



**ICEC 2012**

**PROCEEDINGS OF  
THE FOURTH INTERNATIONAL CONFERENCE  
ON ESTUARIES AND COASTS**

VOLUME 1



**OCTOBER 08 - 11, 2012**

**WATER RESOURCES UNIVERSITY, HA NOI, VIET NAM**

**| Sponsors |**



SCIENCE AND TECHNICS  
PUBLISHING HOUSE



## PREFACE

The 4<sup>th</sup> 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 (Hangzhou, 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

### EXECUTIVE COMMITTEE MEMBERS OF ICEC2012

N. Tamai, Japan  
 M. Larson, Sweden  
 N.K. Dan, France  
 B.H. Choi, Korea  
 J.H. Lee, Hongkong  
 S. Kazama, Japan  
 M.J.F. Stive, the Netherlands  
 N.V.T. Van, Canada  
 H. Chanson, Australia  
 P.H. Burgi, USA  
 J.A. Roelvink, the Netherlands  
 T.M. Thu, Vietnam

N.Q. Kim, Vietnam  
 C.H. Hu, China  
 H. Tanaka, Japan  
 C. Chen, USA  
 V.T. Ca, Vietnam  
 S.K. Tan, Singapore  
 D.V. Uu, Vietnam  
 S. Sana, Oman  
 P. Rigo, Belgium  
 D.M. Tom, Belgium  
 S. Ouillon, France  
 G. Parker, US

### LOCAL ORGANIZING COMMITTEE (LOC) OF ICEC2012

#### Chairman

Nguyen Quang Kim

President of Water Resources University

#### Vice chairman

Trinh Minh Thu  
 Le Dinh Thanh

Water Resources University  
 Water Resources University

#### Secretariat

Nguyen Trung Viet  
 Mai Van Cong  
 Nguyen Cao Don  
 Pham Hong Nga

Water Resources University  
 Water Resources University  
 Water Resources University  
 Water Resources University

## EDITORIAL BOARD

#### Editor-in-chief

Nguyen Quang Kim

President of Water Resources University

#### Editorial members

Trinh Minh Thu  
 Nguyen Trung Viet  
 Mai Van Cong  
 Nguyen Cao Don  
 Pham Hong Nga  
 Pham Van Anh

Water Resources University  
 Water Resources University  
 Water Resources University  
 Water Resources University  
 Water Resources University  
 Water Resources University

# CONTENTS

Preface	3
Conference Organization	5
<b>TOPIC 1: COASTAL AND ESTUARINE HYDRODYNAMICS</b>	11
Flow and sediment transport in a semi-close bay	13
<i>Nguyen Cao Don and Nguyen Thi Minh Hang</i>	
Modelling of tide-wave-surge induced sediment transport at Wentuozi region in Liaodong bay, China	19
<i>Chen Jianguo, Wang Chonghao and Wang Yuhai</i>	
A method to determine the cross-shore varying roller slope in the surf zone	26
<i>Chi Zhang, Jinhai Zheng and Titi Sui</i>	
Cross-waves in a channel with trapezoidal depth	32
<i>Gang Wang, Jinhai Zheng, Tianwen Wang</i>	
A circulation model considering water exchange through rock-filled sea dyke	38
<i>Jung, TS.</i>	
Numerical study of inlet evolution: A case study at the Thuan An inlet, Thua Thien Hue, Vietnam	43
<i>Thanh-Tung Tran and Thi-Thom Nguyen</i>	
Interplay of steady and tidal currents in flushing of water out of Hakodate bay: a lagrangian experiment	51
<i>Quang-Hung Luu, Van-Cuc Tran, Satoshi Nakada, Yoichi Ishikawa and Oshiyuki Awaji</i>	
Using flushing rate to investigate the spatial variation of tide-driven and density-driven exchanges in the Red river estuary	59
<i>Duc Hoang Nguyen, Motohiko Umeyama, Tetsuya Shintani</i>	
Characteristics of internal waves propagating over a gentle slope in a two-layer density-stratified fluid	65
<i>Kim Cuong Nguyen, Motohiko Umeyama and Tetsuya Shintani</i>	
Inferring inlet morphodynamics & hydraulic parameters from tidal records of Avoca Lake, NSW, Australia	74
<i>Thuy T. T. Vu, Peter Nielsen, David P. Callaghan, Lam T. Nghiem</i>	
Employing a high-order scheme for solving the sediment volume conservation equation	81
<i>Pham Thanh Nam, Hocine Oumeraci, Magnus Larson, and Hans Hanson</i>	
The transport pattern of the fine sand in the acrotidal coast	88
<i>Xiujuan Liu</i>	



Application Mike 21 FM model to study the effect of wave and current to mophollogy change of Da Rang river mouth	94
<i>Pham Thu Huong, Nguyen Ba Quy, Le Dinh Thanh, Ngo Le Long</i>	
Validation of near shore wave modeling for Cua Hoi estuary	100
<i>Nghiem Tien Lam and Vu Thi Thu Thuy</i>	
Ariation of scour and silting of the sand bar in Modaomen estuary of Pearl River Delta in China	106
<i>Zhang Yanjing , Li Dashan and Wang Guobing</i>	
Numerical modeling of tides in the Western Atlantic during the Holocene - Regional and Local Results	114
<i>D.f. Hill, G. Hall, S.D. Griffiths, B.P. Horton, W.R. Peltier</i>	
Modelling of salinity distribution and water age in the Mahakam delta, Indonesia	120
<i>Chien Phamvan , Benjamin De Brye , Sandra Soares-Frazao, Eric Deleersnijder and Ton Hoitink</i>	
On the hindered settling of silt-water mixtures	128
<i>S. te Slaa, D.S. van Maren and J.C. Winterwerp</i>	
An wind-induced wave submodel coupled to EFDC	140
<i>Paul .M. Craig and Dang Huu Chung</i>	
A numerical study on tsunami induced sediment transport in vicinity of a submarine canyon off southeast coast of India	148
<i>Jaya Kcumar Seelam</i>	
Study on siltation in Laolonggou mouth bar channel in Caofeidian sea area of Bohai bay, China	156
<i>Zuo Liqin, Lu Yongjun and Ji rongyao</i>	
3D sediment transport modeling for the Sacramento-San Joaquin Delta	164
<i>Paul Micheal Craig, Nghiem Tien Lam, Tran Kim Chau and Nguyen Xuan Tinh</i>	
Wave and tidal modeling of East Sea, Vietnam	175
<i>Hai Le Tuan, Roanh Le Xuan</i>	
Study on wave dissipation solution of breakwater for harbours in island areas of Vietnam	183
<i>Nguyen Trung Anh and Nguyen Trong Tu</i>	
Estimating synthetic unit hydrograph using Nash model with geospatially driven parameters	188
<i>Boosik Kang, Jin-Gyeom Kim, Jong-Min Kim and Byungman Yoon</i>	
Internal generation of waves in shallow water equations with damping using Dirac delta and Gaussian source functions	193
<i>Vu Van Nnghi , Lee Changhoon</i>	
<b>TOPIC 2: ENVIRONMENTAL AND ECOLOGICAL HYDRAULICS</b>	<b>199</b>
Modelling organic matter removal in horizontal subsurface flow constructed wetlands	201
<i>Longhua Gao , Long Xie</i>	
Investigation of stream flow fluctuations by fluvial acoustic tomography	209
<i>Kiyosi Kawanisi , Kazuhiko Ishikawa, Mahdi Razaz and Jyunki Yano</i>	

Measuring stream flow and salinity in a tidal estuary with saltwater intrusions	217
<i>Junki Yano, Kiyosi Kawanisi, Mahdi Razaza and Mohammad Soltaniasl</i>	
Effect of waves on oxygen transfer	223
<i>Manh-Tuan nguyen and Soon-Keat tan</i>	
Impact of high turbidity on the hydrodynamic and biogeochemical functioning of tropical reservoirs: The case study of Cointzio, Mexico	231
<i>Doan ThuyKim Phuong, Valentin Wendling, Marie - Paule Bonnet, Julien Nemery, Nicolas Gratiot</i>	
Environmental factors affecting on juvenile population of <i>Corbicula japonica</i> in Lake Jusan	239
<i>Umedam, Pracoyop, Tanakah and Sasakim</i>	
Numerical simulation of sediment release by a two-phase model	246
<i>Levy Florence, Nguyen Duc Hau, Pham Van Bang Damien, Nguyen Kim Dan, Guillou Sylvain and Chauchat Julien</i>	
Impact of estuarine development on an endangered reshwater fish larvae	254
<i>Kazuaki Ohtsuki and Yukihiro Shimatani</i>	
Effect of open gap in coastal forest on tsunami runup- investigation by experimental and numerical simulation	261
<i>Nguyen Ba Thuy, Nguyen Quoc Trinh</i>	
Optimal configuration of nori aquafarming grounds in the Ariake sea using a two-dimensional convective-dispersion model and an index of nitrogen assimilation rate	269
<i>Tabata T, Hiramatsu K, Harada M and Honda Y</i>	
A comparative study on two nesting techniques of overlap and sponge-layer in two-dimensional numerical calculations of tidal currents in coastal waters	277
<i>Honda Y, Hiramatsu K, Harada M and Tabata T</i>	
Toward a new paradigm of ecosystem fisheries management for Taka Bonerate marine protected area, in Sulawesi-Indonesia	284
<i>Agus Hartoko, I .Kumalasari, Sutrisno Anggoro and Indah Susilowati</i>	
A gpu-cuda implementation of a two-phase model for sediment transport	296
<i>Kim Dan Nguyen, Quoc Lan Phan, Thanh Tam Nguyen and Chi Dung Vo</i>	
<b>TOPIC 3: COASTAL STRUCTURES</b>	<b>303</b>
Predicting the effects of boat generated waves within sheltered waterways	305
<i>G.Jj. Macfarlane, N. Bose and J.T. Duffy</i>	
Simplified assessment of ship impact on navigation lock gates	312
<i>Loïc Buldgen, Pphilippe Rigo and Hervé Le Sourné</i>	
Detached breakwater's stability against solitary Tsunami wave	321
<i>Minoru Hanzawa, Akira Matsumoto and Hitoshi Tanaka</i>	
Effects of water depth on stability of armor block for composite breakwaters	328
<i>Akira Matsumoto, Minoru Hanzawa and Akira Mano</i>	



Bamboo breakwaters as site-specific erosion protection and adaptation to climate change in Soc Trang Province, Vietnam	337
<i>Dr. Klaus Schmitt, Dr. Thorsten Albers and Arndt Von Lieberman</i>	
Investigation of overtopping flows over protective asphaltic embankments	345
<i>Farchad Yazdandoost</i>	
Simulation of solitary wave run up on a sloping beach using SCM method	352
<i>MoHammad BagusAadityawan and Hitoshi Tanaka</i>	
Stability of newly-improved wave dissipating blocks for rubble mound breakwaters	361
<i>Thieu Quang Tuan, Hiroshi Matsushita, Yasuomi Taki and Nguyen Quang Luong</i>	
Update of design standards of sea dikes in Vietnam	370
<i>Mai Van Cong &amp; Tran Quang Hoa</i>	
On the use of wave dissipating blocks in breakwaters and coastal protection works in Vietnam	378
<i>Huong Giang Le Thi, Thieu Quang Tuan, Ho Si Minh</i>	
3d sediment physical model test study on breakwater emergency repairing work for S2P CFPP project, Cilacap, Indonesia	385
<i>Feng Gao, Hanbao Chen and Yufen Cao</i>	
Analysis of inter-locking blocks structure for coastal protection using abaqus software	393
<i>Phan Tan Huy, Nguyen Dang Hung, Nguyen Van Hieu, Phan Duc Tac and Nguyen Van Mao</i>	
VungTau - Go Cong dam mathematical modelling: one size fits all?	402
<i>Gerrit Jan Schiereck, Marcel Stive and Han Vrijling</i>	

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

**QUANG-HUNG LUU<sup>1,2,\*</sup>, VAN-CUC TRAN<sup>2</sup>, SATOSHI NAKADA<sup>3</sup>,  
YOICHI ISHIKAWA<sup>3</sup> and TOSHIYUKI AWAJI<sup>3</sup>**

1) Tropical Marine Science Institute, National University of Singapore  
18 Kent Ridge Road, 119227, SINGAPORE

2) Department of Mechanics, College of Science, Vietnam National University, Hanoi  
334 Nguyen Trai Street, Thanh Xuan District, Hanoi, VIETNAM

3) Department of Geophysics, Kyoto University  
Kitashirakawaoiwake-cho, Sakyo-ku, Kyoto, 606-8502, JAPAN  
\*e-mail: [tmslqh@nus.edu.sg](mailto:tmslqh@nus.edu.sg), [hunglq@vnu.edu.vn](mailto:hunglq@vnu.edu.vn)

### **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.

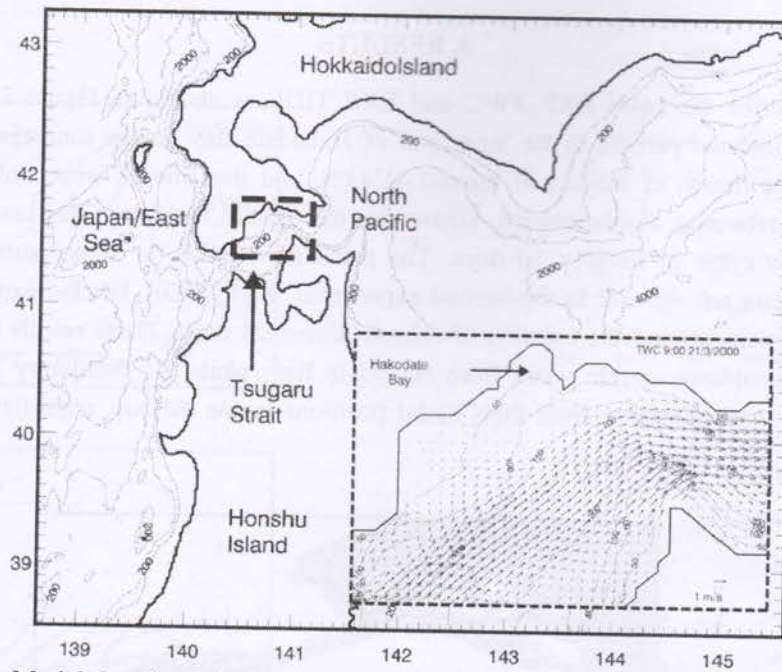
## 2. EXPERIMENTAL DESIGN

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  $1/54^\circ \times 1/72^\circ$  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 (GTSP), 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  $1/12^\circ \times 1/12^\circ$  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

$$Y_{n+1}(X_0, t_0) = Y_n + \int_{t_n}^{t_{n+1}} U_E(Y_n, t') dt' \quad (1)$$

where  $U_E$  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,  $\Delta t$  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  $1/54^\circ \times 1/72^\circ$  (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.

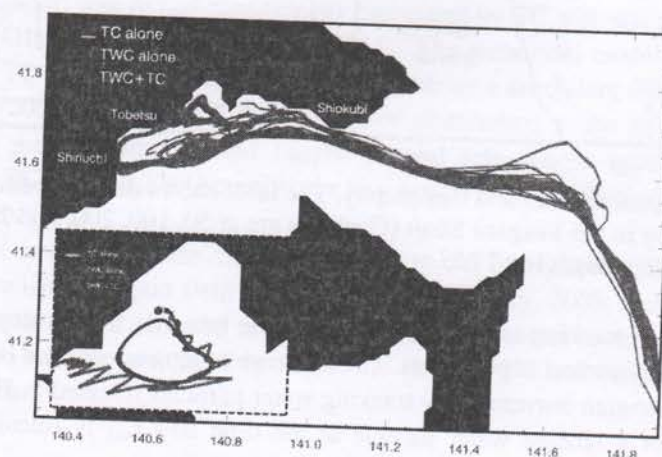
**Table 1.** Settings of three Lagrangian experiments.

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  $41^{\circ}43'N$ , and then moves westward to the coast at  $140^{\circ}45'E$  before returning northeastward almost to the initial location. This anti-cyclonic path is completed over a cycle of roughly 10 days. The paths are similar for some particles released throughout 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.

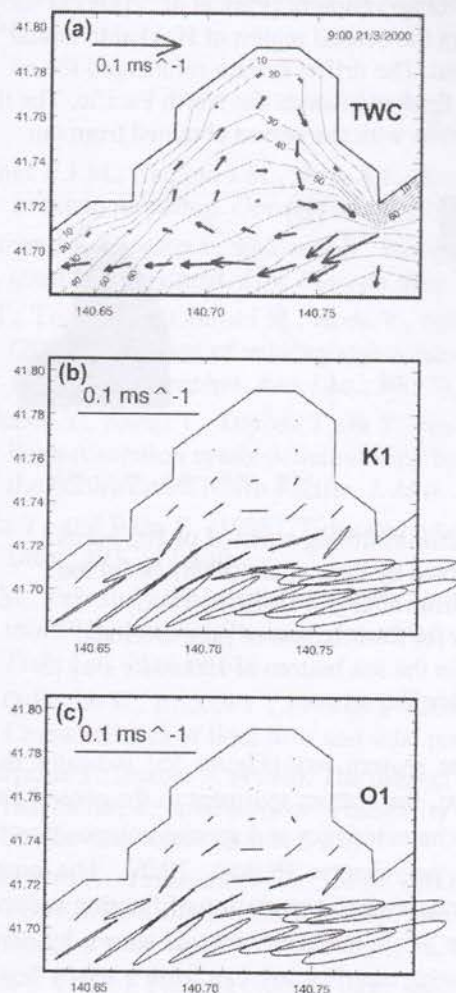
In the EXP\_CPL experiment, the injected particles in the central part of Hakodate Bay move southeastward along the coastal line to the mouth of the bay in variable trajectories around the same path shown in the EXP\_TWC experiment. After moving westward, they reach locations around  $140^{\circ}45'E$  and  $41^{\circ}43'N$ . 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

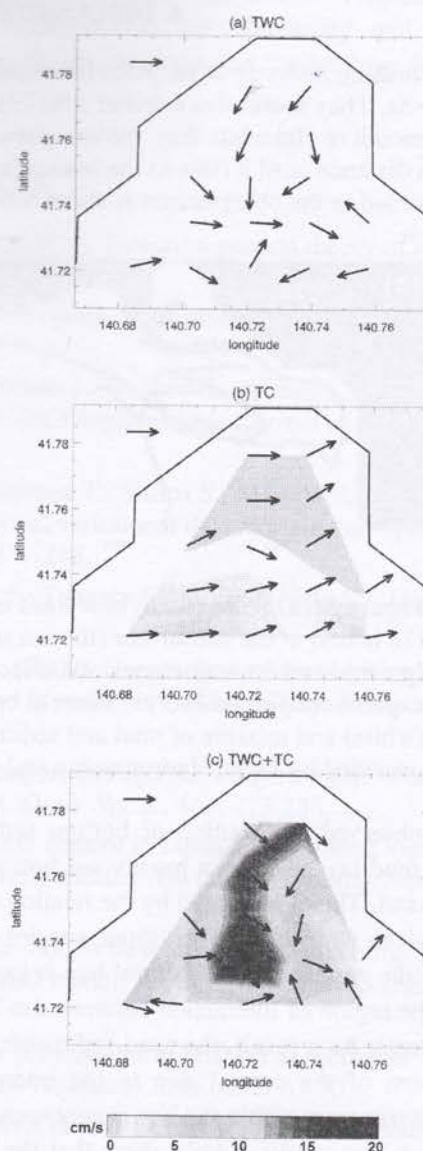
$$U_L(\mathbf{X}_0, t_0, T) = \frac{Y_N - Y_0}{|Y_N - Y_0|} \sum_{k=1}^N \frac{|Y_k - Y_{k-1}|}{\Delta t}, \quad (2)$$

where  $U_L$  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.



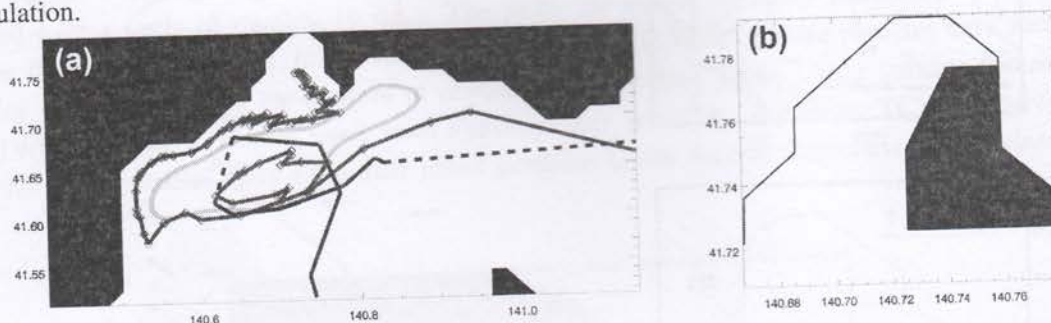
**Figure 4.** Lagrangian velocity averaged over 27.2 days (unit in m/s) for experiments (a) EXP\_TWC, (b) EXP\_TIDE, and (c) EXP\_CPL

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. ACKNOWLEDGEMENTS

The authors wish to thank J. P. Matthews for critical reading, and T. In for providing data of the TWC. We also thank H. Nakao, M. Kurebayashi at the Hokkaido Government Oshima General Sub-



prefectural Bureau. This work was supported by "Hakodate Marine Bio Cluster Project" in the Knowledge Cluster Program from 2009 and the Grand-in-Aid for University and Society Collaboration from the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan.

## 6. REFERENCES

- Delhez E.J.M., Campin J.M., Hirst A.C., Deleersnijder E. (1999). Toward a general theory of the age in ocean modeling. *Ocea. Mod.*, 1, 17-27.
- Hartnett M., Gleeson F., Falconer R., Finegan M. (2003). Flushing study assessment of a tidally active coastal embayment. *Adv. Environ. Res.*, 7, 847-857.
- Ito T., Togawa O., Ohnishi M., Isoda Y., Nakayama T., Shima S., Kuroda H., Iwahashi M., Sato C. (2003). Variation of velocity and volume transport of the Tsugaru Warm Current in the winter of 1999-2000. *Geophys. Res. Lett.*, 30(13), 1678.
- Ishikawa Y., Awaji T., Toyoda T., In T., Nishina K., Nakayama T., Shima S., Masuda S. (2009). High-resolution synthetic monitoring by a 4-dimensional variational data assimilation system in the northwestern North Pacific. *J. Mar. Sys.*, 78(2), 237-248.
- Isoda Y., and Baba K. (1998). Tides and tidal currents in the Tsugaru Strait. *Bull. Fish. Sci. Hokkaido Univ.*, 493, 117-130.
- Joh M., Takasu T., Nakaya M., Yoshida N., Nakagami M. (2009). Comparison of the nutritional transition date distributions of marbled sole larvae and juveniles in Hakodate Bay, *Hokkaido. Fish. Sci.*, 75, 619-628.
- Luu Q-H., Ito K., Ishikawa Y., Awaji T. (2011). Tidal transport through the Tsugaru Strait - Part I: Characteristics of tidal flow and tidal residual current. *Ocea. Sci. J.*, 464, 273-288.
- Maruyama T., Suzuki S. (1998). The present state of effluent control in Japan and pollutant load from fish culture to environment - Possibility of intensive recirculating fish culture systems. *Nippon Suisan Gakkaishi*, 642, 216-226.
- Matsumoto K., Takanezawa T., Ooe M. (2000). Ocean tide models developed by assimilating TOPEX/POSEIDON altimeter data into hydrodynamical model: A global model and a regional model around Japan. *J. Oceanogr.*, 56, 567-581.
- Nakao S. (1976). Feeding types of three species of uncinata polychaetes in relation to sediment: characteristics and species composition. *Bull. Fish. Sci. Hokkaido Univ.*, 272, 63-70.
- Nakao S. (1982). Community structures of the macro-benthos in the shallow waters in Northern Japan. *Memoirs Fish., Hokkaido Univ.*, 282, 255-304.
- Nishida Y. (2003). Transformation of the watermass structures across the Tsugaru Strait in spring. *Oceanogr. Japan*, 126, 593-602.
- Onishi M., Isoda Y., Kuroda H., Iwahashi M., Satoh C., Nakayama T., Ito T., Iseda K., Nishizawa K., Shima S., Togawa O. (2004). Winter transport and tidal current in the Tsugaru Strait. *Bull. Fish. Sci. Hokkaido Univ.*, 552, 105-119.
- Park J.J., Kim K., Yang J-Y. (2008). Aspiration and outflow of the intermediate water in the East/Japan Sea through the Tsugaru Strait. *Geophys. Res. Lett.*, 35, L07601.
- Saitoh Y., Kuma K., Isoda Y., Kuroda H., Matsuura H., Wagawam T., Takata H., Kobayashi N., Nagao S., Nakatsuka T. (2008). Processes influencing iron distribution in the coastal waters of the Tsugaru Strait Japan. *J. Oceanogr.*, 64, 815-830.
- Sandery P.A. (2005). Towards an understanding of the flushing of Bass Strait. In: *Proc. Australia Inst. Physics, 16th Biennial Congr. 1999*, Colla M (eds). ANU: Canberra; pp1-5.
- Takeoka H. (1984). Fundamental concepts of exchange and transport time scales in a coastal sea. *Cont. Shelf Res.*, 33, 311-326.
- Toba Y., Tomizawa K., Kurasawa Y., Hanawa K. (1982). Seasonal and year-to-year variability of the Tsushima-Tsugaru Warm Current system with its possible cause. *La Mer*, 20, 41-51.



- Uchimoto K., Nakamura T., Mitsudera H. (2011). Tracing dense shelf water in the Sea of Okhotsk with an ocean general circulation model. *Hydrological Res. Lett.*, 5, 1-5.
- Unoki S. (2010). *Ryukei no Kagaku - YamaKawaUmi wo tsuranuku mizu no furumai*. Tsukiji-Shokan Press: Tokyo; 364pp (in Japanese).
- Walker S.J. (1999). Coupled hydrodynamic and transport models of Port Phillip Bay a semi-enclosed bay in south-eastern Australia. *Mar. Freshwater Res.*, 50, 469-481.

## **INTERPLAY OF STEADY AND TIDAL CURRENTS IN FLUSHING OF WATER OUT OF HAKODATE BAY FROM A LAGRANGIAN EXPERIMENT**

QUANG-HUNG LUU <sup>1,2,\*</sup>, VAN-CUC TRAN <sup>2</sup>, SATOSHI NAKADA <sup>3</sup>, YOICHI ISHIKAWA <sup>3</sup>  
and TOSHIYUKI AWAJI <sup>3</sup>

1) Tropical Marine Science Institute, National University of Singapore  
18 Kent Ridge Road, 119227, SINGAPORE

2) Department of Mechanics, College of Science, Vietnam National University, Hanoi  
334 Nguyen Trai Street, Thanh Xuan District, Hanoi, VIETNAM

3) Department of Geophysics, Kyoto University  
Kitashirakawaoiwake-cho, Sakyo-ku, Kyoto, 606-8502, JAPAN

\*e-mail: [tmslqh@nus.edu.sg](mailto:tmslqh@nus.edu.sg), [hunglq@vnu.edu.vn](mailto:hunglq@vnu.edu.vn)

### **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.

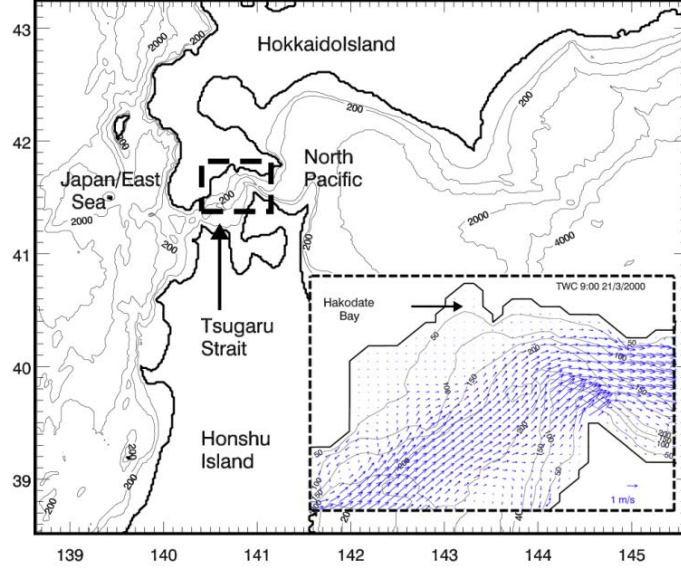
## **2. EXPERIMENTAL DESIGN**

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 (GTSP), 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

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

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,  $\Delta t$  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  $1/54^\circ \times 1/72^\circ$  (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.

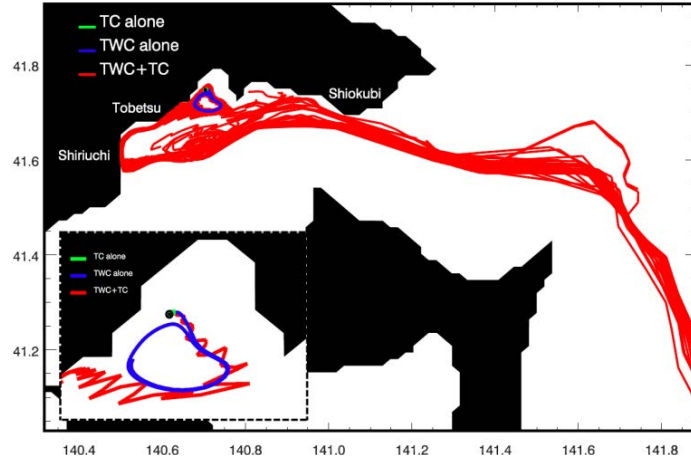
**Table 1.** Settings of three Lagrangian experiments.

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.



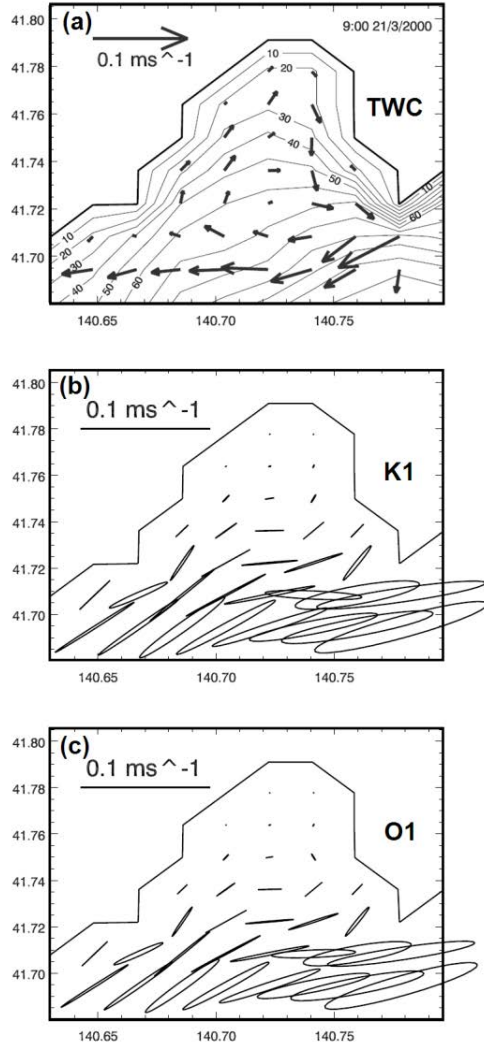
**Figure 2.** Particle paths during 24 days of calculations in experiments EXP\_TWC (blue color), EXP\_TIDE (green color), and EXP\_CPL (red color). The circle marks initial particle positions. Particle positions are plotted once each 6 hours. A magnification of Hakodate Bay is shown in the lower inset.

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.

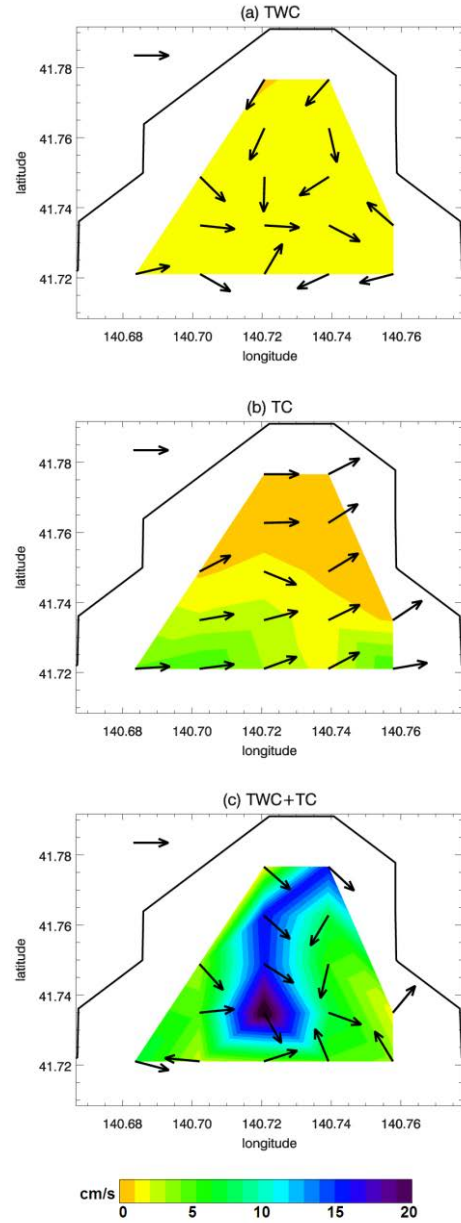
To quantify the differences, we defined the Lagrangian offshore velocity averaged over the period  $T = t_n - t_0$  as

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

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.



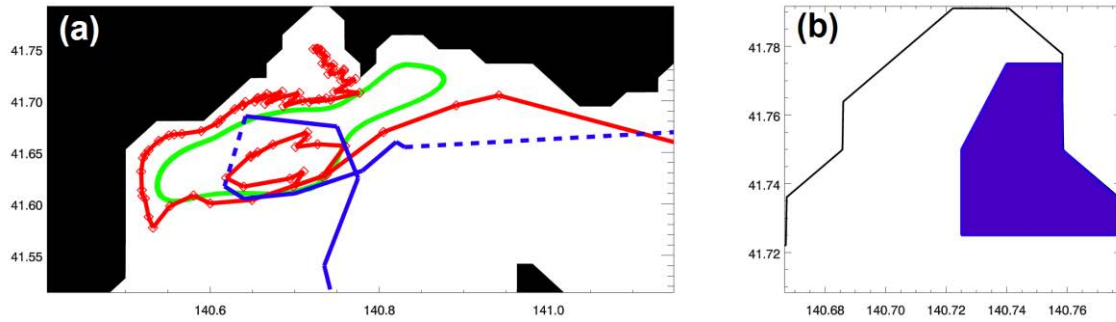
**Figure 4.** Lagrangian velocity averaged over 27.2 days (unit in m/s) for experiments (a) EXP\_TWC, (b) EXP\_TIDE, and (c) EXP\_CPL

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.

## 5. ACKNOWLEDGEMENTS

The authors wish to thank J. P. Matthews for critical reading, and T. In for providing data of the TWC. We also thank H. Nakao, M. Kurebayashi at the Hokkaido Government Oshima General Sub-prefectural Bureau. This work was supported by “Hakodate Marine Bio Cluster Project” in the Knowledge Cluster Program from 2009 and the Grand-in-Aid for University and Society Collaboration from the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan.

## 6. REFERENCES

- Delhez E.J.M., Campin J.M., Hirst A.C., Deleersnijder E. (1999). Toward a general theory of the age in ocean modeling. *Ocea. Mod.*, 1, 17-27.
- Hartnett M., Gleeson F., Falconer R., Finegan M. (2003). Flushing study assessment of a tidally active coastal embayment. *Adv. Environ. Res.*, 7, 847-857.
- Ito T., Togawa O., Ohnishi M., Isoda Y., Nakayama T., Shima S., Kuroda H., Iwahashi M., Sato C. (2003). Variation of velocity and volume transport of the Tsugaru Warm Current in the winter of 1999-2000. *Geophys. Res. Lett.*, 30(13), 1678.
- Ishikawa Y., Awaji T., Toyoda T., In T., Nishina K., Nakayama T., Shima S., Masuda S. (2009). High-resolution synthetic monitoring by a 4-dimensional variational data assimilation system in the northwestern North Pacific. *J. Mar. Sys.*, 78(2), 237-248.
- Isoda Y., and Baba K. (1998). Tides and tidal currents in the Tsugaru Strait. *Bull. Fish. Sci. Hokkaido Univ.*, 493, 117-130.
- Joh M., Takasu T., Nakaya M., Yoshida N., Nakagami M. (2009). Comparison of the nutritional transition date distributions of marbled sole larvae and juveniles in Hakodate Bay, *Hokkaido. Fish. Sci.*, 75, 619-628.
- Luu Q-H., Ito K., Ishikawa Y., Awaji T. (2011). Tidal transport through the Tsugaru Strait - Part I: Characteristics of tidal flow and tidal residual current. *Ocea. Sci. J.*, 464, 273-288.
- Maruyama T., Suzuki S. (1998). The present state of effluent control in Japan and pollutant load from fish culture to environment - Possibility of intensive recirculating fish culture systems. *Nippon Suisan Gakkaishi*, 642, 216-226.
- Nakao S. (1976). Feeding types of three species of uncinata polychaetes in relation to sediment: characteristics and species composition. *Bull. Fish. Sci. Hokkaido Univ.*, 272, 63-70.
- Nakao S. (1982). Community structures of the macro-benthos in the shallow waters in Northern Japan. *Memoirs Fish., Hokkaido Univ.*, 282, 255-304.
- Nishida Y. (2003). Transformation of the watermass structures across the Tsugaru Strait in spring. *Oceanogr. Japan*, 126, 593-602.
- Onishi M., Isoda Y., Kuroda H., Iwahashi M., Satoh C., Nakayama T., Ito T., Iseda K., Nishizawa K., Shima S., Togawa O. (2004). Winter transport and tidal current in the Tsugaru Strait. *Bull. Fish. Sci. Hokkaido Univ.*, 552, 105-119.
- Park J.J., Kim K., Yang J-Y. (2008). Aspiration and outflow of the intermediate water in the East/Japan Sea through the Tsugaru Strait. *Geophys. Res. Lett.*, 35, L07601.
- Saitoh Y., Kuma K., Isoda Y., Kuroda H., Matsuura H., Wagawam T., Takata H., Kobayashi N., Nagao S., Nakatsuka T. (2008). Processes influencing iron distribution in the coastal waters of the Tsugaru Strait Japan. *J. Oceanogr.*, 64, 815-830.
- Sandery P.A. (2005). Towards an understanding of the flushing of Bass Strait. In: *Proc. Australia Inst. Physics, 16th Biennial Congr. 1999*, Colla M (eds). ANU: Canberra; pp1-5.
- Takeoka H. (1984). Fundamental concepts of exchange and transport time scales in a coastal sea. *Cont. Shelf Res.*, 33, 311-326.
- Toba Y., Tomizawa K., Kurasawa Y., Hanawa K. (1982). Seasonal and year-to-year variability of the Tsushima-Tsugaru Warm Current system with its possible cause. *La Mer*, 20, 41-51.



- Uchimoto K., Nakamura T., Mitsudera H. (2011). Tracing dense shelf water in the Sea of Okhotsk with an ocean general circulation model. *Hydrological Res. Lett.*, 5, 1-5.
- Unoki S. (2010). *Ryukei no Kagaku - YamaKawaUmi wo tsuranuku mizu no furumai*. Tsukiji-Shokan Press: Tokyo; 364pp (in Japanese).
- Walker S.J. (1999). Coupled hydrodynamic and transport models of Port Phillip Bay a semi-enclosed bay in south-eastern Australia. *Mar. Freshwater Res.*, 50, 469-481.