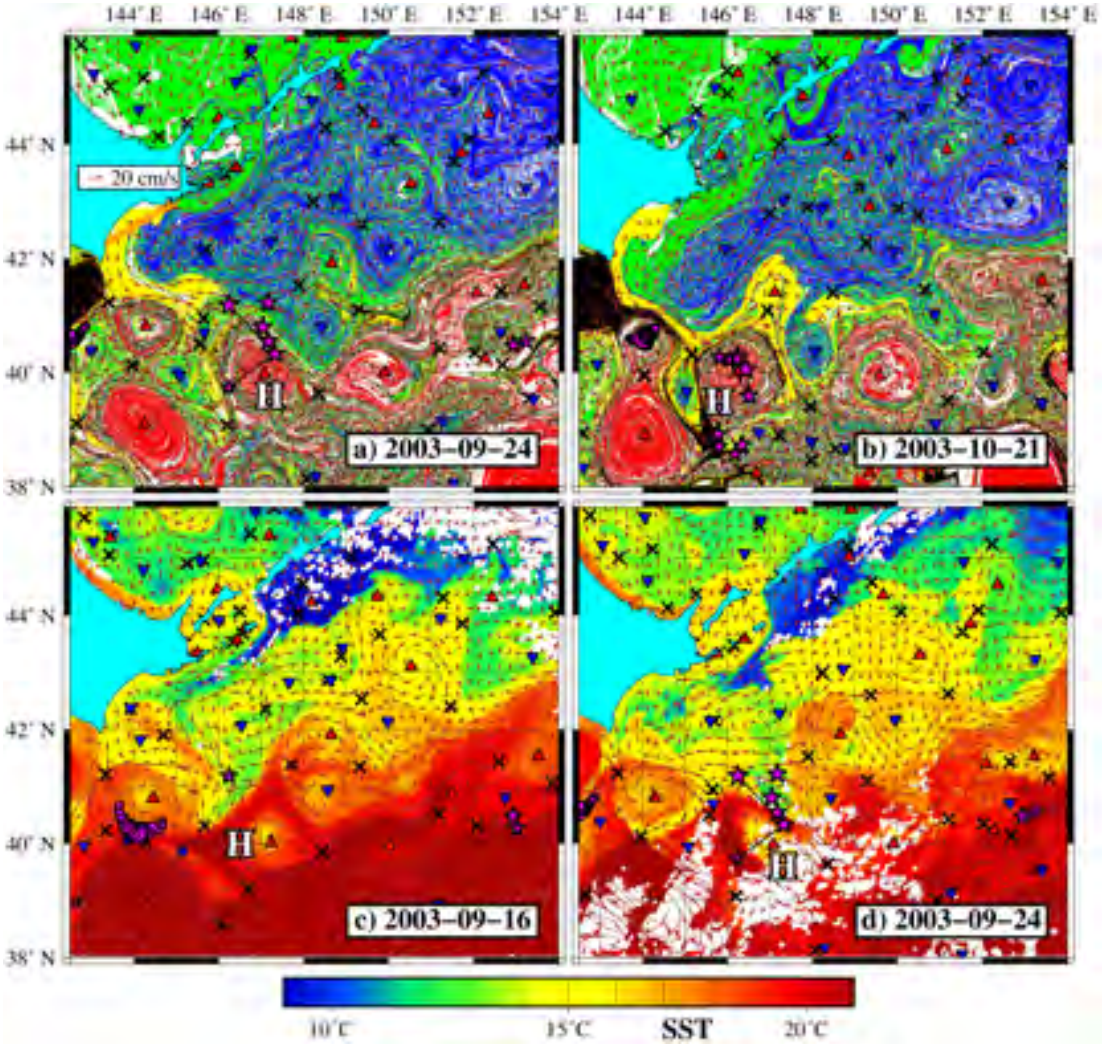


The origin map on 25 Apr 2003 with the shipboard observation stations indicated by diamonds. b) Temperature and c) salinity depth profiles obtained during a cruise by the R/V "Seifu Maru" during 22–26 Apr 2003.

Sampling of the Hokkaido eddy in Sept 2003

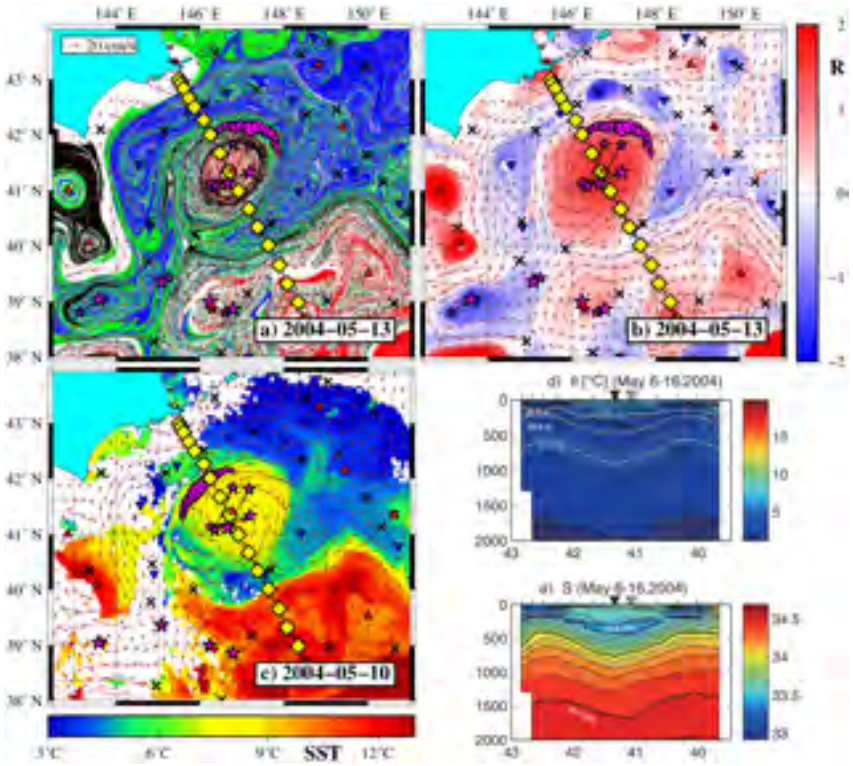


The origin map on 16 Sept 2003 and potential temperature along the A line [Itoh et al. J. Ocean. 2011] that did not cross the Hokkaido ACE but it crossed a smaller ACE with the center at (38.7N, 146.2E) which is clearly seen on the map and in the cross section.



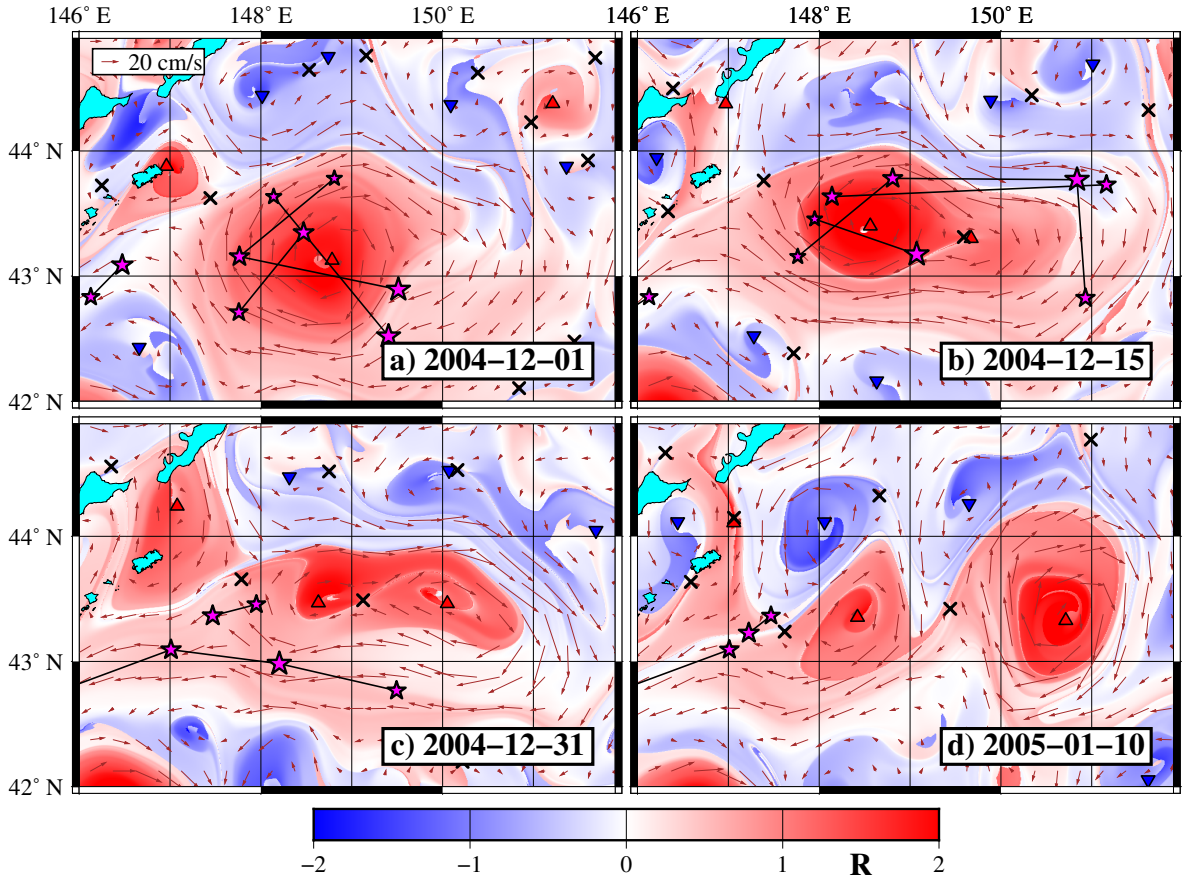
On 24 Sept the eddy began to entrain Oyashio water together with 2 floats. The event was completed by 22 Oct with surface water cooled by 4°C [Itoh et al. J. Ocean. 2011]. The entrainment of Oyashio yellow water on origin maps (a and b). SST (c and d).

Sampling of the Hokkaido eddy in May 2004

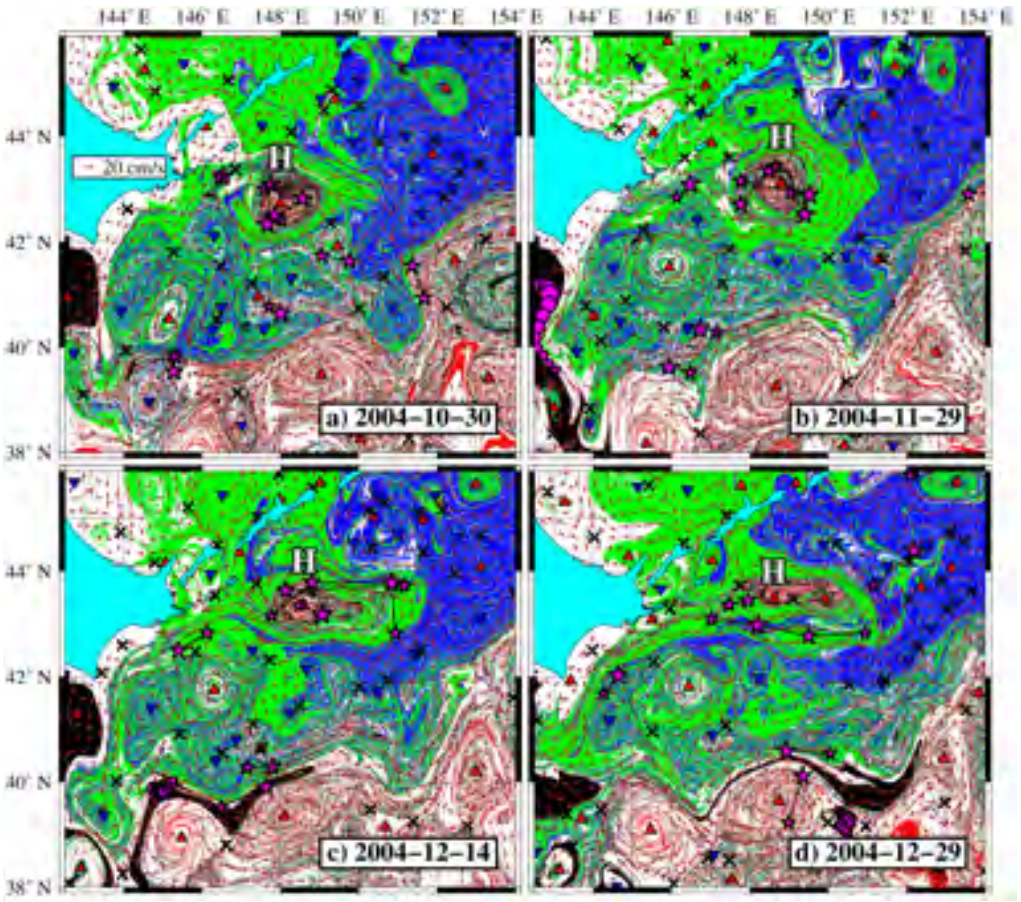


Map of anticyclonic (red) and cyclonic (blue) rotations of particles on 14 May 2004 and potential temperature along the JMA line [Itoh et al. J. Ocean. 2011] crossing the eddy and two divergency areas centered at 42.5N, 146E and 40.2N, 147.5E seen on the map and in cross section with the corresponding depression and elevations of the isopycnal surfaces

Splitting of the Hokkaido eddy in Dec 2004



"Prominent interaction, observed between the eddy and water from the Okhotsk Sea in Dec 2004, caused its marked elongation and detrainment of the floats" [Itoh et al. J. Ocean. 2011] and how it looks on the rotation maps.



Origin maps show entrainment of green Okhotsk Sea water in winter 2004 and a splitting. Newborn ACE moved to northeast along the Kuril Trench. After a few splittings in 2006–2007, the remnants of the eddy H were absorbed on 19 March 2007 by an ACE near the Bussol' Strait at 46° N. It had some Kuroshio water in its core even at such a high latitude after 5 (!) years of its life.

How to use Lagrangian maps in the R/V cruises

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Before planning R/V cruises, it is instructive to compute altimetry-based Lagrangian maps of different kind to know oceanographic situation in the study area: location, type and properties of eddies, currents, streamers and streaks in the area. It would help to plan the marshrute and tasks of the cruise.

- The real-time altimetry-based Lagrangian maps sent to a board allow to save fuel and optimize the vessel's route.
- Lagrangian maps sent to a board allow to fix eddy's centers (elliptic points) in order to optimize cross section locations.
- Lagrangian maps allow to see changes in the oceanographic situation in the study area practically in the real time and allow to adjust a cruise program.

Conclusion

The proposed methodology seems to be more appropriate to identify and track eddies and document their transformation than commonly used techniques because the Lagrangian maps are imprints of history of water masses involved in the vortex motion whereas vorticity, the Okubo-Weiss parameter and similar indicators are "instantaneous" snapshots. That is why one can see eddies and document their transformations more accurately on Lagrangian maps.

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