



Aspiration and outflow of the intermediate water in the East/Japan Sea through the Tsugaru Strait

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[1] Outflow of the intermediate water in the East/Japan Sea through the Tsugaru Strait is inferred from the fact that profiling floats deployed below the sill depth in the central East/Japan Sea moved out to the Northwest Pacific Ocean through the Strait. Careful analysis of the float trajectories reveals that profiling floats parked at 350m, 700m, and 800m could be uplifted from depths below the sill of the Tsugaru Strait and moved over the 140m deep sill with a probability close to 100%. Application of an analytical model for the Bernoulli suction shows that intermediate waters can be aspirated over the sill depth of the Tsugaru Strait in late winter. **Citation:** Park, J. J., K. Kim, and J.-Y. Yang (2008), Aspiration and outflow of the intermediate water in the East/Japan Sea through the Tsugaru Strait, *Geophys. Res. Lett.*, 35, L07601, doi:10.1029/2007GL032981.

1. Introduction

[2] The East/Japan Sea (hereafter EJS) is a deep semi-enclosed marginal basin, which is connected with the North Pacific and the Okhotsk Sea through the Korea/Tsushima, Tsugaru, Soya, and Tatar Straits (Figure 1), whose sill depths are shallower than 140 m or less. The Tsushima Current of warm and saline water flows into the EJS through the Korea/Tsushima Strait and out through the Tsugaru and Soya Strait. The spatial structure and annual variation of the currents in the Tsugaru Strait have been recently revealed by ADCP measurements [Onishi *et al.*, 2004], which indicate that it is the major outlet in terms of volume transport.

[3] The EJS possesses its own deep water which is formed through convective overturning in wintertime and comprises various water masses just like the open oceans [Kim *et al.*, 2004]. The water masses formed in the northern part of the EJS fill up below the thermocline in the entire EJS including the southern part. As the depth of the permanent thermocline in the southern part of the EJS is about 200 m which is deeper than sill depths of not only the Tsugaru Strait but also the other straits, previous studies assumed that the whole water masses formed in the EJS should be isolated from the North Pacific and be consumed only within the EJS by dilution with surface water [Yanagi, 2002].

[4] Little attention has been paid to any possibility of the outflow of water below the permanent thermocline into the

neighboring seas and the North Pacific except for a thin layer of the cold bottom water in the Korea Strait, originating from the northern EJS [Kim *et al.*, 2006]. It is well known that this layer does not extend any farther out of the Korea Strait. Also, it should be noted that Kang *et al.* [2003] recently noted the depletion of the deep water mass and the augmentation of the intermediate waters in the EJS and Kwon *et al.* [2004] has shown the long-term change of the water masses. Heat and salt balances in the EJS require a priori correct water budget including any outflow of deep waters from the EJS. Thus, it is crucial to know whether any water below the thermocline finds a way out of the EJS.

[5] In this paper, we will provide the first observational evidence of intermediate water outflow through the Tsugaru Strait, using the trajectory data of profiling floats. Firstly, the detail characteristics of floats will be introduced, which are essential to demonstrate that the floats drift out with the intermediate water. Secondly, we will present a quantitative probability of which floats moved over the sill and went out of the EJS. Finally, an aspiration process will be proposed as a possible mechanism of the outflow.

2. Data and Result

2.1. Profiling Float Data in the East/Japan Sea

[6] The profiling float cycles vertically between a preset depth and the sea surface, changing its density periodically. It freely drifts for a pre-programmed time interval with the surrounding water at the preset depth (so called parking depth) and measures a temperature and salinity profile during its ascending to the sea surface. Then, while it broadcasts its data, position and time of the float at the surface are observed by satellites. It is important to know that a float drifts an unknown distance after it rises to the sea surface until its position is fixed by the satellite. Floats also drift away after their last contact with a satellite until they start to dive. Therefore, a special treatment of data such as proposed recently by Park *et al.* [2005] is required in order to trace the float trajectory at the parking depth accurately, since a full surface trajectory is not immediately available.

[7] More than 100 floats have been deployed in the EJS since 1996 and most of them moved around in the Ulleung Basin and the Japan Basin. Eight floats approached the Tsugaru Strait within 100 km from the Tappi Sill (Table 1). Five floats passed through the Tsugaru Strait and moved out into the North Pacific. We easily identify from the satellite fixes that two floats, UW229 and 10029, in Table 1 passed over the Tappi sill while they drifted at the surface. However, trajectories of the three floats in Figure 2a have no surface fixes near the sill. We will examine carefully whether those floats moved over the sill while they were at depth, indicating uplift of deep water from a depth below the sill.

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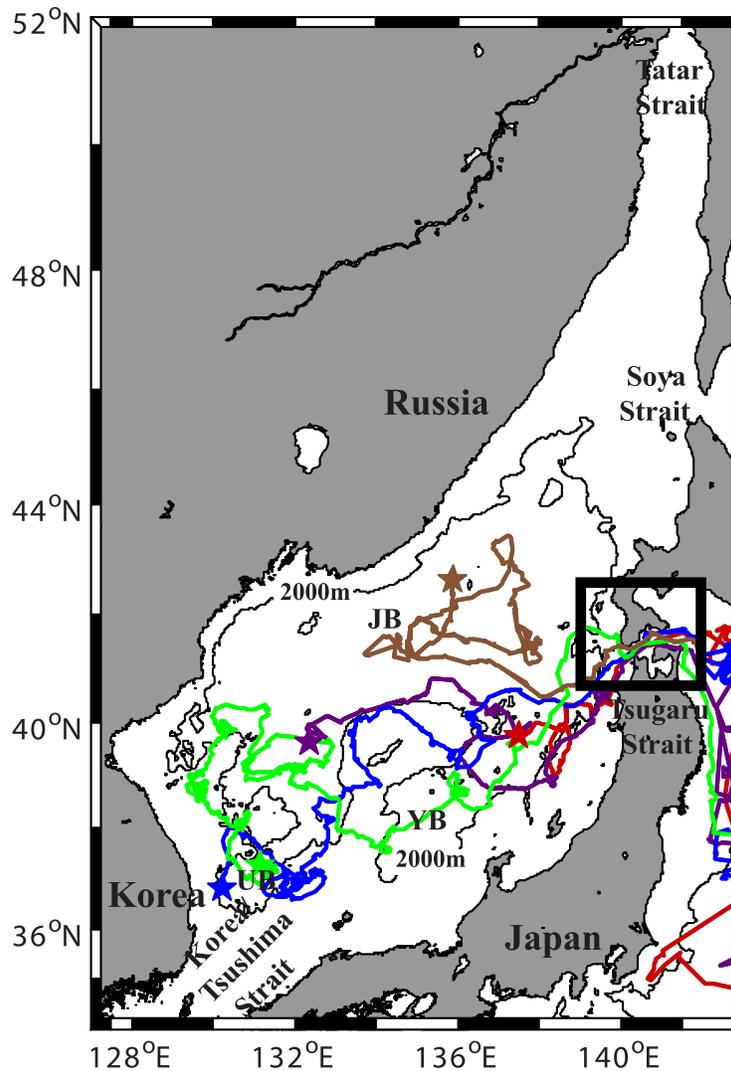


Figure 1. Trajectories of the floats which pass through the Tsugaru Strait. Red: UW213, Violet: SNU350, Blue: 08173, Brown: UW229, Green: 10029. Stars denote deployment positions. Isobath of 2000 m are indicated and three basins (UB: Ulleung Basin, JB: Japan Basin, YB: Yamato Basin).

[8] It is remarkable to note that all three floats, UW213, SNU350, and 08173, passed through the Tsugaru Strait in late winter. However, two other floats, UW272 and UW288 that approached the sill in summer, never went out of the EJS (Table 1).

[9] Figure 2b shows bottom topography near the Tappi Sill and schematic diagrams of float trajectories at the sea surface and at depth. In order to clarify that a float can go over the sill, we have to know the positions (P_{DS} and P_{AS}) in principle where a float reaches the depth equal to the sill

depth, 140 m, during its descent and ascent (Figure 2b). Since it is difficult to directly estimate the positions (P_{DS} and P_{AS}), we will show the possibility that the position of the Tappi Sill (P_S) is located between P_{DS} and P_{AS} .

2.2. Time Information

[10] Besides of the float trajectory data obtained by Argos satellites, additional information on timing when a float starts to dive and arrives to the sea surface can be traced using the cycle period and cycle number of each float

Table 1. Status of Floats Approaching Near the Tsugaru Strait

Float ID	Date	Shortest Distance From the Tappi Sill, km	Parking Depth, dbar	Cycle Period [(UP-time) + (DOWN-time)], hours	Passing Through the Tsugaru Strait
SNU350	March 12, 1998	33.8	350	240 [10 + 230]	Over the sill
UW213	February 24, 2000	35.6	800	186 [18 + 168]	Over the sill
08173	March 14, 2000	33.0	750	120 [18 + 102]	Over the sill
UW229	October 8, 2001	8.9	800	186 [18 + 168]	At the surface
10029	May 8, 2001	2.1	750	120 [18 + 102]	At the surface
UW272	July 16, 2001	92.7	800	186 [18 + 168]	No passing
UW288	July 23, 2001	20.2	800	186 [18 + 168]	No passing

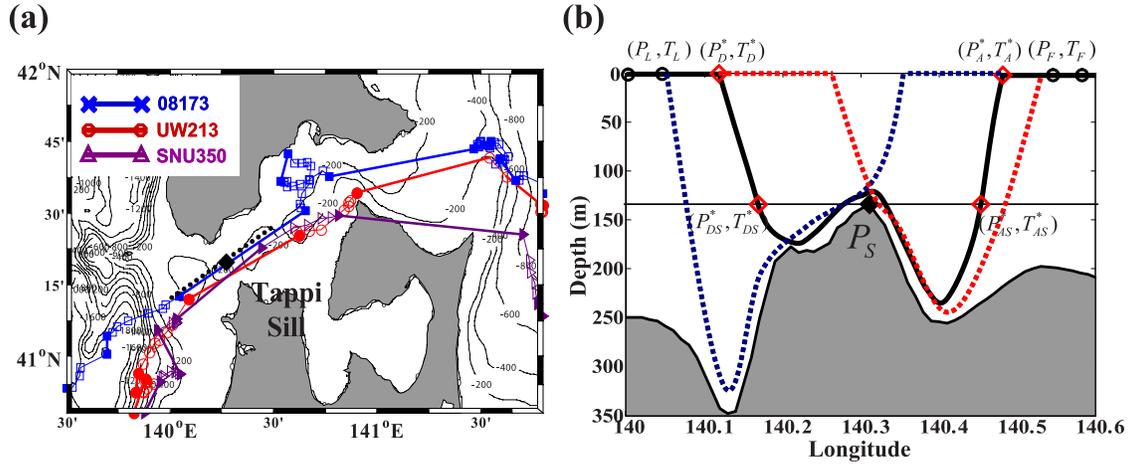


Figure 2. (a) Detailed trajectories in and around the Tsugaru Strait. Open and closed symbols are positions measured by Argos satellites and positions extrapolated using the method by *Park et al.* [2005]. Thick and thin lines are float trajectories at the subsurface and the sea surface. Red: UW213, Violet: SNU350, Blue: 08173. A black diamond denotes the location of the Tappi Sill. (b) A section along the black dotted line in Figure 2a and a schematic diagram of float trajectory. Black open circles are the observed fixes and red diamonds are the estimated fixes. P_S is location of the Sill. P and T denote position and time at each fix. A black curve shows the case that a float sinks below the sill depth as it approaches the Tsugaru Strait and moves over the sill. Dotted lines in red and blue are the extreme cases that a float sinks from the sea surface or rises to the sea surface as it passes the sill depth and enters the Tsugaru Strait. The depth at the Tappi Sill is 140 m.

according to *Park et al.* [2005] within an accuracy of tens of minutes, as follows:

$$T_D^m = T_R + (m - 1)\Delta T_{cyc}, \quad (m = 1, 2, 3, \dots, M) \quad (1a)$$

$$T_A^m = T_R + (m - 1)\Delta T_{cyc} + \Delta T_{down} + \Delta T_{asc} \quad (1b)$$

where T_D^m and T_A^m are Descending-Start-Times and Ascending-End-Times at the m th cycle, ΔT_{cyc} the cycle period of float operation, ΔT_{down} the “DOWN-time” which means the duration from starting to dive to starting to ascend (Table 1), ΔT_{asc} the time from starting to ascend to arriving at the surface.

[11] We know the float ascending speed (typically 0.08 dbar/sec) as well as the deepest depth where a float parks using previous profile data so that we can estimate ΔT_{asc} . Similarly, the time ($T_A - T_{AS}$) taking to ascend from 140 m depth to the surface can be also computed with the ascending rate, which is about 0.49 hours. Even though the time difference between T_D and T_{DS} cannot be directly computed, according to the descent rate test of *Davis et al.* [1992], it takes about a half hour to pass the depth of 140 m after a float dives to the depth.

[12] Therefore, the time differences between T_L and T_{DS} and that between T_{AS} and T_F (ΔT_{LDS} and ΔT_{ASF} , respectively) are

$$\begin{aligned} \Delta T_{LDS} &= (T_{DS} - T_L) = (T_D - T_L) + (T_{DS} - T_D) \\ &\approx (T_D - T_L) + 0.5h \end{aligned} \quad (2a)$$

$$\begin{aligned} \Delta T_{ASF} &= (T_F - T_{AS}) = (T_F - T_A) + (T_A - T_{AS}) \\ &\approx (T_F - T_A) + 0.5h, \end{aligned} \quad (2b)$$

which are listed in Table 2.

2.3. Extrapolation Using Surface Trajectory of Float

[13] The temporal integration of the surface velocities for the unknown drifting periods ($T_D - T_L$ and $T_F - T_A$) could

provide estimates of surfacing and diving positions as extrapolations from the surface trajectories. Closed symbols in Figure 2a show the extrapolated positions where the three floats surface and dive near the Tappi Sill according to *Park et al.* [2005].

[14] In fact, P_{DS} and P_{AS} in Figure 2b are the positions that we have to know in order to demonstrate that the floats dive below the sill depth and yet go over the sill. Even though we have no further information on the vertical structure of current around the sill, we can compute the upper limit of the distance which a float may drift from P_D to P_{DS} and from P_{AS} to P_A under the assumption of homogeneous currents in depth. Maximum current speeds estimated at the surface are 0.85 m/s for 08173, 0.41 m/s for SNU350, and 0.91 m/s for UW213. P_{DS} and P_{AS} may be apart from P_D and P_A by only 1.5 km, 0.7 km, and 1.6 km in maximum, respectively, which are more than 10 times smaller than the distance from the sill (P_S). Therefore, it is clearly evident that all floats sink down before they reach the sill and rise up after passing over the sill.

2.4. Probability of Float Movements Over the Tappi Sill

[15] In this section, we investigate the quantitative probability that the three floats could move over the sill

Table 2. Parameters and Probabilities for Tracking Subsurface Trajectory of Float

Parameter	Float ID	SNU350	UW213	08173
Distance	ΔP_{LS}	33.8 km	35.6 km	33.0 km
	ΔP_{SF}	26.9 km	27.4 km	33.5 km
Time	ΔT_{LDS}	3.2 h	6.2 h	4.6 h
	ΔT_{ASF}	4.3 h	0.6 h	1.2 h
Min. Velocity	V_{LDS}^{\min}	2.9 m/s	1.6 m/s	2.0 m/s
	V_{ASF}^{\min}	1.7 m/s	12.7 m/s	7.8 m/s
Probability of no outflow	$P_{LDS} (V_{LDS} \geq V_{LDS}^{\min})$	0 %	0.7 %	0.1 %
	$P_{ASF} (V_{ASF} \geq V_{ASF}^{\min})$	0.4 %	0 %	0 %
Probability	$P = 1 - (P_{LS} + P_{SF})$	99.6 %	99.3 %	99.9 %

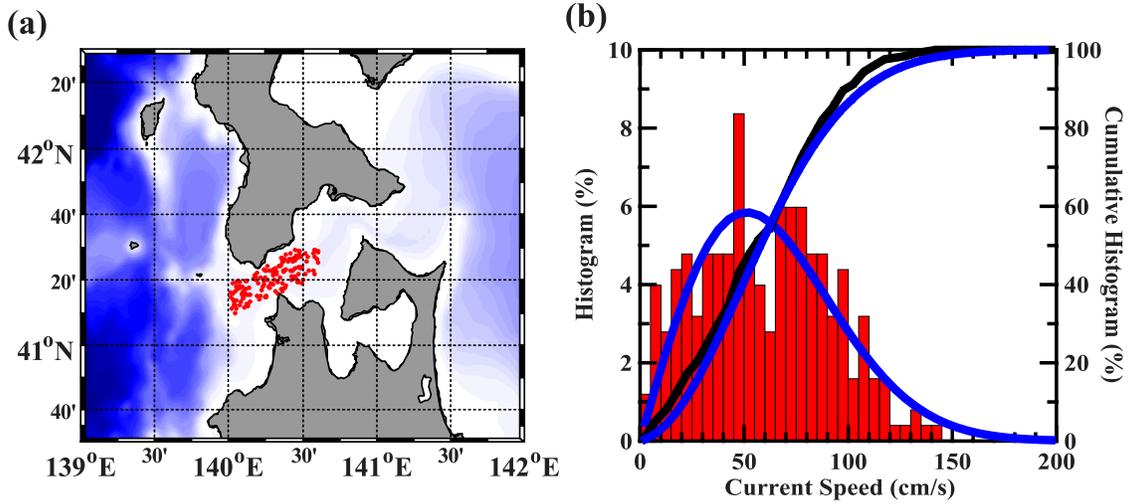


Figure 3. (a) Locations of satellite tracked drifters for estimation of current velocities. (b) Histogram of current speed near the Tsugaru Strait in a bar chart; a black dotted line present the cumulative histogram and a solid line in blue is the fitted curve with a Rayleigh function with its cumulative function as a dotted line in blue.

following the bottom. There are two extreme cases that a float may pass through the Tsugaru Strait without huddling the sill, which are indicated as dotted lines in red and blue in Figure 2b. For the case of the red trajectory, if P_{DS}^* were placed at the eastern side of P_S , a float would pass through above the sill while it is ascending or it is at the surface after ascending. For the case of the blue trajectory, if P_{AS}^* were at the western side of the P_S , a float could go by the sill while it is at the surface before descending or it is descending. Thus, showing that a float trajectory does belong to neither case, we demonstrate that the float must move over the sill if none of two extreme cases are possible in reality.

[16] At this point, P_{DS}^* and P_{AS}^* cannot estimated from the trajectory data directly, but a minimum drifting speed of a float can be obtained, which is required for P_{DS}^* to be at the eastern side of the P_S or P_{AS}^* to be at the western side of P_S . In other words, the drifting speeds means a minimum value for a float to pass through the sill while it is at the depth shallower than the sill depth, which follows as

$$V_{LDS}^{\min} = \frac{\Delta P_{LS}}{\Delta T_{LDS}} = \frac{|P_L - P_S|}{\Delta T_{LDS}} \quad \text{and} \quad V_{ASF}^{\min} = \frac{\Delta P_{SF}}{\Delta T_{LDS}} = \frac{|P_S - P_F|}{\Delta T_{ASF}}. \quad (3)$$

[17] If the mean speed of currents between P_L and P_S (V_{LDS}) exceeds the minimum speed (V_{LDS}^{\min}) or that between P_F and P_S (V_{ASF}) exceeds V_{ASF}^{\min} , a float just passes through the Tsugaru Strait while it is at a depth above the sill. The distances and the minimum velocities are tabulated in Table 2 for each float.

[18] The probability ($P_{no_overflow}$) with which the overflow from depths below the sill never happens are

$$P_{LDS} = P(V_{LDS} > V_{LDS}^{\min}), \quad P_{ASF} = P(V_{ASF} > V_{ASF}^{\min}) \quad (4a)$$

$$P_{no_overflow} = P_{LDS} + P_{ASF}. \quad (4b)$$

[19] Therefore, the probability ($P_{overflow}$) that a float flows over the sill can be calculated as $P_{overflow} = 1 - P_{no_overflow}$.

[20] In order to compute the probabilities in (4a) and (4b), we utilize the current velocity data estimated from satellite

tracked drifter trajectories which passed through the Tsugaru Strait from 1990 to 2005, whose drogoue loss indexes have been quality-controlled by AOML (Atlantic Oceanographic and Meteorological Laboratory). The whole drifter trajectories are interpolated using the method reported by Bograd *et al.* [1999] and the current velocities have been calculated every 3 hours. The total number of current speed samples reaches 460 and the mean current speed is about 0.6 m/s (Figure 3).

[21] The histogram of the surface current speeds in Figure 3b is well fitted into a Rayleigh function with correlation of 0.94. Also, the fitted Rayleigh cumulative function has a high correlation of 0.99 with the observational cumulative histogram. According to this probability distribution function, P_{LDS} and P_{ASF} in (4a) have been computed and listed in Table 2.

[22] The possibilities in Table 2 indicate that the current speeds near the Tappi Sill are mostly smaller than the minimum velocities (V_{LDS}^{\min} and V_{ASF}^{\min}). That is, the surface currents near the sill are not strong enough to let the floats pass through the sill before they dive below the sill depth, with possibility of 99.3%~99.9%. Indeed, the maximum current speed measured by the drifters reaches only about 1.4 m/s which is substantially smaller than the minimum speeds required for a float to pass the sill depth. Therefore, we can conclude that all three floats, SNU350, UW213, and 08173, must sink down below the sill depth and then go over the sill. There is an extremely small chance that these floats moved out of the EJS by drifting at the surface. The mean and tidal currents in the Tsugaru Strait reported by Onishi *et al.* [2004] typically are maximum values of 0.5 m/s and 0.2~0.3 m/s (for dominant constituents of M2, K1, and O1) in winter, respectively, which also support the probability estimated from surface drifters in this paper.

3. Aspiration

[23] An ideal model known as Bernoulli Suction which was used for the Strait of Gibraltar and the Alboran Sea

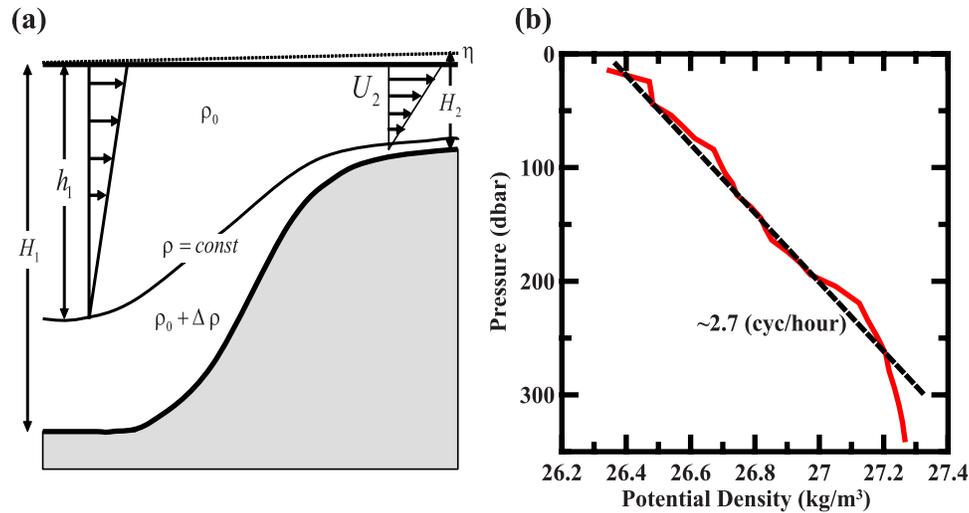


Figure 4. (a) Definition sketch for a steady, stratified flow over a sill. The density linearly increases from the surface to the bottom. (b) An example of a density in red near the Tappi Sill in March 2000. The average buoyancy frequency from the surface to 300 dbar is about 2.7 cycle/hour (in a dotted line).

by *Stommel et al.* [1973] can be applied for the outflow of deep water from the EJS and its seasonal dependence. Later, *Seim and Gregg* [1997] introduced a simple dynamical formulation for the Bernoulli Suction under a constant stratification and showed that the depth of fluid below sill depth which could be aspirated, $h_1 - H_2$, is a function of U_2/N (Figure 4a). According to *Seim and Gregg* [1997] the depth of the offshore streamline (h_1) can be formulated as

$$h_1 = \frac{1}{2}H_2 + \left(\frac{1}{4}H_2^2 + \frac{U_2^2}{N^2}\right)^{1/2}, \quad (5)$$

where $N^2 = g\Delta\rho/\rho_0H_1$, g is the gravitational acceleration, ρ_0 the surface density, and $\Delta\rho$ is the density difference from top to bottom in the deep basin.

[24] Figure 4b is an example of potential density profile right near the Tappi Sill which was obtained in March, 2000, the late winter. Average buoyancy frequency (N) is about $5 \times 10^{-3} \text{ s}^{-1}$. Supposing that current speed in the strait is about 1.4 m/s which is the maximum of the current velocities in Figure 3, h_1 is computed as about 380 m. So, fluid deeper by 240 m than the sill depth of 140 m can go over the sill and enter the Tsugaru Strait. On the other hand, the typical buoyancy frequency in summer reaches about $2 \times 10^{-2} \text{ s}^{-1}$, which is 4 times larger than that in winter, and h_1 becomes about 170 m under the same speed of surface current. Therefore, the late winter is the most favorable season for deep water flows out to the North Pacific because of the weak vertical stratification.

[25] As mentioned in section 2.1, the floats are designed to follow isobaric surfaces. So, the floats of UW213 and 08173 with the parking depth of 800 dbar might be denser than the surrounding water even though they grounded in front of the sill at the ocean bottom of 300 m depths (in-situ density at 300 dbar: 1028.7 kg/m^3 ; density at 800 dbar: 1031.0 kg/m^3). Also there is a possibility that some sediment like mud could be attached on surface of the float (D. Swift,

personal communication, University of Washington, 2007). It should be noted that these behaviors could make a float denser than expected and prevents it from going over the sill with the surrounding fluid. However, all floats move to shallower regions (shallower than about 300 m) while they are at the surface before going over the sill. Indeed, the subsurface drifts of the floats (UW213 and SNU350) near the mouth of the Tsugaru Strait either following isobaths or hardly move around at depth before moving toward the sill at the surface. Even though the floats may be heavier than the surrounding bottom water, it is conjectured that they may slide or walk over the ocean bottom to traverse the sill by advection within strong currents at the bottom.

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