Terr. Atmos. Ocean. Sci., Vol. 31, No. 1, 77-83, February 2020 doi: 10.3319/TAO.2019.07.14.01

Verification of the internal tide off Zhiben coast, Taitung, southeast Taiwan

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Article history:
Received 28 March 2019
Revised 13 July 2019
Accepted 14 July 2019

Keywords:
Nutrients, Pipeline, Internal tide, Taitung

Citation:
Yang, Y.-J., C.-C. Wen, P.-Y. Huang, C.-Y. Wang, K.-S. Chu, and S.-C. Pai, 2020: Verification of the internal tide off Zhiben coast, Taitung, southeast Taiwan. Terr. Atmos. Ocean. Sci., 31, 77-83, doi: 10.3319/TAO.2019.07.14.01

ABSTRACT

An oscillating vertical movement of the undersurface water layers has been verified off the coast of Zhiban, Taitung, southeast Taiwan. It was first suspected to exist by significant variations of CTD temperature profiles observed on Cruises OR3-1769 and OR3-1792 in 2014. A frequency of 12.5 hr^{-1} was estimated from temperature record by a subsurface ADPC moored at a depth of 110 m. Further proofs were obtained in 2016 by chemical measurements of silicate and phosphate in an industrial pipeline which takes up continuously the deep ocean water at a depth of 319 m. The nutrient concentrations varies hour by hour during a 36-hr period (0.88 - 1.11 μM for phosphate and 19.0 - 26.2 μM for silicate), showing a semi-diurnal cycle which matched well with that of the surface tide reported at a near-by tidal station. An amplitude of 60 - 100 m that occurs in a semidiurnal cycle can be commonly observed in this area at depths between 100 and 300 m.

1. INTRODUCTION

The topography off the coast of eastern Taiwan is quite unique in terms of steepness comparing to other parts of the island. The shelf facing the Pacific Ocean side is narrow and the seafloor can drop sharply to more than 1000 m deep only a few km away from the shore line. Due to this reason the eastern Taiwan becomes a potential area for developing deep ocean water industry. Hualien is the first place to choose where five pipelines have already been implemented for obtaining cold/clean deep ocean water (depths between 400 and 718 m) for manufacturing drink water and mariculture (Takahashi et al. 2012; Pai et al. 2015). Taitung coast is another potential area but several prior attempts of deploying pipelines have not been successful due to blockage or breaking by unidentified forces. The reason could be related to the frequent geological activities (earthquake, density flow or subsurface landslide), or the water body itself may not be stable (current, typhoon or internal tide). Although the exact reason has not been identified, it is suspected that the internal tidal movement can affect the buoyance of water, especially in the pycnocline layer, and the velocity shearing force may distort the layout of the pipeline which was lying above the sea floor without protection. The internal tidal waves, which have been observed recently in adjacent areas [in Hualien area by Lien et al. (2014), Pai et al. (2017); and in Luzon Strait by Jan et al. (2007), Alford et al. (2011, 2015)], has not been reported in Taitung area. Its amplitude and frequency need to be identified quantitatively.

2. METHODOLOGY

2.1 CTD Profiles and ADCP Record

Selected offshore hydrographic data were obtained during two physical oceanography cruises, namely the Cruise OR3-1769 (28 to 31 May 2014) and Cruise OR3-1792 (30 August to 2 September 2014). Both cruises have nine CTD stations outside the river mouth of the Zhiben Creek (Fig. 1). On the later cruise, a mooring with a subsurface ADCP was

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deployed at a location ca. 1 km off the coast. Its temperature sensor was bound at a depth of 110 m and the bottom depth was 210 m. A total period of 54 hr was monitored.

2.2 Pipeline

A pipeline was deployed in 2015 as a pioneer project by the Ministry of Economics, Taiwan (Fig. 2, drawn according to information provided by P.-Y. Huang) with an underwater length of 2100 m plus a 300 m distance from the water line to the pumping station. The pumping station is located at 121°3’26.0”E, 22°40’59.4”N, at the southern bank of the river mouth of Zhiben Creek. The average dipping angle on the ocean floor was 8.37°. The intake depth was reported at 319 m. Like all other pipelines, the intake point at the end did not lie directly on the seafloor but was mounted to a metal frame to lift the hose head a few meters above the sea floor. The pipe was made of PVC material with an outer diameter of 160 mm and an internal diameter of 130.8 mm. Accordingly, the total volume of the pipeline was estimated to be 32 m^3. Since the pipeline was operated regularly at a rate of 70 ton per day, the residence time for water to travel in the pipeline was *circa* 11 hr. It means that the water obtained at the pumping station has an 11 hr lag from the intake point. The pumping operation is normally stopped during Typhoon, earthquake or whenever the turbidity turns high. However, the traveling time in the pipeline is long, the turbidity check could be late if any unexpected underwater landslide occurs. In fact, the pipeline studied in this work was blocked few months after the sampling.

2.3 Sampling and Chemical Measurement

Seawater was collected hourly at the Zhiben Pumping Station from 8:00 AM 24 May 2016 to 20:00 PM next day. A total of 36 bottles were obtained. They were put in black plastic bags to shade from the light, dispatched promptly to the laboratory in Taipei for nutrient analyses. Phosphate and silicate concentrations were measured simultaneously in a way as described previously (Pai et al. 2017).

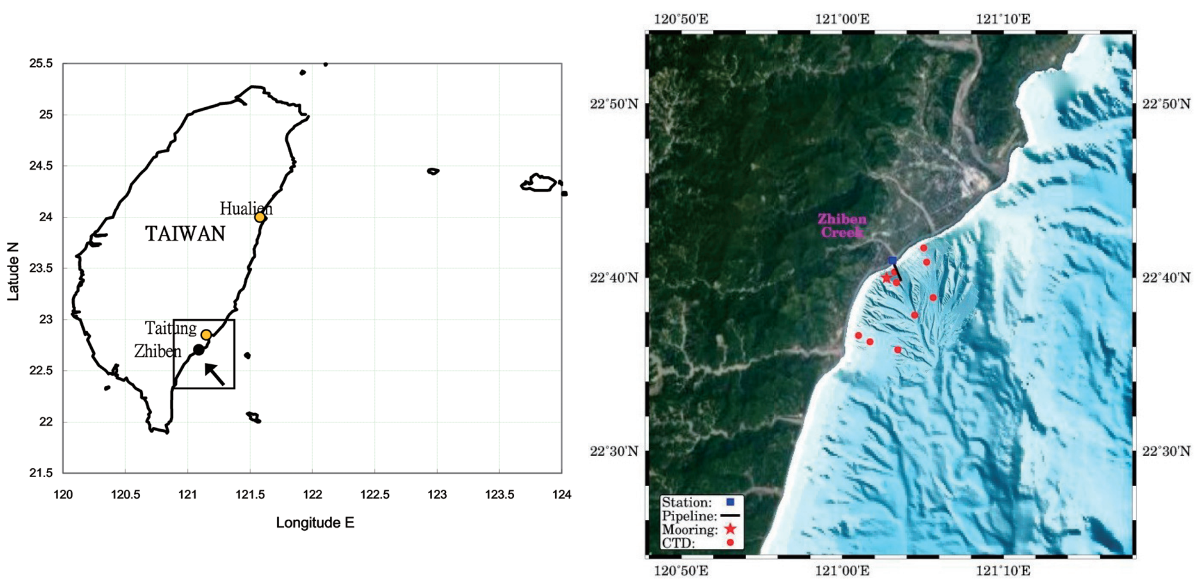

Fig. 1. (Left) The studied area off the coast of Taitung and Zhiben. (Right) Locations of CTD stations of Cruises OR3-1769 and OR3-1792 are marked by dots, and the mooring site of the subsurface ADCP is marked by a star. The pipeline pumping station at the south bank of the Zhiben Creek is marked by a square. A pipeline stretches out from coast toward the sea in SSE direction.

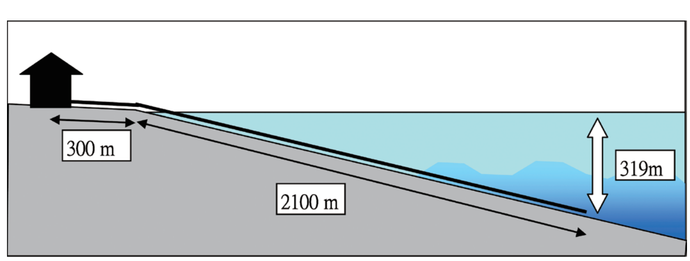

Fig. 2. An illustrative diagram showing the Zhiben Creek pipeline which stretches from the pumping station toward the ocean. The average dipping angle on the seafloor is 8.37°. The end of the pipeline is 121°4’27.6”E, 22°39’53.5”N, with an intake depth of 319 m.

3. RESULTS

3.1 Temperature Profile

Vertical temperature profile data were obtained by CTD during cruises OR3-1769 and OR3-1792 (the operation in each cruise covered a time span of ca. 24 hrs). There were nine stations for each cruise. The composite profiles (see Fig. 3) show scattered patterns beneath the surface layer. At 100 m, temperature ranged from 17 - 24 and 17.2 - 20°C for the two cruises, respectively. At 300 m depth, the ranges were 12.0 - 13.6 and 11.1 - 13.9°C, respectively. Since all CTD casts were not designated to operate in consistent time intervals, the large temperature variations (up to 7°C at 100 m and up to 1.8°C at 300 m) observed can hardly be used directly to quantify the water mass movement. However, the TS diagrams (also in Fig. 3) show that all curves are likely merged with each other, indicating the movement of water mass is in a typical vertical up-and-down direction rather than any lateral intrusion from other water masses.

Nonetheless, a rough estimation could still be made by treating those differences as a relevant measure of the 95% confidence level and dividing them by empirical temperature gradients (e.g., 0.05°C m^{-1} at 100 m and 0.025°C m^{-1} at 300 m). In this way the possible vertical displacements $[\Delta z \fallingdotseq 4\sigma/(dT/dz)]$ at depths of 100 and 300 m would be as large as 140 and 64 m for Cruise OR3-1769, whereas 56 and 110 m for Cruise OR3-1792, respectively.

3.2 ADCP Record

A sub-surface ADCP unit with a temperature sensor tied at 110 m at station CP1 during 30 August to 1 September 2014 for 54 hr. The temperature variations at 110 m as well as current speeds at 100 m are shown in Fig. 4. It is clear that all data show four and a half cycles, matching the surface semi-diurnal tidal frequency. The lowest temperature was 17°C and the highest 22°C with a range difference of 5°C. Following the estimation method in the above section, the vertical variation of the water layer at 100 m depth could be as large as 100 m.

3.3 Variation on Nutrients in Pipeline

The measurement of chemical compositions in pipeline water may provide another approach to estimate the vertical movement. The results of analyses for phosphate and silicate in the pipeline water are given in Table 1. In the 36 hr observation period, the phosphate concentration changed up-and-down three times, from as low as 0.88 to a highest 1.11 μM, with an average of 1.0 ± 0.06 μM. If a 4σ range is taken account for the daily variation, the relative range (95% confidence level) was about 24% of the mean value. As to silicate, the concentration also changed up-and-down three times, between 21.8 and 25.4 μM. with a mean value of 22.96 ± 1.65 μM. The relative daily variation is about 28% of the mean value. The [Si]/[P] molar ratio was 22.9 ± 0.9, indicating that both nutrients were changing in a synchronized way, and the frequency was approximately 12 hr^{-1}.

4. DISCUSSION

4.1 Correlation Analysis

In order to identify the relationship between nutrient variation and surface tidal cycle, an autocorrelation process was made on the data of Table 1. For a set data containing N pair numbers (X_1, Y_1, … X_N, Y_N). The autocorrelation factor $ACF(k)$ at a given lag number k, is defined as:

$$ACF(k) = \frac{\sum_{i=1}^{N-k}(Y_i - \overline{Y})(Y_{i+k} - \overline{Y})}{\sum_{i=1}^{N}(Y_i - \overline{Y})^2} \tag{1}$$

where $\overline{Y}$ is the mean value.

Surface tidal heights (at Fugang Tidal Station, Central Weather Bureau, Taiwan), phosphate and silicate data sets were analyzed and the *ACF* diagrams (Fig. 5) all show a typical semidiurnal pattern with an average period of *circa* 12.5 hr. However, the nutrient peaks appeared some 3 - 4 hr behind that of the surface tide. It should also be borne in mind that the water needs an 11 hr period to reach at the station. With this consideration, the deep internal tide is either leading the nutrient patterns by *circa* 5 hr or adrift by 7.5 hr.

Several recent studies in adjacent areas have revealed that the phase lags between deep and surface tides may differ from place to place. The phases of the 170 m internal tide and the surface tide were almost opposite (-6 hr) in the Hungtsai Trough, southern Taiwan (Pai et al. 2016). The surface tide was ca. +2 hr earlier than that of the internal tide at 400 m off Hualien coast (Pai et al. 2017). The phase difference may be difficult to explain as it could be affected by many geographic factors such as local topography, direction/reflection of wave propagation and the distance travelled from the generation area.

4.2 Vertical Displacement by Nutrient Variation

It is possible to estimate the scale of the vertical displacement (Δz) by taking quadruple standard deviation (95% confidence level) of nutrient concentration and divided it by the average profile gradient at the same depth:

$$\Delta z\ (\mathrm{m}) \fallingdotseq 4\sigma/(d[C]/dz) \tag{2}$$

By referring to historic data, the nutrient vertical gradient values dC/dz at 300 m can be estimated graphically as 0.004 μM m^{-1} for phosphate and 0.1 μM m^{-1} for silicate. In

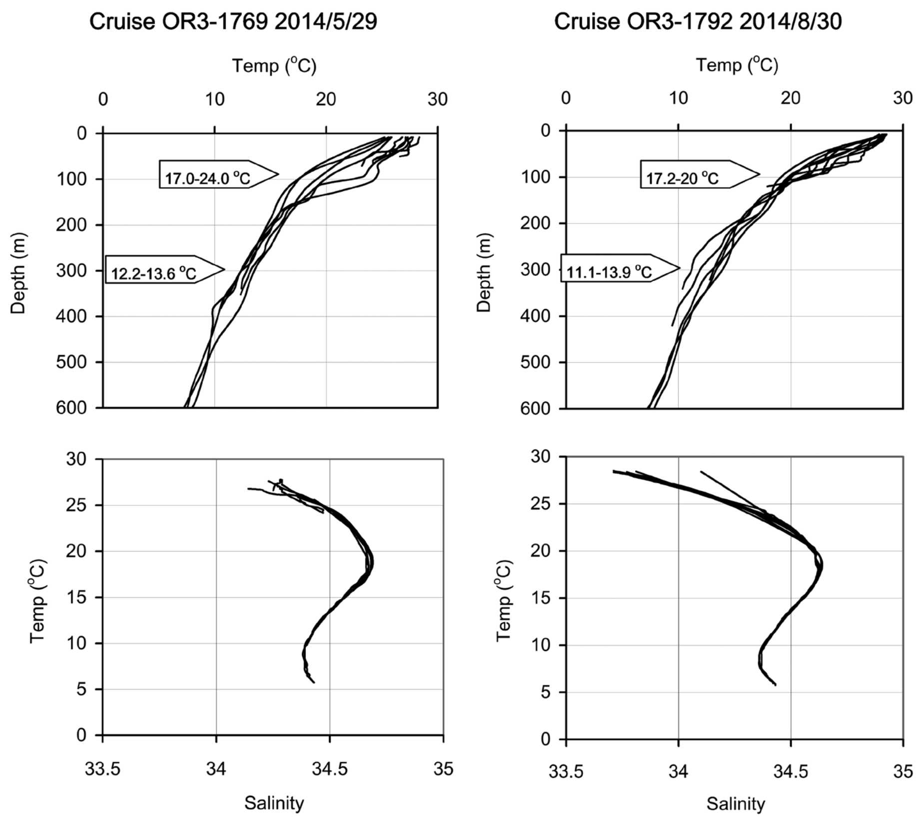

Fig. 3. (Up) Composite CTD temperature profiles for Cruises OR3-1769 and OR3-1792. The variation ranges for temperature at 100 and 300 m were 7 and 1.4°C for OR3-1769, whereas 2.3 and 2.8°C for OR3-1792. (Down) Merged lines in TS diagrams showing the variations were induced by a simple vertical movement.

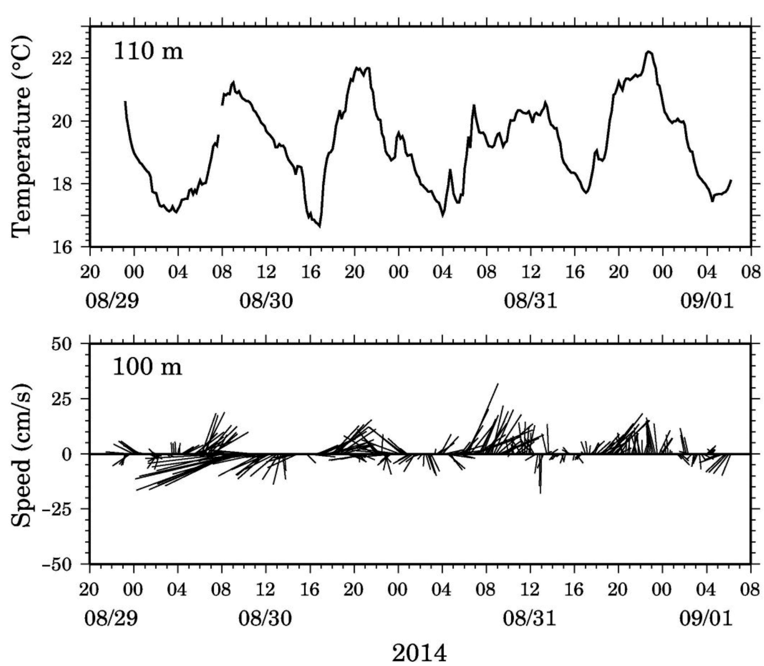

Fig. 4. Records (29 August to 1 September 2014) of a bottom-mounted ADCP at Station CP1 (121°02.742'E, 22°39.963'N). The temperature sensor was bound at 110 m and the water depth was 210 m. The current speed and direction at 100 m level were presented in the lower diagram. All data show typical semi-diurnal tidal cycles.

Table 1. Hourly variations of nutrients in seawater from the Zhiben 319 m pipeline.

Sampling date	Time (hh:mm)	Tidal ht (m)	[PO4] (μM)	[Silicate] (μM)	[Si]/[P] ratio
2016/5/24	08:00	0.86	1.06	22.55	21.3
	09:00	0.65	1.06	24.88	23.5
	10:00	0.35	1.11	24.35	22.0
	11:00	0.02	1.06	24.42	23.1
	12:00	-0.29	1.06	23.56	22.3
	13:00	-0.48	1.01	25.15	24.9
	14:00	-0.54	1.01	23.64	23.4
	15:00	-0.47	0.96	21.79	22.7
	16:00	-0.22	0.96	21.84	22.7
	17:00	0.03	0.91	22.42	24.5
	18:00	0.29	0.96	21.44	22.3
	19:00	0.51	0.96	21.39	22.2
	20:00	0.6	0.96	21.34	22.2
	21:00	0.6	1.01	22.58	22.4
	22:00	0.48	1.06	23.66	22.4
	23:00	0.32	1.11	26.16	23.7
2016/5/25	00:00	0.11	1.11	25.86	23.4
	01:00	-0.04	1.06	25.89	24.5
	02:00	-0.05	1.06	23.31	22.0
	03:00	0.09	1.01	22.42	22.2
	04:00	0.28	0.88	19.01	21.7
	05:00	0.54	0.96	20.28	21.1
	06:00	0.76	0.89	20.01	22.5
	07:00	0.9	0.96	21.39	22.2
	08:00	0.9	0.96	22.04	22.9
	09:00	0.76	1.01	22.78	22.6
	10:00	0.51	1.01	23.74	23.5
	11:00	0.19	1.06	24.88	23.5
	12:00	-0.13	1.06	24.67	23.3
	13:00	-0.39	1.01	23.54	23.3
	14:00	-0.52	1.01	23.74	23.5
	15:00	-0.55	0.96	22.45	23.3
	16:00	-0.4	0.97	22.45	23.2
	17:00	-0.17	0.91	22.22	24.3
	18:00	0.1	0.96	21.89	22.8
	19:00	0.34	0.96	22.60	23.5
	20:00	0.5	1.01	23.33	23.1
		Mean	1.00	22.96	22.92
		σ	0.06	1.65	0.87
		4σ	0.24	6.59	
		dC/dz	0.004	0.1	
		Δ*z*	60	66	

Note: Tidal height data were obtained from Fugong Tidal Station, Taitung.

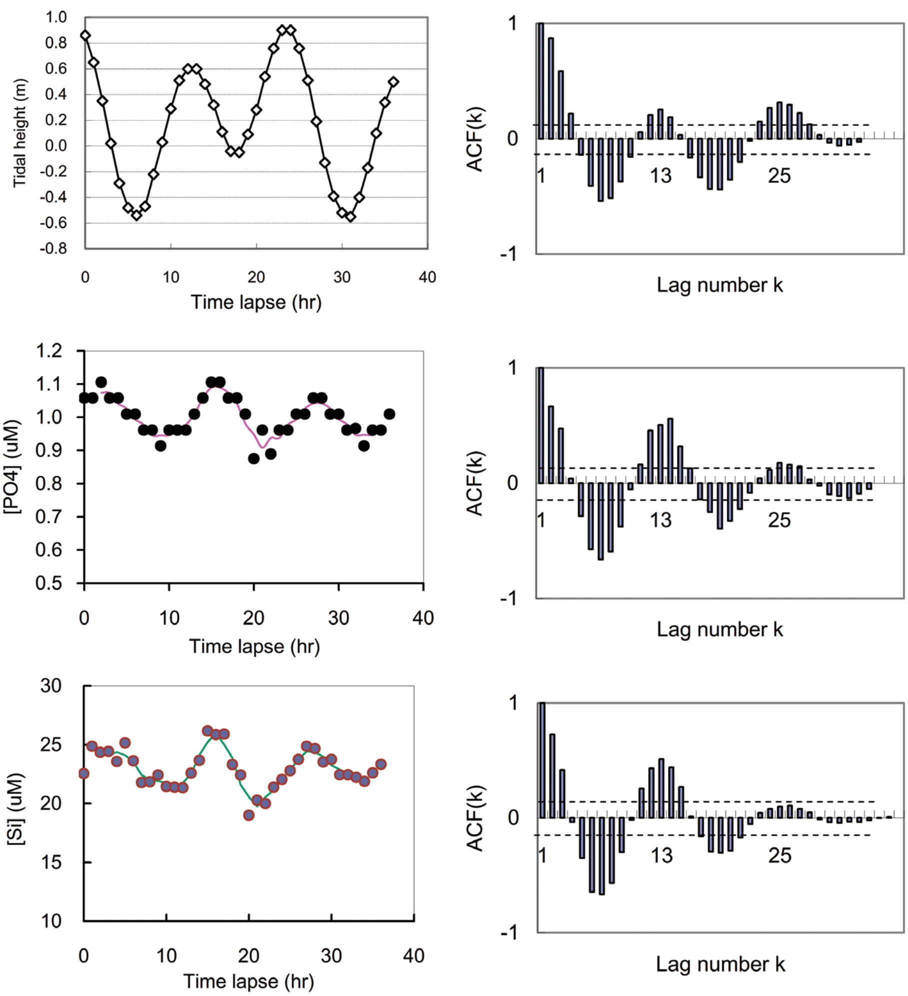

Fig. 5. Temporal variation of (top) surface tidal height at Fugang Harbor, Taitung (source: Central Weather Bureau, Taiwan), (middle) phosphate and (bottom) silicate concentrations in the pipeline during the 36 hr period starting at 8:00 24 May 2016. The corresponding correlograms are shown on the right indicating typical semidiurnal cycles of ca. 12.5 hr. Dashed lines remark the 95% confidence intervals.

this case it is readily to obtain Δz = 60 m by phosphate data and Δz = 66 m by silicate data (see Table 1). These values are comparable to that estimated by CTD temperature data. It is also similar in scale to that reported in Hualien area (nearly 90 m at 300 m, Pai et al. 2017).

4.3 Verdict by Temperature Variation

An empirical relationships between temperature (°C) and silicate concentration (μM) have been proposed for the off shore water column in the eastern Taiwan area (Pai et al. 2017):

$$T\,(^{\circ}\mathrm{C}) = 1 \Bigg/ \left\{ 0.04 - \frac{1}{10.5} \ln\left[1 - \left(\frac{[\mathrm{Si}] - 1}{147} \right)^{0.588} \right] \right\} \qquad (3)$$

By putting the silicate data in Table 1 into the above equation, the temperature range at the 319 m depth intake point was be estimated to be 12.3 - 13.8°C with a difference of 1.5°C. At 300 m, by taking account of a gradient value of dT/dz = 0.025°C m^{-1}, the 1.5°C variation may be regarded as a vertical displacement of 60 m on that day.

5. CONCLUSION

Only two decades ago most people would think that the deep ocean off Taiwan should be very stagnant, therefore it is reasonable to expect obtaining temperature-consistent clean/cold seawater from several hundred meters below the surface. Nowadays scientists have found that internal tides can affect significantly the intermediate layers. In this work, we have confirmed that in Taitung area, there indeed exists a consistent vertical movement of water layers in the thermocline. The variations, frequencies and displacements were first estimated by CTD measurements on two cruises and records from a subsurface mooring ADCP. Those physical judgements were consolidated by chemical measurements in water collected from a local industrial pipeline with an intake depth of 319 m. The nutrient concentration variations in a 36 hr period (for both phosphate and silicate) were as large as 24 - 28%, which reveal a vertical displacement of 60 - 66 m. It is also noticed that in Taitung area the depth of maximum oscillations is much shallower than that have been found in Hualien area (400 - 800 m), but similar to that reported in the South China Sea. The internal wave in Hualien area is likely generated at the southern flank of the Ryukyu Ridge (Pai et al. 2017) whereas the internal wave found in the present study may be related to the ridges in the Luzon Strait (Jan et al. 2007; Alford et al. 2011, 2015). For further information, readers may refer to a previous numerical study by Jan et al. (2008). Apart from scientific discussion, the data presented in this study and the phenomenon revealed can be of great value to marine engineers in further deployment of deep ocean water pipelines in Taitung area.

Acknowledgements The hydrography data were generously provided by the Water Resources Planning Institute, Water Resources Agency, Ministry of Economic Affairs, ROC (Ref. no. 10807009450). The authors would also like to express their gratitude to F. M. Chang and Taiwan Society of Deep Ocean Water Resources Application (TW-SOWA) for providing sampling facilities.

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