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Article

Long-Term Oceanographic Survey for Social Implementation of OTEC Plant in Okinotorishima (Seawater Temperature, Salinity, Dissolved Oxygen, Inorganic Nutrients and Density)

Masaki Ariyoshi [1], Hideyuki Yoshimura [1], Junichi Ohara [1], Masateru Ishida [1], Junji Koga [1], Tatsuhiko Tanaka [1], Kiyohiko Fukami [1], Takayuki Hirano [1], Takafumi Morisaki [2], Kazuya Urata [2] and Yasuyuki Ikegami [2,*]

[1] Department of Ocean Mechanical Engineering, National Fisheries University, 2-7-1, Nagatahonmachi, Shimonoseki 759-6595, Yamaguchi, Japan; ariyoshi@fish-u.ac.jp (M.A.)
[2] Institute of Ocean Energy, Saga University, Honjo-machi 1, Saga 840-8502, Saga, Japan
* Correspondence: ikegami@cc.saga-u.ac.jp

Abstract

In order to implement ocean thermal energy conversion (OTEC), it is necessary to maintain a stable temperature difference between surface seawater and deep seawater. Accordingly, numerous oceanographic surveys have been conducted to select sea areas suitable for OTEC deployment, not only around Japan but also in other countries around the world. However, long-term oceanographic survey data for the Okinotorishima area, a promising candidate for OTEC, are not yet available. While many studies have addressed OTEC design under generic conditions, designs based on specific areas have remained limited. However, the availability of oceanographic data necessary for conducting such studies is still limited. Therefore, a long-term oceanographic survey was conducted, starting in 2006. This study presents a systematic compilation of oceanographic survey results to lay the groundwork for evaluations for the installation of an OTEC plant. The survey items included the vertical profiles of seawater temperature, salinity, dissolved oxygen, and nutrients at each observation station. The results indicate that the temperature difference between surface seawater and deep seawater, which is the most important factor for OTEC, almost exceeded the threshold of 20 °C required for the realization of an OTEC plant. This study provides a foundational dataset for evaluating the feasibility of OTEC deployment, performing economic assessments, and organizing comprehensive long-term oceanographic data in Okinotorishima from an engineering perspective.

Keywords: Okinotorishima; ocean thermal energy conversion; deep ocean water; conductivity temperature depth profiler; OTEC plant

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1. Introduction

To achieve carbon neutrality by 2050, it is necessary to develop sustainable energy sources that do not rely on fossil fuels. Ocean thermal energy conversion (OTEC), which converts thermal energy generated by the temperature difference between surface seawater and deep seawater into electrical energy, is seen as a promising power generation method that can contribute to solving this problem.

Many studies regarding installation sites and conceptual designs for OTEC are currently being conducted in Japan and around the world. OTEC also requires a stable temperature difference between surface seawater and deep seawater, and numerous oceanographic

surveys are being conducted around the world, including around Japan, to select areas suitable for OTEC installation.

Wolff et al. (1979) identified sea areas suitable for OTEC installation using data on surface seawater and deep seawater temperatures at depths of 1000 m around the world [1]. Uehara et al. (1988) conducted an oceanographic survey in the Philippine Sea and estimated the construction and operating costs of a 25 MW offshore power plant and a 5 MW onshore power plant to evaluate their economic feasibility [2]. Inui et al. (1994) conducted an oceanographic survey along a route departing from Shimonoseki; passing through the South China Sea, the Pacific Ocean, the Indian Ocean, the Suez Canal, the Mediterranean Sea, the Atlantic Ocean, and the Panama Canal; and returning to Japan, examining marine energy sources [3]. Nakaoka et al. (2003) conducted an oceanographic survey in the Fiji Sea in the South Pacific to optimize the design of a hybrid OTEC system combined with a seawater desalination unit and evaluated the power generation potential [4]. In addition, Thirugnana T.S et al. (2021) revealed from oceanographic data that the sea areas off the northwestern and southeastern coasts of Sabah, Malaysia, are suitable for OTEC [5].

Focusing on sea areas around Japan, Inui et al. (1990) conducted an oceanographic survey in the Okinoerabu Sea off Kagoshima Prefecture, a leading candidate site for OTEC, and reported data on surface and deep seawater temperatures, salinity, seabed topography, and tidal current speed and direction [6]. Ichinose et al. (2007) conducted an oceanographic survey to evaluate the feasibility of OTEC in the Tsushima Sea off Nagasaki Prefecture and reported the results for seawater temperature, salinity, seabed topography, and tidal current speed and direction [7].

As mentioned above, oceanographic surveys are being actively conducted in various sea areas to evaluate the introduction of OTEC, but few studies have focused on long-term surveys focusing on a single sea area. Therefore, Yoshimura et al. (2022) conducted oceanographic surveys from 2016 to 2022 to install an OTEC plant in the Kumejima sea area, Okinawa Prefecture, a promising candidate site for OTEC, assessing the feasibility of OTEC deployment and examining temporal changes in seawater properties [8]. To promote the multiple uses of deep seawater used for OTEC, Urata et al. (2021) revealed basic data on nutrients in the east of Kumejima, as there were almost no data on the vertical profile of nutrients and major elements in the area [9]. Ikegami et al. (2008) analyzed nutrients to obtain data necessary for the multiple use of OTEC around Okinawa and reported the distribution of high nutrients [10]. Nakaoka (2009) conducted oceanographic surveys in the Tsushima sea area, including nutrient analysis for multiple uses, and showed that the nutrient distribution is similar to the deep seawater in Kochi and Toyama prefectures [11].

In recent years, evaluations based on statistical data and numerical models have also become increasingly important, rather than relying solely on direct oceanographic surveys. Posterari (2024) estimated thermal energy resources in Pacific Island regions including Saipan using Argo profile data and satellite-derived surface seawater temperature data [12]. Langer (2021) reported on the economic feasibility of OTEC around Indonesia using the HYCOM model, indicating that many studies have not considered evaluation of seawater temperature and depth as economic viability and profitability compared with regional electricity sales schemes [13]. While this report is noteworthy for including water depth as a parameter for installation, particularly because steep seabed topography can enable shorter intake pipes while reducing the burden on mooring lines, the authors also noted limitations of the methodology, such as the dependence of results on the accuracy of the HY-COM model, the fact that the data used only average temperature without seasonal fluctuations, and the exclusion of effects such as salinity. Langer (2022) evaluated the impact of fluctuations in seawater temperature on the cost of OTEC power generation, citing the lack of research addressing seasonal and other water temperature fluctuations [14]. By

using 19 years of seawater temperature data at three-hour intervals obtained from HYCOM, this study used combinations of the maximum, minimum, and median values of surface and deep seawater temperatures as design parameters. Liu (2020) conducted a simulation considering the effects of tides, evaluated the potential of the Aguni Basin, and found that sustainable power generation could be achieved on the slope northeast of Kumejima [15]. Nihou (2007) developed a one-dimensional model of vertical heat balance when intake seawater is discharged into the sea and evaluated the potential, taking into account the effects of drainage and thermal diffusion [16].

As mentioned above, although many papers utilize various data such as HYCOM or satellite data, there has been little actual data from long-term oceanographic surveys that simultaneously observe not only water temperature but also salinity, dissolved oxygen and nutrients every 1 m, and there are not many papers about this. Recently, argo float data have been used in many studies, which reveals the vast sea area mesh. But argo float does not remain at a fixed location, the density is insufficient, and in some sea areas, the data obtained are inadequate. For this reason, it will continue to be useful to utilize oceanographic survey results in potential assessments. In particular, oceanographic survey results for nutrients, which require on-site surveys, will be valuable.

Shiozaki et al. (2009) reported that when considering the circulation of nitrogen dioxide in tropical and subtropical oligotrophic waters, rather than eddy diffusion as it was previously thought that eddy diffusion supplies nitrate, multiple processes on spatial and temporal scales contribute, and it is important to accumulate observational data that account for the spatial and temporal variations of each process [17]. With regard to the environment, Kakuma et al. (2017) cited the negative effects of high concentrations of nutrients, such as an increase in seaweed that competes with coral for light, an increase in phytoplankton that reduces water clarity and inhibits the photosynthesis of symbiotic algae within coral, and an increase in phytoplankton that feeds crown-of-thorns starfish larvae, leading to an outbreak of predatory species [18]. They reported the results of experiments that the higher the nutrient concentration, the lower the survival rate of juvenile corals. In terms of fisheries and aquaculture, Fujiwara et al. (2020) reported a correlation between total nitrogen and the growth of shrimp and other organisms around Osaka [19]. They noted that the effects of eutrophication on the growth rates of small organisms are not generally recognized as a factor in damage to fisheries. Eto et al. (2012) focused on phosphorus supply as a factor in the poor harvest of seaweed in Fukuoka Bay, reporting that dissolved phosphorus caused seaweed discoloration and thallus runoff [20]. Tsuge et al. (2024) investigated the relationship between nitrogen and phosphorus concentrations, clam and seaweed fisheries in Mikawa Bay and determined that the concentrations required for production are dissolved nitrogen of 80–100 μg/L and dissolved phosphorus of 8–10 μg/L [21]. Kakuma et al. (2021) utilized OTEC seawater to cultivate the expensive, fast-growing Ulva prolifera and developed technology to collect nutrients contained in seawater [22].

Okinotorishima is the only island within Japan's exclusive economic zone that is located in the tropics and is considered one of the most promising candidate sites for an OTEC plant in Japan. Okinotorishima is also a significant area in Japan. Kaji (2020) reported on the issues surrounding Okinotorishima and the strategy related to marine security in the Western Pacific [23]. The sea area around Okinotorishima is rich in fishery resources and seabed mineral resources. He suggests that securing energy, a long-standing issue for Japan, will be achieved.

As such, Okinotorishima holds great potential in terms of marine strategy and marine resources, and oceanographic surveys are being conducted by some organizations, not just with a view on OTEC. As previously mentioned, we compiled statistics on Argo float data

and JODC data frequently used in oceanographic analyses. For the grid area surrounding Okinotorishima (covering 0.06° × 0.06° in latitude and longitude, including the island itself), there are only 15 data points in total across the surface, 600 m, and 800 m depths throughout the year; even when using a 1° × 1° grid, the total amounts to just 2268 data points. Therefore, oceanographic surveys around Okinotorishima are summarized in Table 1. Oceanographic surveys have weaknesses, which are considered in only specific locations and are costly. Furthermore, it is difficult to accumulate the detailed data needed to observe the diurnal temperature range. But there are verified sources that are useful in the localized area, which has little Argo float data such as Okinotorishima. The Central Meteorological Observatory (CMO) (1942) conducted a survey of meteorological and oceanographic conditions around Okinotorishima, reporting on the relationship between depth and seawater temperature [24]. The Japan Agency for Marine-Earth Science and Technology (JAMSTEC) conducted fixed-line observations, including observations in the sea area around Okinotorishima, using an XCTD from 1998 to 2000 [25]. JAMSTEC also published the results of long-term oceanographic and meteorological observation around Okinotorishima from 2002 to 2015 using the research vessel Natsushima [25–31]. The Japan Meteorological Agency (JMA) publishes seawater temperatures analyzed using ocean general circulation models and observations from satellites, buoys, and ships. This dataset includes the sea area around Okinotorishima [32]. The Japan Oceanographic Data Center (JODC) collects and publishes oceanographic data such as water temperature obtained from oceanographic surveys in Japan and overseas [33]. However, oceanographic surveys and statistics conducted by such public institutions are limited to the results, and no consideration has been given from an OTEC perspective.

Yoneyama et al. (2006) conducted an oceanographic survey around Okinotorishima in response to the limited availability of oceanographic observations in the Okinotorishima area and reported the vertical profiles of seawater temperature, salinity and nutrients in spring and autumn/winter [34]. In order to obtain basic data for the maintenance, conservation, and utilization of Okinotorishima, the Tokyo Metropolitan Government (2022) conducted an oceanographic survey using a research vessel owned by Tokai University and reported the results of its seawater temperature and salinity [35]. IDEA Consultants, Inc. (2023 and 2024) conducted oceanographic surveys using CTD to obtain biota data and reported vertical profiles of seawater temperature, salinity, and density, as well as T-S diagrams over a two-year period [36,37]. Additionally, the University of Tokyo (2023) noted that published results of scientific research and projects concerning Okinotorishima had not been widely shared, and so they compiled a report and database that comprehensively collected relevant materials [38,39]. This report pointed out the need for collaboration among government ministries and agencies in implementing related projects and the insufficient international communication. These issues should be taken into consideration as future research on Okinotorishima proceeds.

In oceanographic surveys for OTEC, one of the most important parameters is the vertical profile of seawater temperature. A greater temperature difference between surface and deep seawater reduces the total heat transfer area required for the heat exchangers and the amount of seawater. Fuji et al. (2006) reported that even high-efficiency plate heat exchangers require approximately 1500 tons of titanium for a 100,000 kW class power generation output [40]. The temperature difference has a significant impact on initial investment and running costs. Therefore, understanding the temperature difference helps estimate the power generation capacity and intake depth, providing important information for determining the feasibility of an OTEC plant. However, feasibility depends not only on power generation capacity and costs but also by evaluating the entire system, including the economic benefits of multiple uses of seawater used for OTEC, such as aquaculture,

air conditioning, and other purposes (multi-uses). For this reason, oceanographic surveys related to OTEC also measured the vertical profile of dissolved oxygen, which is relevant to multi-use, and analyzed nutrient concentrations. Salinity is an essential parameter for calculating seawater density and thermal conductivity.

Regarding research into the installation of an OTEC plant around Okinotorishima, Ueda et al. (2014) conducted an oceanographic survey to evaluate the feasibility of OTEC around Okinotorishima and reported analyses of seawater temperature, salinity, dissolved oxygen, and nutrients [41]. Ishida et al. (2020) conducted oceanographic surveys to evaluate OTEC in the waters around Kumejima, Okinawa Prefecture, and Okinotorishima, Tokyo, and assessed the performance of an OTEC using an integrated hybrid cycle [42]. As these studies demonstrate, evaluating OTEC performance from an engineering perspective using the ocean survey data is essential for assessing its practical feasibility.

Table 1. The surveys and data statistics related to OTEC around Okinotorishima.

Name	Method	Period	Seawater Temp	Salinity	Dissolved Oxygen	Report
CMO	unknown	1939–1941	yes	no	no	1942
JAMSTEC	XCTD XBT	1998–2000	yes	yes	no	-
JODC	Organize Data	1772–2025	yes	yes	no	-
JMA	Analyze	Past 3 years	yes	yes	no	-
Yoneyama	CTD XBT	2005	yes	yes	yes	2006
Ueda	CTD	2006	yes	yes	yes	2014
Mikami [43]	STD	2006	yes	yes	yes	2007
Ishida	CTD	2015, 2019	yes	yes	yes	2020
Tokyo	CTD	2021	yes	yes	no	2022
IDEA	CTD	2022, 2023	yes	yes	no	2023, 2024
Ariyoshi [44]	CTD	2020–2024	yes	yes	yes	2025

Although several reports regarding Okinotorishima have been published, most of these are based on oceanographic surveys over only one or a few years, and long-term oceanographic survey data have not been made public. Consequently, studies of OTEC design tailored to specific oceanographic conditions have remained limited.

Therefore, this study compiles oceanographic survey data gathered by the authors since 2006, including the latest observations from October 2024, with survey data obtained by other organizations around Okinotorishima. The aim is to establish a foundational dataset to support the evaluation and deployment of OTEC. Specifically, we considered the seasonal variations in the vertical profiles of surface and deep seawater temperature, which are critical to OTEC performance. We also analyzed the vertical profiles of seawater density calculated from water temperature and salinity, as well as the vertical profile of dissolved oxygen and nutrient concentrations. Although there is currently no economic activity on Okinotorishima, the potential for multi-use, such as aquaculture, should be considered if OTEC is implemented in the future. Therefore, this study also provides a foundation for multi-use. The dataset is expected to support future comprehensive and quantitative assessments of OTEC feasibility, considering power generation capacity and the associated costs, which are influenced by seawater temperature, as well as the potential economic

benefits of multi-uses. The results of this study will be used for engineering perspectives, as well as Ishida's paper.

As described above, this study comprehensively summarizes long-term oceanographic data in Okinotorishima, with an engineering focus, on evaluating the feasibility of OTEC deployment and future economic assessments, including multi-uses.

2. Methodology

2.1. Sites and Period of Survey

Figure 1 shows the survey area. The main observation area is 20°21′ N~20°31′ N, 135°58′ E~136°12′ E. Table 2 summarizes the survey periods and the vessels. A total of nine surveys were conducted between January 2006 and October 2024. However, the survey in 2024 was excluded from analysis because of data deficiency.

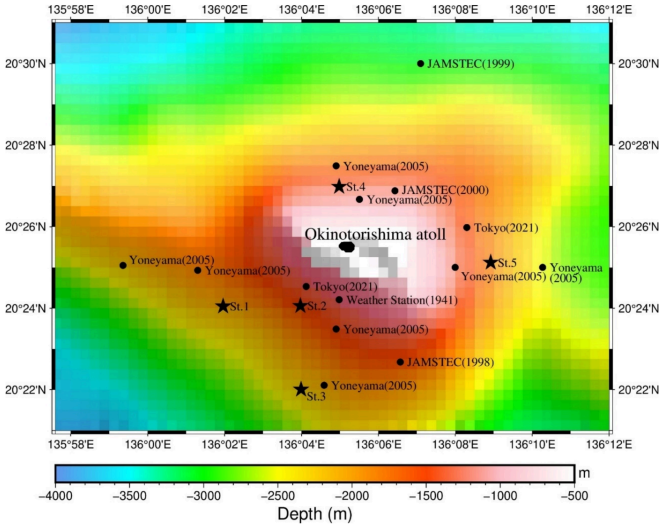


Figure 1. Survey area; ★ means sites of our observation, St.1~5; ● means sites of other organizations' observation, cited by Central Meteorological Observatory (1942), Japan Agency for Marine Earth Science and Technology, Yoneyama (2005), Tokyo Metropolitan Government (2021) [24,25,34,35].

Table 2. Outline of our survey. Observation period, the number of observations and vessel.

Year	Month	Number of Observations	Observation Points	Vessel
2006	January	5	St.1~St.5	Koyomaru
2013	December	5	St.1~St.5	Tenyomaru
2015	November	3	St.1~St.3	Tenyomaru
2019	October	5	St.1~St.5	Koyomaru
2020	November	5	St.1~St.5	Koyomaru
2021	November	5	St.1~St.5	Koyomaru
2022	November	5	St.1~St.5	Koyomaru
2023	October	5	St.1~St.5	Koyomaru
2024	October	5	St.1~St.5	Koyomaru

2.2. Method of Survey

The survey was conducted using the National Fisheries University training ships, Koyomaru and Tenyomaru. The main specifications of the Koyomaru are 87.59 m (length) × 13.60 m (width) × 8.8 m (depth), international gross tonnage 2703 t, cruising speed 14.0 knots, and a total capacity of 109 people (42 crew members, 7 faculty members, and

60 students). The main specifications of the Tenyomaru are 64.67 m (length) × 11.90 m (width) × 6.98 m (depth), international gross tonnage 1354 t, cruising speed 12.0 knots, and a total capacity of 87 people (28 crew members, 8 faculty members, 50 students, and 1 reserve member) [45]. Table 3 shows the observation items. Observations were conducted using a Conductivity Temperature Depth profiler (CTD) (Sea-Bird Electronics, Inc. (Bellevue, WA, USA) SBE 9 Plus). The CTD collects the depth, seawater temperature, salinity, dissolved oxygen, and other data at each water pressure. The winch (Φ9.53 mm × 5000 m) drops the CTD into the sea at 1.0 m/s or less, and measurements are taken from the surface to close to the seafloor. Observations were conducted using the onboard multi-cylinder water sampler (12 × 10 L Niskin bottles). Figure 2 shows the observation work in progress. Table 4 shows the CTD sensor specifications. Furthermore, because in situ temperature depends on pressure, particularly in deep water, potential temperature was used to account for the effects of pressure.

Table 3. Survey items are pressure, temperature, conductivity and dissolved oxygen.

No.	Item	Unit
1	Pressure (Depth)	Db
2	Temperature	°C
3	Conductivity (Salinity)	S/m (PSU)
4	Dissolved oxygen	mL/L



(**a**) (**b**)

Figure 2. (**a**) Preparation of observation work. (**b**) CTD released into the sea.

Table 4. Sensor specifications of CTD used in observation.

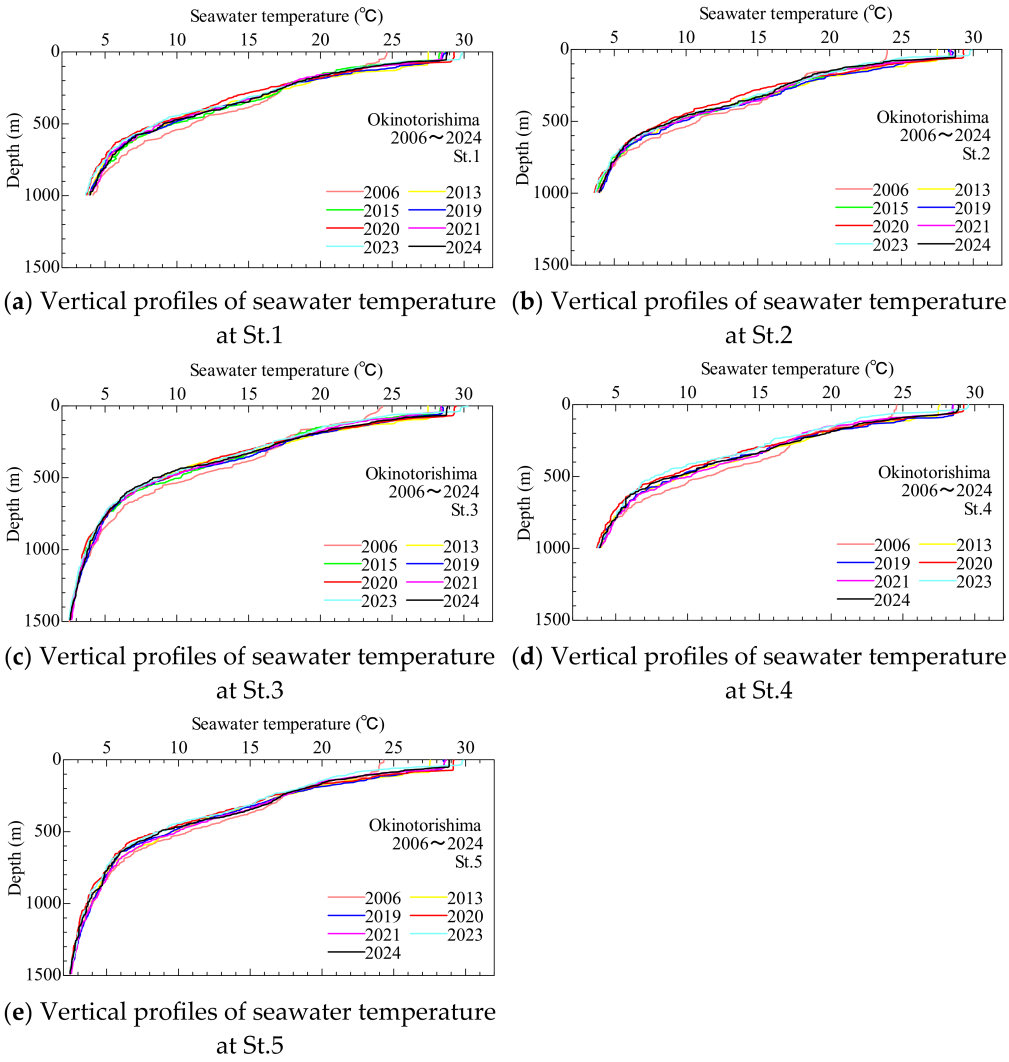
Item	Range	Accuracy	System
Temperature	−5–+35 °C	±0.002 °C	Thermistor
Conductivity	0–7 S/m	±0.0003 S/m	Electrode
Pressure	0–6800 m	±0.015%FS (±1.02 m)	Quarts

3. Results and Consideration

3.1. Seawater Temperature

Figure 3 shows the vertical profiles of seawater temperature as the results of our oceanographic survey from January 2006 to October 2024. As shown in Table 2, the surveys were conducted in different months, from October to January. The surface seawater temperature ranged from 24.4 °C to 29.8 °C. Seawater temperature remained relatively constant in the upper 50 m and decreased sharply with depth down to 600 m. It is called thermocline. The profile with a surface temperature of approximately 25 °C corresponds to

the survey conducted in January 2006. Below 600 m, seawater temperature decreased more gradually and stabilized at approximately 3–5 °C below 1000 m.



(**a**) Vertical profiles of seawater temperature at St.1

(**b**) Vertical profiles of seawater temperature at St.2

(**c**) Vertical profiles of seawater temperature at St.3

(**d**) Vertical profiles of seawater temperature at St.4

(**e**) Vertical profiles of seawater temperature at St.5

Figure 3. Vertical profiles of seawater temperature obtained in our observations of each year are summarized in each observation point.

Figure 4 shows an enlarged view of the vertical temperature profiles presented in Figure 3 over the depth range of 0–500 m. The profile obtained in 2006 exhibits distinctive features not limited to the surface temperature. Specifically, the temperature gradient is observed near the mixed layer, and the thermocline structure also differs from those in other years. The survey in January was conducted only once, unlike the other surveys. Therefore, these features should not be generalized based solely on this single observation.

Table 5 shows the descriptive statistical data from our observations at each depth. The standard deviation and variance generally decrease with depth. This suggests that deep seawater can provide a more stable temperature difference for OTEC.

Figure 5 shows the monthly variations in seawater temperature at each depth, summarizing our oceanographic survey data and other organization data, JAMSTEC, Yoneyama, Tokyo Metropolitan Government and IDEA Consultants, Inc., from quote tables or from graphs through visual inspection. In the figure, an individual point represents oceanographic survey data, and a line represents monthly average surface temperature published on the JMA website. Both the plot and line are lower in January to March, with the minimum in February. The monthly temperature variation decreases

with depth. There is no temperature change below a depth of 400 m. If surface water is taken, floating debris such as marine litter may cause a pump accident and disposal costs. So, the actual design of intake surface water should be set below a depth of 20 m. As discussed above, it is no problem for the temperature difference, because the mix layer extends to 50 m.

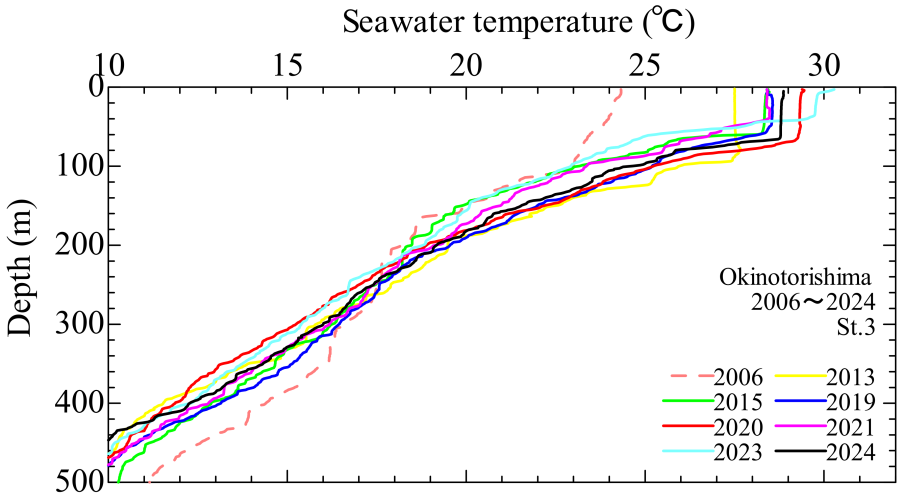


Figure 4. Vertical profiles of seawater temperature zoomed up to surface.

Table 5. Fundamental statistical data of temperature in our observations at each depth.

Item	Unit	Surface	100 m	200 m	400 m	600 m	800 m
average	[°C]	28.2	24.0	18.9	12.7	7.1	4.9
max	[°C]	29.8	25.8	19.4	14.3	8.4	5.2
min	[°C]	24.4	22.5	18.5	11.6	6.5	4.7
deviation	[-]	1.568	1.054	0.323	0.761	0.549	0.161
variance	[-]	2.458	1.112	0.104	0.579	0.301	0.026

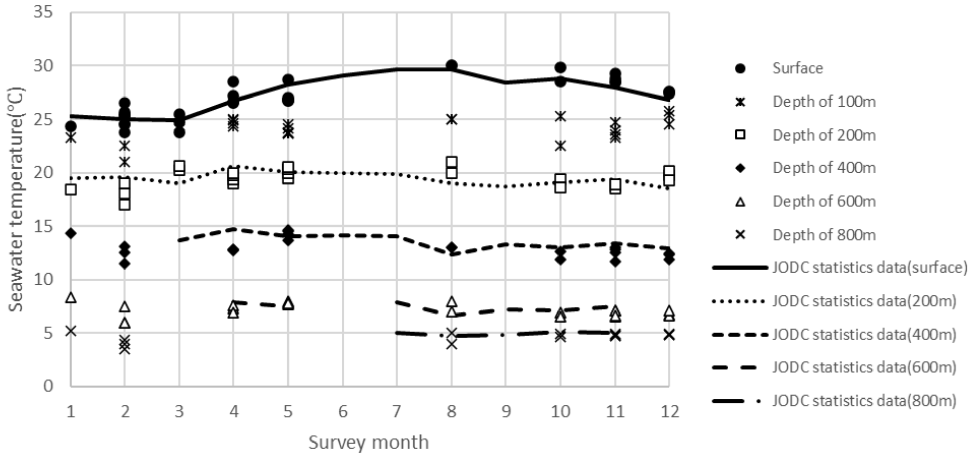


Figure 5. Change in seawater temperature by month including the data from JAMSTEC, CMO, Yeneyama, Tokyo Metropolitan Government, IDEA Consultants, Inc. and JODC.

Determining the intake depth of deep seawater is very important. The New Energy and Industrial Technology Development Organization (NEDO) reported that a temperature difference of 20 °C is required for economic viability [46]. Based on this report, it is necessary to compare deep seawater temperature, which remains constant throughout the year

with surface seawater in January to March, when conditions are most unfavorable. Based on the results of an oceanographic survey, the surface seawater temperatures in January, February, and March are 24.4 °C, 23.8 °C, and 24.7 °C, respectively; the seawater temperature at depths of 600 m and 800m is 7.1 °C and 4.7 °C throughout the year. Accordingly, temperature differences in January, February, and March are 17.3 °C, 16.7 °C and 17.6 °C, respectively, at a depth of 600 m and 19.7 °C, 19.1 °C and 20.0 °C, respectively, at a depth of 800 m. In conclusion, intake at a depth of 600 m does not meet the required condition. Intake at a depth of 800 m meets this condition for most of the year, slightly below the required value in January and February.

The feasibility depends on the specifications of the alternative power generation system, economic benefits of multi-uses and the operation conditions such as the electricity demand, which may allow for slight temperature differences.

This analysis did not consider diurnal range variations. Nozawa (1999) reported that surface temperature peaks around 3 p.m. and reaches its minimum around 7 a.m., with a maximum difference of up to 3 °C in extremes [47]. All our surveys were conducted during the daytime, and the observation time of other organization surveys is unknown. Therefore, it is important to note that diurnal range variations also require consideration. It should be noted that, as stated in the Introduction, the results of this survey do not account for diurnal variations, which is a limitation of the methodology. Additionally, as shown by the results of IDEA Consultants, Inc., the mixed layer is shallow in summer. Therefore, caution is required when drawing surface water from shallow depths.

Table 6 shows the net power calculated using the formula proposed by Nihous [48]. Net power increases with increasing intake depth. Below the thermocline, the increase in net power diminishes. The intake depth should be determined, considering the cost and output associated with the intake pipe.

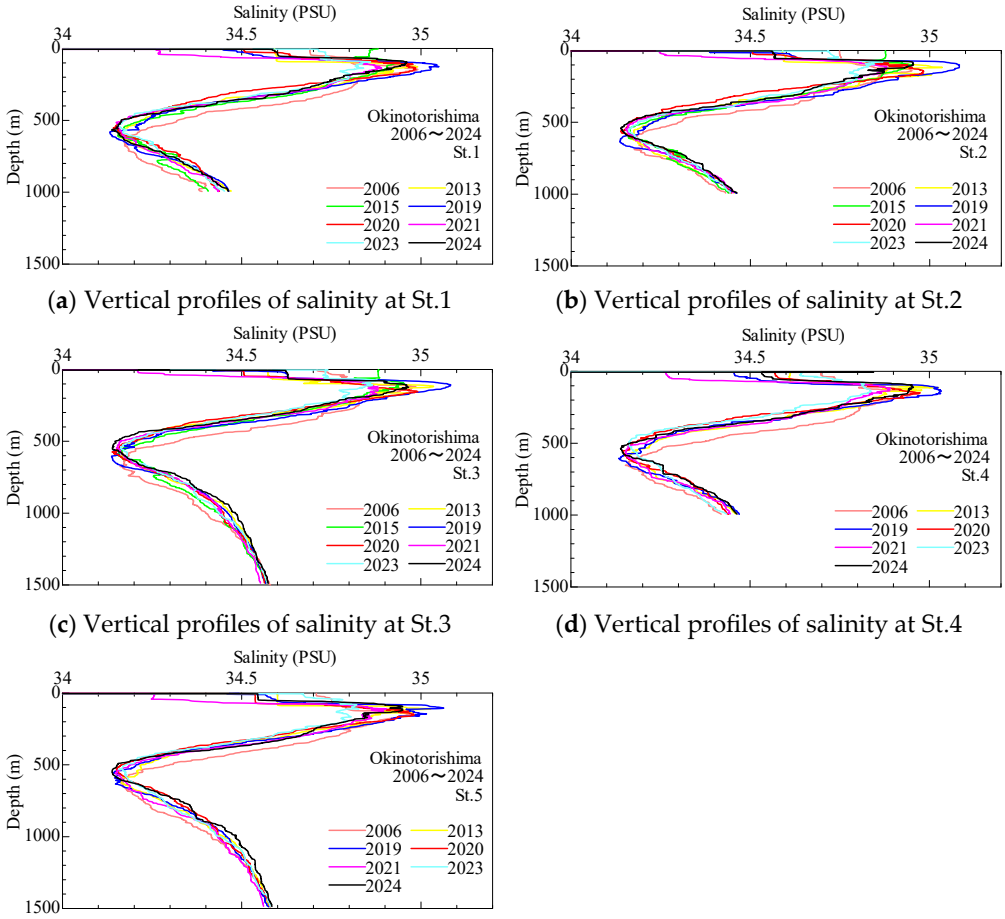
Table 6. The net power at each depth. The calculation quarts and the average of our observation results in each month.

Month	Unit	400 m	600 m	800 m	1000 m
January	[MW]	0.505	0.803	0.961	1.024
October	[MW]	0.835	1.106	1.204	1.252
November	[MW]	0.804	1.084	1.185	1.236
December	[MW]	0.756	1.013	1.128	1.169

3.2. Salinity

Figure 6 shows the vertical profiles of salinity based on the results of our oceanographic survey from January 2006 to October 2024. Salinity increases with depth from the surface to a depth of 150 m, decreasing toward depths of 600 m. Below 600 m, salinity increases gradually with depth, with the variations becoming less pronounced. Salinity ranges from 34.84 to 35.03 PSU at a depth of 150 m and from 34.15 to 34.19 PSU at a depth of 600 m. As mentioned by Yoneyama (2006), the water mass has a local minimum at a depth of 600 m known as North Pacific Intermediate Water [34].

Salinity is an essential parameter for heat exchanger design. Salinity affects the thermophysical properties, specifically its viscosity coefficient and thermal conductivity. These properties influence fluid flow and heat transfer in heat exchangers. Therefore, the salinity shown in this study will be used as a reference for future calculations of heat transfer areas in the future.



(**a**) Vertical profiles of salinity at St.1

(**b**) Vertical profiles of salinity at St.2

(**c**) Vertical profiles of salinity at St.3

(**d**) Vertical profiles of salinity at St.4

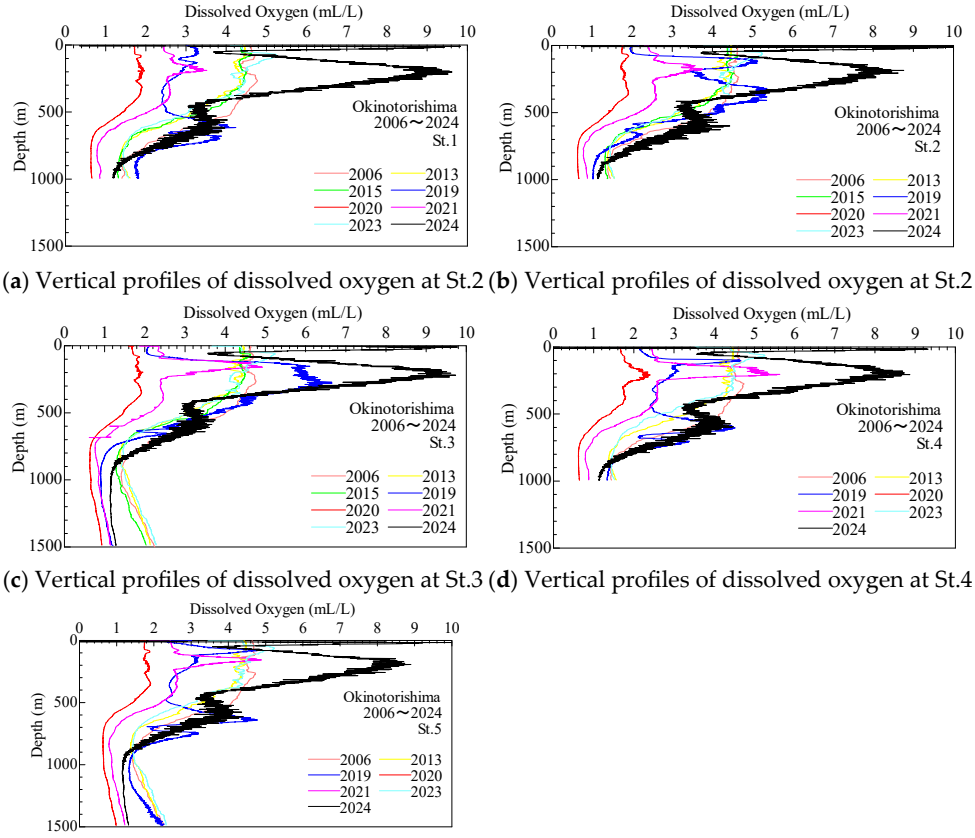
(**e**) Vertical profiles of salinity at St.5

Figure 6. Vertical profiles of salinity obtained in our observations of each year are summarized in each observation point.

3.3. Dissolved Oxygen

Figure 7 shows the vertical profiles of dissolved oxygen based on the results of our oceanographic survey from January 2006 to October 2024. Although dissolved oxygen varies considerably from year to year, it peaks around a depth of 200 m and minimum between depth of 800 and 1000 m. Below this range, the vertical change tends to decrease gradually. The profiles of 2019, 2021 and 2024 show pronounced fluctuations in Figure 5, but no specific meteorological or oceanographic records such as wave and wind data explain these variations. Abnormal events of organisms or typhoons may influence oceanographic surveys. For example, typhoon No. 20 in 2019 passed west of the survey site four days before the survey. The potential effects of such events should be considered.

Assuming deep seawater is utilized for aquaculture, dissolved oxygen is 1.0 mL/L at a depth of 800 m around Okinotorishima. According to Yanagi (1989), hypoxic water mass is often defined as below 2.5 mL/L [49]. Because the dissolved oxygen around Okinotorishima is below the threshold and is even lower than that used for aquaculture at the Kochi Prefecture Deep Seawater Research Institute, it is necessary to control the dissolved oxygen through aeration.



(**a**) Vertical profiles of dissolved oxygen at St.2 (**b**) Vertical profiles of dissolved oxygen at St.2

(**c**) Vertical profiles of dissolved oxygen at St.3 (**d**) Vertical profiles of dissolved oxygen at St.4

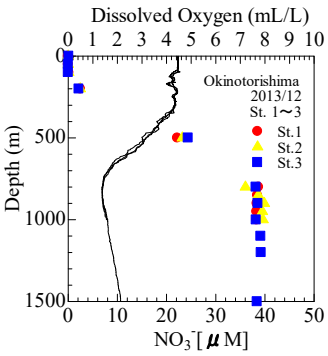
(**e**) Vertical profiles of dissolved oxygen at St.5

Figure 7. Vertical profiles of dissolved oxygen obtained in our observations of each year are summarized in each observation point.

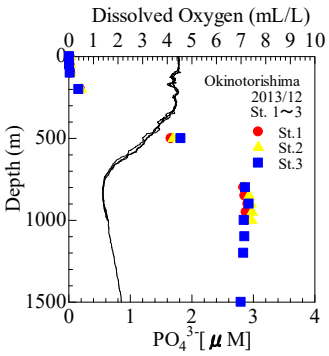
Figure 8 shows the vertical profiles of inorganic nutrients based on the results of our oceanographic survey from January 2013 to November 2024. Phosphate and nitrogen concentrations are negatively correlated with dissolved oxygen, whereas silicon concentration increases with depth. This pattern explains the decomposition of organic matter, which consumes oxygen and releases phosphate and nitrogen, whereas silicate is released through the dissolution of biogenic silica without directly consuming oxygen. From the figure, the ratio of N/P, which is the indicator of cell growth of natural algal communities, was 14 (2023, st1,800 m). Falkowski (2005) reported that the vertical profiles of N/P ranged from 13 to 15 at depths of 800 m in the Pacific Ocean. The ratio of N/P around Okinotorishima is within that of the common Pacific Ocean [50].

3.4. Density

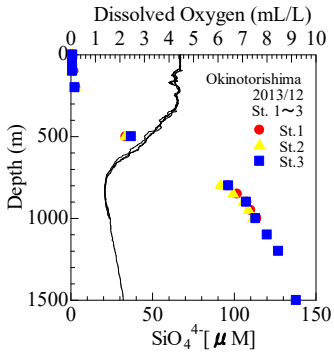
Figure 9 shows the vertical profile of seawater density calculated using TEOS-10 [51]. This determines seawater density as a nonlinear function of seawater temperature, salinity, and depth (pressure). There is a slight difference among points and survey years. Considering that density generally increases with decreasing temperature and increasing salinity, the temperature and salinity profiles shown in Figures 2 and 3 can explain the variations in the density profiles shown in Figure 9. Below 1000 m, potential density changes slightly with depth because of small variations in temperature and salinity. On the other hand, in situ density increases linearly with depth because of the increase in pressure. In the OTEC plant, the power required for each pump accounts for a very large proportion of the total generator power. Uehara (1982) estimated that pump power reaches approximately 23% of gross power in the case of a 100,000 kW system. Therefore, accurate estimation of the power required for each pump is essential for OTEC design [52].



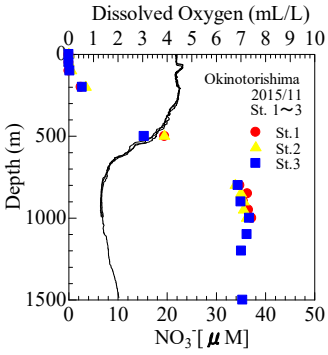
(**1-a**) Vertical profiles of nitrogen in 2013.



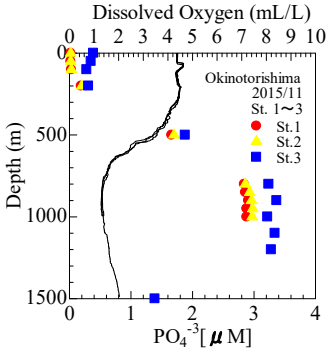
(**1-b**) Vertical profiles of Phosphoric in 2013.



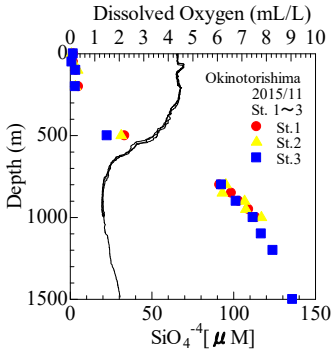
(**1-c**) Vertical profiles of silicon in 2013.



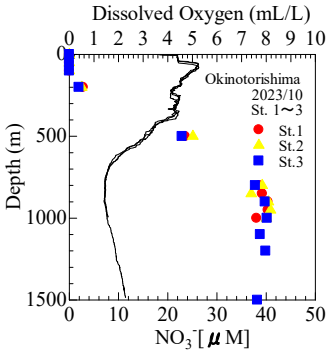
(**2-a**) Vertical profiles of nitrogen in 2015.



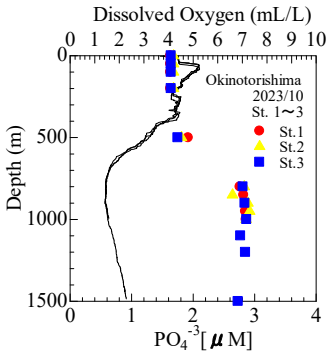
(**2-b**) Vertical profiles of Phosphoric in 2015.



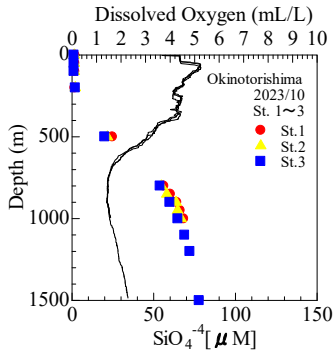
(**2-c**) Vertical profiles of silicon in 2015.



(**3-a**) Vertical profiles of nitrogen in 2023.

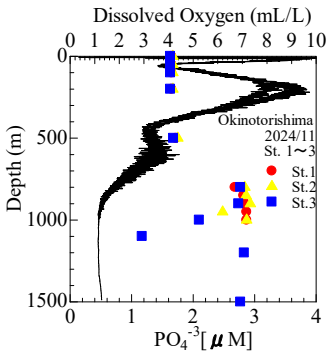


(**3-b**) Vertical profiles of Phosphoric in 2023.

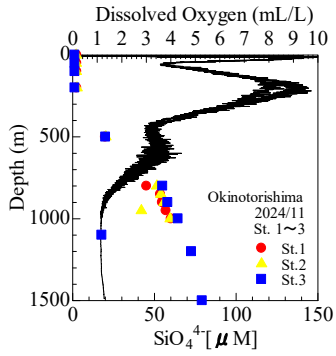


(**3-c**) Vertical profiles of silicon in 2023.

(**4-a**) Vertical profiles of nitrogen in 2024 (No data).



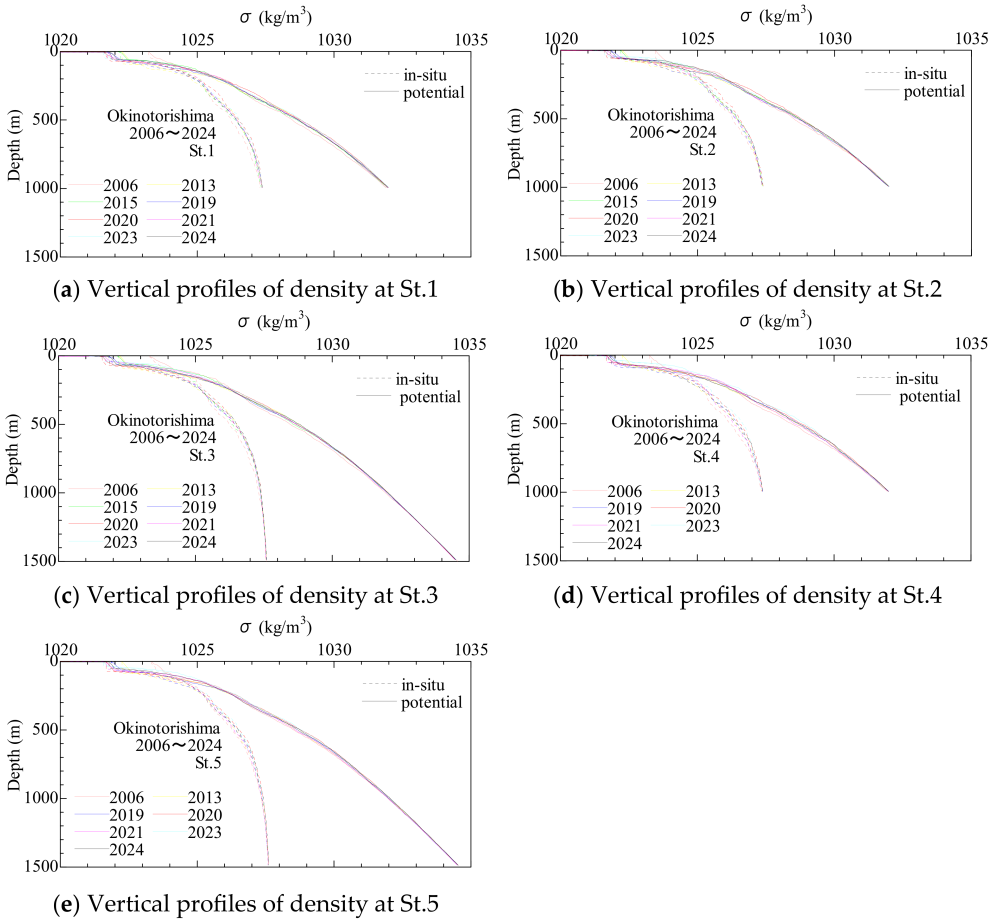
(**4-b**) Vertical profiles of Phosphoric in 2024.



(**4-c**) Vertical profiles of silicon in 2024.

Figure 8. Vertical profiles of inorganic nutrients. Survey of nutrients had been implemented in st.1 to st.3, and limited survey years. Branch numbers are assigned by survey year—type of nutrients. It

is noted that phosphoric acid data are below 1.68μmol/L at depth of 0 to 200 m in 2023, below 1.67 μmol/L at depth of 0 to 200 m in 2023, while plots in the figure are at 1.68 μmol/L and 1.67 μmol/L for convenience.



(**a**) Vertical profiles of density at St.1

(**b**) Vertical profiles of density at St.2

(**c**) Vertical profiles of density at St.3

(**d**) Vertical profiles of density at St.4

(**e**) Vertical profiles of density at St.5

Figure 9. Vertical profiles of density obtained by calculation from our observations result of each year are summarized in each observation point. The solid lines mean in situ density, which is at that depth. The dashed lines mean potential density, which is at surface without Adiabatic heating by pressure.

To estimate the power of the deep seawater pump, the head losses due to pipe friction and seawater density difference must be considered. The pipe friction depends on pipe length and seawater density and can be calculated using general formulas of fluid mechanics. Additionally, this calculation needs the intake flow rate. Because this study does not address engineering aspects of OTEC such as determining flow rates and pipe diameter, the discussion is limited to the head loss associated with seawater density differences. The density difference means that density at surface seawater and that of deep seawater at the bottom of the pipe is different. In other words, there is a difference between the head in pipe and intake depth, when the pressure from seawater at the bottom of the pipe is equal to the pressure from surrounding seawater. Because accurately calculating the detailed density difference loss needs the vertical profiles of density, simplified calculations were performed in most cases. iJitsuhara et al. (1994) and Giostri et al. (2018) calculated the density difference loss. In their study, surrounding seawater density is estimated using the average density of surface seawater density and deep seawater density at the bottom of the pipe, and seawater density in the pipe is estimated using deep seawater density at the bottom of the pipe [53,54]. Density difference loss is often calculated using a similar simple calculation. However, comparing simple calculation with precise calculation, integrating actual vertical profiles of density has not been sufficiently evaluated.

Equation (1) presents a simplified calculation, in which the density difference is defined as the difference between average surface seawater density and deep seawater density at the bottom of the pipe and deep seawater density at the bottom of the pipe.

$$loss_{density} = dep_{csw} - (\rho_{csw} + \rho(t(dep_{csw}), S(dep_{csw}), P(0))) \times \frac{dep_{csw}}{2\rho_{csw}} \quad (1)$$

Precise calculation determines head suction by solving Equation (2). The left side means the pressure from the surrounding seawater, adding the density at each depth from the surface to intake depth in order based on vertical profiles of density. The right side means the pressure at the bottom of the pipe has the same temperature and salinity regardless of depth; only pressure varies.

$$\int_{dep_{surface}}^{dep_{csw}} \rho(t(z), S(z), P(z))dz = \int_{dep_{surface}}^{head_{suction}} \rho(t(dep_{csw}), S(dep_{csw}), P(z))dz \quad (2)$$

Quoiting $head_{suctin}$ from Equation (2), the result of calculation using Equation (3) is the density difference loss.

$$loss_{density} = dep_{csw} - head_{suction} \quad (3)$$

Figure 10 shows the results calculated using the above equation for the 2024 survey, with st.3 as an example. In both simplified and precise calculations, density difference loss increases with depth in a range from the surface to a depth of 800 m. However, below 800 m, while the simplified calculation continues to increase, the precise calculation decreases with the change of loss. At depths of 600 m, the loss is 0.80 m and 1.44 m via simplified calculation, respectively. At depths of 800 m, the loss is 1.06 m and 1.31 m via precise calculation.

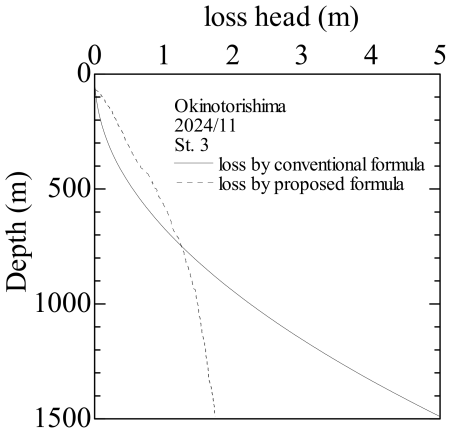


Figure 10. Vertical profiles of density different loss. St.3 in 2024 is used as the representative point for calculation. The solid lines mean result of simple calculation. The dashed lines mean precise calculation.

As shown in Figure 6, the bottom of the thermocline is located around 600 m, and the change with depth becomes small below 600 m, with almost no change around a depth of 1000 m. Therefore, it is unlikely that the intake depth of deep seawater is as deep as 1000 m. The simplified loss calculation used by Jitsuhara (1994) or Ikegami (1989) is valid for use in OTEC calculations [53,55].

4. Conclusions

The oceanographic survey conducted from January 2006 to October 2024 and other observation survey results are summarized below.

1. Surface seawater temperature ranged from 24.4 °C to 29.8 °C. Seawater temperature remained relatively constant in the upper 50 m and decreased sharply with depth down to 600 m. The profile with a surface temperature of approximately 25 °C corresponds to the survey conducted in January 2006. Below 600 m, seawater temperature decreased more gradually and stabilized at approximately 3–5 °C below 1000 m.
2. Temperature differences in January, February, and March were 17.3 °C, 16.7 °C and 17.6 °C, respectively, at a depth of 600 m and 19.7 °C, 19.1 °C and 20.0 °C, respectively, at a depth of 800 m. In conclusion, intake at a depth of 600 m does not meet the required condition. Intake at a depth of 800 m meets this condition for most of the year, slightly below the required value in January and February.
3. Salinity increases with depth from surface to a depth of 150 m and drops down to a depth of 600 m. Below 600 m, salinity increases gradually with depth, with the variations becoming less pronounced.
4. Although dissolved oxygen varies considerably from year to year, it peaks around a depth of 200 m and minimum between depths of 800 and 1000 m. Below this range, the vertical change tends to decrease gradually.
5. Phosphate and nitrogen concentrations are negatively correlated with dissolved oxygen, whereas silicon concentration increases with depth. The ratio of N/P around Okinotorishima is within that of the common Pacific Ocean.
6. Density generally increases with decreasing temperature and increasing salinity. Below 1000 m, potential density changes slightly with depth. On the other hand, in situ density increases linearly with depth.
7. The simplified density difference loss calculation is valid for use in OTEC calculations.
8. By comprehensively organizing long-term oceanographic data in Okinotorishima from an engineering perspective focused on OTEC deployment, the dataset presented in this study provides a foundation for OTEC design, economic assessments including multi-uses, and studies on its societal implementation.

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Data Availability Statement: The observation data presented in this study are open available in Okinotorishima WebPage (https://www.jamstec.go.jp/j/database/okitori/index.html, accessed on 20 September 2026), JAMSTEC DATABASES (https://www.jamstec.go.jp/e/database/, accessed on 20 September 2026). JODC data is open available in Japan Oceanographic Data Center (https://www.jodc.go.jp/jodcweb/JDOSS/index_j.html, accessed on 20 September 2026).

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

$loss_{density}$	Density difference loss [m]
dep_{csw}	Depth of deep seawater (cooling fresh water) intake [m]
ρ_{csw}	Density of deep seawater intake [kg/m^3]
$\rho(t, S, P)$	Density of seawater with temperature, salinity and pressure as variables [kg/m^3]
$t(z)$	Seawater temperature with depth as variable [°C]
$S(z)$	Salinity with depth as variable [kg/m^3]
$P(z)$	Pressure with depth as variable [dbar]
$dep_{surface}$	Depth of surface [m]
$head_{suction}$	Head of seawater in intake pipe

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