Some High-Frequency Variability of Currents Obtained by “GeoDrifters” in the Tsushima Current Region

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Abstract: The “GeoDrifter” is a newly-developed surface drifter with high temporal resolution. It is the first time that high-frequency drifters have been deployed in the East/Japan Sea. The purpose of this study is to introduce the phenomena experienced by these drifters flowing along with the Tsushima Current across the East/Japan Sea, focusing on high-frequency variability, and to discuss them in comparison with previous observations. The observed basin-scale circulation of the Tsushima Current generally coincides well with the known schematic circulation. The GeoDrifter trajectories also show inertial oscillations almost everywhere in the oceanic regions of the East/Japan Sea, strong semi-diurnal tidal currents in the western part of Korea Strait, diurnal currents much stronger than semi-diurnal currents in the upstream region of the Nearshore Branch off the Japanese coast, and many warm eddies in the Yamato Basin, all comparable to the observational results reported in the previous studies. An interesting point is that the semi-diurnal tidal currents undergo a great spatial variation in the western part of the Korea Strait. The observed features that cannot be explained are, among others, strong counter-clockwise motions with oscillating period about 51 hours appearing in the upstream region of the Nearshore Branch off the Japanese coast and the different tidal behaviors between upstream and downstream regions of the latter.

Key words: high-frequency variability of current, GeoDrifter, Tsushima Current region

1. Introduction

The satellite-tracking drifters have long been proved to be effective tools for examining ocean dynamics over a wide range of time and space scales, the WOCE surface drifter project being a good example (McNally et al. 1983; Niiler et al. 1987; Krauss and Böning 1987; Thomson et al. 1997). Most of studies using satellite drifters have focused on large-scale features or low frequency variability, such as ocean circulations and mesoscale eddies. In most cases, these drifters employ the Argos-type positioning system with time interval longer than 2–3 hours so that it is difficult to accurately resolve high-frequency motions with periods shorter than one day, such as inertial and tidal currents, currents associated with inertia-gravity and shelf waves and so on (hereafter, simply the high-frequency motions), although there has been an attempt to derive a global statistics of inertial motions by estimating inertial amplitudes from surface trajectories of Argos profiling floats in the major oceans (c.f., Park et al. 2005; Chanigneau et al. 2008). In fact, surface drifter trajectory data with sufficiently high temporal resolution would facilitate studies of the high-frequency motions mentioned above with much lower cost than point moorings of current meters. An example of using high-resolution surface drifters in investigating...
the high-frequency motions is the work by Thomson et al. (1997) performed in the northwestern Pacific. In order to cover as large an area as possible with a limited battery capacity, they used short and long sampling intervals alternately. The obtained results for the high-frequency motions were therefore intermittent.

The circumstances are similar for the East/Japan Sea where many Argos-type SVP drifters have been deployed and used in studying basin-scale circulation of the Tsushima Current (TC) and the mesoscale eddy variability associated with it (e.g., Lee and Niiler 2005, 2010). The TC enters the East/Japan Sea through the Korea Strait from the East China Sea and flows out to the Northwest Pacific through the Tsugaru Strait and Soya Strait (Fig. 1a). Upon entering the Korea Strait, the TC bifurcates into two branches, the western branch called the East Korean Warm Current (EKWC) flowing northward along the Korean coast and the eastern branch called the Nearshore Branch (NB) flowing northward along the Japanese coast (Fig. 1a, also refer to Chang et al. 2016). It is known that there is a bifurcation of the EKWC soon after it is separated from the main stream of TC. The flow thus bifurcated, probably being transient and unstable, is believed to finally join to the NB (Fig. 1a). The conventional SVP drifters are mainly for studying large-scale circulation because the Argos-type positioning system with which the SVP drifters are equipped has irregular sampling intervals, usually longer than a few hours, and positioning less accurate than GPS-type positioning system. This may be the reason why the abundant data set obtained with the

Fig. 1a. (a) Trajectories made by the surface drifters D1 through D6 (except D4). The East/Japan Sea is enlarged and overlaid by schematic TC paths in shaded arrows (provided by Korea Hydrographic and Oceanographic Agency, http://www.khoa.go.kr/koofs/kor/webzine/viewer.do?pub_seq=2014029&pub_type=5). The dotted arrow between the EKWC (East Korean Warm Current) and the NB (Nearshore Branch) is a current believed to be formed by bifurcation of the former. The boxes marked by I through X are sub-regions SR I through SR X for which rotary spectral analyses of trajectories are made. KS, TS and SS are respectively, Korea Strait, Tsushima Strait and Soya Strait.
SVP drifters have not yet been fully analyzed for high-frequency variability, although the statistics of inertial motions has been estimated from surface trajectories of Argo profiling floats (Park et al. 2004). In fact, studies of the high-frequency motions have been done mostly by current meter moorings at a very few locations (e.g., Isoda and Murayama 1993; Teague et al. 2001; Chang et al. 2016).

To measure high-frequency motions with significantly lower costs than traditional moored measurements, the new surface drifters with temporal resolution of about tens of minutes enough to resolve the high-frequency motions, called “GeoDrifters”, have been developed, and are deployed in the region dominated by the Tsushima Current (TC) to check their performances. This is the first time that surface drifters with high temporal resolution are deployed in the East/Japan Sea. The aim of this study is therefore twofold: One is to validate the GeoDrifter by comparing the obtained results with previous ones and the other is to confirm, and hopefully increase, our knowledge about the high-frequency variability of the East/Japan Sea.

2. GeoDrifter

The GeoDrifter is manufactured by GeoSystem Research Corporation (www.geosr.com) of Korea following the SVP drifter specification (Sybrandy et al. 2009) except that the Argos-type transmitter is replaced by the GPS-type transmitter with iridium-communication and a submergence sensor is equipped at the lower part of the float for automatic drogue detection (Fig. 2). The GPS-type transmitter has much higher temporal resolution and better accuracy in positioning than the Argos-type transmitter although it consumes more battery power than the latter. Here, the sampling time interval is set to 30 minutes. The
3. General behaviors of drifters

Eight GeoDrifters were deployed at several locations in the TC upstream region. The three GeoDrifters failed in communication 2–3 days after the deployment. The rest five survived sufficiently long time, mostly for a few months from spring to fall, and successfully arrived at the outflow openings or their vicinity carried by the TC (Table 1). Exceptionally, the GeoDrifter D3 flowed out of the East/Japan Sea through the Soya Strait to the Northwest Pacific, and joined the Kuroshio extension (c.f., Fig. 1a). For the sake of convenience, the whole region is divided into ten sub-regions. There is not any special criterion in subdividing the region except that in some parts of the region, oscillatory motions in sub-regions are seen to be distinctively different from one another (Table 2, Fig. 1a and Fig. 1b).

All drifters except D1 generally flow along with the EKWC and its offshore extension. The drifter D1 shows an exceptional behavior. It leaves the EKWC near 129°E, 36°N and shortly joins the NB, thereafter flows along with the NB (Fig. 1a and Fig. 1b). On basin-scale, these trajectories might be compared with the well-known schematic mean surface circulation pattern of the TC (Fig. 1a). Indeed, the main stream of the TC, the offshore extension of the EKWC represented by the trajectories of D2 and D3, seems to flow approximately along the subpolar front forming between the region with higher sea level to the south and the region with lower sea level to the north (Fig. 3). On smaller-scales, however, they locally exhibit various types of oscillatory motions with different time scales (Fig. 1a and Fig. 1b).

### Table 1. Surviving periods, initial and final locations of the five drifters from which time series data were obtained

| Drifter | Period (year, month, day) | Initial position (Latitude\(^{\circ}\), Longitude\(^{\circ}\)) | Final position (Latitude\(^{\circ}\), Longitude\(^{\circ}\)) |
|---------|---------------------------|----------------------------------------------------------|--------------------------------------------------|
| D1      | 2014. 04. 03 – 2014. 12. 01 | 34.99, 129.11                                           | 38.45, 139.24                                    |
| D2      | 2014. 04. 03 – 2014. 09. 05 | 34.99, 129.10                                           | 42.63, 141.68                                    |
| D3      | 2014. 04. 03 – 2015. 08. 06 | 34.99, 129.10                                           | 30.44, 170.71                                    |
| D4      | 2014. 04. 02 – 2014. 10. 26 | 36.68, 129.57                                           | 45.37, 141.65                                    |
| D5      | 2014. 04. 02 – 2014. 07. 30 | 36.68, 129.57                                           | 39.32, 133.07                                    |
| D6      | 2014. 04. 02 – 2014. 07. 30 | 36.68, 129.57                                           | 45.37, 141.65                                    |

### Table 2. Locations of the sub-regions where drifters show significant oscillations. For each sub-region, the drifters and the periods during which they are present in that sub-region are specified

| Sub-region | Latitude range \((^{\circ}\text{N})\) | Longitude range \((^{\circ}\text{E})\) | Period (Year, Month, Day) | Drifter |
|------------|---------------------------------|---------------------------------|----------------------------|---------|
| SR I       | 34.86 – 35.24 129.09 – 129.50  | 2014. 04. 03 – 2014. 04. 06 D1 |                           | D1      |
| SR II      | 35.14 – 35.82 130.96 – 132.51  | 2014. 04. 15 – 2014. 05. 02 D1 |                           | D1      |
| SR III     | 36.40 – 38.16 133.62 – 135.73  | 2014. 05. 06 – 2014. 07. 17 D1 |                           | D1      |
| SR IV      | 37.55 – 38.59 138.34 – 139.36  | 2014. 08. 08 – 2014. 08. 20 D1 |                           | D1      |
| SR V       | 35.86 – 36.56 130.09 – 131.62  | 2014. 04. 09 – 2014. 04. 27 D3 |                           | D3      |
| SR VI      | 36.41 – 37.71 129.73 – 131.26  | 2014. 04. 17 – 2014. 05. 11 D2 |                           | D2      |
| SR VII     | 37.09 – 39.98 130.77 – 134.74  | 2014. 05. 14 – 2014. 06. 25 D2 |                           | D2      |
| SR VIII    | 38.00 – 40.05 136.34 – 138.48  | 2014. 07. 30 – 2014. 08. 10 D2 |                           | D2      |
| SR IX      | 40.74 – 45.82 137.90 – 141.84  | 2014. 07. 24 – 2014. 11. 05 D3 |                           | D3      |
| SR X       | 29.11 – 41.62 146.64 – 171.47  | 2014. 12. 24 – 2015. 08. 06 D3 |                           | D3      |
Several features can be remarked as follows. First, the bifurcation of the EKWC toward the NB is confirmed here as shown by the behavior of the drifter D1 described above. It should be reminded, however, that the bifurcation is expected to be highly variable depending on various oceanic conditions. Second, both the EKWC and the NB seem to interact with nearby eddies. The two drifters on the EKWC, D2 and D3, leave the main stream to enter, respectively, the sub-regions SR V and SR VI, approximately coinciding with the Ulleung Basin (not shown here; refer to Fig. 1.1 in Chang et al. 2016), where they show large rotary motions - about one cyclonic rotation in about 18 days for D3 and about two anti-cyclonic rotations in about 24 days for D2 - before they rejoin the main stream (Fig. 1a). The anti-cyclonically rotating feature mentioned above is quite comparable with the known “Ulleung Warm Eddy” (Chang et al. 2016; Shin et al. 2005) which is about 100 km in size and is located approximately inside the Ulleung Basin. The cyclonically rotating feature can be compared with the known “Dok Cold Eddy” (Chang et al. 2016; Mitchell et al. 2005) which often appears south or southeast of the “Ulleung Warm Eddy”, although it looks here somewhat too elongated in the east-west direction. The average speeds of those rotary motions are about 20 cm/sec for D2 and slightly larger for D3. The above explanation can be further supported by comparing the trajectories with the surface dynamic topography (Fig. 3). The latter shows the situation about 17 days after the release of D2 and D3. Indeed, the drifter D2 seems to turn anti-cyclonically around the local maximum near 37.0°N, 130.5°E, the “Ulleung Warm Eddy”; and D3 seems to turn cyclonically approximately around the local minimum near 36.0°N, 131.0°E, the “Dok Cold Eddy”. On the other hand, the drifter D1 on the NB leaves the main stream to enter the sub-region SR III, approximately coinciding with the Yamato Basin (not shown here; refer to Fig. 1.1 in Chang et al. 2016), where it shows complicated rotary motions before it rejoins the main stream (Fig. 1a). The sub-region SR III mentioned above seems to be close to the region of strong eddy activity discussed by Isoda (1994). Third, some complicated trajectories are also seen in some interior regions, the sub-regions SR VI and SR VII, and west of Hokkaido, the sub-region SR IX (Fig. 1a). The first two may also be related with eddy activities near the sub-polar front mentioned previously (Isoda 1994). However, it is hardly explainable how these trajectories are formed. Fourth, the drifter D3 joins the Kuroshio extension, present in the sub-region SR X, after flowing out of the East/Japan Sea through the Soya Strait. While flowing eastward along with the Kuroshio extension, it stays longtime in the region around 32°N 162°E. This region may be the “subtropical convergence zone” of the North Pacific (c.f., Tomczak and Godfrey 1994; Seki et al. 2005). Finally, inertial-like high-frequency oscillations are observed in almost all sub-regions, mostly superimposed on larger-scale motions except in the coastal sub-regions SR I, SR II and SR IV where motions associated with semi-diurnal or diurnal tidal currents seem to be dominant (Fig. 1b).

4. High-frequency variability

Time series of the selected five GeoDrifter trajectories have very few gaps, and they are filled in by using linear interpolation before rotary spectral analyses. From a time series of \((u, v)\) pairs, where \((u, v)\) are (eastward, northward) components of drifter velocity deduced from the trajectory, a kinetic energy density function, \(F(\omega)\), is estimated through rotary spectral analysis. The results are presented in the variance-conserving form, i.e., are plotted in \(\log(\omega) - \omega F(\omega)\) coordinates, such that the area under the curve \(\omega F(\omega)\), \(\int \omega F(\omega) d[\log(\omega)] = \int F(\omega) d\omega\) is proportional to the kinetic energy contained around the frequency \(\omega\) considered. By this method, spectral dominance can be seen more clearly. Each whole time series in each sub-region is put into rotary spectral analysis. The resulting spectral estimates have different degrees of freedom and confidence intervals depending.
on frequencies, the former increasing and the latter decreasing with frequency (Emery and Thomson 2001).

In the sub-region SR I, the variability shown in the drifter trajectories comes predominantly from semi-diurnal tidal and either near-inertial or diurnal tidal currents, which seems to undergo a significant change in time for all three drifters, D1, D2 and D3, in a similar fashion, as described in what follows (Fig. 1b). To capture the stream-wise change of variability, three different segments of time series obtained by drifter D1 are analyzed with each segment containing different amount of upstream portion of trajectory. Due to the limited data length of these segments, the inertial (period about 21 hours) and diurnal (period 24 hours) motions cannot be resolved one from the other in frequency domain, i.e., they appear mixed up at one frequency around either inertial or diurnal frequencies - hence they are named “mixed-daily motions”. Energy peaks at “mixed-daily” and semi-diurnal frequencies thus obtained have considerably large confidence intervals due to the limited amount of data (Fig. 4a). It seems, however, that the energy peak near semi-diurnal frequency is marginally significant. The same results are obtained for drifters D2 and D3 (not shown). What should be remarked here is that the clockwise rotating semi-diurnal currents become progressively more important as one goes downstream, while it happens oppositely for counter-clockwise rotating semi-diurnal tidal current (Fig. 4a). It means that semi-diurnal tidal current is predominantly counter-clockwise and clockwise in, respectively, the upstream and downstream parts of trajectory, probably being almost rectilinear somewhere in between. This tendency is further evident from the following results obtained by using the Extended Complex Demodulation (ECD) with time span of 24 hours (Fig.

Fig. 4. (a) Variance-conserving form (see text) of rotary spectral kinetic energy for drifter D1 in sub-region SR I obtained for the following three different segments of time series (from left to right): (1) 2:00 April 3 through 00:00 April 7, (2) 12:00 April 3 through 00:00 April 7, and (3) 18:00 April 3 through 00:00 April 7. 90% confidence interval is marked around the peak at semi-diurnal period $T_{sd}$. Another peak (arrow) appears at “mixed-daily” (inertial and diurnal) frequency, (b) Amplitudes of clockwise and counter-clockwise components of semi-diurnal tidal currents, shown as functions of time, estimated by using the ECD method with time span of 24 hours for drifters D1 through D3 in sub-region SR I.
High-Frequency Variability in Tsushima Current Region

4b). The ECD method is to determine the temporal change of a particular frequency component for velocity or scalar time series (Emery and Thomson 2001). For each of three drifters, D1, D2 and D3, tidal current ellipse is indeed changing progressively from counter-clockwise in the first half to clockwise in the second half of the period (Fig. 4b). The results about semi-diurnal tidal current obtained here can be compared with those obtained previously by current meter moorings (Teague et al. 2001). According to them, semi-diurnal tidal current ellipse is slightly clockwise at a point near the downstream end of trajectories in sub-region SR I, named point N2 (35.20°N, 129.67°E), and slightly counter-clockwise at a point about a hundred kilometers upstream of sub-region SR I, named point S1 (34.32°N, 127.90°E). (For locations of N2 and S1 in comparison with sub-region I, see Fig. 1b.) Hence, the tidal current seems indeed to be spatially very variable such that the rotational sense of tidal current ellipse reverses somewhere inside the sub-region SR I. This possibility may also be supported by the fact that the sub-region SR I is actually the transition zone between the semi-diurnal tidal wave propagating from the northwest Pacific into the East/Japan Sea basin and the outgoing reflected tidal wave from the East/Japan Sea basin (c.f., Odamaki 1989).

In the sub-region SR II, variability of currents is quite different from that in the sub-region SR I because diurnal currents are much stronger than semi-diurnal currents and the motions with period 51 hours, rather than near-inertial motions, appear to be dominant (Fig. 5). Semi-diurnal currents are clockwise as they are in sub-region SR I, diurnal currents are also clockwise and the motions with period 51 hours are counter-clockwise. The similar diurnal motions have already been observed near this region by current meters moored at two points in a north-south section along 132°E (for location, see Fig. 1b), and have been identified to be diurnal shelf waves, the first mode continental shelf waves with diurnal tidal period (Isoda and Murayama 1993). Compared to astronomical tides, diurnal shelf waves produce small sea level change but strong tidal currents. Diurnal shelf waves have been observed at many mid-latitude sites in the world (e.g., Cartwright 1969; Yefimov and Rabinovich 1980; Crawford and Thomson 1982; Clarke 1991; Thomson et al. 1990). Considering these facts, the diurnal currents observed here may also be associated with the first mode continental shelf waves. The first mode continental shelf wave has counter-clockwise and clockwise current ellipses in, respectively, upper and lower parts of slope with a nodal...
point in between (Appendix), hence indicating that the sub-region II occupied by the drifter D1 belongs to the upper part of slope. For reference, there is an indication from the historical AOML data set, obtained by SVP drifters, that similar diurnal motions are frequent around this area (Fig. 6), although it is not known whether they are also related with shelf waves. However, the spectral peak of counter-clockwise motions at period 51 hours (Fig. 5) is hardly explainable. Close inspection of trajectory in sub-region SR II (Fig. 1b) indicates indeed a few large-scale counter-clockwise rotary motions accompanied by much smaller-scale clockwise rotary motions. The former may be associated with 51 hours-period motions and the latter with diurnal or semi-diurnal motions. The period of the former is about two times longer than that of diurnal motions, but the particle excursion length of the former is likely to be larger than two times that of the latter. Considering the fact that one rotation is completed in one period, it means that the 51 hours-period motions are much stronger than diurnal motions. They may be suspected to be a manifestation of higher mode continental shelf waves, the second mode for example, associated with the diurnal shelf waves observed by Isoda and Murayama (1993) because, on one hand, the second mode has lower frequency than the first mode and, on the other hand, these two modes can have current ellipses rotating oppositely to each other over the same upper part of slope (Appendix). A significant energy peak at period about 55 hours, similar to that at 51 hours (Fig. 5), has also occurred around this area in December, 2005 (Fig. 6). However, it is unlikely that the second mode has a particle excursion length scale much larger and current much stronger than the first mode. In this respect, the 51 hours-period motions may be associated more likely with barotropic basin oscillations with periods around three days arising from Helmholtz resonance that manifest themselves in volume transport through the Korea Strait (Lyu and Kim 2005). Further discussion is beyond the scope of present study.

In the sub-region SR III, a significant spectral peak appears at clockwise component of period about 6.1 days, in addition to inertial oscillations (Fig. 7). The former may be associated with warm eddies which are known to be frequently observed in this region (Isoda 1994). Taking the typical diameter of these warm eddies as 100 km (c.f., Isoda 1994), the typical speed of current encircling around the warm eddies would be about 20 cm/s.

In the sub-region SR IV, spectral peaks appear at counter-clockwise components of the semi-diurnal and diurnal periods (Fig. 8). The rotational sense is opposite to that observed in the sub-region SR II for both semi-diurnal and diurnal tidal current. In fact, the rotational sense of current ellipse is determined by many factors (Carbajal and Gavino 2007). For the problem considered here, the difference in geometry and bottom configuration, or probably the stratification condition, between the two
sub-regions, together with amphidromic system of the East/Japan Sea, may be important factors. It is also not clear whether the observed diurnal currents are also the same diurnal shelf waves observed in the sub-region SR II. If this is the case, the sub-region IV occupied by the drifter D1 should belong to lower part of slope. However, this possibility seems to be unlikely because the sub-region IV may not actually be considered as lower part of slope (Fig. 1b). The problem of different tidal current rotational behaviors between the sub-regions II and IV is beyond the scope of present study.

In the sub-regions SR V and SR VI, the cyclonic and anti-cyclonic motions associated with, respectively, “Dok Cold Eddy” and “Ulleung Warm Eddy”, remarked earlier in the trajectories (Fig. 1a), are not identified in frequency domain probably because these signals are not strong enough. Meanwhile, inertial oscillations appear to be prominent (not shown). In the sub-regions SR VII through IX, spectral peaks occur only at the inertial period (not shown) despite many oscillating motions on much larger scale clearly seen in time domain (Fig. 1a). It seems that the latter oscillating motions are almost chaotic without having any particular periodicity. For the present, it is hard to physically identify these oscillations. In the sub-region SR X, spectral peaks appear at clockwise component of period about 12.2 days and at counter-clockwise component of period about 5.7 days, as well as inertial oscillations (Fig. 9). These oscillations with periods a few days seem to be due to warm and cold eddies staying around the “subtropical convergence zone”. It is quite interesting to remark that the warm eddies found here have about two times longer periods, hence probably two times larger scales, than either the warm eddies observed in the Yamato Basin of the East/Japan Sea (Fig. 7) or the cold eddies found in the same region.

5. Concluding remarks

A new surface drifter with high temporal resolution, called “GeoDrifter”, is developed and deployed for the first time in the East/Japan Sea. The results obtained by them seem to match well with the previous observations: The observed basin-scale circulation of the TC generally coincides well with the known schematic circulation. They indicate that the bifurcation of the EKWC takes place toward the NB and that both the EKWC and the NB interact with nearby eddies, the former with the Ulleung Warm Eddy and the Dok Cold Eddy present in the Ulleung Basin and the latter with many warm eddies present in the Yamato Basin. They also indicate that the Kuroshio extension in the northwest Pacific interacts with warm and cold eddies present in the subtropical convergence zone.

The obtained results also show that inertial oscillations are prominent almost everywhere in the oceanic regions of the East/Japan Sea, confirming the results obtained previously by Park et al. (2004). In the western part of Korea Strait, semi-diurnal tidal current is dominant in accordance with the results obtained by Teague et al. (2001). An interesting result obtained in this study is that semi-diurnal currents are spatially very variable in this region. In the upstream region of the NB off Japanese coast, clockwise rotating diurnal tidal currents, much stronger than those of semi-diurnal tidal currents, have been observed, as they have already been observed and identified as diurnal shelf waves by Isoda and Murayama (1993). However, the strong counter-clockwise motions with period of about 51 hours are not physically identified. In the downstream region of the NB off Japanese coast, the semi-diurnal and diurnal tidal current ellipses have rotational senses different from those upstream. The reason of this different tidal behavior is not yet clear. The complicated trajectories observed in some interior regions of the East/Japan Sea do not have any particular periodicity, indicating that they are almost chaotic and physically unidentifiable. Meanwhile, in the
convergence zone of north Pacific, warm eddies appear to be about two times larger than both the cold eddies found in the same region and the warm eddies found in the Yamato Basin of the East/Japan Sea.

The purpose of this study is only to describe the results obtained by some newly-developed drifters and not to demonstrate the variability of currents representative of the regions considered. For the latter purpose, analyses of much more data are needed. Overall, the GeoDrifters seem to have successfully captured the previously observed large- and smaller-scale features and further have helped understand high-frequency variability in the East/Japan Sea, being proved to be a cost-efficient tool for measuring motions of sea water over a wide range of time and space scales.

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References

Carabajal N, Gavino JH (2007) A new theory on tidal currents rotation. Geophys Res Lett 34:L01609
Cartwright DE (1969) Extraordinary tidal currents near St. Kilda. Nature 223:928–932
Chanigneau A, Pizarro O, Rojas W (2008) Global climatology of near-inertial current characteristics from Lagrangian observations. Geophys Res Lett 35:L13603
Chang KI, Ju SJ, Zhang CI, Lee SH, Park C, Wimbush M, Kang DJ (2016) Oceanography of the East Sea (Japan Sea). Springer, Basel, 460 p
Clarke AJ (1991) The dynamics of barotropic tides over the continental shelf and slope (review). In: Parker BB (ed) Tidal Hydrodynamics. John Wiley & Sons, New York, pp 79–108
Crawford WR, Thomson RE (1982) Continental shelf waves of diurnal period along Vancouver Island. J Geophys Res 12:9516–9522
Emery WJ, Thomson RE (2001) Data analysis methods in physical oceanography. Elsevier, Amsterdam, 638 p
Gill AE (1982) Atmosphere-ocean dynamics. Academic Press, Haryana, 662 p
Isoda Y, Murayama T (1993) Diurnal shelf waves off Hamada on San’in coast. J Oceanogr 49:71–88
Isoda Y (1994) Warm eddy movements in the Eastern Japan Sea. J Oceanogr 50:1–15
Krauss W, Böning CW (1987) Lagrangian properties of eddy fields in the northern North Atlantic as deduced from satellite-tracked buoys. J Mar Res 45:259–291
Lee DK, Niiler PP (2005) The energetic surface circulation pattern of the Japan/East Sea. Deep-Sea Res Part II 52:1547–1563
Lee DK, Niiler PP (2010) Surface circulation in the southwestern Japan/East Sea as observed from drifters and sea surface height. Deep-Sea Res Part I 57:1222–1232
Lyu SJ, Kim K (2005) Subinertial to interannual transport variations in the Korea Strait and their possible mechanisms. J Geophys Res 110:C12016. doi:10.1029/2004JC002651
McNally GJ, Patzert WC, Kirwan AD, Vastano AC (1983) The near-surface circulation of the North Pacific using satellite-tracked drifting buoys. J Geophys Res 88:7507–7518
Mitchell DA, Teague WJ, Wimbush M (2005) The Dok Cold Eddy. J Phys Oceanogr 35:273–288
Niiler PP, Davis RE, White HJ (1987) Water-following characteristics of a mixed layer drifter. Deep-Sea Res 34:1867–1881
Niiler PP, Sybrandy AS, Bi K, Poulain PM, Bitterman D (1995) Measurements of the water-following capability of holey-sock and TRISTAR drifters. Deep-Sea Res Part I 42:1957–1964
Odamaki M (1989) Co-oscillating and independent tides of the Japan Sea. J Oceanogr Soc Japan 45:217–232
Park JJ, Kim K, Crawford WR (2004) Inertial currents estimated from surface trajectories of ARGO floats. Geophys Res Lett 31:L13307
Park JJ, Kim K, King BA (2005) Global statistics of inertial motions. Geophys Res Lett 32:L14612
Seki MP, Flint E, Howell EA, Ichii T, Polovina JJ, Yatsu A (2005) Transition zone. In: PICES (ed) Marine ecosystems of the North Pacific, PICES, Sidney, pp 201–209
Shin HR, Shin CW, Kim C, Byun SK (2005) Movement and structural variation of warm eddy WE92 for three years in the western East/Japan Sea. Deep-Sea Res Part II 52:1742–1762
Sybrandy AL, Niiler PP, Martin C, Scuba W, Charpentier E, Meldrum DT (2009) Global drifter programme barometer drifter design reference. DBCP Report No.4 REVISION 2.2, 47 p
Teague WJ, Perkins HT, Jacobs GA, Book JW (2001) Tide observations in the Korea-Tsushima Strait. Cont. Shelf Res 21:545–561
Thomson RE, LeBlond PH, Emery WJ (1990) Analysis of deep-drogued satellite-tracked drifter measurements in the northeast Pacific. Atmospheric-Ocean 28:409–443
Current Ellipses of Continental Shelf Waves

In the right-handed Cartesian coordinate system, consider a current ellipse with major axis forming an angle \( \phi_0 \) with the x-axis measured in counter-clockwise (positive) direction. The corresponding current can be expressed as a sum of counter-clockwise and clockwise circularly rotating components with magnitudes, respectively, \( U_r(>0) \) and \( U_l(>0) \). The current ellipse is counter-clockwise rotating if \( U_r > U_l \) and vice versa. The (x, y) components of current velocity, \( (u, v) \), are expressed as

\[
\begin{align*}
   u &= U_r \cos(\omega t + \phi_0 + \Delta \phi) + U_l \cos(-\omega t + \phi_0 - \Delta \phi) \quad (A.1) \\
   v &= U_r \sin(\omega t + \phi_0 + \Delta \phi) + U_l \sin(-\omega t + \phi_0 - \Delta \phi) \quad (A.2)
\end{align*}
\]

where \( \omega \) is frequency, \( t \) is time and \( \Delta \phi \) is half the phase difference between the two circularly rotating components.

Now, specify the problem to the continental shelf waves. Consider a semi-infinite homogeneous ocean in the region \( y > 0 \) bounded by a straight coastline, coinciding with x-axis, whose depth, \( H \), is given by \( H(y) = H_0 e^{2\lambda y} \) where \( H_0 \) is depth at \( y = 0 \) and \( \lambda \) measures the bottom slope. The continental shelf wave over this bottom configuration has stream function, \( \psi \), and frequency, \( \omega \), given as follows (Gill 1982):

\[
\psi = \sqrt{H_0} e^{2\lambda y} \sin(ly) \cos(kx - \omega t) \quad (A.3)
\]

\[
\omega = 2f/k \lambda (k^2 + l^2 + \lambda^2) \quad (A.4)
\]

where \( f, k \) and \( l \) are, respectively, Coriolis’ parameter and along- and across-slope components of wave number. The \( (x, y) \)-components of velocity, \( (u, v) \) are

\[
\begin{align*}
   u &= \frac{\partial \psi}{\partial y} = -\{\lambda \sin(ly) + l \cos(ly) \} \sqrt{H_0} e^{2\lambda y} \cos(kx - \omega t) \\
   &= \{\lambda \sin(ly) + l \cos(ly) \} \sqrt{H_0} e^{2\lambda y} \cos(\omega t - kx - \pi) \quad (A.5) \\
   v &= \frac{\partial \psi}{\partial x} = -k \sqrt{H_0} e^{2\lambda y} \sin(ly) \sin(kx - \omega t) \\
   &= -k \sqrt{H_0} e^{2\lambda y} \sin(ly) \sin(\omega t - kx - \pi) \quad (A.6)
\end{align*}
\]

The current ellipse of the continental shelf wave considered here can be known by comparing (A.5) with (A.1) and (A.6) with (A.2), i.e., it can be found for the present continental shelf wave that \( \phi_0 = 0, \Delta \phi = -\pi y \), \( U_r + U_l = \lambda \sin(ly) + l \cos(ly) \sqrt{H_0} e^{2\lambda y} \) and \( U_r - U_l = -k \sqrt{H_0} e^{2\lambda y} \sin(ly) \) with \( (x_0, y_0) \) being a fixed point where current is measured. Hence, the current ellipse of the continental shelf wave considered here is always aligned in the along-slope direction (\( \Phi_0 = 0 \)) and its rotating sense is determined by the sign of \( U_r - U_l \) being a fixed point where current is measured.

The smallest value of \( l \), i.e., the across-slope components of wave number corresponding to the first mode, is usually close to \( \lambda \). Then, consider a first mode continental shelf wave with \( l = \lambda \). In the upper part of slope area, \( 0 < y < \pi \lambda \), \( -\sin(ly) \) is negative, and hence the current ellipse is clockwise; in the lower part, \( \pi \lambda < y < 2\pi \lambda \), it is counter-clockwise. Consider next the second mode where \( l = 2\lambda \). At some locations in the upper part of slope area, \( \pi 2\lambda < y < \pi \lambda \), \( -\sin(ly) \) is negative for first mode but positive for second mode, hence the two modes have current ellipses oppositely rotating to each other at these locations. It is clear from (A.4) that the second mode has lower frequency than the first mode for the same along-shore wave number \( k \).