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Original

Kuroshio or Oyashio—Sources of the 700 m Deep Ocean Water off Hualien coast, eastern Taiwan

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Abstract

The deep ocean water obtained by pipe lines deployed at ca. 700 m depth off Hualien coast, eastern Taiwan has been characterized by its physical properties to be the result of mixing of three far distance sources: (1) the Deep Arctic/Circumpolar Water (DACW), (2) the North Pacific Intermediate Water (NPIW) which is originated from the sinking of the mixture of Okhotsk Sea Water/Oyashio Water/Kuroshio Extension Water (OKW+OYW+KEW) and (3) the Kuroshio Tropical Water (KTW). By calculating the mixing ratio, the contribution fractions of the three end-members are approximately 34%, 59% and 7%, respectively. If judging by water column type at 27.0 σ_θ, the water shows 66% and 34% resemblance to the water of the Philippine Sea and the South China Sea, respectively. The measurement of silicate content in the intake water (range 78–92 μM Si at 700 m) is a convenient way to monitor the stability of the water layer as the resolution can reach 0.04℃ μM^{-1}. The risk of the radioactive pollution due to the 2011 Fukushima Nuclear Event has been evaluated by analyzing the water mass movements along the isopycnal lines.

***Key Words*:** Deep ocean water, Hualien, Kuroshio, Oyashio

1. Introduction

Deep ocean water is an important resource for the water industry in eastern Taiwan where three pipe lines (see Fig. 1, Table 1) have already been deployed on the Pacific coast of Hualien to collect water for commercial use at 710, 618 and 662 m depths, respectively (Takahashi *et al.*, 2012). The water has a quite consistent salinity ranging from 34.2 to 34.4 with an apparent temperature around 10℃ at the on-shore pumping station. This temperature is a few degrees higher (3–4℃) than that at the intake location due to the long distance pumping (a few hours through a few km long pipeline). At present, the deep ocean water is mainly used to produce bottled drinking water. Therefore its stability and quality have received extensive attention. One of the major concerns is: "Where does the water come from?" Some believe that the water is pumped up from the bottom of the Kuroshio current, so it should be clean, with less bacteria and rich in nutrients. Another believe is that the deep ocean water originates from the arctic regions (including both Arctic Ocean and Antarctic Circumpolar Current) where cold seawater sinks to and moves along the ocean bottom by a global conveyer belt. Both ideas may be partially true but the reason why there is a low salinity layer in the intermediate depth (400–600 m) needs to be further explained. This low salinity water layer is normally named the Kuroshio Intermediate Water (KIW) by local scientists (Chen, 1988; Chen, 1996; Chen and Wong, 1998), and it is apparently from a distance source east of Japan

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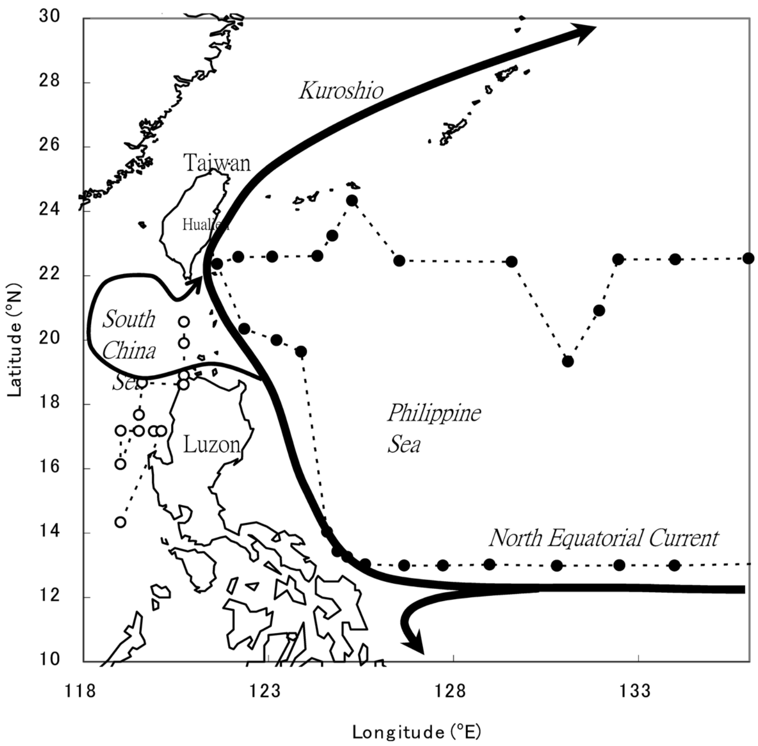

Fig. 1. Location of Hualien in eastern Taiwan where three deep ocean water pipe lines were deployed and the flow pattern of the nearby Kuroshio current. The surface water also receives substantial influence from the South China Sea as a branch of the Kuroshio flows in and out of the Bashi Channel, north of Luzon, then rejoins the Kuroshio main stream. Hydrographic data from stations of the INDOPAC Leg-3 cruise (dots) and the ORI-266 cruise (circles) were analyzed in this study.

Table 1. Information of three deep ocean water pipe lines deployed off Hualien.

Company	Intake depth (m)	Pipe length (m)	Pipe i.d. (cm)	Intake volume (m^3/day)
EB	710	4200	15.5	800
KB	618	2900	15.5	950
TF	662	4300	25.5	2400

EB: Eastlife Biotech Co. Ltd.; KB: Kung-Long Biotech Co. Ltd.; TF: Taiwan Fertilizer Co. Ltd. Hualien Factory.

(Tally 1993; Tally *et al.*, 1995) which is customarily named the "North Pacific Intermediate Water" (NPIW). The present study will present a quantitative way to connect the Hualien 700-m water layer to NPIW and other sources. In addition, since the source of NPIW is very near to the north-eastern coast of Japan, the possibility of radioactive pollution due to the 2011 Fukushima Nuclear Plant Event will also be discussed.

2. Water mass analysis

General information

Hualien is a harbor city located at the east coast of Taiwan. The city faces the Philippine Sea and a strong north-bound current, the Kuroshio, flows just as near as 20 km from the shore. The seafloor off Hualien harbor is very steep and the bottom depth can drop to as deep as few thousand meters within 10 km from the coastline. In these environment most people would think that the pumped-up deep ocean water should come from either the Kuroshio current or the deep Philippine Sea. However, Wong and Chern (1988) and Chen and Wong (1998) have found that the outflow of the South China Sea Intermediate Water has strong influence. Chern *et al.* (2010) have indicated that a branch of the Kuroshio current enters the South China Sea and then turns out through the Bashi Channel to rejoin the Kuroshio main stream. Jan *et al.* (2010) have confirmed the pathway through a numerical model. As a result, the water column off Hualien, from surface down to 1000 m, may well receive characteristics from both seas (Mensah *et al.*, 2014). Below 500 m depth, the water columns of the two seas may intrude upon each other in a horizontal way along the isopycnal surface.

To further describe the hydrographic background two historic data sources are used: the INODOPAC Leg-3 cruise (or IP-3 cruise, 1976) which covered almost the entire western Philippine Sea and the ORI-266 cruise (1990) which sailed through the Luzon Strait and the northern South China Sea. Overlapped profiles of temperature and salinity as well as *T*–*S* diagrams are shown in Figs. 2 and 3. The temperature profiles are shown by

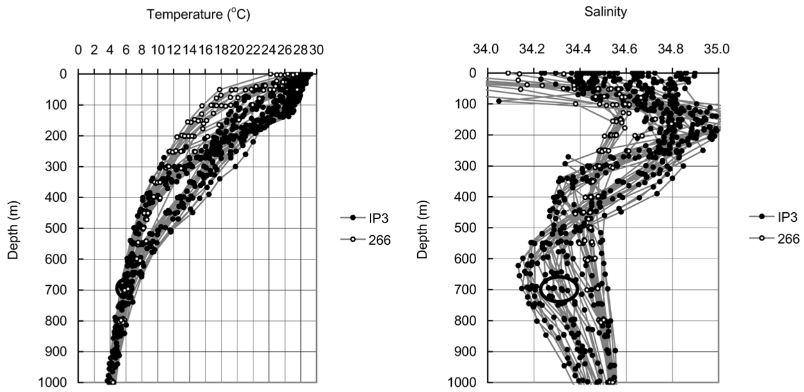

Fig. 2. Profiles of temperature and salinity of the Philippine Sea (dot data taken from INDOPAC Leg-3 or the IP3 cruise) and the South China Sea (circle data taken from the ORI-266 cruise). Circles indicate the possible temperature range of 5.5–6.5℃ and salinity range of 34.25–34.35 at 700 m for stations near eastern Taiwan.

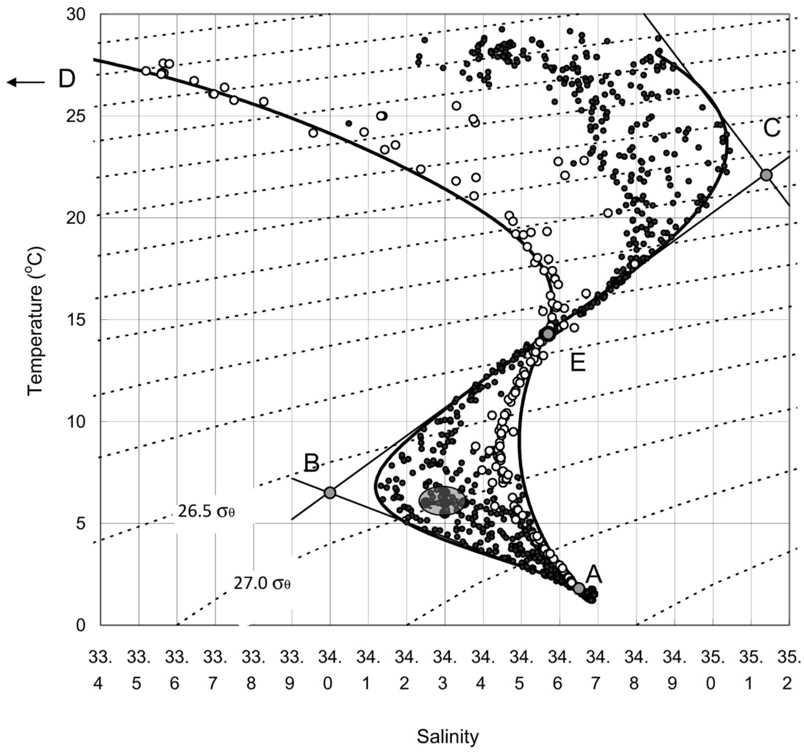

Fig. 3. Scattered *T*–*S* plot from data of INDOPAC Leg-3 Cruise (dot) and ORI-266 Cruise (circle). The two "S" lines indicate boundaries of two water column types namely the Philippine Sea type (A–B–C) and the South China Sea type (A–E–D). Several end members can be defined at cross points of extended lines. A: the Deep Arctic/Circumpolar Water, T=1.8℃, S=34.65; B: the North Pacific Intermediate Water, T=6.5℃, S=34.0; C: the Kuroshio Tropical Water, T=22.1℃, S=35.14; D: surface freshwater. The two "S" lines intersect at point E (T=14.3℃, S=34.57, σ_θ=25.8) showing the existence of a horizontal front between the surface and intermediate layers. The shaded circle (the center refers to Point X in the text) marks the range of the 700-m deep ocean water off Hualien.

roughly three groups of lines. In the South China Sea, the temperature drops more sharply with increasing depth whereas in the Philippine Sea the surface mixing zone is thicker and the temperature gradient becomes larger at a deeper depth. However, all three types indicate that at 700 m depth the temperature range is narrowed down to ca. 6.0 ± 0.5℃. For salinity, the South China Sea type water is less saline in the surface but more saline at a depth deeper than 500 m. At stations near Taiwan, the Kuroshio impact is obvious as the salinity can be higher than 35 at a core position of 150 m. A minimum of 34.1–34.2 at 450–600 m is found, with a density anomaly of 26.7 σ_θ. Below this level salinity increases slightly to 34.25–34.35 at a 700 m depth and the corresponding density anomaly increases to 27.0–27.1 σ_θ.

End members on the T–S diagram

If all these information is plotted on a T–S diagram (Fig. 3), the first thing to be noted is that there are two "S" shaped boundaries revealing two major "water column" types, i.e. the Philippine Sea type (A–B–C) and the South China Sea type (A–E–D). The curvature of the "S" curves may also show the diffusion process of the water column or the age of the mixing. Second, there are apparent end-members. By drawing three straight lines along the data boundaries and finding the cross points, three distinct water mass end-members can be defined, namely:

Point A: The Deep Arctic/Circumpolar Water (DACW), defined here as $S = 34.65$, $T = 1.8$℃, $\sigma_\theta = 27.7$.

Point B: The North Pacific Intermediate Water (NPIW), characterized by $S = 34.0$, $T = 6.5$℃, $\sigma_\theta = 26.7$.

Point C: The Kuroshio Tropical Water (KTW), here we choose $S = 35.14$, $T = 22.1$℃, $\sigma_\theta = 24.3$.

Besides, there exists a surface freshwater source, the end-member D with $T \approx 30$℃ and $S = 0$, and a cross-over Point E of the two "S" curves. The Point E is at $S = 34.57$, $T = 14.3$℃ with a density anomaly of $\sigma_\theta = 25.8$, and it exists in water columns over a vast area of the western Philippine Sea and the northern South China Sea. It can be explained as a sharp horizontal front (at 250–300 m depth) lying between the surface and intermediate waters. All vertical mixing processes must occur through Point E, and the vertical mixing across it is slow and the scale is small. In other words, the less saline surface water does not have much effect on the underlying intermediate water.

Source of the low salinity water

The intermediate low salinity water (400–600 m) has been named the Kuroshio Intermediate Water by Chen (1988) who suggested that its origin should be connected to the North Pacific Intermediate Water (NPIW). The latter is a mode water body (density range 26.6–26.8 σ_θ) located at 300–700 m depth in the subtropical north Pacific Ocean (Tally, 1993). It was believed that the water is formed in the area east of Japan by mixing of the southwest-turning-east Oyashio current, the outflow of the Tsugaru current, and the comparatively saline and warm Kuroshio Extension Current (Tally *et al.*, 1995; Qiu, 2001). However, Yasuda (1997) has indicated that the Kuril Basin of the Okhotsk Sea has a 26.7–26.9 σ_θ layer which should be the origin of the NPIW. This idea was endorsed by Watanabe and Wakatshchi (1998) who traced the density range and water properties of the Okhotsk Sea. Their assumption is based on the identification of density along the isopycnal surface, but whether the scale of sinking in the Okhotsk Sea is large enough to support a vast mode water body in the Pacific Ocean remains questionable.

A later experiment by Shimizu *et al.* (2004) gave a better explanation by using six floats to drift along the 26.7 σ_θ isopycnal level and observed the moving tracks for more than a year. They have concluded that the NPIW is a result of vigorous mixing of the very cold surface Oyashio water (2–3℃) and comparatively warm and saline Kuroshio Extension waters (ca. 10℃) in the 35–41°N, 160°E region. The mixed surface 26.7 σ_θ water has a temperature of 5.5–6.0℃ and a salinity of 33.9 and the formation time is about 1–1.5 year. It sinks along the 26.7 σ_θ isopycnal surface in three directions including a southward direction leading to the western Philippine Sea. The low salinity layer can reach as deep as 700 m in the central North Pacific Gyre, goes up to ca. 600 m at 25°N and can be shallower at even lower latitudes. This water layer will gradually merge with surface layer of the ocean currents, or the edge of the North Pacific Gyre. We may say that the Oyashio Water meets the Kuroshio Water again, not in the surface east of Japan, but at a depth of 200–300 m East of Taiwan.

In the study of Shimizu *et al.* (2004), the residence time of NPIW has been estimated to be about 20 years. The southward-sinking water mass shows an end member of ca. $T=5.5$℃, $S=33.9$, $\sigma_\theta=26.7$ on the T–S diagram, which is very close to the water end-member B defined in this study and both end-members are actually on the same isopycnal line.

Contribution of end-members

The contribution of each source of a given deep ocean water mass can be readily identified by calculating the mixing fractions of known end-members. For example, a sample water of X with a temperature T_X and a salinity S_X is a mixed result of three water masses A, B, C with known temperatures T_A, T_B, T_C and salinities S_A, S_B, S_C respectively. Their mixing fractions are defined as a, b and c (small Italic letters for end members A, B and C):

$$T_x = aT_A + bT_B + cT_C$$
$$S_X = aS_A + bS_B + cS_C$$
$$a+b+c=1$$

The contribution of each end-member (a, b and c) can be identified by solving the following equations.

$$aT_A + bT_B + (1-a-b)T_C - T_x = 0$$
$$aS_A + bS_B + (1-a-b)S_C - S_x = 0$$

Thus, a, b and c are obtained as:

$$a=\frac{\left(\frac{T_x-T_C}{T_B-T_C}\right)-\left(\frac{S_X-S_C}{S_B-S_C}\right)}{\left(\frac{T_A-T_C}{T_B-T_C}\right)-\left(\frac{S_A-S_C}{S_B-S_C}\right)}$$

$$b=\frac{\left(\frac{T_x-T_C}{T_A-T_C}\right)-\left(\frac{S_X-S_C}{S_A-S_C}\right)}{\left(\frac{T_B-T_C}{T_A-T_C}\right)-\left(\frac{S_B-S_C}{S_A-S_C}\right)}$$

$$c=1-a-b$$

Several approaches have been tried to identify the possible sources of the 700 m Hualien water. First, we suppose that in the west Philippine Sea where there is no influence from the South China Sea, the water column is a mixing result of three piled-up end-members namely A, B and C (see Fig. 3). In this case the fractionation of the 700 m deep water (Point X) is calculated as $a=0.34$, $b=0.59$ and $c=0.07$ (see Table 2). The end-member B (or NPIW) is apparently dominant. In the Philippine Sea the fractionation of the water at Point E becomes simply $b=0.50$ and $c=0.50$.

However, inside the South China Sea where the influence of NPIW does not exist but the intrusion of the surface Kuroshio Tropical Water (KTW) can be detectable, the water column is formed by the mixing of three piled-up end-members A, C and D (also see Fig. 3). The water mass at Point E may be attributed to $a=0.39$, $c=0.60$ and $d=0.01$. The identification of sources of Point E should refer to not only the location but also the underwater intrusion or interleaving between the two water column types.

If the analysis of the Point E water mass is ambiguous, then one may treat Point E as a relative end-member, as in the studied area all mixing processes between the surface and intermediate layers must pass through this point. In this case, the water mass X is a mixed result of end-members A, B and E. The fractionation of X becomes $a=0.34$, $b=0.52$ and $e=0.14$. The contribution of the end-member B (NPIW) is still prevailing. Since half of the NPIW water is the surface Oyashio Water, the water collected at 700 m off Hualien consists of more

Table 2. Fractionation analysis of a given water mass by the three end-member mixing equations.

Water mass			End members	Fraction ratio				
Point	Temp (℃)	Salinity		*a*	*b*	*c*	*d*	*e*
X	6.0	34.30	*A–B–C*	0.34	0.59	0.07		
E	14.3	34.57	*A–B–C*		0.50	0.50		
E	14.3	34.57	*A–C–D*	0.39		0.60	0.01	
X	6.0	34.30	*A–B–E*	0.34	0.52			0.14

a, *b*, *c*, *d* and *e* are fraction ratios of end members of *A*, *B*, *C*, *D* and *E*.

X: the 700 m deep water off Hualien; *E*: the intersect point on the *T–S* diagram. Point *E* can be the mixing result of either *A–B* or *A–C–D* depending on location.

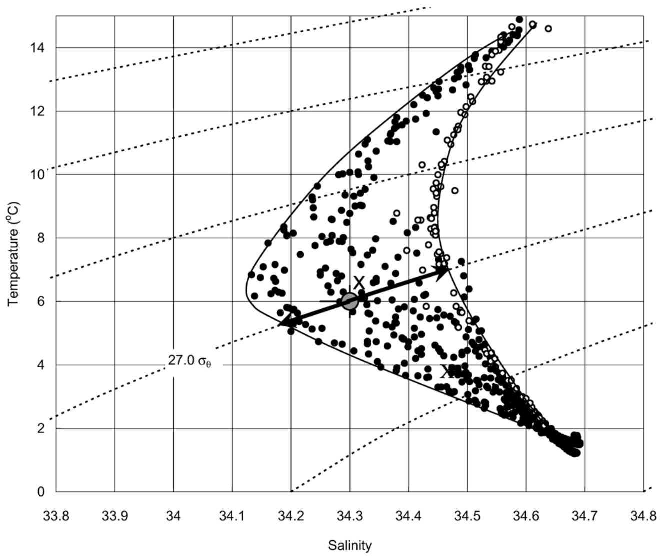

Fig. 4. Analysis of the water column type by measuring the distances between Point *X* (S=34.3, T=6℃) to the boundaries of the Philippine Sea type (left) and the South China Sea type (right) along the 27.0 σ_θ isopycnal line, showing that the X water mass resembles 2/3 of the Philippine Sea type and 1/3 of the South China Sea type.

than 25% of Oyashio Water, which is much more than the 7% fraction of the Kuroshio Tropical Water.

On the *T–S* diagram, the 700-m water (Point X) can also be the horizontally mixed result on the isopycnal surface. If judging by the distances between Point X and the two boundaries along the isopycnal 27.0 σ_θ line, the contribution of the Philippine Sea type is roughly 2/3 and the South China Sea type is 1/3 (Fig. 4). This evaluation coincides well with the conclusion made by Mensah *et al.* (2014). In other words, the 700-m deep water may be described as 66% of the Philippine Sea type and 34% of the South China Sea type.

Silicate concentration

The monitoring of temperature and salinity of the pumped-up deep ocean water at the on-shore station is of little meaning as the resolutions of measuring these two parameters may not be clear enough to show the minute variation. The salinity will always be within a narrow range between 34.2 and 34.4 and the temperature at the on-shore station has already been changed from that of the intake position. One of the alternatives is to measure the concentration of nutrients. Among the three nutrients (nitrate, phosphate and silicate), silicate has the highest concentration and the sample can be easily stored after sampling. In both the Philippine Sea and South China Sea, silicate concentration and temperature are closely related, so an empirical curve can be created to check the stability of the silicate concentration in the pumped up water.

The range of silicate concentration may be predicted by historical data. An empirical polynomial equation can be established as:

$$[\mathrm{Si}]\ (\mu\mathrm{M}) = a_0 + a_1T + a_2T^2 + a_3T^3 + a_4T^4$$

where T is temperature in℃ units. The empirical coefficients for the water column of the Philippine Sea type (PS), the South China Sea type (SCS) and a mixture (2/3 PS + 1/3 SCS) are listed in Table 3. The concentrations of silicate calculated according to the coefficients at 5.5–6.5℃ are also presented. At 5.5℃, the extreme concentrations are 86.7 and 101.7 μM, and decrease to 72.2 and 89.9 μM at 6.5℃, respectively. If the 700-m water shows characteristics of 2/3 PS and 1/3 SCS, then the reasonable verdict for silicate at 6℃ should be 84.6 μM. The sensitivity of d [Si]/dT is ca. 13.6 μM℃$^{-1}$. Since the minimum resolution of measuring silicate by the yellowish molybdenum method can reach to 0.5 μM, the method can literally detect a variation of as small as 0.04℃ at the intake position.

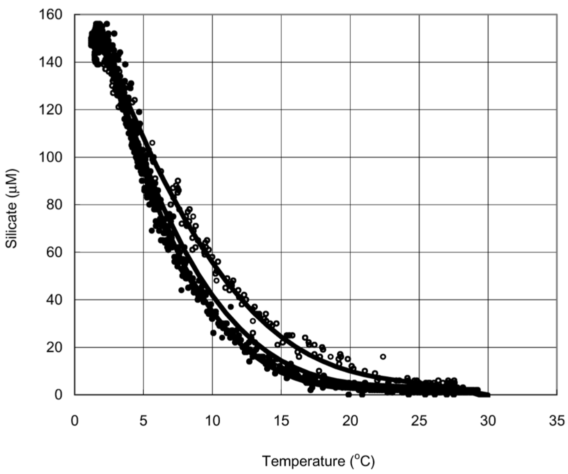

Fig. 5. The relationship between silicate concentration and temperature. Lines are plotted according polynomial equations with data of (dot) the Philippine Sea from the INDOPAC Leg-3 Cruise and (circle) the South China Sea from the ORI-266 Cruise. The central line is calculated according to 2/3 PS and 1/3 SCS as seen in Table 3.

Influence of the 2011 Fukushima Nuclear Event

Since the sinking of the NPIW water mass occurs in the area just off northeast coast of Japan, many people may worry about the effect of the 2011 Fukushima Nuclear Event (location 37.23°N, 141.01°E) which might bring radioactive cesium down to the bottom of the North Pacific Gyre and could eventually influence the water quality of the deep ocean water. A recent study by Kaeriyama *et al.* (2014) who have reported that the Cs-137 maximum has already intruded to a 200–300 m depth at a latitude of 30°N and continues in a southwest direction. Kumamoto *et al.* (2014) have also measured Cs-134 and Cs-137 activities along the latitude and found that the sinking of the radioactive-bearing water takes place at the latitude of 35–40°N where the density anomaly is 26.0–26.4 σ_θ, The southward spreading plume (defined by a contour line of 2 Bq m^{-3}) is now confined in a layer of 250–350 m or between 25.0 to 26.0 σ_θ.

A schematic 3D diagram (Fig. 6) shows the possible spreading route of the radioactive plume to lower latitudes. The migration pattern is separated from that of the NPIW (sinks at 40–45°N with a heavier density) and therefore, even the radioactive water arrives eventually at 25°N or near Taiwan area, the core position would be at a depth of 300 m, well above the salinity minimum, albeit the concentration will have been largely diluted. The pipe line intake water at 700 m off Hualien should be uninfluenced.

Table 3. Empirical coefficients and calculated concentrations for [Si]=function (T).

Water column type	a_0	a_1	a_2	a_3	a_4	[Si] (μM) 5.5℃	6℃	6.5℃
PS	207.1255	−29.1276	1.4788	−0.03084	0.000208	86.7	79.2	72.2
SCS	182.1034	−16.935	0.3986	0.005194	−0.000215	101.7	95.7	89.9
2/3PS + 1/3SCS	198.8682	−25.10404	1.12233	−0.01895	0.000068	91.6	84.6	78.0

Valid range: 2℃ < T < 28℃

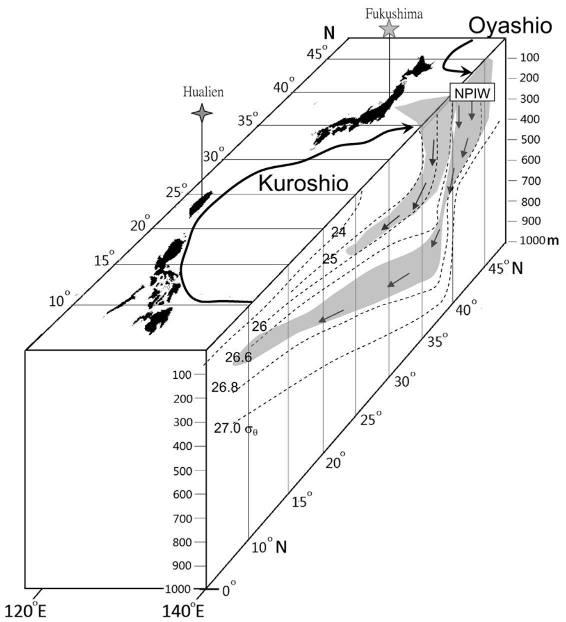

Fig. 6. Schematic 3D diagram showing the sinking movements of NPIW between 40–45°N and the radioactive-bearing water between 35–40°N which originates from the Fukushima Dai-ichi Nuclear Plant at 37.2°N. The southward spreading plume is marked by a shaded area between 25 and 26 σ_θ which is based on data provided by Kumamoto *et al.* (2014) and Kaeriyama *et al.* (2014). Both authors have detected C-134 and Cs-137 at 25–30°N with maxima found at ca. 200–300 m. The deep water described in this study is pumped up at a latitude of 24°N and the intake depth is at ca. 700 m (27.0 σ_θ) which is deeper than the NPIW layer.

3. Conclusion

The present study traces the origins of the 700 m deep ocean water off Hualien coast and links its properties to three far distance sources. The mixing fractionations (not considering the influence of surface layers) are 59% from the North Pacific Intermediate Water (NPIW), 34% from the Deep Arctic/Circumpolar Water (DACW) and only 7% from the Kuroshio Tropical Water (KTW). This is a big surprise as most people would think the water should receive substantial influence from the surface Kuroshio current but actually it does not. If judging by the resemblance of the vertical water column with that of the Philippine Sea (PS) and the South China Sea (SCS), the water mass shows 2/3 PS type and 1/3 SCS type. As a conclusion, more than half of the Hualien pipeline water is composed of NPIW, no matter what evaluation method is used.

The NPIW is generated by mixing waters of the Oyashio and the Kuroshio Extension in the region east of Japan. The former carries waters from the north Pacific subarctic gyre current which combines off-flows from the Bering Sea, the Okhotsk Sea, and the Tsugaru Strait. It merges with the warmer and more saline Kuroshio Extension water to form NPIW at latitudes between 35–41°N. The newly formed NPIW sinks and part of it is transported southward. At 24°N (latitude of Hualien), the depth of the low salinity layer is about 500～600 m.

The spreading route of the NPIW shown in Fig. 6 provides a safety guidance to the industry and general public. The present evidences indicate that the core of the downward penetration is still confined in layers between 25.0–26.4 σ_θ, well above the NPIW layer (26.7 σ_θ) and the 700 m deep water layer (27.0 σ_θ) off Hualien. Although we cannot deny that, on a very long time scale, the leaked radioactive cesium will eventually spread out all over the North Pacific Gyre, but the concentration will be as low as close to the background.

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黒潮または親潮か—台湾東部の花蓮沖水深700 mの海洋深層水の起源

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要　旨

台湾東部の花蓮沖水深約700 mに設置された取水管より得られた深層水は，物理特性から遠く離れた以下の3水塊が混合された特徴を有する．(1) 北極深層流/南極周極流水（DACW）と (2) オホーツク水/親潮/黒潮続流の混合水の沈降により形成された北太平洋中層水（NPIW），および (3) 黒潮熱帯水（KTW）である．上記3水塊をエンドメンバーとした混合率の計算結果から，取水された深層水中の各々の水塊の割合は，34%, 59%および7%であった．27.0 σ_θの等密度海水の水柱タイプは，66%がフィリピン海および34%が南シナ海の水に類似性を示している．取水深層水のケイ酸塩濃度（水深700 mで78–92 μM Siの変動範囲）は，海洋深層水の安定性を示す有効な指標であった（0.04℃ μM^{-1}の解像度）．また，これらの知見を元に，2011年の福島原子力発電所事故による取水深層水への放射能汚染リスクを評価した．

キーワード：海洋深層水，花蓮，黒潮，親潮