Fine-Scale Measurements of Hydrophysical and Bio-Geo-Optical Properties by the Autonomous Moored Profiling Probe Winchi in the Waters of the Coastal Zone of the Northwestern Sea of Japan

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Abstract: In May–June 2024, an automatic mobile tethered Winchi profiler equipped with a YSI EXO2 Multiparameter Sonde was used to conduct fine-scale measurements of thermohaline stratification and bio-geo-optical parameters in Vityaz Bay (Peter the Great Bay, the Sea of Japan) for the first time. The data quality was improved by correcting the depth profiles of sea water temperature and absolute salinity to account for the response time of the temperature sensor, resulting in a reduction of the root-mean-square-error (RMSE) relative to reference profiles by factors of 5 and 6, respectively (final RMSE = 0.13 °C and 0.1 g/kg). The analysis revealed the presence of quasi-inertial (~18 hours) and diurnal (~24 hours) oscillations, as well as significant shifts in near-surface layer properties, through analysis of collocated thermohaline and bio-geo-optical data.

Keywords: automatic underwater measurements, vertical profiles, real-time, sensor inertia correction, temporal variability, quasi-inertial internal waves.

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Research Article

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Introduction

Under the POI FEB RAS projects investigating the multi-scale variability of circulation in the Far Eastern Seas, this study focuses on the time variability of the vertical structure of temperature, salinity, turbidity, and fluorescent dissolved organic matter (FDOM) in the coastal zone of the northwestern Sea of Japan. Vertical profiling is conducted using a Winchi modified moored automatic mobile profiler equipped with the multi-parameter probe of YSI EXO2, specifically adapted to the thermohaline conditions of the southern part of Peter the Great Bay, the Vityaz Bay.

In operational oceanography, automatic mobile vertical-profiling systems equipped with multiple sensors are increasingly used for long-term measurement of vertical structures of hydro-physical, chemical, and bio-geo-optical processes [*Carlson et al.*, 2014; *Lucas et al.*, 2016; *Park et al.*, 2021; *Poulain*, 2024; *Stepanov et al.*, 2024]. Among these profiling systems, a notable class includes moored profilers equipped with built-in winches [*Ostrovskii et al.*, 2022; *Shvoev et al.*, 2024] or moorings with self-contained winches [*Lochthofen et al.*, 2021; *Send et al.*, 2013], enabling measurement of the vertical water structure from the sea surface to the bottom and real-time data transmission. This approach to underwater automatic measurements shows promise as other commonly used systems have various drawbacks. For instance, sea surface buoys are susceptible to vandalism and the impact of tropical cyclones [*Dunne et al.*, 2002; *Kolding and Sagstad*, 2013; *Pinkel et al.*, 2011]. The automatic mobile profilers, moving along the vertical string or crawlers [*Doherty et al.*, 1999; *Ostrovskii et al.*, 2013], cannot conduct measurements up to the sea surface because their crawling range is limited at the top by the submerged buoy. When using temperature strings [*Novotryasov et al.*, 2016; *Wijesekera et al.*, 2022; *Yaroshchuk et al.*, 2016], one needs to deploy many temperature loggers at fixed depths, which is expensive due to the high cost of oceanographic sensors.

In order to accurately measure the vertical structure of a water column using an automatic mobile underwater vertical-moving system equipped with multiple sensors, it is essential to consider the sensor inertia effects [*Lazaryuk*, 2008; *Xiao et al.*, 2023], in particular, for the measurements of the ocean fine structure and the turbulent exchange [*Ostrovskii et al.*, 2021; *Stepanov et al.*, 2024; *Stepanov et al.*, 2023], especially given the high vertical gradient of the measured variables [*Yaroshchuk et al.*, 2023]. Furthermore, when conducting measurements over several days or longer, biofouling of the equipment in the marine environment becomes a significant issue.

At present, the appropriate choice of an underwater profiler is a compromise between the number of measured variables, the sensor inertia effects, measurement accuracy, as well as the resistance to biofouling.

Description of the Winchi Profiler

To carry out detailed observations of the vertical structure of the water column, the Winchi profiler (ver. WP-02) was used [*Ostrovskii et al.*, 2022] (Figure 1). The profiler is equipped with a YSI EXO2 Multiparameter Probe (hereafter – EXO2) [*YSI Inc.*, 2025d] and has positive buoyancy. It contains a winch with a rope whose lower end is fixed to the bottom anchor. This profiler is a new version of the original profiler that had been successfully tested at the "Gelendzhik" observational site in the coastal zone of the Black Sea [*Ostrovskii et al.*, 2022; *Shvoev et al.*, 2024].

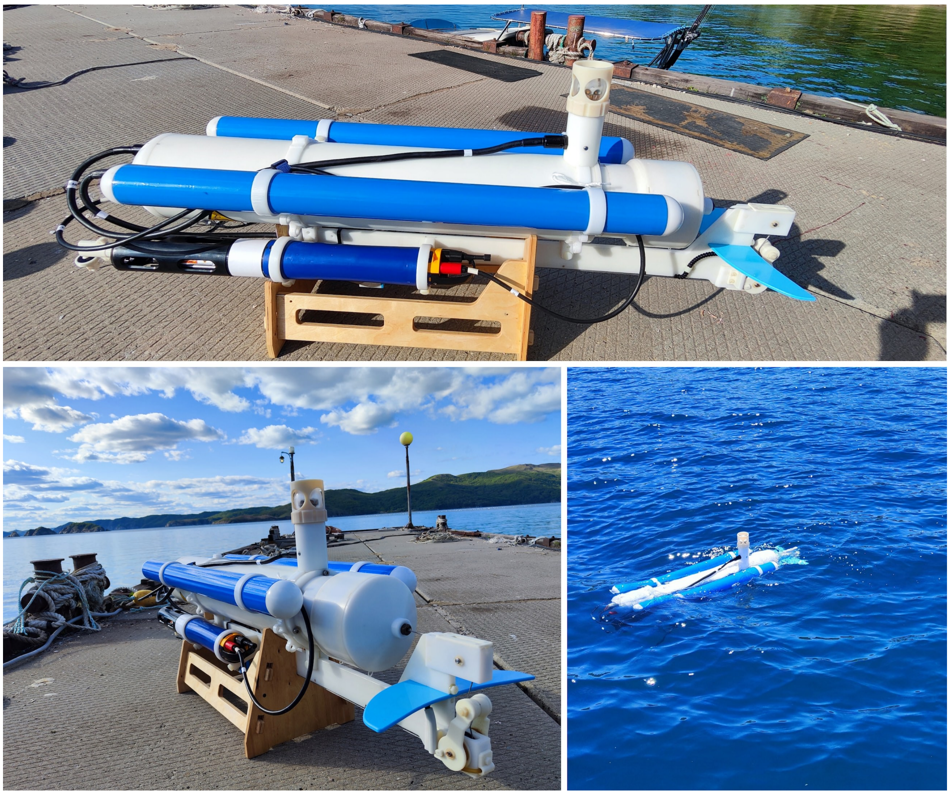

Figure 1. The Winchi profiler (ver. WP-02) during the deployment in the sea bay in the vicinity of Marine Experimental Station "Cape Shults" from May 30 to June 10, 2024. Photos by O. Yu. Kochetov.

Table 1 presents the key technical features of the Winchi profiler, crucial for accurate measurements of the vertical structure of the sea water column, as outlined below:

- The EXO2 probe conducts automatic measurements of hydro-physical (temperature, conductivity, pressure) and bio-geo-optical parameters (FDOM and turbidity) of the sea water.
- The probe is biofouling resistant due to its built-in brushes.
- The control system includes a telemetry module collecting information on winch rope length, rope tension, hydrostatic pressure, current consumption, battery voltage, pitch, roll, and compass heading.
- Profiling is frequent, with minimal time intervals between profiles ranging from 6 to 17 minutes at depths of 0 to 50 meters, depending on profiler speed (0.1 to 0.3 m/s).
- Profiling is energy-efficient, utilizing an NMC battery capable of 400–500 profiling cycles.
- The profiler descends from the sea surface to the seabed and resurfaces to transmit the observational data in real-time.

Table 1. The specifications of the Winchi profiler (ver. WP-02)

Specification	Value
Profiling depth range	0–40 m (can be extended up to 50 m).
Profiling speed	0.1–0.3 m/s
Sampling frequency of EXO2	4 Hz
Minimal period between the adjacent profiling cycles	$\sim$ 10 min. Minimal period can be decreased to $\sim$ 6 min with an increased profiling speed.
Number of the profiling cycles per battery charge	$\sim$ 400–500 profiling cycles at profiling speed of 0.2 m/s
Measurement of hydrostatic pressure	Honeywell MLH300PSL06A sensor with the sampling rate of 10 Hz and an accuracy of ±0.50% of full scale at a pressure of 100 psi (689.5 kPa) and a response time < 2 m/s [*Honeywell*, 2025].
Measurements of sea water conductivity and temperature	The accuracy of the "Wiped Conductivity and Temperature Sensor" is ±1% of the measured conductivity range or 0.002 mS/cm with a response time (T63*) < 2 s; ±0.2 °C of the measured temperature range with a response time (T95*) < 30 s; the accuracy of the calculated salinity is ±2% or 0.2 g/kg [*YSI Inc.*, 2025c]
Measurement of the fluorescent dissolved organic matter (FDOM)	The "FDOM Smart Sensor" with a sensitivity threshold of 0.07 ppb QSU (Quinine Sulfate Units) and linearity $R^2 > 0.999$ for the sequential dilution of a 300 ppb QS solution with a response time (T63*) < 2 s [*YSI Inc.*, 2025a]
Measurement of turbidity	The accuracy of the "Turbidity Digital Smart Sensor" is 0.3 FTU or ±2% of the reading in the range 0–999 FTU with a response time (T63*) < 2 s [*YSI Inc.*, 2025b].
Protection from contamination and biofouling	Automatic mechanical brushes

Note: *"(TYY) < XX s" – the sensor takes less than XX seconds to detect YY% of an instant, sudden change in the measured variable.

Using the collected vertical profiles of hydro-physical variables, post-processing of the profiles was carried out, which included processing of sea water salinity and density by the TEOS-10 Matlab package [*McDougall and Barker*, 2011]. Using the bio-geo-optic data, the concentration of dissolved organic carbon [*Carstea et al.*, 2020] and mass of the suspended solids [*Pfannkuche and Schmidt*, 2003] could be estimated.

Thus, the Winchi profiler allows for fine-scale measurements from the sea surface to a depth of 40–50 m over a four-day period with a time-step between profiles equal to 10 min, over a twenty-one-day period with an interval between profiles equal to 60 min or over a forty-day period with an interval between profiles equal to 120 min. The collected fine-scale profiles of the sea water characteristics allow us to investigate both high- and low-frequency hydrodynamic processes in the coastal sea zone and the influence of these processes on the concentrations of the bio-geo-optic characteristics. The profiler is useful for continuous ecological and biological monitoring of the sea water column.

Observation Survey

The testing of the Winchi profiler was carried out in Vityaz Bay of Peter the Great Bay (the northwestern Sea of Japan) at Marine Experimental Station "Cape Shults" from May 30 to June 10, 2024. The depth of the mooring station was approximately 27 m and the measurements were carried out from the sea surface to a depth of 24 m. The Winchi profiler moved at a speed of 0.1–0.2 m/s and the mean duration of a profiling cycle was about 10 min. Between cycles the Winchi profiler parked (turned off) near the sea bottom.

Figure 2 shows the satellite image of the Vityaz Bay with the marked locations of the moored Winchi profiler and the CTD profiling with the RBRconcerto profiler [*RBR Ltd.*, 2025]. Figure 3 shows the layout diagram of the observation survey. To validate sea water temperature and salinity data obtained using the Winchi profiler at 4:14 (UTC) on June 2, 2024, the CTD cast was carried out from a boat with the RBRconcerto CTD at 4:37 (UTC) on June 2, 2024. The difference between these measurements was 23 min and the distance between the cast locations was ~ 100 m. The Winchi profiler descent at a speed of 0.12–0.13 m/s while the downcast speed of the RBRconcerto profiler was ~ 0.5 m/s.

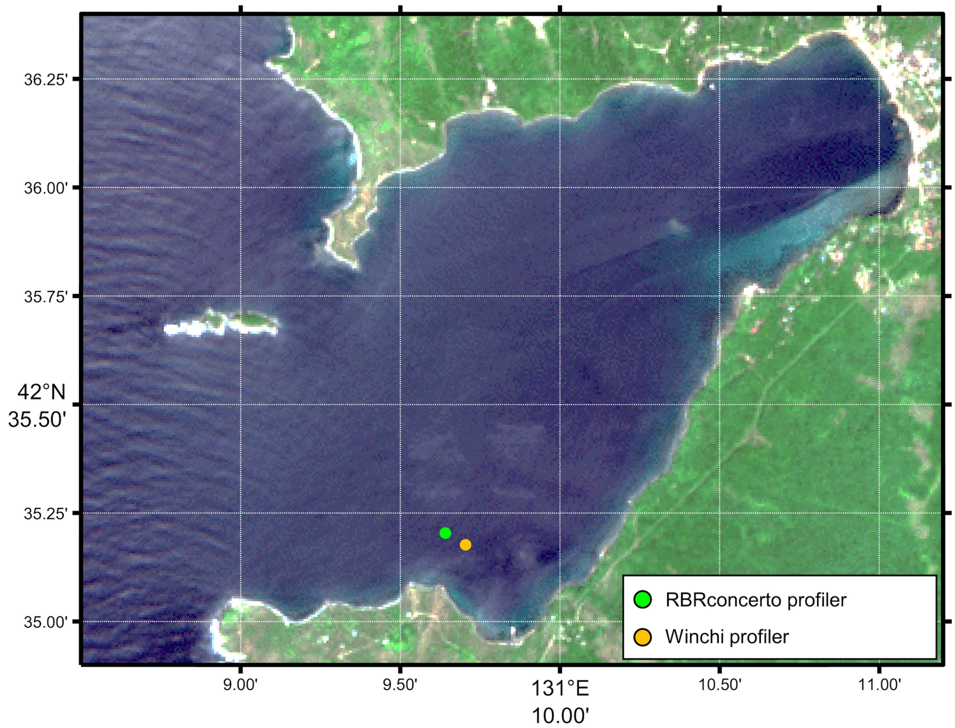

Figure 2. A satellite true color image of the research area obtained by Sentinel-2 on May 28, 2024. The orange circle marks the location of the Winchi profiler mooring, while the green circle marks the location of the ship-borne cast using the RBRconcerto CTD profiler.

The profiles of temperature T_{Winchi}, conductivity C_{Winchi} and pressure P_{Winchi} collected by the Winchi profiler were processed and the absolute salinity of the sea water S_{Winchi} was calculated using the TEOS-10 Matlab package [*McDougall et al.*, 2009]. In addition, the depth of the Winchi profiler was estimated from the hydrostatic pressure measurements.

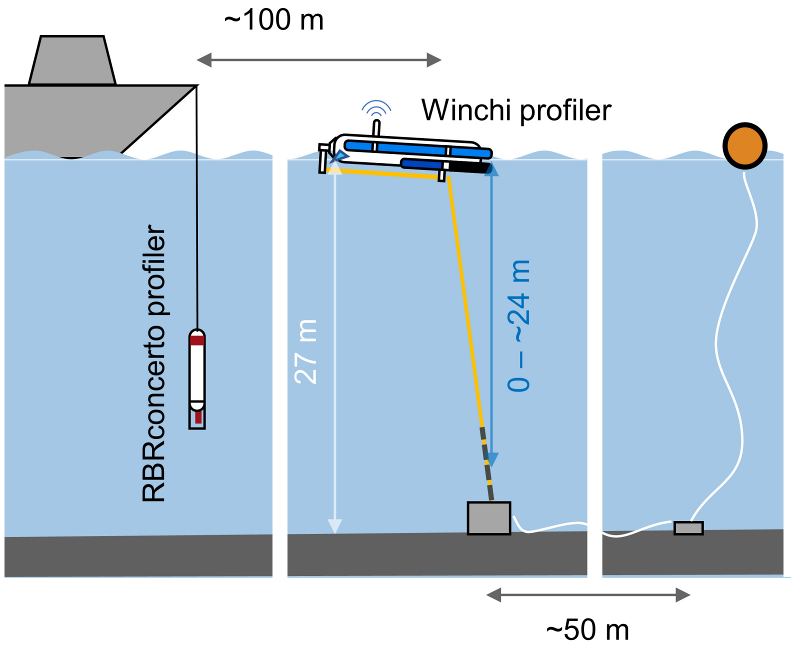

Figure 3. Schematic drawing of the observation survey using the Winchi profiler from May 30 to June 10, 2024. The profiler moved vertically through the water column at one-hour intervals. The CTD cast with the RBRconcerto profiler was conducted on June 2, 2024, at 4:37 UTC.

Notably, the depth measurements by the Honeywell MLH300PSL06A sensor were corrected taking into account more accurate data collected by the EXO2 probe. The profiles of T_{Winchi} and C_{Winchi} were binned into 1-m layers from the sea surface to the depth of 24 m.

To account for the inertia effects of the temperature sensor, the depth profiles of T_{Winchi} were corrected following the approach developed by [*Lazaryuk*, 2008] based on the study of [*Giles and McDougall*, 1986]. This method suggests that the relation between the measured and corrected values of temperature is given by:

$$T_{\mathrm{Winchi}}(t,R) = \frac{T_{\mathrm{Winchi}}(t,0) - T_{\mathrm{Winchi}}(t-\Delta t,0)\cdot \exp\left(\frac{-\Delta t}{R}\right)}{\left(1-\exp\left(\frac{-\Delta t}{R}\right)\right)}, \tag{1}$$

where t is time, Δt is the time increment of 0.25 s, R is the inertia coefficient, $T_{\mathrm{Winchi}}(t,0)$ is the measured temperature at time t, and $T_{\mathrm{Winchi}}(t,R)$ is the corrected temperature for a chosen value of R. The reference profiles of seawater temperature and conductivity, measured by the RBRconcerto profiler (T_{RBR} and C_{RBR}, respectively), were processed according to [*Yaroshchuk et al.*, 2023]. Then, the absolute salinity (S_{RBR} in g/kg) was calculated using the TEOS-10 procedures. The profiles of T_{RBR}, C_{RBR} and S_{RBR} were averaged into one-meter bins from the sea surface to the depth (D) of 24 m.

To estimate the similarity between the profiles of $T_{\mathrm{Winchi}}(D)$, $C_{\mathrm{Winchi}}(D)$, $S_{\mathrm{Winchi}}(D)$ and the profiles of $T_{\mathrm{RBR}}(D)$, $C_{\mathrm{RBR}}(D)$, $S_{\mathrm{RBR}}(D)$, the root-mean-square-error (RMSE) values were calculated. In a layer from D_1 to D_2, the RMSE values depend on coefficient R as follows:

$$\mathrm{RMSE}_T(R,D_1,D_2) = \sqrt{\frac{1}{N}\sum_{D=D_1}^{D_2}\left(T_{\mathrm{RBR}}(D) - T_{\mathrm{Winchi}}(D,R)\right)^2}, \tag{2}$$

$$\mathrm{RMSE}_C(D_1,D_2) = \sqrt{\frac{1}{N}\sum_{D=D_1}^{D_2}\left(C_{\mathrm{RBR}}(D) - C_{\mathrm{Winchi}}(D)\right)^2}, \tag{3}$$

$$\mathrm{RMSE}_S(R, D_1, D_2) = \sqrt{\frac{1}{N} \sum_{D=D_1}^{D_2} (S_{\mathrm{RBR}}(D) - S_{\mathrm{Winchi}}(D, C_{\mathrm{Winchi}}(D), T_{\mathrm{Winchi}}(D, R)))^2} \quad (4)$$

where D is the depth value from 0 m to 24 m with 1 m increment, $N = (D_2 - D_1 + 1)$ is the number of summands. The upper and bottom layers were excluded from the calculations. The layer from D_1 to D_2 was defined such that $\mathrm{RMSE}_C(D_1, D_2)$ reached its minimal value, serving as an indicator of minimal natural uncertainties between the considered and reference measurements.

Results and Discussion

Figure 4 presents the results of a comparative analysis between Winchi and RBRconcerto measurements using formulas (1)–(4). The following optimal values were obtained: $D_1 = 7$ m, $D_2 = 13$ m, $R^* = 10.9$. Figure 5 displays the T, C, and S profiles obtained from both the Winchi profiler and the RBRconcerto CTD profiler. The profiles were corrected using the selected coefficient R^*.

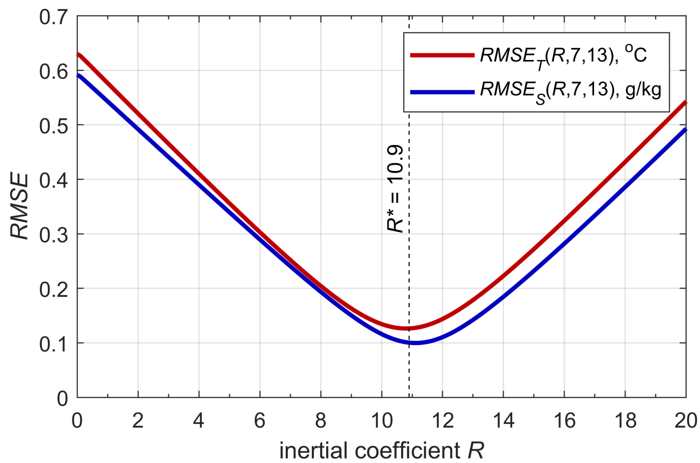

Figure 4. The RMSE in relation to the inertia coefficient (R) for both the reference and corrected profiles of temperature (T) and salinity (S). The black dashed line represents the selected value of $R^* = 10.9$.

A comparison reveals that the maximum difference between the reference and corrected T profiles is around 0.8 °C with an RMSE_T of 0.63 °C (or 6% of the mean value of T_{RBR}) (refer to Figure 4 and Figure 5a). After adjustment, the maximum difference between the reference and corrected T profiles was approximately 0.2 °C, and the RMSE_T value decreased to 0.13 °C (1.2% of the mean value of T_{RBR}) (refer to Figure 4 and Figure 5a).

While discussing the results, we should take into account that the estimation of RMSE_T includes the inherent measurement errors from both profilers and the specific natural changes in the sea water temperature in the research area. Figure 5b shows that in the chosen layer from D_1 to D_2 the profiles of C_{Winchi} and C_{RBR} are very similar and the corresponding value of RMSE_C is equal to 0.07 mS/cm or 0.2 % of the mean value of C_{RBR}. Despite the similarity of both profiles of conductivity, the higher inertia of the temperature sensor resulted in artificial features associated with an abrupt decrease in salinity for the layers with high temperature gradients (about 1 °C/m): from 2 to 4 m and from 10 to 12 m (Figure 5c). The comparison between the corrected and reference profiles of absolute salinity shows that the difference between them reaches the value of 0.5 g/kg and the value of RMSE_S is equal to 0.59 g/kg (or 1.8 % of the mean value of S_{RBR}) (Figure 4 and Figure 5c). After correction, the difference between profiles decreased approximately by the factor of three and the value of RMSE_S was reduced by six times to 0.1 g/kg (0.3% of the mean value of S_{RBR}).

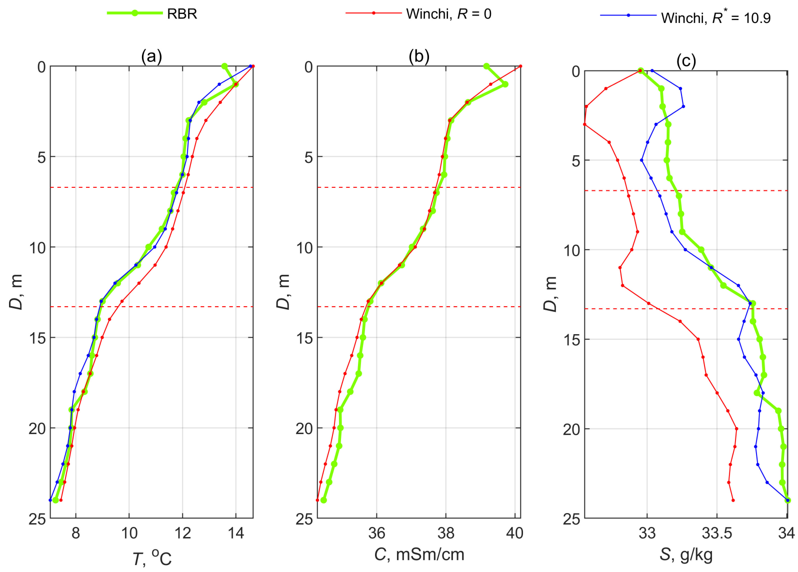

Figure 5. Comparison of temperature (a), conductivity (b), and absolute salinity (c) profiles obtained by the Winchi profiler and the RBRconcerto profiler at 4:14 and 4:37 on June 2, 2024 (UTC). The red dashed lines represent the 7 to 13 m layer used for $\mathrm{RMSE}_{\{T,C,S\}}$ estimations. The raw and corrected Winchi profiles are shown by red and blue lines, respectively, and green lines represent the measurements obtained with the RBRconcerto profiler.

The raw profiles of T collected by the Winchi profiler during the whole survey from May 30 to June 10, 2024 were corrected by applying the above mentioned correction procedure. After that, we calculated the profiles of absolute salinity and potential density. Figure 6 shows the time-depth plots of the sea water characteristics: corrected potential temperature, corrected absolute salinity, FDOM and turbidity.

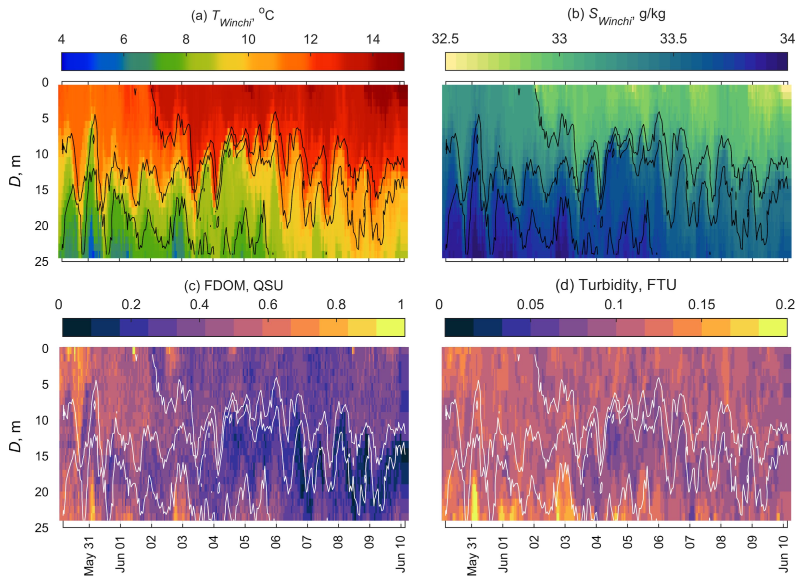

Figure 6. The depth profiles of corrected sea water temperature (a), corrected absolute salinity (b), fluorescent dissolved organic matter (FDOM) (c) and turbidity (d) from the Winchi data over the period from May 30 to June 10, 2024. The profiles of turbidity were smoothed to enhance the main features.

During the survey, two periods from May 30 to June 3 and from June 3 to June 10 can be distinguished in the upper layer. During the first observational period, the temperature ranged from 11 to 12 °C and salinity reached 33 g/kg in the upper layer from the sea surface to ~ 10 m. The thermohaline structure of the second period featured a sharp increase in temperature, reaching 13–14 °C. In addition, the absolute salinity decreased from 33 to 32.7 g/kg, the content of FDOM decreased from 0.7 to approximately 0.2–0.3 QSU and the turbidity decreased from approximately 0.15 to 0.1 FTU. That is, the upper-layer waters became warmer and clearer, which was reflected in both hydro-physical and bio-geo-optical measurements.

In the thermocline, quasi-inertial oscillations with a frequency close to the inertial frequency (~ $1/18\,h^{-1}$) and diurnal oscillations with a frequency of about ~ $1/24\,h^{-1}$ clearly appeared. These scales were confirmed by a fast Fourier transform analysis and power spectrum calculation for the depths of the 10 °C isotherm (figure not shown).

Also, pronounced turbidity peaks and corresponding FDOM peaks with vertical scales of about 10 m were observed in the bottom layer (Figure 6c, d). These peaks are likely caused by the uplift of suspended solids and dissolved organic matter from the seafloor into the near-bottom boundary layer. Bottom friction is the probable driver of this variability.

Conclusions

For the first time, vertical underwater multiparameter measurements were conducted regularly as frequently as once per hour for more than 10 days in Vityaz Bay of Peter the Great Bay in the northwestern Sea of Japan. The new Winchi profiler with a YSI EXO2 multi-parameter probe was employed in the survey that focused on intraday and inter-day variations of fine-scale thermohaline stratification and bio-geo-optical characteristics of seawater. Reference profiles of temperature and absolute salinity were collected in Vityaz Bay using the RBRconcerto profiler.

At the data processing stage, the response time of the EXO2 temperature sensor was accounted for by applying a dynamic correction based on its exponential response function. The chosen inertia coefficient allowed for a reduction of the RMSE values between the reference and the corrected profiles of temperature and salinity by factors of five and six, respectively.

The time series of the corrected profiles of temperature and salinity revealed interesting features of the vertical structure changes in the waters of Vityaz Bay. The variability of bio-geo-optical characteristics of the sea water was associated with the thermohaline and dynamic processes in the upper and bottom layers. During the survey, near-inertial and diurnal oscillations were observed.

In the future, the Winchi profiler will be upgraded with a low-inertia temperature sensor and will be used to conduct long-term surveys in different seasons in order to study the influence of multi-scale ocean dynamics (waves, eddies and currents) and atmospheric forcing (tropical cyclones and storm winds) on the thermohaline stratification and vertical distribution of bio-geo-optical characteristics. The in-situ measurements with the Winchi profiler will be used to validate regional thermodynamic models and to improve the algorithms for satellite remote sensing data processing.

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