Long-term observation of current at the mouth of Tokyo Bay

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ABSTRACT

Current patterns at the mouth of Tokyo Bay have been observed since the 1970s. However, earlier studies using short-term observations and numerical analyses were too limited in their spatiotemporal scale. This study analyzed long-term observations (over a decade) obtained using an acoustic Doppler current profiler mounted on a ferry that crosses the mouth of the bay. This long-term observation dataset revealed that tidal currents dominated at the bay mouth, and that an estuarine circulation of residual current was associated with inflow into the bay along topographic pathways formed by the Tokyo Submarine Canyon and the Uraga Channel. The water volume of the inflow was substantially greater than the discharge of the four major rivers flowing into Tokyo Bay. Although the mean residual current of the surface layer on the east side was outflow, it was variable with substantial and frequent inflow from the ocean, which might have caused an oceanic environment on the east side. Analysis of the long-term observations elucidated the spatial mean picture and temporal variability of the current patterns at the mouth of Tokyo Bay. This improved knowledge and the extended dataset will help answer remaining questions regarding the water quality in Tokyo Bay.

1. Introduction

An estuary is a marine area governed by physical interactions between fresh and ocean waters (MacCready and Geyer 2010; Geyer and MacCready 2014). Tokyo Bay is an estuary where water discharged from rivers interacts with Pacific Ocean inflow, restricting vertical mixing and producing salinity stratification between spring and autumn (Yamao 2004, 2006; Suzuki 2010). Salinity stratification causes bottom hypoxia in central–northern parts of the bay (Kodama and Horiguchi 2011). Additionally, change in the volume of ocean water within the bay is considered to govern the variation of water temperature (Yagi et al. 2004), which affects the local fisheries of Tokyo Bay (Hayashi 2019).

The mouth of Tokyo Bay is the inlet through which water from the Pacific Ocean enters the bay (Figure 1a), and where the waters of the inner bay interact with ocean water. Many previous studies have conducted observational and numerical analyses to investigate the current patterns associated with such interactions (Nagashima and Okazaki 1979; Yanagi et al. 1989, 1992; Hinata et al. 2001; Yagi et al. 2003). However, because these analyses were performed using short-term datasets, the known patterns remain uncertain and are inadequate for predicting associated impacts on the environment of the inner bay. Consequently, long-term observations are required to elucidate fully the current patterns and to predict their environmental impacts.

A moving platform enables long-term observation of tidal and residual currents (Buijsman and Ridderinkhof 2007), and changes in water quality (Kikas and Lips 2016) and bathymetry (Okabe and Kato 2018) in areas where setting a fixed platform is problematic. For example, a moving platform is the ideal solution for monitoring current patterns at the mouth of Tokyo Bay because setting a fixed platform would represent a risk to shipping. Since 2003, the Port and Airport Research Institute of Japan has observed currents and water quality at the mouth of Tokyo Bay by collaborating with a company that operates ferries in that area (Suzuki and Kato 2004; Suzuki, Takeda, and Hashimoto 2005). The observations reveal that seawater exchange at the mouth of the bay is relatively important in comparison with the amount of river water discharged into the bay (Suzuki 2010).

This acquisition of ferry-based observations has led to the development of a dataset extending over a decade, which has enabled initial reassessment of the residual current patterns in Tokyo Bay (Suzuki and Takeda 2006; Suzuki 2010). The objective of this study was to further elucidate the long-term spatial mean picture and temporal variability of the current patterns at the mouth of Tokyo Bay.
Study

2. Materials and methods

2.1. Study site

Tokyo Bay is a semi-enclosed bay, open to the Pacific Ocean (Figure 1a), which covers an area of 920 km² with areal mean depth of 17 m (Japan Coast Guard: https://www1.kaiho.mlit.go.jp). The residence time of seawater in the bay is between 20 days in summer and 40 days in winter (Takao et al. 2004; Suzuki 2010). Thus, the residence time of water in the bay is more than 10-times lower than that of water in lakes of similar areal extent (Messager et al. 2016). However, bottom hypoxia does occur in summer in the bay (Kodama and Horiguchi 2011).

The topography of the mouth of Tokyo Bay is characterized by the Tokyo Submarine Canyon (TSC) and the Uraga Channel route (UCR). The most impressive current is the inflow into the inner bay of the residual current in the intermediate layer (depth: approximately 20–80 m) on the slope between TSC and UCR (Figure 1b), which are known to be key bathymetric features for the refraction of swell that damages the west side of the inner bay (Tamura et al. 2021). The inflow was predicted by Nagashima and Okazaki (1979) and subsequently observed in other studies (Yanagi et al. 1989, 1992; Hinata et al. 2001). In the surface layer of the bay mouth, inflow on the east side of Tokyo Bay (Kanaya side) and outflow on the west side (Kurihama side) have been considered to represent the mean circulation pattern (Nagashima and Okazaki 1979; Yagi et al. 2003).

2.2. Observations

The Kanaya Maru (Figure 1c) is a ferry (draft: 3.4 m) operated on the route between Kurihama and Kanaya (Figure 1d). To promote environmental conservation in Tokyo Bay, water quality is measured at eight stations operated by the Kanto Regional Bureau (Ministry of Land, Infrastructure, Transport and Tourism in Japan), and the ferry route traverses the bay further seaward than the innermost six stations (Figure 1a). Generally, water temperature at the bay mouth was at an intermediate level between that of the inner and outer parts of the bay, while salinity at the bay mouth was broadly greater than that of the inner bay. A single
crossing by the ferry takes 40 min at a speed of 6.2 m/s, and six or seven round trips are undertaken daily between 06:00 and 20:00 Japan Standard Time.

Current velocity is measured using an acoustic Doppler current profiler (ADCP; Workhorse Mariner 300 kHz, Teledyne RD Instruments Inc., California). The ADCP is mounted on the bottom of the hull of the ferry. The downward-looking ADCP measures the current velocity profile in 4-m layers from the depth of 7.2 m beneath the hull to the maximum range of this ADCP, i.e. approximately 100 m, (Figure 1c). Bottom tracking is used to measure the ship’s velocity with accuracy of a few millimeters per second (Teledyne RD Instruments 2011). The standard deviation of the current velocity profile is 1.0 cm/s, which is reduced from the standard deviation of 3.6 cm/s for a single ping using 12 pings with a 20-s sampling interval. The current velocity profile is calculated by subtracting the ship’s velocity from the measured current velocity in post-processing procedures. Quality control for the current velocity of the water is performed using two standard processes and our original data-rejection process (Supplemental Information A).

Water is diverted from the intake of engine-cooling water to measure water temperature and salinity using a system installed onboard the ferry (Figure 1c). Water temperature is measured using an SBE 38 digital thermometer (Sea-Bird Electronics Inc., Washington), and salinity is measured using an ETSG 2 instrument (Falmouth Scientific Inc., Massachusetts). These measurements are performed at 1-min intervals during the ferry crossing. The Global Positioning System (GPS) and a gyrocompass are used to measure the location and heading of the ferry. An MX421 GPS (Leica Geosystems Inc., Heerbrugg) and a TG-5000 compass (Tokyo Keiki Inc., Tokyo) were used before July 2014. A V102 GPS compass (Hemisphere Inc., Arizona) was used between June 2014 and August 2021, and a V123 GNSS compass (Hemisphere Inc., Arizona) has been used since August 2021. The current velocity of the water is corrected by heading to northward and eastward current velocities.

2.3. Data analysis

2.3.1. Analysis term and spatial separation

The term of analysis of ADCP data adopted in this study was from January 2010 to October 2021. Water temperature and salinity were analyzed from March 2012 to October 2021; however, data were not obtained from April 2013 to June 2014 (Supplemental Information B). Because the spatial variation of the ferry course was problematic in terms of analysis that deals with time series data acquired at a fixed location, we defined 32 grids that covered the area of the ferry course (Figure 1d). Each grid was identified on the basis of row and column, e.g. grid A1 is row A and column 1. The ferry passed each site at an interval of 1–2 h.

2.3.2. Least squares harmonic analysis without any assumption of spatial similarity

Least squares harmonic analysis was applied to determine the tidal and residual currents. The current velocity of water \(u_i\) \(i = 1, 2, \ldots, N\) where \(N\) is the number of data) is approximated by the harmonic fit \(\hat{u}_i\) (Emery and Thomson 2001):

\[
\hat{u}_i = A_0 + \sum_{q=1}^{M} \left[ a_q \cos(\omega_q t_i) + b_q \sin(\omega_q t_i) \right],
\]

where \(A_0\) is the tidal mean (equal to the mean of the residual currents), \(a_q\) and \(b_q\) are the q–th tidal constituents, \(\omega_q\) is the frequency of the q–th constituent, \(t_i\) is the time of data i, and \(M\) is the number of tidal constituents. It is known that the \(M_2\) (the period of tidal constituent, \(T = 0.518\) d), \(S_2\) (\(T = 0.500\) d), \(K_1\) (\(T = 0.997\) d), and \(O_1\) (\(T = 1.076\) d) constituents are the main contributors to the tidal currents in Tokyo Bay (Tanaka et al. 2007). Therefore, we also used these four tidal constituents in the harmonic analysis (\(M = 4\)), which was performed for north–south and east–west orientations.

This study employed harmonic analysis without any assumption of spatial similarity between neighboring sites to exploit the advantage of the large volume of data. This policy was also applied in the vertical direction. We avoided analyzing adjacent layers where the current velocity was measured using the same signal (Teledyne RD Instruments 2011). Therefore, we analyzed the 1st and 3rd layers, because of the possible variability in the upper layers, and every fourth layer lower than the 3rd layer. Because of the different criteria used between layers, we categorized the different quality of data in each layer (Supplemental Information A): high quality (HQ) categorized for data in the 1st, 3rd, 7th, and 11th layers, and low quality (LQ) categorized for data in the 15th, 19th, and 23rd layers.

Spatial analysis of the tidal mean and constituents obtained by least squares harmonic analysis was performed for the layers of HQ data, i.e. between the 1st and 11th layers. The fitness of the tidal mean and constituents was checked using the standard deviation of the residual \(\sigma\) and the coefficient of determination \(r^2\) (e.g. Emery and Thomson 2001; Buijsman and Ridderinkhof 2007):

\[
\sigma = \sqrt{\frac{SSR}{N - (2M + 1)}}
\]

\[
r^2 = \frac{SSR}{SST}
\]

where \(SSR = \sum_{i=1}^{N} (u_i - \bar{u})^2\), \(SST = \sum_{i=1}^{N} (\hat{u}_i - \bar{u})^2\), and \(\bar{u}\) is the arithmetic mean. These evaluations of fitness were performed for north–south and east–west orientations. Additionally, the distribution of current velocity was evaluated to check the results of the tidal
constituents analyzed at three times the eigenvalue, which shows the range over which 98.8% of data are distributed. Harmonic analysis was also performed for a two-year period using different data to check the variability of the tidal mean and constituents over time.

2.3.3. Daily mean residual current
The residual current was analyzed as the tidal mean by the harmonic analysis. However, the variability of the residual current is also important for understanding the current patterns in the mouth of Tokyo Bay. Here, we evaluated the daily mean residual current (DMRC) from the residual current at $i (A_0 + u_i - \bar{u})$ as follows:

$$ DMRC = E[A_0 + (u_i - \bar{u})] $$

where $E[\cdot]$ means the daily mean. Statistical error is included in the residual current at $i$; however, it is expected to be canceled out by the averaging. The DMRC was calculated at five selected sites (see Figure 1d) for the layers of HQ data and layers including LQ data at sites B3 and D5.

The frequency of the DMRC in the period from January 2010 to October 2021 was analyzed to understand the variability of the residual current at the mouth of Tokyo Bay. The DMRC was converted to the daily mean volume of seawater moving northward (toward the inner bay) by multiplying the observed current velocity in the 4-m layers by the horizontal width of a grid (887.9 m). The daily mean volume of seawater was summarized using a box-and-whisker plot.

2.3.4. River discharge
River discharge is an important reference for assessing the impact of the residual current. The Edogawa, Arakawa, Tama, and Tsurumi rivers are the four largest rivers that discharge into Tokyo Bay. Data of daily mean discharge by each of these rivers were collected from the Water Information System of the Ministry of Land, Infrastructure, Transport and Tourism (http://www1.river.go.jp/) for the period 2010–2018. Because discharge data for these rivers were unavailable for 2019 and 2020, we estimated the discharge of each river to fill this data gap on the basis of the water level–discharge relationship in 2018 and the observed water level in each year.

There are a number of relatively small rivers that discharge into Tokyo Bay that are not included in this system. Because the watershed area of all the rivers that flow into Tokyo Bay is at most twice the total watershed area of the Edogawa, Arakawa, Tama, and Tsurumi rivers, we compared the daily mean volume of seawater in a layer to the total discharge recorded for the four main rivers and to a value of twice the total discharge.

3. Results
3.1. Environmental location of the ferry observations
Water temperature in inner and outer parts of Tokyo Bay varied seasonally but differed between inner and outer parts of the bay in winter (Figure 2a). The difference in water temperature was 5.2°C (median value: 10.9°C at Nakanose route and 16.1°C at Tomiura) in January, and 5.7°C (median value: 9.7°C at Nakanose route and 15.4°C at Tomiura) in February. Salinity differed between the upper (depth: 1 m) and lower (depth: 20 m) layers at the Kawasaki artificial island in summer months (Figure 2b).

Water temperature measured by the ferry at the mouth of Tokyo Bay was at an intermediate level between that of the inner and outer parts of the bay throughout the year, but it was close to the water temperature in the outer bay in winter (Figure 2a). Salinity measured at the bay mouth was greater in terms of the median value than that in the lower layer of the Kawasaki artificial island between December and March (Figure 2b). However, salinity at the bay mouth was at an intermediate level between that of the upper (depth: 1 m) and lower (depth: 20 m) layers at the Kawasaki artificial island in summer months. These results show that the route of the ferry crossing represents a suitable place at which to observe the interaction between water from the inner bay and water from the ocean. Additionally, water temperature and salinity were both greater (in terms of median values) on the east side of the bay than on the west side throughout the year (Figures 2c and d).

3.2. Measured current and tidal current
The shape of the current distribution measured by the ferry-mounted ADCP is presented as a unidirectional ellipse with NNE–SSW orientation in the 1st layer at all sites (Figure 3a), and as an ellipse oriented with topography in lower layers (Figure 3b–d, and see Figure 6a–d for the plotted current). The tidal ellipse analyzed by least squares harmonic analysis is similar to the shape of the current distribution on the slope between TSC and UCR in all shown layers. However, it differs from the shape of the current distribution at sites far from the slope and in the lower layers.

The long axial radius of the ellipse for the $M_2$ tide, determined by least squares harmonic analysis for the term of two years, is $23.9 \pm 0.7$ cm/s in the 1st layer at site B3 on the slope between TSC and UCR (Table 1), which is approximately the same as that reported by Suzuki (2010), i.e. 28 cm/s. On this basis, the least squares harmonic analysis of this study is considered consistent. Additionally, because the standard deviations of the tidal constituents and tidal mean were within a few percent of their mean values, the results
obtained by least squares harmonic analysis for the period from January 2010 to October 2021 were adjudged to lead to plausible interpretations.

The numbers of current data accepted by the quality control processes were greater on the line between Kurihama and Kanaya in the 1st and 3rd layers and greater only on the line and at deep sites in the 7th and 11th layers (Figure 4a). The standard deviation of the residual determined by least squares harmonic analysis was similar between north–south (Figure 4b) and east–west orientations (Figure 4c). However, the coefficient of determination was greater in the north–south orientation (Figure 4d) than in the east–west orientation (Figure 4e). The coefficient of determination in the north–south orientation exhibited a spatial gradient that decreased on the east side (Kanaya side) in the 1st and 3rd layers. This spatial gradient means that the current explained by least squares harmonic analysis was nonlinear on the east side of Tokyo Bay.

The coefficients of determination at sites A1 and D8 were specific in the 1st and 3rd layers in the north–south and east–west orientations (Figure 4d and e). The current in these layers at site A1 would be affected by the shape of the land around Kurihama (Figure 3a and b). These layers at site D8 had small data numbers (Figure 4a), and the standard deviation of the residual in the north–south orientation was greater than that at surrounding sites (Figure 4b). These results indicate that data scarcity caused bias at site D8; therefore, this site was ignored in further discussion.

### 3.3. Residual current

#### 3.3.1. Tidal mean

The spatial trend of the tidal mean differed among the various layers (Figure 3). The tidal mean in the 1st layer was unclear between the west side of the bay (Kurihama side) and the slope between TSC and UCR, whereas it was directed toward the ocean between the center of the bay mouth and the east side (Kanaya side) (Figure 3a). However, the tidal mean in the 7th and 11th layers was directed to UCR along the topography (Figures 3c and d). The tidal mean in the 3rd layer was intermediate between that in the 1st layer and that in the 7th layer (Figure 3b).

The vertical profile of the DMRC shows a northward peak (inflow into the bay) in the 7th layer, whereas it is neutral in the 19th and 23rd layers at site B3, which is located on the slope between UCR and TSC (Figure 5a). The water volume moving into the bay was 203.9, 289.1, and 206.6 m$^3$/s in the 3rd, 7th, and 11th layers, respectively. The water volume moving into the bay in each layer was greater than the median discharge of the main four rivers into Tokyo Bay (101.1 m$^3$/s), but comparable with or greater than the value of twice the discharge. The median value of the total water volume between the 3rd and 11th layers, interpolated as the water volume moving into the bay in the layers interpolated between 3rd and 7th layers and between 7th and 11th layers, was calculated as 2183 m$^3$/s. This volume was greater than 20 times the discharge of the main four rivers.
Figure 3. Tidal ellipses of four constituents (left panels) and the tidal mean (right panels) in (a) the 1st (11–15 m depth), (b) 3rd (19–23 m), (c) 7th (35–39 m), and (d) 11th layers (51–55 m). Four tidal constituents ($M_2$, green; $S_2$, Orange; $O_1$, blue; $K_1$, magenta) were considered in the least squares harmonic analysis. The distribution of 98.8% of current velocity data (gray) is also shown in the left-hand panels. N.A. means "not analyzed" because of limited data numbers. Radius of circles in left panels represents 30 cm/s for tidal ellipses and 90 cm/s for current velocity. TSC and UCR are the Tokyo Submarine Canyon and the Uraga Channel route, respectively.
3.3.2. Variability in the residual current

The discharge of the main four rivers into Tokyo Bay had a probability density function with a peak around the median discharge (Figure 5a). The frequency of the water volume moving into the bay was 87.7% in the 7th layer at site B3, which was the peak inflow, and 90.3% in the 3rd layer at site B3. The frequency of the water volume in the 1st layer at sites D5 (the center of the bay mouth) and E7 (the...
Figure 5. Vertical daily mean volume of seawater northward at the five selected sites (A1, B3, D5, E7, and F9) and river discharge into Tokyo Bay. (a) Box-and-whisker plot of the daily mean volume of seawater northward, converted from daily mean residual current, analyzed using high-quality data between the 1st and 11th layers, and low-quality data between the 15th and 23rd layers. (b) Probability density of discharge of main four rivers into Tokyo Bay observed between 2010 and 2020 by the Ministry of Land, Infrastructure, Transport and Tourism. The five panels in (b) are the same, with Orange and magenta dashed lines representing the median and 95th percentile of river discharge, respectively, of the four rivers.

The spatial structure of the tidal and residual currents was revealed by least squares harmonic analysis at the 32 sites (Figure 3). Although techniques for determining the spatial structure of the residual current using data from a ship-mounted ADCP were employed in previous studies by adopting an assumption of spatial similarity (Foreman and Freeland 1991; Candela, Beardsley, and Limeburner 1992; Münchow, Garvine, and Pfeiffer 1992; Suzuki, Takeda, and Hashimoto 2005), the spatial structure established in this study without any assumption of spatial similarity, i.e. independent of near sites, is considered a reliable result. The abundance of data accumulated during the long-term observational campaign (over a decade) enabled us to arrive at this conclusion.

Conversely, the mechanisms causing nonrandom data misses must be understood to avoid misleading conclusions based on biased results (Rubin 1976; National Research Council 2010). The possible mechanisms for nonrandom missing data are scheduled periods during which the ferry was out of service 1) at night and 2) for 2–3 weeks for maintenance, unscheduled periods out of service owing to 3) bad weather and high waves, and 4) low-quality ADCP data attributable to high waves and degradation of transducer performance because of biological effects before maintenance (Supporting Information B). However, because these mechanisms would not synchronize to the periods of tidal constituents considered, the pattern of missing data might be randomized by analyzing long-term observational time series (i.e. over a decade). Therefore, it should cancel out the effects of these missing data on the estimation of tidal currents. However, if a specific current occurred during a period of missing data, the possibility remains that tidal means were estimated with certain bias.

4. Discussion

4.1. Summary of the current at the mouth of Tokyo Bay

The spatial structure of the tidal and residual currents was revealed by least squares harmonic analysis at the 32 sites (Figure 3). Although techniques for determining the spatial structure of the residual current using data from a ship-mounted ADCP were employed in previous studies by adopting an assumption of spatial similarity (Foreman and Freeland 1991; Candela, Beardsley, and Limeburner 1992; Münchow, Garvine, and Pfeiffer 1992; Suzuki, Takeda, and Hashimoto 2005), the spatial structure established in this study without any assumption of spatial similarity, i.e. independent of near sites, is considered a reliable result. The abundance of data accumulated during the long-term observational campaign (over a decade) enabled us to arrive at this conclusion.

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4.2. Mean structure of the residual current

The three-dimensional picture of the residual current was characterized by outflow to the ocean between the center and east side of the bay in a layer at the depth of 11–15 m, and inflow to the inner bay along the topography formed by TSC and UCR in a layer with depth of 35–55 m. Inflow on the slope between TSC and UCR into Tokyo Bay was substantially greater in layers at depths of 19–55 m than the volume of river discharge. The inflow in the intermediate layer on the slope between TSC and UCR has previously been considered driven as a gravity flow by the salinity structure between the inner bay and the Pacific Ocean (Yanagi et al. 1992; Yanagi and Hinata 2004). This spatial scale is ordinal in the estuarine circulation (Giddings and MacCready 2017). However, the topographic convergence from the broad TSC to the narrow UCR with great inflow suggests its importance in the physical environment of the inner bay. The topography is also important for the swell that originates in the open ocean and damages coastal areas of the inner bay (Tamura et al. 2021).
The horizontal residual current of the surface layer of the bay mouth has previously been considered dominated by inflow on the east side and outflow on the west side (Nagashima and Okazaki 1979; Yagi et al. 2003) (Figure 1b). This study also showed that the water on the east side of Tokyo Bay is more oceanic than that on the west side (Figures 2c and d), supporting the supposition of inflow on the east side. However, least squares harmonic analysis revealed that the tidal mean of the 1st layer differs from the horizontal current of the surface layer previously considered (Figure 3a).

Although our ferry-mounted ADCP cannot measure the current of the surface layer to the depth of 11 m (Figure 1c), the tidal mean directed toward the ocean is predicted in the surface layer based on extrapolation between the outflow in the 1st layer and inflow in the 7th layer. Additionally, assuming that the large inflow into Tokyo Bay between the 3rd and 11th layers on the slope between TSC and UCR (2.2 × 10^3 m^3/s) and the median discharge of the main four rivers (0.1 × 10^3 m^3/s) exits the bay via the surface and 1st layers (15-m depth), a tidal mean current of 10 cm/s is estimated to occur across a width of 1.5 km of the approximately 10-km-wide bay mouth. This estimation might be approximate but it consists of the tidal mean of the 1st layer (Figure 3a). These predictions by extrapolation and estimation would be sufficient to understand that the tidal mean directed toward the ocean would be acceptable in the surface layer. In other words, discord exists between our results regarding the cross-sectional gradients of water temperature and salinity, and the tidal mean.

### 4.3. Variability in the residual current

The current at the bay mouth is governed by the tidal force and the estuarine circulation (Figures 3 and 4); however, the long-term observations also reveal that the residual current is variable. The low coefficient of determination determined by least squares harmonic analysis for the east side (Figure 4d) should reflect that the variability occurred on this side. Although the 1st layer at site E7 on the east side is where the tidal mean was found directed toward the ocean (Figure 3a), it is quite possible that the water mass becomes an oceanic environment owing to the great and frequent inflow from the ocean (Figure 5a). This variability might be caused by variation in river discharge (Guo and Yanagi 1998), wind-induced currents in the bay (Guo and Yanagi 1996; Nakayama et al. 2014), penetration of oceanic water into the bay (Yanagi and Hinata 2004), and interaction between the penetration and the Coriolis force at the bay mouth (Nagashima and Okazaki 1979; Yagi et al. 2003).

### 4.4. Importance and limitation of the long-term observational dataset

The mean structure of the residual current along the topography between TSC and UCR represented inflow twenty times greater than the discharge of the main four rivers. This great inflow suggests that oceanic water interacts with the water of the inner bay and governs the physical environment on the bay scale (Figure 6). Moreover, because residual currents transport water mass, and chemical and biochemical substances, it is suggested that the residual current of the estuarine circulation governs the water quality of the inner bay (MacCready and Geyer 2010; Geyer and MacCready 2014). The residual current observed by our ferry-mounted ADCP has been used to estimate that the magnitude of the nutrient input from the Pacific Ocean is of the same order as the input from land (Aoki et al. 2022). This estimation might contribute to clarifying the question of why the water quality of the bay has not improved despite reduction of the external load from land (Kodama and Horiguchi 2011). The question of whether the increase in the water temperature of Tokyo Bay is related to the change of inflow into the bay from the ocean remains to be answered (Yagi et al. 2004). Although current understanding of the mean structure of the residual current at the bay mouth is inadequate to answer this question, it will support comprehensive resolution of the matter via subsequent data analysis and model simulations.

The analysis in this technical note did not include individual residual currents hidden within the variability of the overall residual current (Figure 6). As described above, intermittent forces might drive such individual residual currents, upon which the scale of the associated environmental impact is dependent. However, the intermittent residual and tidal currents driving turbulence would cause local environmental impacts in areas around the bay mouth, such as the damage to nori cultivation associated with fish feeding around the sites (Hayashi 2019). Additionally, these currents might also have bay-scale impact on water quality. Analysis of the currents that might occur during periods of missing ferry observational data is limited and problematic. However, additional new currents are expected to be revealed and validated by our dataset in the future.
5. Conclusions

In this study, analysis of long-term observations acquired using an ADCP mounted on a ferry revealed the current structure at the mouth of Tokyo Bay. The three-dimensional structure of the residual current was characterized by the main route of inflow into the bay on the slope between TSC and UCR associated with the estuarine circulation. However, the long-term observations also revealed that the structure of the residual currents varied frequently, which might reflect changes in the physical balances between the waters of the inner bay and oceanic water. Because of the advantage of the observational location and the volume of the precise data acquired, the long-term observations represent a comprehensive data source that will help answer the remaining questions associated with the water quality in Tokyo Bay via subsequent analysis of other datasets and numerical models.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability

The current data observed by the ferry-mounted ADCP are available on https://pari.mpat.go.jp/bdhome/.

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