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Surface circulation in the southwestern Japan/East Sea as observed from drifters and sea surface height

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ABSTRACT

The mean circulation of the surface layer of the southwestern Japan/East Sea (JES) was examined using current measurements collected at 15 m by satellite-tracked drifters and merged sea level anomalies from satellite altimeters. The study of circulation patterns in this paper focused on the inflow passing through the western channel of the Korea Strait from the East China Sea. Empirical Orthogonal Function (EOF) analysis of non-seasonal sea level anomalies revealed that significant energy in the circulation pattern of Ulleung Basin was controlled by the inflow conditions through the Korea Strait. Three circulation patterns were identified that depended on the initial relative vorticity of the inflow. When inflow had initially large negative vorticity, the flow gained more negative vorticity due to deepening of the bottom (stretching) and then turned right after entering the JES. The inflow then followed the path of the Tsushima Warm Current along the coast of Japan. When the inflow was strong, with a speed in excess of 55 cm/s and with a large positive vorticity, potential vorticity appeared to be conserved. In this case, the EKWC followed isobaths along the coast and then left the coast, following topographic features north of Ulleung-Do. The northward flowing jet developed inertial meandering after leaving the coast, which is a characteristic of many western boundary currents. The regular, bimonthly deployments of drifters in the western portion of the Korea Strait revealed that splitting or branching of the flow through the western channel of the Korea Strait occurred only 15% of the time. And splitting or branching rarely occurred during the fall and winter seasons, when the inflow splitting was previously reported in hydrographic surveys. The time-averaged circulation map of the EKWC and its seaward extension were considerably enhanced by using regularly sampled geostrophic velocities calculated from sea level anomalies to remove biases in the mean velocity that were caused by irregular spatial and temporal drifter observations. The East Korean Warm Current, a mean coastal current along the Korean coast, behaved like the simple model by Arruda et al. (2004) in which the generation of the Ulleung Warm Eddy and the meandering circulation pattern were well reproduced.

1. Introduction

In the traditional view, the Tsushima Warm Current (TWC) splits into three branches upon entering the Japan/East Sea (JES) from the East China Sea (Naganuma, 1977): the East Korean Warm Current (EKWC) that follows the southern Korean coast, the Offshore Branch that flows along the outer edge of Japan's continental shelf and the Nearshore Branch that flows along the coast of Japan. This view is based on historical hydrographic observations and current measurements by shipboard Acoustic Doppler Current Profilers (ADCP). Because the current observations by ADCP have spatial and temporal limitations for defining mean currents and because the estimation of absolute geostrophic currents from hydrographic data alone is not reliable for shallow coastal regions, the time variations or patterns in those three branches have not been well defined. Improved descriptions of the surface circulation patterns are being achieved by regular repeated deployments of satellite-tracked drifters in the JES. Drifter observations (Lee et al., 2000; Lee and Niiler, 2005) indicate that surface circulation in the JES has distinctive circulation patterns during the rainy southwest monsoon between June and August and the dry northeast monsoon between September and May. The EKWC is present all year long. Between June and August, the TWC flows eastward along the north coast of Japan, and the North Korean Cold Current (NKCC) flows southward along the North Korean coast (Fig. 1). The focus of this study is to describe the more complete view of the EKWC that has been provided by enhanced drifter observations since 2003.

Although the EKWC is present in the western channel of the Korea Strait in all seasons, several distinct circulation paths can be discerned when the flow is also well defined in the eastern channel. Katoh (1994) used historical hydrographic data to study

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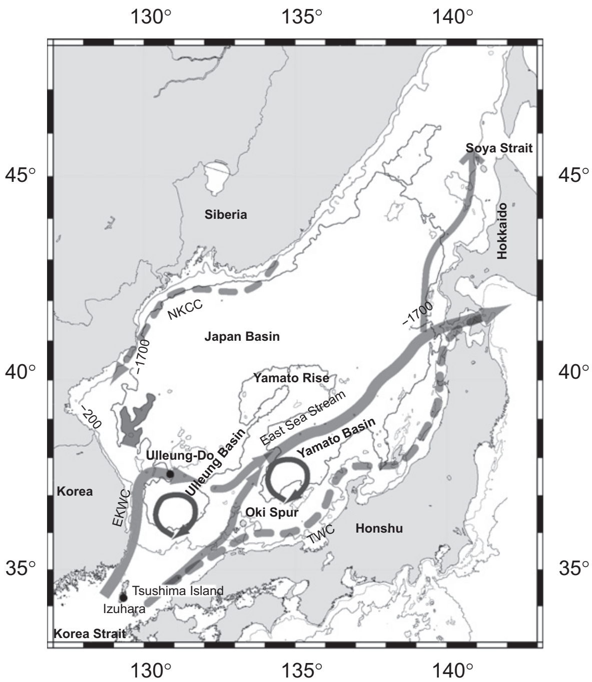

Fig. 1. Schematic map of the surface currents in the Japan/East Sea based on Lee and Niiler's (2005) drifter observations. Dotted paths (Tsushima Warm Current [TWC] and North Korean Cold Current [NKCC]) represent the currents observed only during spring and summer, and solid paths (East Korean Warm Current [EKWC] and East Sea Current) represent the currents observed all the year.

circulation patterns and noted their relationship to intermittent branching of the TWC, which he considered the entire flow in the Korean Strait. Using two years of current measurements from bottom-moored ADCPs, Teague et al. (2005) found significant variations in seasonal transport in the entire Korea Strait. According to their observations, maximum transport occurred in October, two months after the season when the TWC was well developed. Currents observed by Takikawa et al. (2005) using a ferryboat-mounted ADCP across the entire Korea Strait also showed maximum transport in October and minimum transport in January. Based on acoustic travel-time measurements from bottom-mounted inverted echo sounders, Mitchell et al. (2005a) presented five circulation patterns in the Ulleung Basin. However, they were not able to relate these circulation patterns to the transport properties in the Korea Strait that were measured when their acoustic array was operational. Those direct current observations suggested that the EKWC and the TWC were not directly related to the strength of the transport through the Korea Strait. As we discover from the drifter data, the horizontal flow structure in the western channel does indeed determine the flow patterns in the western portion of the Japan-East Sea, including the EKWC north of the Strait.

The Ulleung Warm Eddy (UWE) and the Dok Cold Eddy (DCE) have been known to occasionally persist for over a year. Those eddies have also been found to influence the path of the EKWC in the southwestern JES (Lie et al., 1995). Using hydrographic data, Shin et al. (2005) traced a single warm eddy circling counter-clockwise around Ulleung-Do for over 30 months. Using a reduced-gravity model, Arruda et al. (2004) showed that the generation of UWE was due to neither instability nor the collision of the EKWC with the NKCC. Instead, it was due to nonlinearities in the EKWC and the β-effect acting in the fluid circling the UWE. Using thin jet theory (Cushman-Roisin et al., 1993), Mitchell et al. (2005b) explained the eddy generation and meandering of the EKWC after its separation from the coast.

Two dynamical interpretations of the circulation patterns in the Ulleung Basin, specifically, the "branching of the TWC (Ou, 2001; Cho and Kim, 2000)" and the "meandering of the EKWC (Katoh, 1994; Mitchell et al., 2005a)," relied on data sets of limited temporal and spatial resolution. These limitations were also true in the interpretation of the circulation patterns in the southwestern JES given by Lee and Niiler (2005) because their observations of EKWC were based on only 40 drifters. In this study, 143 satellite-tracked drifters deployed from 1988 to 2006 and weekly sampled satellite sea surface height anomalies from 1992 to 2007 were used to enhance observations of the near-surface circulation of the southwestern portion of the JES. Therefore, this study presents a more complete picture of the circulation structures of the time-averaged EKWC and its seaward extension.

2. Data

From 2003 to 2006, the Korea Hydrographic and Oceanographic Administration (KHOA) deployed 103 ARGOS satellite-tracked drifters in the Korea Strait on a bi-monthly basis. Before 2003, 40 additional drifters had passed through the eastern channel of the Korea Strait. Both drifter data sets were used in this study to derive the directly observed velocity data set. We used the methodology described by Niiler (2001) for filtering and interpolating positions from the ARGOS-derived fixes and for correcting the derived velocity vectors for slip due to winds. All drifter positions were further smoothed over two inertial periods using spline interpolation, after which daily mean positions and velocities were computed from interpolated positions every six hours.

Weekly gridded (1/3° grid) Merged Sea Level Anomaly (MSLA) fields from all available altimeter satellites (TOPEX/Poseidon, GFO, ERS-1, ERS-2, Jason-1 and Envisat) were obtained from Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO) from October 1992 to May 2007. Pascual et al. (2006) described the processing procedures of the global MSLA data sets used in this study. The error of MSLA in the Ulleung Basin due to tide and aliasing of the high frequency fluctuations was estimated about 2–3 cm (Choi et al., 2004) and the Root Mean Square (RMS) value of the difference between the sea level anomaly observed at Ulleung-Do and MSLA after removing seasonal variation is 2.7 cm with correlation coefficient of 0.93 (Choi et al., 2004).

3. Empirical orthogonal function of MSLA and circulation patterns

After individually analyzing 144 drifter tracks in the study area, tracks with similar paths were grouped together depending on the entry path to the Ulleung Basin. To relate these grouped drifter paths to temporal and spatial fluctuations, non-seasonal MSLA variations in the southwestern part of the JES were first examined by Empirical Orthogonal Function (EOF) analysis. We were seeking a dynamical consistency between the drifter flow patterns and the non-seasonal variations of the SLA. Our analysis replicated several aspects of the horizontal structure and time variation of the principal EOF components that were computed by Choi et al. (2004) from the MSLA (TOPEX/Poseidon, ERS-1 and ERS-2) prior to 2001. However, large inter-annual MSLA variations from six additional years of data and additional altimeter satellite missions (GFO, Jason-1 and Envisat) rendered a different set of patterns.

3.1. EOF analysis of non-seasonal sea level anomaly

In order to examine the circulation patterns in the Ulleung Basin, EOF analysis of sea level anomalies was performed on