Deep current structure in the Toyama Deep-Sea Channel in the Japan Sea

Tomoharu Senjyu

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Abstract

The flow field in the Toyama Deep-Sea Channel (TDSC) in the Japan Sea was investigated based on mooring observations. An asymmetric current system accompanying offshore and onshore currents over the east- and west-side slopes in the channel, respectively, is suggested. A bottom intensified flow characteristic was observed at the offshore stations in the Yamato Basin. The asymmetric current system in the channel is also suggested by the asymmetric distribution of water characteristics across the TDSC in Toyama Bay; a cold dense water mass with higher dissolved oxygen (DO) and higher transmittance (Tr) was found over the west-side slope of the channel, whereas a water mass with lower DO and lower Tr was distributed over the east-side slope, suggesting a turbidity current from the head of Toyama Bay. The currents facing the shallower depth on their right-hand-side, along with the density distribution in the TDSC, suggest a density current system under the influence of the earth's rotation. The dissolved oxygen concentration in the TDSC was significantly lower than that in the offshore region of the same temperature range. This suggests that the water mass over the west-side slope in the TDSC is a modified offshore water mass which experienced significant mixing with the low DO water mass over the east-side slope in the TDSC, probably due to strong shear between the offshore and onshore currents in the narrow channel.

Keywords Toyama Bay · Toyama Trough · Toyama Deep-Sea Channel · Japan Sea · Mooring observations · Asymmetric current system · Earth’s rotation effect · Turbidity currents · Land–deep sea material transport · Deep currents

1 Introduction

Toyama Bay is one of the deepest bays in Japan that is characterized by a deep trough called the Toyama Trough (Fig. 1b). At the head of the Toyama Bay, there are many canyons incised into the floor of the shelf margin that are known as a good fishing ground called “Fuke” or “Aigame” by local fishermen. Several deep-sea fish species such as oarfish (Regalecus russelii) and giant squid (Architeuthis sp.) have occasionally been beached or caught in coastal fisheries set-nets in the bay head (Hirasawa and Nambu 2016; Kimura et al. 2020, 2021). This suggests that the trough and canyons are a means for the deep-sea fishes to approach the coastal area. In fact, many fisheries set-nets in the coastal area are set taking into account the location and direction of the canyons (Okei et al. 2008). The Toyama Trough is the southern part of the Toyama Deep-Sea Channel (TDSC) that extends approximately 750 km from the Toyama Bay to the east of the Yamato Rise in the Japan Basin across the Yamato Basin (Fig. 1a). The bottom depth in the TDSC varies from less than 1000 m in Toyama Bay to 3500 m in the Japan Basin via 1200–2300 m in the Toyama Trough and 2300–3000 m in the Yamato Basin (Nakajima et al. 1998). Material transport from land to deep sea through the TDSC has been suggested from the turbidite distributions and the sediment core samples obtained in and around the TDSC (Nakajima et al. 1998). In fact, terrigenous sediment depositions have been detected from the deep-sea fan at the end of the TDSC in the Japan Basin (Okamura et al. 2002; Nakajima 2006). This suggests the existence of an offshore current directed away from the Toyama Bay toward the deep ocean in the TDSC. The occurrence of small-scale turbidity currents triggered by a seasonal flood is suggested, although the mean recurrent period of the large-scale turbidity currents reaching the terminal zone of the TDSC is estimated to be approximately 70 years during the last millennium.
In contrast, dominant southward currents in the direction of Toyama Bay have been observed in the TDSC in the Yamato Basin through the direct current observations (Fukushima and Kojima 2011). Nakada and Hirose (2009) showed the occurrence of seasonal upwelling in a wide area along the Japanese coast including the Toyama Bay area, based on the historical observational dataset. This also implies an onshore current from the deep sea toward Toyama Bay in the TDSC. Thus, an inconsistency of deep currents in the TDSC has been suggested by previous studies.

The purpose of this study is to depict the flow configuration in the TDSC based on direct current observational datasets. Because of difficulties to conduct both deep moorings and hydrographic observations down to the seabed on a steep slope in the narrow channel, the oceanographic data in the TDSC are extremely limited. Therefore, we conducted mooring observations three times with current meters in the TDSC, as well as a hydrographic observation once. The deep current system in the TDSC is discussed by compiling our datasets with those of the previously reported currents. The next section introduces our observations along with the previously reported datasets. In Sect. 3, a general description of the currents in the TDSC is provided. The deep current system in the TDSC is discussed in Sect. 4 based on the current and hydrographic datasets. Finally, our concluding remarks are provided in Sect. 5.

2 Observations and data

The mooring observations of deep currents in the TSDC were conducted during the periods 2006–2007, 2007–2008, and 2010–2011 (Fig. 1b and Table 1). In the first observations at Sta. N06, the RCM8 type current meters manufactured by Aanderaa Instruments were
deployed at depths of 710, 935, and 1300 m during August 2006–August 2007 (Fig. 2b). A similar mooring line with two current meters at 900 and 1380 m was subsequently deployed at Sta. S07 during August 2007–August 2008 (Fig. 2a). Both mooring stations are located in the Toyama Trough between Noto Peninsula and Sado Island where the water depth is approximately 1500 m (Fig. 1b). The third mooring observations were performed at Sta. A10, an off-shore region further in the Yamato Basin where the water depth is greater than 2000 m, during October 2010–October 2011. In the observations at Sta. A10, acoustic single-point Doppler current meters (Seaguard instruments with a Z-Pulse sensor manufactured by Aanderaa Instruments and a DW-Aquadopp by Nortek Inc.) were deployed at 1000, 1540, and 2000 m (Fig. 2c). The measurement interval in the first and second observations was set at 1 h, whereas that in the third observation was set at 30 min. All the deployment and recovering of the mooring lines were conducted by T/V Nagasaki Maru of Nagasaki University.

In addition to our observational datasets, the current data measured by the Japan Coast Guard at Sta. K03 in the TDSC in the Yamato Basin are analyzed (Fig. 1b and Table 1). In these observations, two acoustic current meters (RCM11, Aanderaa Instruments) were deployed at 2104 and 2154 m (Fig. 2d) during the period July 2003–September 2004 with a measurement interval of 1 h (Fukushima and Kojima 2011).

As the RCM8 type current meter measures flow speeds with a mechanical rotor, its response to a weak flow is slow and the nominal starting velocity is 2.0 cm s^{-1}, although its accuracy of flow speed is nominally ± 1.0 cm s^{-1}. By contrast, RCM11, Seaguard, and Aquadopp current meters which determine flow speeds by measuring the Doppler shift of back-scattered supersonic sound signal provide superior performance with the

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**Table 1** Location, water depth, instrument depth, duration, and instrument type at each observation site

| Sta | Lat (N) | Long (E) | W. depth (m) | Inst. depth (m) | Duration      | Inst. type |
|-----|---------|----------|--------------|-----------------|---------------|------------|
| N06 | 37° 40.0’ | 137° 44.7’ | 1650         | 710             | 23 Aug. 2006–14 Aug. 2007 | RCM8       |
|     |         |          |              | 935             | 23 Aug. 2006–14 Aug. 2007 | RCM8       |
|     |         |          |              | 1300            | 23 Aug. 2006–14 Aug. 2007 | RCM8       |
| S07 | 37° 24.8’ | 137° 46.8’ | 1475         | 900             | 14 Aug. 2007–13 Aug. 2008 | RCM8       |
|     |         |          |              | 1380            | 14 Aug. 2007–13 Aug. 2008 | RCM8       |
| A10 | 38° 44.0’ | 137° 43.0’ | 2249         | 1000            | 12 Oct. 2010–3 Oct. 2011 | Seaguard   |
|     |         |          |              | 1540            | 12 Oct. 2010–3 Oct. 2011 | Aquadopp   |
|     |         |          |              | 2000            | 12 Oct. 2010–3 Oct. 2011 | Seaguard   |
| K03 | 38° 49.8’ | 137° 40.4’ | 2204         | 2104            | 6 Jul. 2003–2 Sep. 2004 | RCM11      |
|     |         |          |              | 2154            | 6 Jul. 2003–2 Sep. 2004 | RCM11      |

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**Fig. 2** Sectional distributions of current meters (blue circles connected by a blue line) and bottom topography across the channel (shaded area): a Sta. S07, b N06, c A10, and d K03. The bottom topography along a latitude line nearby each station is drawn based on the JTOPO30 (color figure online)
nominal accuracies of ± 0.15, ± 0.15, and ± 0.5 cm s⁻¹, respectively, without starting velocity. A comparison of performance between RCM8 and RCM11 was reported in Nakano et al. (2008).

Hydrographic observations across the Toyama Trough in Toyama Bay were conducted at Stas. C1–C5 on 15 November 2020 using a conductivity-temperature-depth profiler (CTD; SBE911plus, Sea-Bird Scientific) with a dissolved oxygen (DO) sensor (SBE43, Sea-Bird Scientific) and a transmittance (Tr) sensor (C-Star transmissometer, Sea-Bird Scientific) (Fig. 1). The transmissometer measures beam transmittance in the 25 cm path length using a light of 410 nm of wavelength. Therefore, lower Tr water indicates more turbid water.

As a reference of the water mass around the TDSC, the hydrographic observation data obtained at Stas. G2 and G3 in an offshore region were analyzed (Fig. 1b). These observations were conducted by the Japan Meteorological Agency (JMA) on 7 November 2020, 8 days before our observations, as Stas. KS5901 and KS5900, respectively.

The bathymetry in this study relies on the JTOPO30 version 2 provided from the Marine Information Research Center (MIRC), Japan Hydrographic Association, which provides the gridded bottom topography with 30 s (approximately 1 km) spatial resolution in both latitude and longitude. According to the MIRC, the bottom topography in this study area was derived from the high precision multi-beam sounding data (http://www.mirc.jha.jp/products/JTOPO30v2/).

### 3 Results

As our specific interest was in the low frequency currents, the general features of the currents in the TDSC are described based on the low-pass filtered current data using a 48-h tide killer filter (Hanawa and Mitsudera 1985). The stick diagrams shown in this section are drawn using the daily subsampled current data. Since currents in the TDSC are strongly influenced by the bottom topography, we defined the two orthogonal principal axes: the major principal axis in the direction which the standard deviations are maximal in a hodograph (Kundu and Allen 1976) and the minor principal axis perpendicular to the major principal one (Table 2). The mean and standard deviation for the observed currents were evaluated for the major (V) and minor (U) principal axis components, as well as the vector mean.

The currents at Sta. A10 exhibited dominant north to northeastward currents throughout the year, particularly at 1540 and 2000 m (Fig. 3), which is consistent with the offshore material transport in the TDSC suggested by Nakajima et al. (1998). The currents exhibited a bottom-intensified characteristic; the vector-mean current speed at 2000 m (3.65 cm s⁻¹) was 1.9 and 2.7 times larger than that at 1540 (1.89 cm s⁻¹) and 1000 m (1.34 cm s⁻¹), respectively (Table 2). This bottom-intensified characteristic was also reflected in the large values of the direction stability that is defined by the ratio of the vector mean speed to the scaler mean speed, although standard deviation of the major principal axis component (Vsd) increased with depth. Accordingly, the eddy kinetic energy (Ke) also increased with depth; however, the ratio of Ke to the mean kinetic energy (Km) at 2000 m showed the lowest value among the three layers.

### Table 2 Basic statistics of the currents at each observation site. Directions of the mean current and the major principal axis are measured clock-wise from the north

| Station | Inst depth (m) | Major principal axis (˚T) | Mean Direction (˚T) | Mean Speed (cm s⁻¹) | Vsd (cm s⁻¹) | Usd (cm s⁻¹) | Direction stability | Kinetic Energy (cm² s⁻²) |
|---------|----------------|---------------------------|--------------------|---------------------|--------------|--------------|----------------------|--------------------------|
|         |                |                           |                    |                     |              |              |                      |                          |
| N06     | 710            | 0.9                       | 204.2              | 0.93                | −0.85        | −0.37        | 2.81                 | 2.04                     |
|         | 935            | 28.7                      | 206.5              | 1.07                | −1.06        | 0.04         | 1.86                 | 0.86                     |
|         | 1300           | 39.0                      | 216.3              | 0.97                | −0.97        | 0.05         | 1.91                 | 0.77                     |
| S07     | 900            | 41.0                      | 43.9               | 0.65                | 0.65         | 0.03         | 1.97                 | 0.72                     |
|         | 1380           | 16.8                      | 147.8              | 0.47                | −0.30        | 0.35         | 1.79                 | 0.80                     |
| A10     | 1000           | 26.1                      | 55.0               | 1.34                | 1.18         | 0.65         | 1.88                 | 1.22                     |
|         | 1540           | 30.7                      | 41.2               | 1.89                | 1.85         | 0.34         | 1.93                 | 1.25                     |
|         | 2000           | 23.2                      | 25.3               | 3.65                | 3.64         | 0.13         | 2.91                 | 1.15                     |
| K03     | 2104           | 178.2                     | 168.3              | 2.59                | 2.55         | −0.45        | 1.92                 | 2.29                     |
|         | 2154           | 170.7                     | 167.5              | 3.11                | 3.11         | −0.18        | 2.07                 | 2.45                     |
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In contrast, the currents at Sta. N06 were directed south-westward which corresponds to the onshore water movement toward Toyama Bay (Fig. 4). A notable intermittent characteristic of the currents was observed, although part of the intermittency may be due to the less sensitivity to weak flows of the RCM8 type current meters. Three strong current events exceeding 8 cm s\(^{-1}\) occurred in March, June, and late July in 2007 at all the layers, following the moderate current period of approximately 5 cm s\(^{-1}\) from August 2006 to February 2007. The large flow amplitude at 710 m during the events suggests an influence of the upper layer flow condition. In fact, the satellite infrared images indicated a meandering of the Tsushima Current (Fig. 5b) and an intrusion of warm water around the mooring site (Fig. 5c) during the second and third events, respectively, although remarkable oceanic features were indiscernible during the first event (Fig. 5a). Correspondingly, the largest \(K_e\) was found at 710 m, although the direction and speed of the mean currents for the observation period were almost the same between the three layers (Table 2).

Similar onshore deep currents were observed at Sta. K03 throughout the observation period at both 2104 and 2154 m, as described by Fukushima and Kojima (2011) (Fig. 6). However, unlike the currents at Sta. N06, the flows at Sta. K03 fluctuated zonally with approximately a 2-month periodicity, which is reflected in the larger standard deviation of the minor principal axis component \((V_{sd})\) than \((U_{sd})\) (Table 2). The vector mean current speeds indicated a slight bottom intensification similar to Sta. A10, although the mean current directions were almost opposite between Stas. K03 and A10.

Sta. S07 showed bidirectional currents toward the north-east or south that occurred alternatively at an interval of approximately 20 days at both 900 and 1380 m (Fig. 7), which were reflected in the low direction stabilities (Table 2). Although the mean current direction at 900 m (43.9°) coincided with the direction of major principal axis (41.0°), that at 1380 m (147.8°) was nearly perpendicular to the major principal axis (16.8°) because of the stronger southward flows than that at 900 m. The level of \(K_e\) at Sta. S07 was comparable to that at similar depths at other stations (i.e., 935 and 1300 m at Sta. N06 and 1000 and 1540 m at Sta. A10); however, the values of \(K_e/K_m\) were greater than 10 because of the small \(K_m\).

Although the top and intermediate current meters at Stas. N06 and A10 were positioned far from the seabed where topographic constrains are absent (Fig. 2b and 2c), the mean current at the levels showed a similar direction to that at the bottom current meter along the channel (Fig. 8), suggesting a topographic influence throughout the depths. The vertically coherent flow structure (quasi-barotropic characteristic) has been reported commonly in the abyssal Japan Sea (Takematsu et al. 1999; Senjyu et al. 2005). However, the topographic influence seems to weaken with distance from the bottom; the mean currents at Sta. A10 rotated clockwise upward and the major principal axis at the top current meter at Sta. N06 was deviated from the channel direction.

### 4 Discussion

The mean currents at each station are directed either off-shore or on-shore in several directions (Fig. 8). Notably, the mean currents of almost opposite directions appeared at Stas. A10 and K03 which are approximately only 10 km...
apart across the channel (Fig. 8a). If we take into account the location of the ravine in the channel, a common feature of the mean currents is revealed. Stas. K03 and N06 showing onshore mean currents are located on the west-side of the ravine. In contrast, Sta. A10 showing the offshore mean currents is located on the east-side slope in the channel. In summary, the mean flow at a station is in the direction facing the shallower depth on their right-hand-side. The bidirectional flows at Sta. S07 are ascribed to the fact that the mooring site was located on the bottom of the channel (ravine) rather than on the slope (Fig. 2a). Flows over the ravine are likely to be susceptible to fluctuations in deep currents over both east- and west-side slopes. A similar asymmetric current system with opposite currents facing shallower depths on their right-hand-side in the channel has been reported from the Izu-Ogasawara Trench southeast of Japan (Fujio et al. 2000), although the geographical scale of the TDSC is much smaller than that of the trench.

The opposing currents in the TDSC are also suggested by the sectional distributions of water characteristics across the channel. DO and Tr clearly depicted asymmetric distributions across the channel below approximately 800 m (Fig. 9c and d, the location of the section is shown in Fig. 1). Over the west-side slope in the channel, a water mass of higher DO and higher Tr than that over the east-side slope was distributed. The contours of 0.3 °C and 27.34σθ indicated that this water mass is colder and denser than that over the east-side slope at the same depth level (Fig. 9a and b). At Sta. C3 over the ravine of the channel, the water mass of higher DO and higher Tr from the
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west-side slope underlies the lower DO and lower Tr water mass from the east-side slope. Such flow and density distributions in the channel suggest a density current system under the influence of the earth’s rotation (Griffiths 1986).

Considering the mass and vorticity conservations, the onshore current over the west-side slope should be returned to offshore along an isobath on the east-side slope in the channel, unless the water mass obtains buoyancy. Therefore, the water mass of higher DO and higher Tr on the west-side slope was likely to be advected horizontally by the onshore current over the west-side slope at the depth level. In contrast, the lower DO and lower Tr (turbid) water mass over the east-side slope appears to be intruded from the head of Toyama Bay along the eastern flank of the channel under the influence of the Coriolis force. The cause of the low Tr in the water mass is unknown; however, if the low Tr was owing to suspension of materials such as mud and silt, the water mass could hold a negative buoyancy and flow down the channel toward the bay mouth as a turbidity current (Simpson 1997). The low DO concentration in the water mass is possibly due to the active oxygen consumption in the high turbidity water (Sato 1979; Senjyu et al. 2001).

The water masses at Stas. G2 and G3 in the offshore area were compared with those over the east-side (Stas. C1 and C2) and west-side (Stas. C4 and C5) slopes in the TDSC (Fig. 1). The θ–DO diagram reveals that the DO concentration in the TDSC was significantly lower than that in the offshore region in the range of θ < 0.7 °C (Fig. 10). The water mass over the west-side slope lies between that on the east-side slope and the offshore water mass below the range of θ < 0.4 °C, where the east–west contrast in Tr was clear (Fig. 9). This suggests that the water on the west-side slope is the modified offshore water mass which underwent significant mixing with the low DO water on the east-side slope in the TDSC, probably due to strong shear between the offshore and onshore currents in the narrow channel.

The turbidity currents on the east-side slope anticipate a bottom-intensified offshore flow over the east-side slope. At Sta. A10, the offshore currents exhibited the bottom-intensified characteristic, whereas the onshore currents were almost the same amplitude throughout the observation depths (Fig. 3). In fact, the mean speeds of the offshore current along the major principal axis increased with depth (1.95, 2.37, and 4.23 cm s⁻¹ at 1000, 1540, and 2000 m, respectively). In contrast, those for the onshore currents showed no significant difference among the depths (−1.08, −0.91, and −1.58 cm s⁻¹ at 1000, 1540, and 2000 m). This suggests the existence of turbidity currents at Sta. A10 in the offshore region, although the distribution of water properties at this station is unknown. The occurrence of hyperpycnal flow triggered by a seasonal river flood has been suggested in Toyama Bay (Nakajima 2006). The hyperpycnal flows, which are “autosuspended” turbidity currents, occur when the density of flooding river effluent exceeds that of the ambient sea water in the river mouth area and can propagate over a long distance due to its “autosuspended mechanism” with strong turbulence (Wright et al. 1986).

5 Concluding remarks

The flow field in the TDSC was investigated based on mooring observations. An asymmetric current system, offshore and onshore currents over the east- and west-side slopes in the channel, respectively, is suggested in the TDSC (Fig. 8). The offshore (onshore) current transports the lower (higher) DO and lower (higher) Tr water mass over the east-side (west-side) slope, suggesting a turbidity current from the
Fig. 9 Sectional distributions of (a) potential temperature (θ, unit °C), (b) potential density (σθ), (c) dissolved oxygen (DO, μmol kg^{-1}), and (d) transmittance (Tr, %) across the channel (Stas. C1–C5 in Fig. 1b). The bottom topography (shaded area) is based on the ship-mounted echo sounder records at the observations.
head of Toyama Bay (Fig. 9). The current and density distributions in the TDSC suggest a density current system controlled by the earth’s rotation. The θ–DO diagram suggests significant mixing between the lower DO water mass on the east-side slope and the higher DO water mass originating from the offshore region due to horizontal shear between the offshore and onshore currents in the TDSC.

As our results are based on the mooring observations conducted at different periods at the four stations, concurrent mooring observations on the east- and west-side slopes across the channel are essential to confirm the asymmetric current system in the TDSC. In addition, the driving mechanism governing this asymmetric current system could not be clarified, although the possibility of turbidity currents in the TDSC was suggested. Furthermore, the periodical flow fluctuations at Sta. K03, along with the bottom-intensified characteristic (Figs. 6 and 8), suggest the existence of bottom-trapped topographic Rossby waves (TRWs) in the channel (Rhines 1970). Although the dynamics of TRWs in the TDSC is out of scope of this study, the TRWs are probably a key factor controlling current fluctuations in the channel, together with the occurrence of turbidity currents and the meandering of the Tsushima Current in the upper layer. To clarify the source and modification process of water masses and the TRWs propagation in the TDSC, mooring and hydrographic observations along the channel are desired.

If the asymmetric current system in the TDSC is durable and robust, it can influence the material transport between land and deep sea. The asymmetric height of the levees along the TDSC, the east-side levee higher than the west-side one (Nakajima et al. 1998), is probably attributable to the asymmetric current system in the channel. Asymmetric features between the east- and west-side slopes may be found in size and composition of the deposited sediments and the habitat of benthic organisms in the channel, in accordance with the asymmetric distribution of water mass.

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