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PROCEEDINGS OF THE FOURTH INTERNATIONAL CONFERENCE ON ESTUARIES AND COASTS

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PREFACE

The 4th International Conference on Estuaries & Coasts (ICEC2012) will be held in Hanoi Vietnam, co-organised by Water Resources University (WRU), Vietnam and the International Research and Training Center on Erosion and Sedimentation (IRTCES). This conference was successfully organized in 2003 (Hangshou, China), in 2006 (Guangzhou, China), in 2009 (Sendai, Japan).

Action is now required for the development of new technologies to protect and develop estuarine and coastal zones and to solve hydrodynamic and environmental problems currently faced in these regions. The objective of ICEC2012 is therefore to bring together researchers and engineers working in estuaries & coast regions, from a broad range of disciplines, in order to present their research results, exchange information, facilitate networking, and to promote and advance technologies related to estuarine and coastal development.

For the ICEC2012, the following specific themes are selected as the platform topics:

- Climate Change
- Water Resources and Hydrology
- Environmental and Ecological Hydraulics
- Coastal and Estuarine Hydrodynamics
- Estuarine and Coastal Management
- Maintenance and Management of Waterways in Estuaries and Harbors
- Research Technologies for Estuarine Engineering
- Coastal Hazards

It is our great pleasure to organise this conference with the keynote lectures and heartfull contribution from participants and with very nice colaboration from Water Resources University, Vietnam. We do hope that this conference will bring a good appotunity for researcher/practitioners to well-mutual understanding in the field of estuarine and coastal issues.

On behalf of the Local Organizing Committee (LOC), sincere appreciation is expressed to all authors contributing to our conference. Special thanks are also due to all keynote speakers and chairpersons for the efforts in preparing the manuscripts and managing the sessions, respectively.

Prof. Dr. Nguyen Quang KIM

Chairman of the LOC of ICEC2012

President of Water Resources University

Hanoi, Vietnam

CONFERENCE ORGANIZATION

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4th International Conference on Estuaries and Coasts
8-11 October 2012, Water Resources University, *Vietnam*

INTERPLAY OF STEADY AND TIDAL CURRENTS IN FLUSHING OF WATER OUT OF HAKODATE BAY: A LAGRANGIAN EXPERIMENT

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Abstract

The flushing of waters off Hakodate Bay facing the Tsugaru Strait is clarified as its understanding is important to the preservation of local marine environment. Current fields from very high-resolution models for the Tsugaru Warm Current (TWC) and tidal current (TC) are coupled in a Lagrangian experiment. The simulated results show that the interplay between the TWC and TC flushes significant volumes of water away from Hakodate Bay and out to distances of several hundred kilometers from initial locations, while maintaining this water in the bay in cases of either steady TWC or oscillatory TC alone. Water particles released in the eastern and central inner part of the bay will be flushed away to the North Pacific after 27.2 days with an average speed that is one order of magnitude larger than in the individual cases. Our flushing simulation is consistent with drifter observations and explains reasonably the distribution of bottom sediment off the bay. This study emphasizes the effective interplay between TC and steady current in enhancing transport and mixing.

Keywords: Tsugaru Strait; Hakodate Bay; Tsugaru Warm Current; tidal current; water flushing; Lagrangian experiment.

1. INTRODUCTION

The flushing of local waters offshore assumes an important role in the preservation of the marine environment (Takeoka, 1984; Delhez et al., 1999; Walker 1999; Hartnett et al., 2003; Sandery, 2005). Hokodate Bay is a coastal region facing the Tsugaru Strait, a complex channel connecting the semi-enclosed Japan/East Sea (JES) to the open North Pacific (NP). This small region supports a diverse ecosystem and offers various kinds of habitats for species such as marbled sole, its larvae and juveniles (Joh et al., 2009). It is reasonable to assume that the riverine discharges are polluted by fertilization and seafood processing (Unoki, 2005). The coastal ocean around Hakodate Peninsula is also influenced by terrestrial loading (Maruyama and Suzuki, 1998) since the coastal ocean interfaces with crop fields and the seafood industry. In addition, the sea bottom is occupied by sand that is classified as fine and very fine (Nakao, 1982) and which can be transported by flow. As a result, Hakodate Bay is vulnerable and may be affected by a wide range of potential pollutants or contaminants. A fuller understanding of the flushing of the bay thus contributes to a better sustainable maintenance of this environment.

Nakao (1982) pointed out that Hakodate Bay waters are greatly influenced by transport through the Tsugaru Strait on the basis of temperature, chlorinity and dissolved oxygen observations. It is well known that this throughflow transport is characterized by both the Tsugaru Warm Current (TWC) and tidal current (TC). The TWC, driven by the pressure gradient in the along-strait direction, mainly flushes the warm and low density waters toward the NP. It is basically barotropic and predominant in the central portion of the strait with seasonal transport variability ranging from 1.0 Sv to 2.1 Sv (Toba et al., 1982; Ito et al., 2003). It forms a reversal current in coastal region around Hakodate (Conlon, 1981). However, the flushing of waters off coastal regions of the Tsugaru Strait, particularly Hakodate Bay, has not so far been identified. For example, the profiling float (namely 08173) in a recent observation (Park et al., 2008) moved around the mouth of Hakodate Bay during about 7-8 days before being flushed out. The slowly-varying TWC alone is unable to produce such contorted float trajectories.

The throughflow transport was in fact significantly fluctuated by TC with the speed as large as 0.9 m/s (0.8 m/s) for K1 (O1) constituent (Luu et al., 2011). The numerical model of Isoda and Baba (1998) showed that the TC can interact with the TWC to generate a secondary flow in the along-strait direction. Saitoh et al. (2008), while investigating the iron distribution in the strait, also pointed out that the TWC can be predominantly mixed by the diurnal tide. These results suggest that the interaction between the TC and the TWC contributes to a better understanding of enhanced transport and mixing in the Tsugaru Strait.

In present study, we investigated the flushing of waters out of Hakodate Bay by a numerical experiment. Since the realistic transport field is in Lagrangian (Sandery, 2005; Uchimoto, et al. 2011), trajectories of water parcels initially located in the bay are hereby tracked to reveal the flushing. The Lagrangian approach also enables us to flexibly couple the steady TWC and oscillatory TC fields in a wide range of experiments.

2. EXPERIMENTAL DESIGN

We use the ocean general circulation model (OGCM) developed at Kyoto University and its variant to simulate the TWC and TC, respectively. They are three-dimensional primitive-equation models based on spherical coordinates with hybrid sigma-z vertical axis. The model domains cover a broad region spanning from 138°40'E to 145°35'E and from 38°35'N to 43°20' (Figure 1) with a horizontal spacing of 1/54° x 1/72° and a vertical grid of 78 levels. Both models use the same bathymetry of 30-s resolution grid (JTOPO30) edited by the Marine Information Center of the Japan Hydraulic Association.

For better reproducing TWC, a downscaling technique is applied to force calculated data from a medium-resolution model covering the NP near to Japan, the southern part of the Okhotsk Sea and the JES at open boundaries (In et al., 2012, in preparation). We also assimilated hydrographic data collected through the Global Temperature-Salinity Profile Program (GTSPP), sea surface temperature (SST) and sea surface height (SSH) observed by satellites using a four-dimensional variational method of data assimilation (Ishikawa et al., 2009). A steady TWC was obtained from March of 2010 as this season is significant for the survival of marbled sole larval and similar observational period of mentioned drifter (Park et al., 2008).

In order to well simulate TC, a regional tide model is developed incorporating the effect of tidal equilibrium and resolving the overestimation of tidal energy (Luu et al., 2011). At the open boundary, we smoothly interpolated harmonic constants in 1/12° x 1/12° grid spacing of NAO.99Jb (Matsumoto et al., 2000). The calculated results agreed well with data from 67 widely-spread coastal tide gauge stations established around this region and TC measurements as shown in Luu et al. (2011). As suggested by Saitoh et al. (2008) and Luu et al. (2011), we used currents induced by major diurnal tides (K1 and O1) which are dominant components associated with mixing in the Tsugaru Strait (Figure 3).

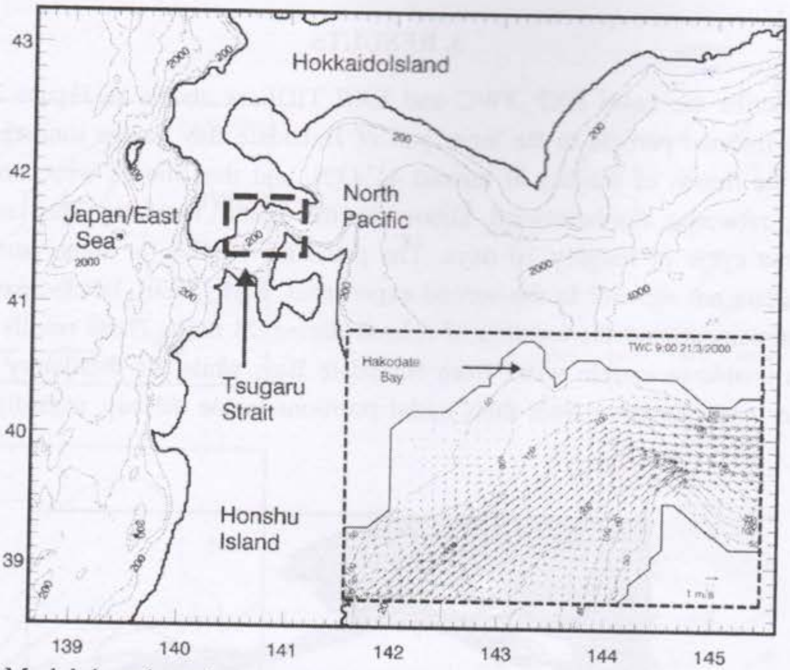

Figure 1. Model domain and topography. The inset shows detailed bathymetry around Hakodate Bay in the Tsugaru Strait (Contours are at 50, 100, 200, and 250-m depths). Blue vector represents the TWC.

Lagrangian particle tracking is used to investigate the interplay of barotropic components of both the TWC and TC in numerical experiments. The Eulerian structures obtained in those models are used to calculate the Lagrangian movement by tracking water particles released in Hakodate Bay. Here, the new position Y_{n+1} of a labeled water particle at the time step t_{n+1} is calculated from its previous position Y_n at t_n so that

$$\mathbf{Y}_{n+1}(\mathbf{X}_0, t_0) = \mathbf{Y}_n + \oint_{t_n}^{t_{n+1}} \mathbf{U}_E(\mathbf{Y}_n, t')dt' \tag{1}$$

where $\mathbf{U}_E$ is the Eulerian velocity at location Y_n, $Y_0 = X_0$ is the initial position of the labeled particle, t_0 is the initial release time, Δt is the time interval, and t_n is defined as $t_n = n\Delta t + t_0$.

We have performed 3 experiments as shown in Table 1. Experiment EXP_TWC uses the TWC model data as the background Eulerian velocity to calculate movement of 16 water particles initially released in Hakodate Bay and its mouth in the spacing of 1/54° x 1/72° (Figure 1). Experiment EXP_TIDE calculates the movement of water particles released from the same locations using the tide model data. Experiment EXP_CPL combines both Eulerian fields of the TWC and TC. In two latter experiments, EXP_TIDE and EXP_CPL, we release one water particle at each of 16 locations after every day and track all of them for 54.4 days starting from ebb tides.

Table 1. Settings of three Lagrangian experiments.

Experiments	TWC	Tides	Release	Particles	Duration
EXP_TWC	O	x	initial	16	653 hours
EXP_TIDE	x	O	every 1 day	870	1306 hours
EXP_CPL	O	O	every 1 day	870	1306 hours

3. RESULTS

First, we describe the cases EXP_TWC and EXP_TIDE as shown in Figure 2. In experimer EXP_TWC, the injected particle in the inner part of Hakodate Bay moves southeastward along th coastal line to the mouth of the bay at around 41°43'N, and then moves westward to the coast a 40°45'E before returning northeastward almost to the initial location. This anti-cyclonic pat completed over a cycle of roughly 10 days. The paths are similar for some particles released t Hakodate Bay (data not shown). In the second experiment, EXP_TIDE, labeled particles have shor oscillatory excursions around the location of release during 24 days. These results indicate that th steady TWC is unable to entrain water from Hakodate Bay, while the oscillatory TC alone barely carries the water particles away from their initial positions inside the bay, regardless of the release time.

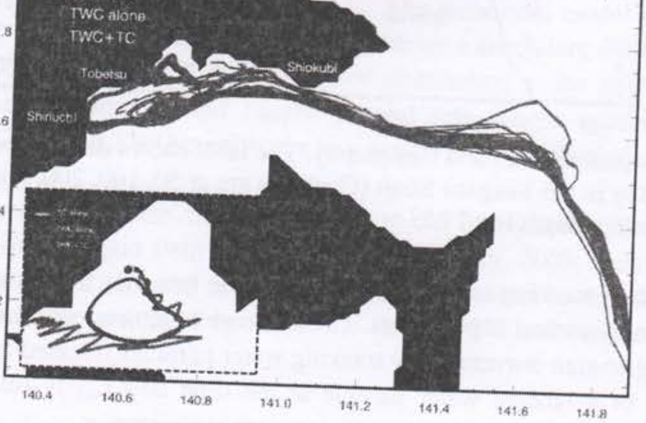

Figure 2. Particle paths during 24 days of calculations in experiments EXP_TWC (blue color), EXP_TIDE (green color), and EXP_CPL (red color). The circle marks initial particle positions. Particle positions are plotted once each 6 hours. A magnification of Hakodate Bay is shown in the lower inset.

In the EXP_CPL experiment, the injected particles in the central part of Hakodate Bay move southeastward along the coastal line to the mouth of the bay in variable trajectories around the same path shown in the EXP_TWC experiment. After moving westward, they reach locations around 140°45'E and 41°43'N. Here some particles return to the inner region of the bay to begin a new cycle. However, others move through the outer region of Hakodate Bay and along the western coast of Tobetsu to reach the region offshore from Shiriuchi. They then accelerate westward to Shiokubi and many of them reach the North Pacific after 16 days from the release time. These water particles travel a net distance of about one hundred kilometers from Hakodate Bay. This result clearly shows that the coupling between the TWC and the TC causes a significant flushing of water out of Hakodate Bay to offshore regions.

To quantify the differences, we defined the Lagrangian offshore velocity averaged over the period $T = t_n - t_0$ as

$$\mathbf{U}_L(\mathbf{X}_0, t_0, T) = \frac{\mathbf{Y}_N - \mathbf{Y}_0}{|\mathbf{Y}_N - \mathbf{Y}_0|} \sum_{k=1}^{N} \frac{|\mathbf{Y}_k - \mathbf{Y}_{k-1}|}{\Delta t}, \qquad (2)$$

where $\mathbf{U}_L$ is the Lagrangian velocity at time t_n of the labeled particle initially released at location $\mathbf{X}_0$ and time t_0. In the present study, an average period of two fortnightly cycles (T=27.2 days) is used. It is a typical period when the speeds in EXP_TWC and EXP_TIDE experiments change slightly.

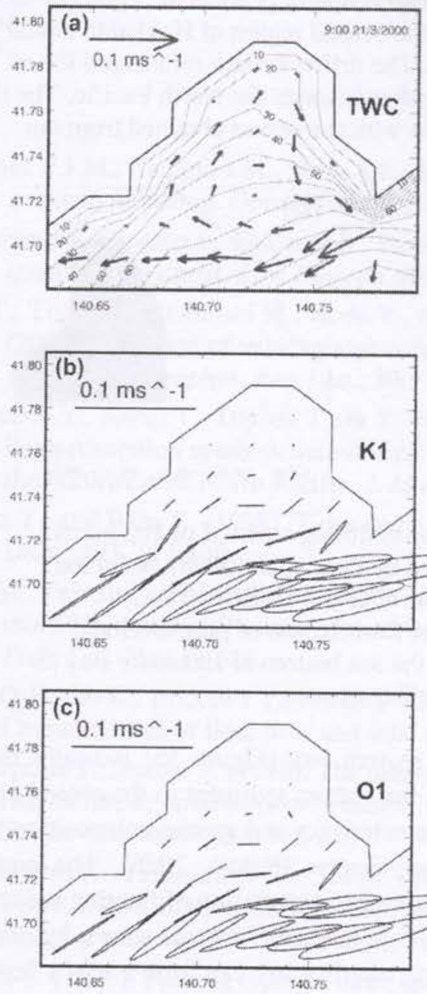

Figure 3. *(a)* Detailed bathymetry around Hakodate Bay (Contours are at every 10-m depth intervals). Vectors represent the TWC. (b) Tidal ellipses of K1. (c) That of O1.

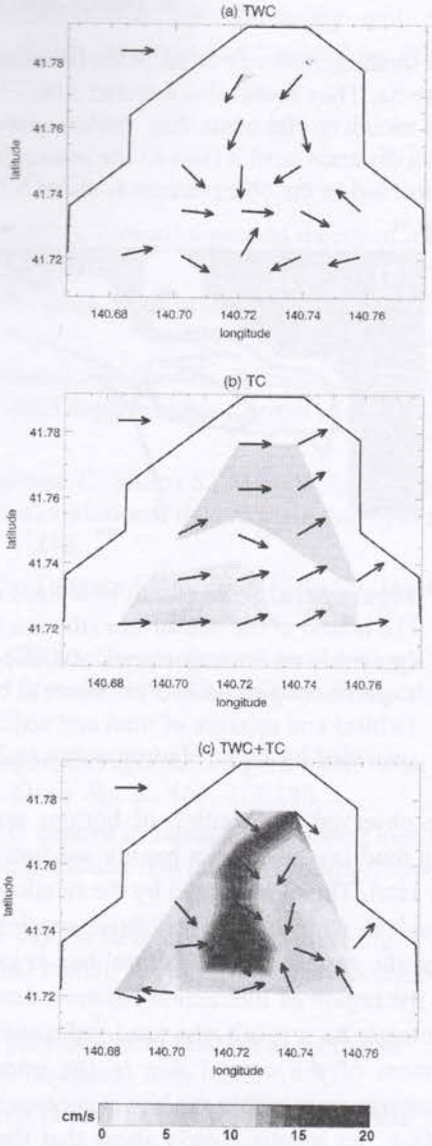

Figure 4. Lagrangian velocity averaged over 27.2 days (unit in m/s) for experiments (a) EXP_TWC, (b) EXP_TIDE, and (c) EXP_CPL

The offshore velocity distribution for experiments EXP_TWC, EXP_TIDE, and EXP_CPL are shown in Figure 4. In the EXP_TWC experiment, the offshore speeds in Hakodate Bay are uniformly around 0.02 m/s. This corresponds to the fact that the TWC is unable to entrain water from Hakodate Bay. In the EXP_TIDE experiment, the offshore speeds are increasing toward the mouth, but the magnitudes are less than 0.02 m/s in the inner region, and about 0.05 m/s at the mouth of the bay. In the experiment EXP_CPL, the offshore speed is reach 0.18 m/s in the eastern side of inner region of Hakodate Bay. In other locations, its value ranges from 0.03 m/s to 0.09 m/s. As a result, the interaction between the TWC and TC can significantly flushes the water parcels from eastern side of inner part of Hakodate Bay to offshore regions with an average speed of one order of magnitude larger than the individual cases.

4. DISCUSSION AND CONCLUSIONS

The flushing pathway of particles is consistent with the observation of (Park et al., 2008) as shown in Figure 5a. They found that a drifter (08173), which enters the coastal region of Hokkaido Island near the mouth of Hakodate Bay, moves eastward to Tobetsu. The drifter is then submerged for an unknown distance until it rises to the sea surface. It is then flushed towards the North Pacific. The time scale recorded in the observations is about 5-6 days, consistent with the period obtained from our simulation.

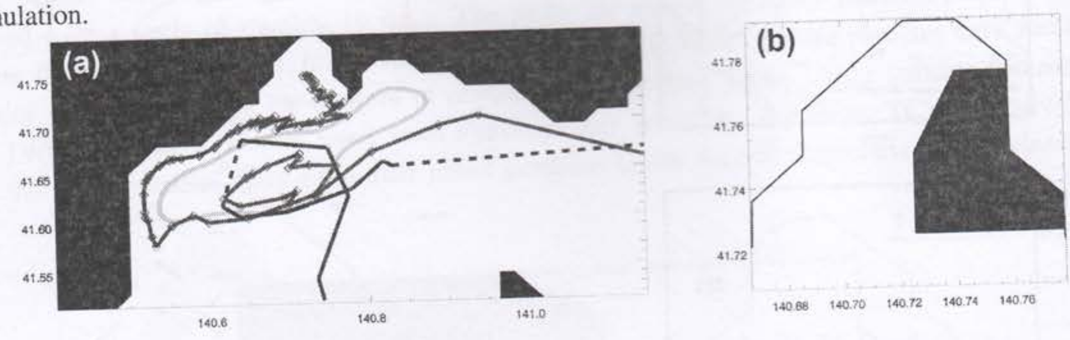

Figure 5. *(a)* Solid (dash) blue lines are float trajectories during a period of 102 hours (18 hours) at the subsurface (the sea surface) observed by Park et al. (2008). Solid red (green) lines are trajectories of a selected particle from EXP_CPL (EXP_TWC) experiment plotted every 6 hours at open symbols. (b) Distribution of pure sediment (white) and mixture of mud and sediment (violet) in the sea bottom of Hakodate Bay as provided by Japan Hydrographic and Oceanographic Department.

The observed distribution of bottom sediments in the eastern bay (Figure 5b) indicates that a floating mud layer lies on a muddy sea bottom. In contrast, the bottom sediment in the central bay is largely sand. This is indicated by the relation to sediment characteristics and species composition from chorological investigation of three species of Unicida polychaetes (Nakao, 1976). The contrast between the eastern and the central bay is explained by enhanced transportation of floating sediments within the region of interaction between the TWC and the TC in the center bay, as shown by particle experiments. As a result, the sand sediments discharged with runoff water can form a sandy layer in the bottom of the central due to the interplay. However, a more detailed study associated with sediment transport within the bay is necessary to better simulate such temporal process.

In fact, our results clearly show that the interplay between the TWC and TC flushes significant volumes of water out of Hakodate Bay to locations about 100 km distant, and in a fashion that cannot be produced by the steady TWC or the oscillatory TC acting alone. In the interaction of these two flow regimes, most of the particles released at the eastern and central inner parts of the bay will be flushed away to the North Pacific, with an average speed of one order of magnitude larger than the individual cases.

Of course, more elaborate treatments will be required in future, and these may employ a higher resolution for Hakodate Bay, or use a direct simulation of sediment transport. These advances are left for future work as the present study remains solely a model simulation.

In conclusion, our simulation reproduces typical drifter movements well and is able to explain the distribution of bottom sediment in the coastal regions of Hokkaido Island. To our knowledge, this study is the first to consider water flushing from either Hakodate Bay or the coastal regions of Tsugaru Strait. Our results emphasize the effective interplay of TC and steady current in enhancing the transport and mixing.

5. ACKNOWLEGEMENTS

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We use the ocean general circulation model (OGCM) developed at Kyoto University and its variant to simulate the TWC and TC, respectively. They are three-dimensional primitive-equation models based on spherical coordinates with hybrid sigma-z vertical axis. The model domains cover a broad region spanning from 138°40'E to 145°35'E and from 38°35'N to 43°20' (Figure 1) with a horizontal spacing of 1/54° x 1/72° and a vertical grid of 78 levels. Both models use the same bathymetry of 30-s resolution grid (JTOPO30) edited by the Marine Information Center of the Japan Hydraulic Association.

For better reproducing TWC, a downscaling technique is applied to force calculated data from a medium-resolution model covering the NP near to Japan, the southern part of the Okhotsk Sea and the JES at open boundaries (In et al., 2012, in preparation). We also assimilated hydrographic data collected through the Global Temperature-Salinity Profile Program (GTSPP), sea surface temperature (SST) and sea surface height (SSH) observed by satellites using a four-dimensional variational method of data assimilation (Ishikawa et al., 2009). A steady TWC was obtained from March of 2010 as this season is significant for the survival of marbled sole larval and similar observational period of mentioned drifter (Park et al., 2008).

In order to well simulate TC, a regional tide model is developed incorporating the effect of tidal equilibrium and resolving the overestimation of tidal energy (Luu et al., 2011). At the open boundary, we smoothly interpolated harmonic constants in 1/12° x 1/12° grid spacing of NAO.99Jb (Matsumoto et al., 2000). The calculated results agreed well with data from 67 widely-spread coastal tide gauge stations established around this region and TC measurements as shown in Luu et al. (2011). As suggested by Saitoh et al. (2008) and Luu et al. (2011), we used currents induced by major diurnal tides (K1 and O1) which are dominant components associated with mixing in the Tsugaru Strait (Figure 3).

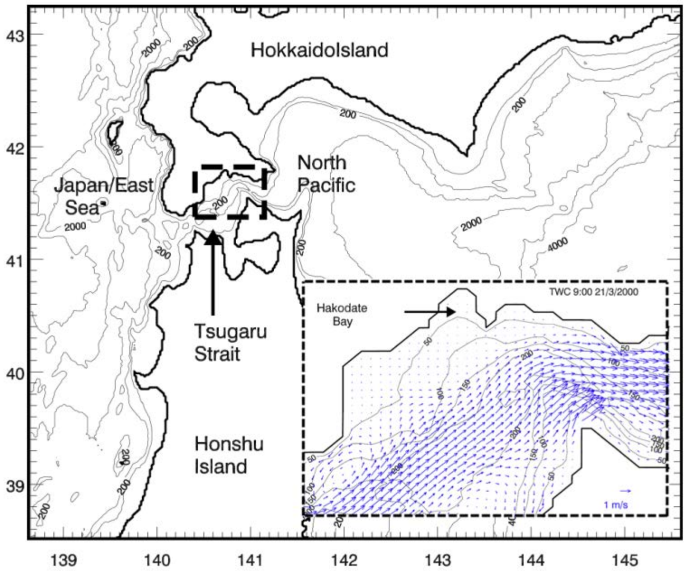

Figure 1. *Model domain and topography. The inset shows detailed bathymetry around Hakodate Bay in the Tsugaru Strait (Contours are at 50, 100, 200, and 250-m depths). Blue vector represents the TWC.*

Lagrangian particle tracking is used to investigate the interplay of barotropic components of both the TWC and TC in numerical experiments. The Eulerian structures obtained in those models are used to calculate the Lagrangian movement by tracking water particles released in Hakodate Bay. Here, the new position $\mathbf{Y}_{n+1}$ of a labeled water particle at the time step t_{n+1} is calculated from its previous position $\mathbf{Y}_n$at t_n so that

$$\mathbf{Y}_{n+1}(\mathbf{X}_0, t_0) = \mathbf{Y}_n + \oint_{t_n}^{t_{n+1}} \mathbf{U}_E(\mathbf{Y}_n, t')dt' \tag{1}$$

where $\mathbf{U}_E$ is the Eulerian velocity at location $\mathbf{Y}_n$, $\mathbf{Y}_0 = \mathbf{X}_0$ is the initial position of the labeled particle, t_0 is the initial release time, Δt is the time interval, and t_n is defined as $t_n = n\Delta t + t_0$.

We have performed 3 experiments as shown in Table 1. Experiment EXP_TWC uses the TWC model data as the background Eulerian velocity to calculate movement of 16 water particles initially released in Hakodate Bay and its mouth in the spacing of 1/54° x 1/72° (Figure 1). Experiment EXP_TIDE calculates the movement of water particles released from the same locations using the tide model data. Experiment EXP_CPL combines both Eulerian fields of the TWC and TC. In two latter experiments, EXP_TIDE and EXP_CPL, we release one water particle at each of 16 locations after every day and track all of them for 54.4 days starting from ebb tides.

Table 1. *Settings of three Lagrangian experiments.*

Experiments	TWC	Tides	Release	Particles	Duration
EXP_TWC	O	x	initial	16	653 hours
EXP_TIDE	x	O	every 1 day	870	1306 hours
EXP_CPL	O	O	every 1 day	870	1306 hours

3. RESULTS

First, we describe the cases EXP_TWC and EXP_TIDE as shown in Figure 2. In experiment EXP_TWC, the injected particle in the inner part of Hakodate Bay moves southeastward along the coastal line to the mouth of the bay at around 41°43'N, and then moves westward to the coast at 40°45'E before returning northeastward almost to the initial location. This anti-cyclonic path completed over a cycle of roughly 10 days. The paths are similar for some particles released to Hakodate Bay (data not shown). In the second experiment, EXP_TIDE, labeled particles have short oscillatory excursions around the location of release during 24 days. These results indicate that the steady TWC is unable to entrain water from Hakodate Bay, while the oscillatory TC alone barely carries the water particles away from their initial positions inside the bay, regardless of the release time.

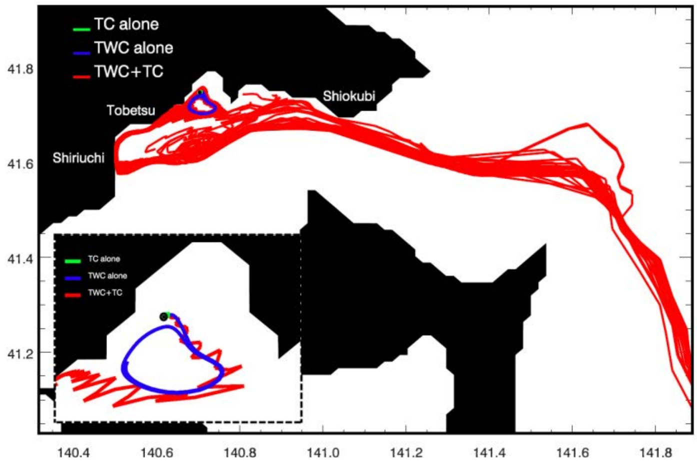

Figure 2. *Particle paths during 24 days of calculations in experiments EXP_TWC (blue color), EXP_TIDE (green color), and EXP_CPL (red color). The circle marks initial particle positions. Particle positions are plotted once each 6 hours. A magnification of Hakodate Bay is shown in the lower inset.*

In the EXP_CPL experiment, the injected particles in the central part of Hakodate Bay move southeastward along the coastal line to the mouth of the bay in variable trajectories around the same path shown in the EXP_TWC experiment. After moving westward, they reach locations around 140°45'E and 41°43'N. Here some particles return to the inner region of the bay to begin a new cycle. However, others move through the outer region of Hakodate Bay and along the western coast of Tobetsu to reach the region offshore from Shiriuchi. They then accelerate westward to Shiokubi and many of them reach the North Pacific after 16 days from the release time. These water particles travel a net distance of about one hundred kilometers from Hakodate Bay. This result clearly shows that the coupling between the TWC and the TC causes a significant flushing of water out of Hakodate Bay to offshore regions.

To quantify the differences, we defined the Lagrangian offshore velocity averaged over the period $T = t_n - t_0$ as

$$\mathbf{U}_L(\mathbf{X}_0, t_0, T) = \frac{\mathbf{Y}_N - \mathbf{Y}_0}{|\mathbf{Y}_N - \mathbf{Y}_0|} \sum_{k=1}^{N} \frac{|\mathbf{Y}_k - \mathbf{Y}_{k-1}|}{t}, \quad (2)$$

where $\mathbf{U}_L$ is the Lagrangian velocity at time t_n of the labeled particle initially released at location $\mathbf{X}_0$ and time t_0. In the present study, an average period of two fortnightly cycles (T=27.2 days) is used. It is a typical period when the speeds in EXP_TWC and EXP_TIDE experiments change slightly.

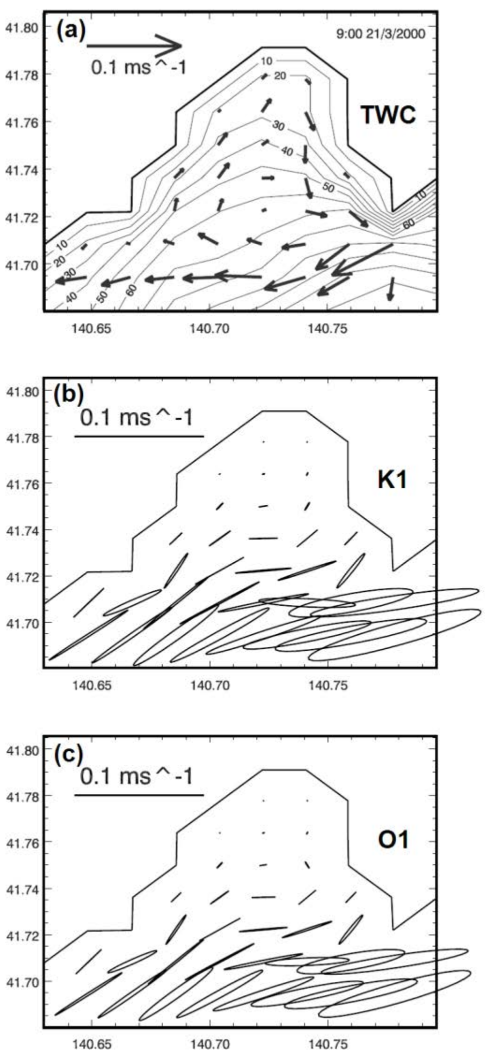

Figure 3. *(a) Detailed bathymetry around Hakodate Bay (Contours are at every 10-m depth intervals). Vectors represent the TWC. (b) Tidal ellipses of K1. (c) That of O1.*

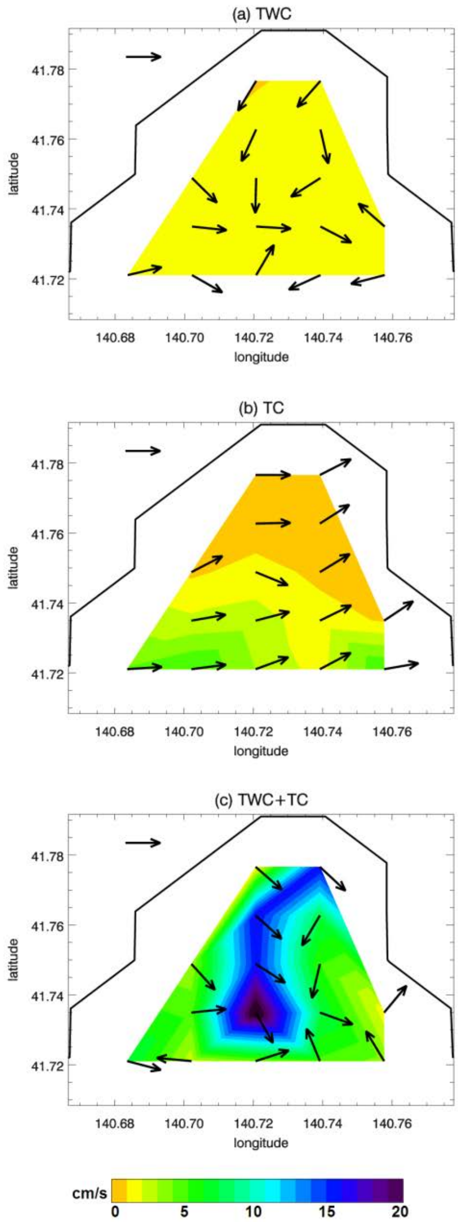

Figure 4. *Lagrangian velocity averaged over 27.2 days (unit in m/s) for experiments (a) EXP_TWC, (b) EXP_TIDE, and (c) EXP_CPL*

The offshore velocity distribution for experiments EXP_TWC, EXP_TIDE, and EXP_CPL are shown in Figure 4. In the EXP_TWC experiment, the offshore speeds in Hakodate Bay are uniformly around 0.02 m/s. This corresponds to the fact that the TWC is unable to entrain water from Hakodate Bay. In the EXP_TIDE experiment, the offshore speeds are increasing toward the mouth, but the magnitudes are less than 0.02 m/s in the inner region, and about 0.05 m/s at the mouth of the bay. In the experiment EXP_CPL, the offshore speed is reach 0.18 m/s in the eastern side of inner region of Hakodate Bay. In other locations, its value ranges from 0.03 m/s to 0.09 m/s. As a result, the interaction between the TWC and TC can significantly flushes the water parcels from eastern side of inner part of Hakodate Bay to offshore regions with an average speed of one order of magnitude larger than the individual cases.

4. DISCUSSION AND CONCLUSIONS

The flushing pathway of particles is consistent with the observation of (Park et al., 2008) as shown in Figure 5a. They found that a drifter (08173), which enters the coastal region of Hokkaido Island near the mouth of Hakodate Bay, moves eastward to Tobetsu. The drifter is then submerged for an unknown distance until it rises to the sea surface. It is then flushed towards the North Pacific. The time scale recorded in the observations is about 5-6 days, consistent with the period obtained from our simulation.

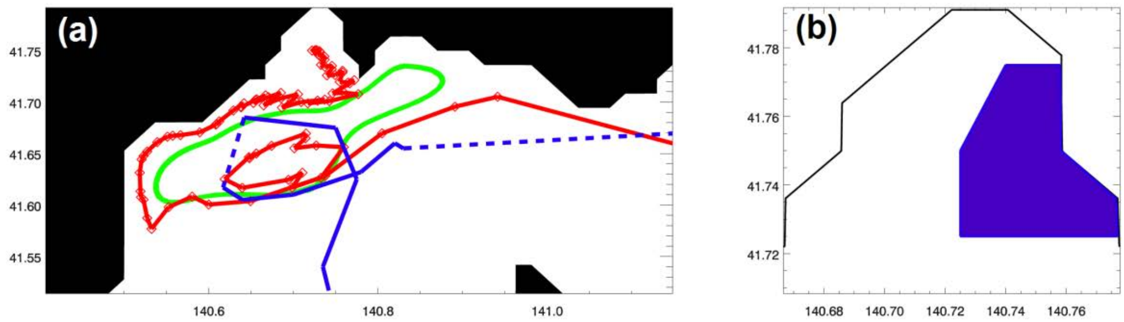

Figure 5. *(a) Solid (dash) blue lines are float trajectories during a period of 102 hours (18 hours) at the subsurface (the sea surface) observed by Park et al. (2008). Solid red (green) lines are trajectories of a selected particle from EXP_CPL (EXP_TWC) experiment plotted every 6 hours at open symbols. (b) Distribution of pure sediment (white) and mixture of mud and sediment (violet) in the sea bottom of Hakodate Bay as provided by Japan Hydrographic and Oceanographic Department.*

The observed distribution of bottom sediments in the eastern bay (Figure 5b) indicates that a floating mud layer lies on a muddy sea bottom. In contrast, the bottom sediment in the central bay is largely sand. This is indicated by the relation to sediment characteristics and species composition from chorological investigation of three species of Unicida polychaetes (Nakao, 1976). The contrast between the eastern and the central bay is explained by enhanced transportation of floating sediments within the region of interaction between the TWC and the TC in the center bay, as shown by particle experiments. As a result, the sand sediments discharged with runoff water can form a sandy layer in the bottom of the central due to the interplay. However, a more detailed study associated with sediment transport within the bay is necessary to better simulate such temporal process.

In fact, our results clearly show that the interplay between the TWC and TC flushes significant volumes of water out of Hakodate Bay to locations about 100 km distant, and in a fashion that cannot be produced by the steady TWC or the oscillatory TC acting alone. In the interaction of these two flow regimes, most of the particles released at the eastern and central inner parts of the bay will be flushed away to the North Pacific, with an average speed of one order of magnitude larger than the individual cases.

Of course, more elaborate treatments will be required in future, and these may employ a higher resolution for Hakodate Bay, or use a direct simulation of sediment transport. These advances are left for future work as the present study remains solely a model simulation.

In conclusion, our simulation reproduces typical drifter movements well and is able to explain the distribution of bottom sediment in the coastal regions of Hokkaido Island. To our knowledge, this study is the first to consider water flushing from either Hakodate Bay or the coastal regions of Tsugaru Strait. Our results emphasize the effective interplay of TC and steady current in enhancing the transport and mixing.

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