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Variability of the oceanographic structures of the Southern Ocean by the FerryBox data

Abstract. During Antarctic summers in the 2018—2021 period, physical, chemical, and biological parameters of the upper layer of seawater were continuously recorded using the FerryBox (FB) software and measuring system installed on-board the Ukrainian krill fishing trawler F/V More Sodruzhestva. The main hydrological fronts of the South Atlantic and the Southern Ocean were crossed from Cape Town to the Antarctic Peninsula. About 800,000 one-minute FB measurements were used in this research to determine and identify marine structures. The paper aims to estimate the spatial-temporal variability of oceanographic parameters of the surface layer of water in the Southern Ocean based on the FB data analysis. We use classical methods of analysis of hydrological structures, graphical, comparative, and statistical types of analysis of the field data, as well as data from the Copernicus Marine Environment Monitoring Service (CMEMS). Trawling areas were considered as hydrological landfills. We found a decrease in the total number of front crosses: from 8.6% in the 2018—2019 season to 3.9% in the 2020—2021 season. Analysis of the quality of information obtained from the FB showed that after adjustment the measurements allow solving various oceanographic problems, such as identifying frontal zones and detailing their hydrological structure, determining surface water masses and variability of their distribution limits, highlighting significant cycles in time of the measured parameters, studying the gas component of the upper sea layer water. A comparative analysis of the results of the FB observations with the CMEMS data showed their qualitative consistency.

Keywords: continuous observations, hydrological structure, Southern Polar Front, surface waters

1 Introduction

Over the half of the world ocean waters are in contact with the atmosphere in the surface layer of the Southern Ocean; the local dynamics can have fundamental consequences for climate change on the planet (Sallée, 2018). Therefore, a comprehensive study of the current processes in the Southern Ocean is one of the priorities of world oceanography, when *in situ* monitoring is of particular value.

The software and hardware complex FerryBox (FB) was designed for quasi-continuous measurements within the framework of GOOS (Global Ocean Observing System) and Euro GOOS (https://www.ferrybox.org/routes_data/routes/mediterranean_sea/index.php.en). It is used to study physical, chemical, and biological parameters of the upper layer of seawater during the vessel movement. The parameters include temperature, electrical conductivity, dissolved oxygen, pH, partial pressure of carbon dioxide

(pCO_2), turbidity, the fluorescence of chlorophyll, and nutrients. The FB complex used in this paper was installed on the Ukrainian krill fishing trawler F/V *More Sodruzhestva* in 2018.

The FB network is a successful European project of equipping the ferry with measuring systems to economically and efficiently gather scientific information on the marine environment on regular European routes, from the Eastern Mediterranean to the Baltic. More information on the project can be found at http://www.ferrybox.org. As a rule, the research based on FB measurements was carried out in the Europe northern waters. For example, Petersen et al. (2018) tested the operation of the FB sensors on-board two ferries that ran daily between the ports of Cuxhaven (Germany) and Harwich (UK) and concluded that they yielded fairly high-quality data providing an image of the spatio-temporal variability of oceanographic parameters in the area.

Voynova et al. (2018) combined data from three FBs to characterize regional water masses in the German Bight and the North Sea and showed the dependence of dissolved inorganic carbon on salinity. Macovei et al. (2021) used the FB to study the average annual variability of pCO_2. They showed that the trend of partial pressure of carbon dioxide in the surface layer of seawater in 2014—2018 in the southern and central North Sea increased larger than in the atmosphere, and this caused a rise in the average flow of CO_2 from the sea to the atmosphere. From these studies it is clear that the tool provides great opportunities for marine environment monitoring. Ukrainian scientists have experience in conducting continuous observations of the ocean surface temperature (OST) in the South Atlantic and Southern Oceans on-board R/V *Ernst Krenkel* of the Ukrainian Scientific Center of Ecology of the Sea (USCES), in 1997 and 1998 (Artamonov et al., 2000; Ukrainsky et al., 2000).

We provide measurements on-board the trawler F/V *More Sodruzhestva*, which is equipped with the FB to carry out the oceanography research during industrial fishery in the Atlantic sector of the Southern Ocean. It was the first opportunity to use the FB to collect data in the extreme environment of high latitudes and to evaluate its performance. We present the primary results of the FB measurements made in 2018—2021 and discuss the oceanographic structure of the seawater surface layer in the Southern Ocean.

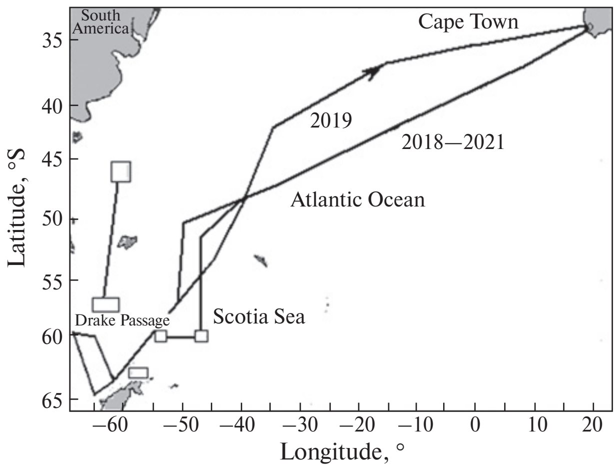

Figure 1. Krill fishing trawler F/V *More Sodruzhestva* routes in 2018—2021 from Cape Town to Antarctic Peninsula. Trawling areas are marked with squares

2 Materials and methods

The FB measurements were carried out with the one-minute temporal resolution during the expeditions in the summer seasons from November 2018 to June 2021. The observation cycle includes 21 parameters: date, time, measurement coordinates, speed, the direction of the vessel, and key marine characteristics such as temperature, conductivity/salinity (C/S), dissolved oxygen, pCO_2, pH, the water sound speed, and technical information. Daily observations represent one set, which consists of 1440 cycles of measurements if there are no lost data. In total, about 800.000 one-minute FB measurements were used for analysis.

The water in the FB system was collected through the Kingston valve using a pump, and then it went through a reservoir receiver to the flow-measuring instruments and analyzers. The depth of water intake was usually within the first 5—7 m from the surface. The vessel route is shown in Figure 1.

The work used classical methods of analysis of hydrological structures, graphical and statistical analysis. The Copernicus Marine Environment Monitoring Service (CMEMS, https://marine.copernicus.eu/) information was used in an additional study of the spatial and time variability of oceanographic fields of the ocean's upper layer and assessment of the quality of FB's performance in polar conditions. The USCES programs were used for the primary data processing and the Microsoft Excel software was used as the main data processing tool. The oceanographic data analysis was provided using the Golden Software Surfer v13 package.

3 Results and discussion

3.1 Stability of the FB operation

Observational data were screened before further manipulations to avoid distortions. Firstly, the completeness of the dataset was checked. This operation was performed separately for every month data, with daily subsets being compared with the total complete set of 1440 observations. The only exceptions were made for the incomplete arrays of the first and last days of the trawling season.

The first expedition of 2018/19 began in November, and the other two, 2019/20 and 2020/21, were started in December, i.e., at the beginning of the Antarctic summer. Each expedition ended at the beginning of winter in June. The rate of missed measurements for every month is shown in Table 1.

The FB measurements failure rate decreased from 8.6% in the season 2018/2019 to 3.9% in 2020/2021,

Table 1. Monthly number of the missed FB measurements (%)

Month	2018–2019 (%)	2019–2020 (%)	2020–2021 (%)
November	11.50	—	—
December	**17.70**	14.60	4.70
January	**5.40**	**2.30**	**2.60**
February	**11.20**	**0.35**	**2.10**
March	**0.50**	**13.50**	**6.60**
April	**5.70**	**0.38**	**4.10**
May	**3.70**	**8.20**	**1.30**
June	13.20	6.30	5.70
Total	8.60	6.50	3.90
Antarctic zone (values in bold)	7.40	4.90	3.40

due to the improved technical skill of the staff. The starting months significantly contribute to the total number of missed records. As a rule, the gaps formed two or three days "clusters". For example, in the first three days of December 2019, the number of omissions was 28%. Note, that in the Antarctic zone, the data gaps were significantly fewer than in the transatlantic crossings, presumably because of the lesser speed of the vessel. The usual speed was of 2 knots during trawling, and up to 12 knots in transatlantic crossing.

The next type of data failure is outliers, i.e., the unrealistic values for a given place and time based on the climatic characteristics. They are easily detected visually on graphs or with simple data control software. Analysis of the FB data shows that outliers are usually associated with pauses and re-starts in the FB operation, which is less than 0.1% of the total measurements. The FB output is reasonably stable and reliable for each parameter. The screened data can be used to study a range of oceanographic parameters.

3.2 Analysis of the FB data

One of the most important tasks of oceanography is the study of the variability of frontal zones (Artamonov et al., 2009; Chapman, 2017). As an example of the application of FB measurements, we chose the Southern Polar Front (SPF) transect when F/V *More Sodruzhestva* was coming back from Antarctica to Cape Town in 2020. Figure 2 shows a graph of the temperature and water salinity distribution in the meridional transect on June 3, 2020, which was directed perpendicular to the SPF line.

The path length shown in Figure 2 is 140 miles, and the segment between the vertical dotted lines, denoted as the SPF, is 18 miles. North of the SPF the temperature of the upper layer of water leaps from 2.1 °C to 4.7 °C, with salinity in the range from 33.76 psu to 33.88 psu. If we extend the concept of the front to the frontal zone, the temperature of the polar frontal zone varies from 1.5 °C to 5.0 °C, and salinity from 33.73 psu to 33.95 psu.

The histogram in Figure 3 shows the differences in temperature between adjacent one-minute measurements at the SPF intersection.

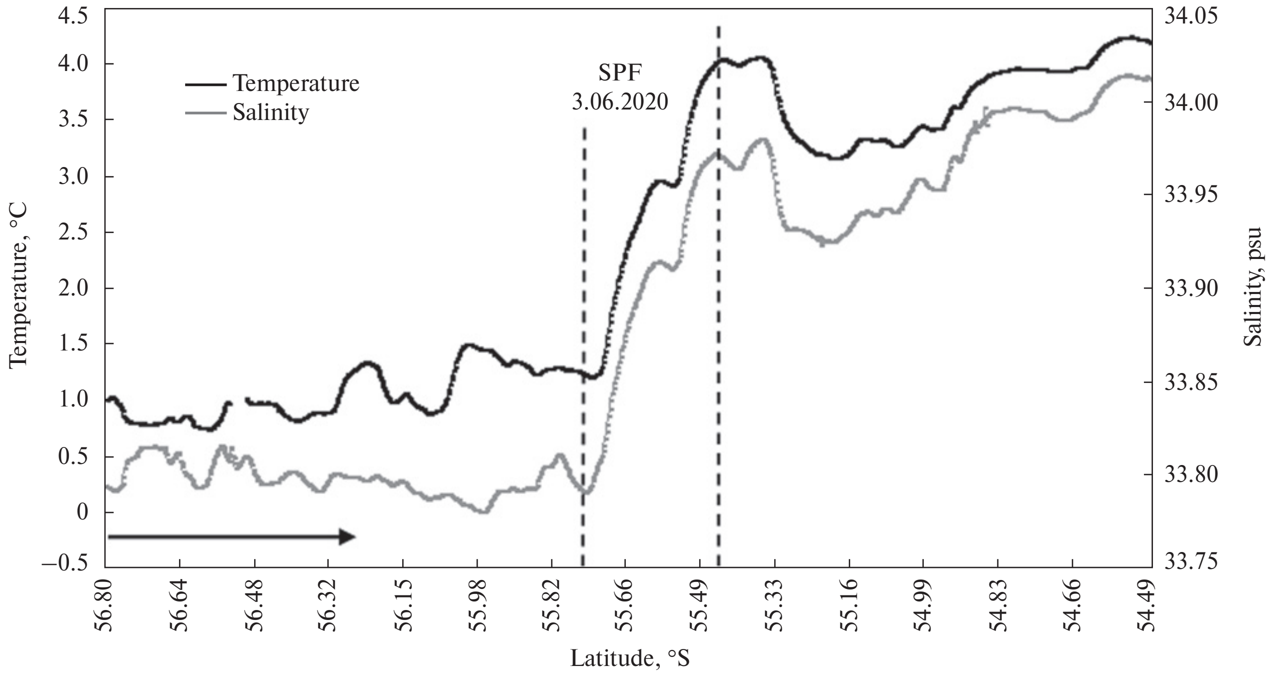

Figure 2. Distribution of temperature and salinity of water in the meridional transect at the crossing of the SPF on June 3, 2020. The arrow indicates the sailing direction of the vessel

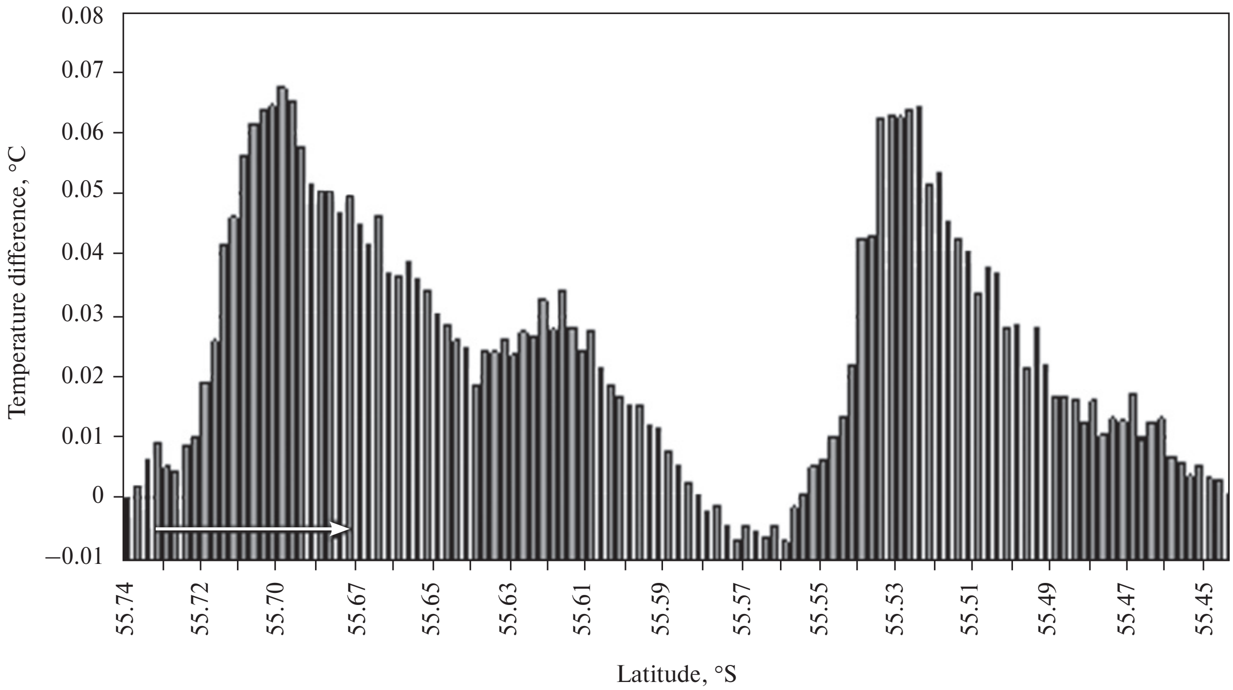

Figure 3. Differences in adjacent minute-by-minute temperature measurements in the meridional transect of the SPF on June 3, 2020. The arrow indicates the sailing direction of the vessel

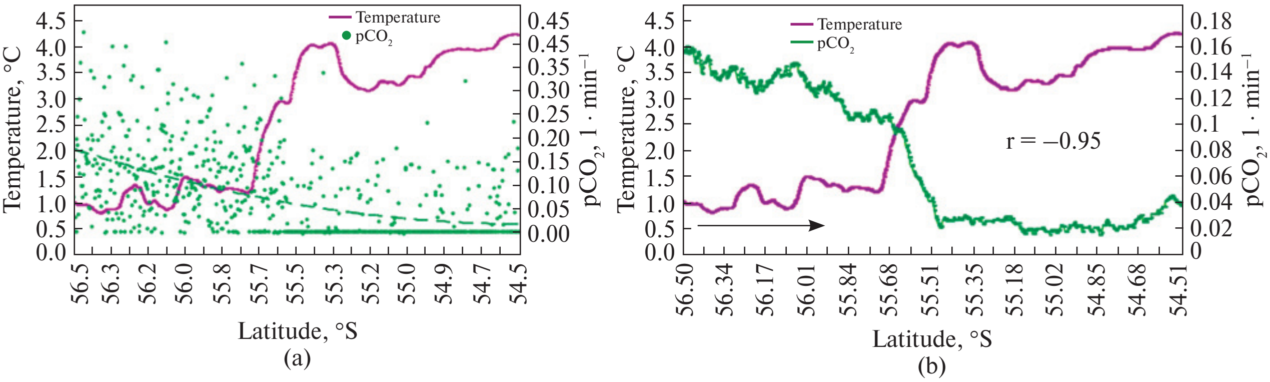

Figure 4. Distribution of temperature and the pCO_2 parameter at the crossing of the SPF on June 3, 2020: (a) one-minute values, (b) averaged over 60 observations; green dashed line — the hyperbolic regression

Here we demonstrate the possibility to use the FB for detection fine details of marine structures. In Figure 3, the frontal zone consists of two "waves" — two zones of high gradients. They are separated by a narrow zone, where the temperature no longer rises but decreases during ten minutes of the vessel movement.

It is interesting, for example, to compare the average temperature gradient over the entire transect of the route shown in Figure 2 with the average gradient in the frontal zone, and with the temperature maximum at 55.7 °S in Figure 3. The average vessel speed over the entire transect was of 9.4 knots. The corresponding distance between the measurements was of 290 m. Therefore, the image in Figure 3 can be interpreted as an image of the spatial temperature gradients in units of 1 °C per 290 m. For comparison, all gradients must be reduced to the same unit of measurement in $°C \cdot m^{-1}$. The statistics of the comparison are presented in Table 2.

The average water temperature gradient in the 18-mile front zone is 5.6 times greater than the average in the 140-mile transect in the center of the zone location (Table 2). The maximum of the gradient in the frontal zone is 14 times larger than the 18-mile average.

Table 2. Comparison of the average water temperature gradients (*a*) for the whole transect, (*b*) for the SPF, and (*c*) maximum for the SPF

Subject	Latitude, °S	Distance, miles	ΔT, °C	Gradient T, $°C \cdot m^{-1}$
a	54.49–56.80	141	4.25	1.63E–05
b	55.44–55.74	18	3.03	9.10E–05
c	55.695–55.698	0.16	0.067	22.94E–05

In addition to temperature and salinity, the other parameters changes in the same transect were considered. For example, the distribution of pCO_2 is shown in Figure 4a, b.

In Figure 4a, the set of one-minute measurements for 13 hours during the passage of this transect appears as a chaotic cloud of points. However, the hyperbolic regression (green dashed line in Fig. 4a) exhibits the trend, which indicates the progressively less amount of the dissolved carbon dioxide in the northern warmer waters. This pattern becomes quite obvious in Figure 4b, where the graph of the averaged over hourly intervals pCO_2 is shown. As expected, the negative correlation of pCO_2 values and temperature is observed with correlation coefficient $r = -0.95$ (Fig. 4b).

The experience suggests that according to the FB data, it is possible to reliably identify frontal areas, determine the values of parameters at their boundaries, and detail their spatial-temporal variability (Komorin et al., 2019).

Trawling areas consist of numerous tacks and can be considered as hydrological landfills. The FB GPS data allows tracing the vessel movement precisely. Figure 5a shows the monthly movements of the vessel during the measurements in the Bransfield Strait in 2021.

The surface waters of the Bransfield Strait are formed by mixing local shelf waters, warmer and more freshened waters of the South Branch of the Antarc-

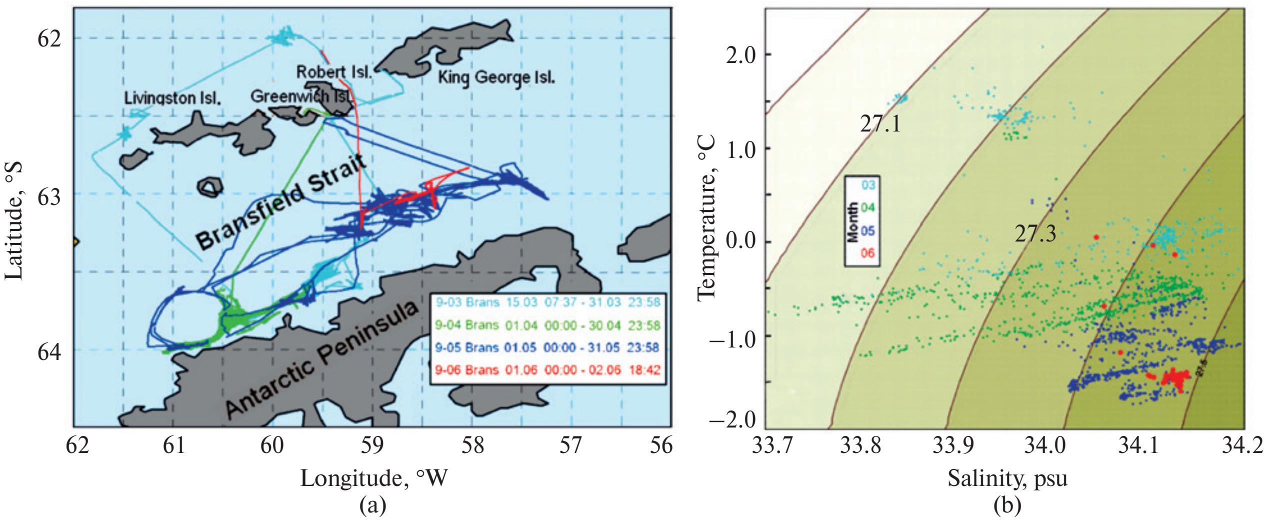

Figure 5. Monthly transects of the krill fishing trawler F/V *More Sodruzhestva* in the Bransfield Strait and adjacent aquatories according to the GPS data (a) and TS diagram based on the field of relative density of seawater observations in the Bransfield Strait (b), March 15 — June 2, 2021. Brown isolines show conditional density

tic Circumpolar Current, and cold and saline surface waters of the Weddell Sea, leading to the formation of so-called mixed waters of the Bransfield Strait, which play a dominant role in the formation of the hydrological environment and have a positive impact on the biological and industrial productivity, nurturing their own population of krill *Euphausia superba* (Zhuk, 2011/2012; Zhuk & Korzun, 2016).

To analyse the spatiotemporal variability of the hydrophysical parameters, we used a well-developed apparatus of the TS-analysis (Mamaev, 1970). A TS diagram (Fig. 5b) built on all observations in the Bransfield Strait in the fall of 2021 gives a clear idea of the monthly distribution of the TS indices of surface waters in the field of the conditional density. The diagram clearly shows how the temperature decreases from one autumn month to the next. This conclusion is reached by comparing Figure 5a with Figure 5b, where the T and S indices of different months are very different in temperature and practically do not overlap. In March measurements, the scatter of blue points on the TS diagram in temperature and salinity can be explained by the duration of survey of 15 days only, both north and south of the South Shetland Islands. Further comparison of the two figures presents a significant concentration of points in the area of high salinity and the fact that such points exist for all four months. These facts agree with the hypothesis of the constant presence of waters of high salinity (above 34 psu) from the Weddell Sea. As for the waters of low salinity (below 33.85 psu), they wash the South Shetland Islands. The lowest salinity, 33.7 psu, is observed in the bay on the northeast coast of Greenwich Island, which lies east of Livingston Island (Fig. 5a).

These conclusions were confirmed by monthly analyses of the temperature and salinity in the upper layer of seawater (Fig. 6b, Fig. 7b). For comparison we use the maps of these parameters at a depth of 5 meters obtained from the CMEMS website (Fig. 6a, Fig. 7a). The combination of the CMEMS and the FB datasets unites the broad scope of the former with the fine detailing of the latter and raises the value of them both.

In mid-March (the first month of autumn), the surface temperature everywhere in the Bransfield Strait varied from 0 to 1 °C, and on the eastern edge of the Antarctic Peninsula, there was an invasion of the Weddell Sea with water temperatures below zero. This invasion intensified sharply; the relatively cold waters occupied most of the strait. By mid-May, the water temperature in the strait had decreased everywhere due to local cooling and advection from the southeast by 0.4÷0.5 °C (Fig. 6a, b).

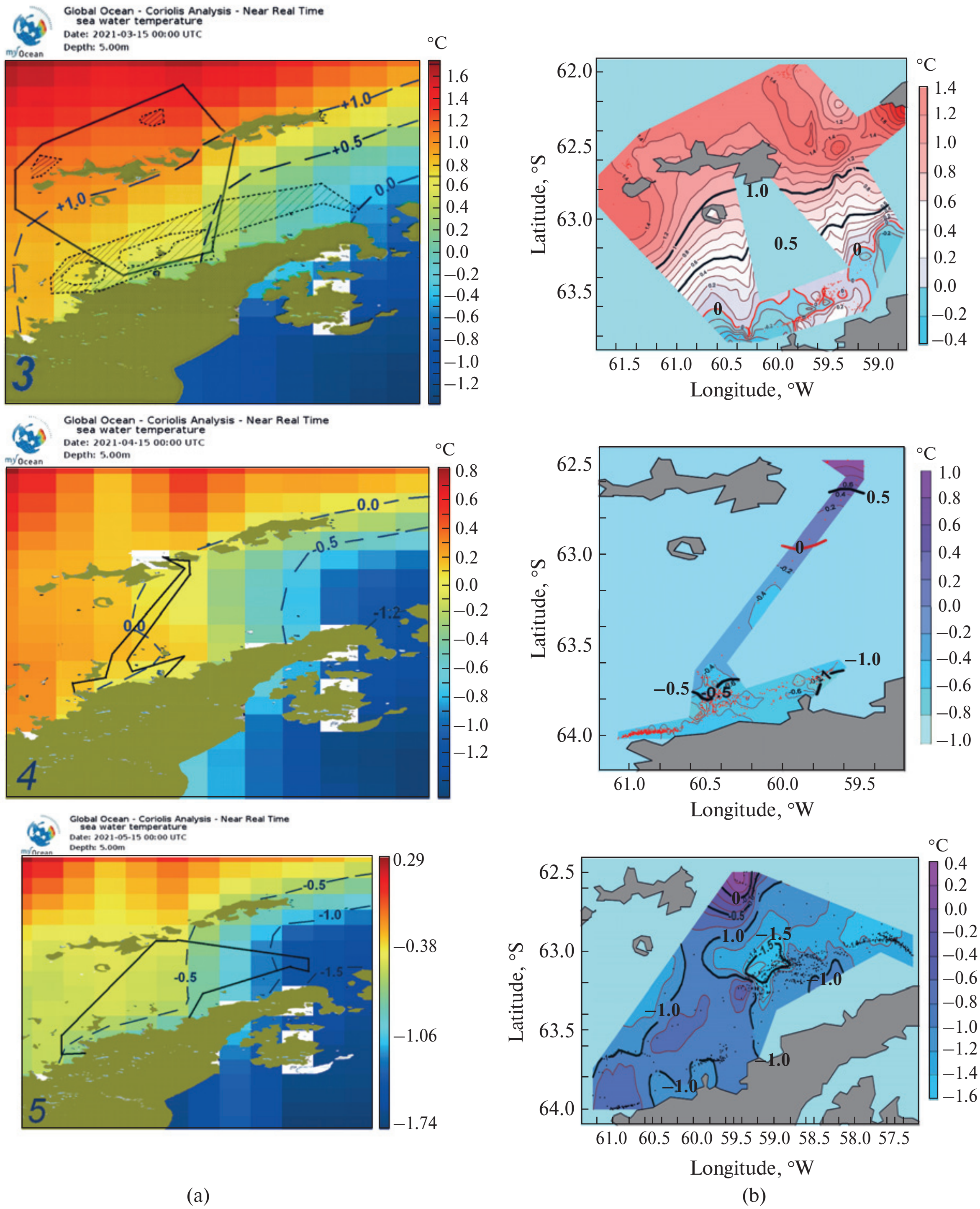

Figure 6. Combined distribution of the near-surface average monthly water temperature in the Bransfield Strait in March 2021, according (a) to the CMEMS and (b) the FB measurements. The area of the krill trawls is highlighted by shading in (b). Transects of work for each month are marked with a black line in (a). The numbers in left bottom corners in (a) indicate the months March, April, May

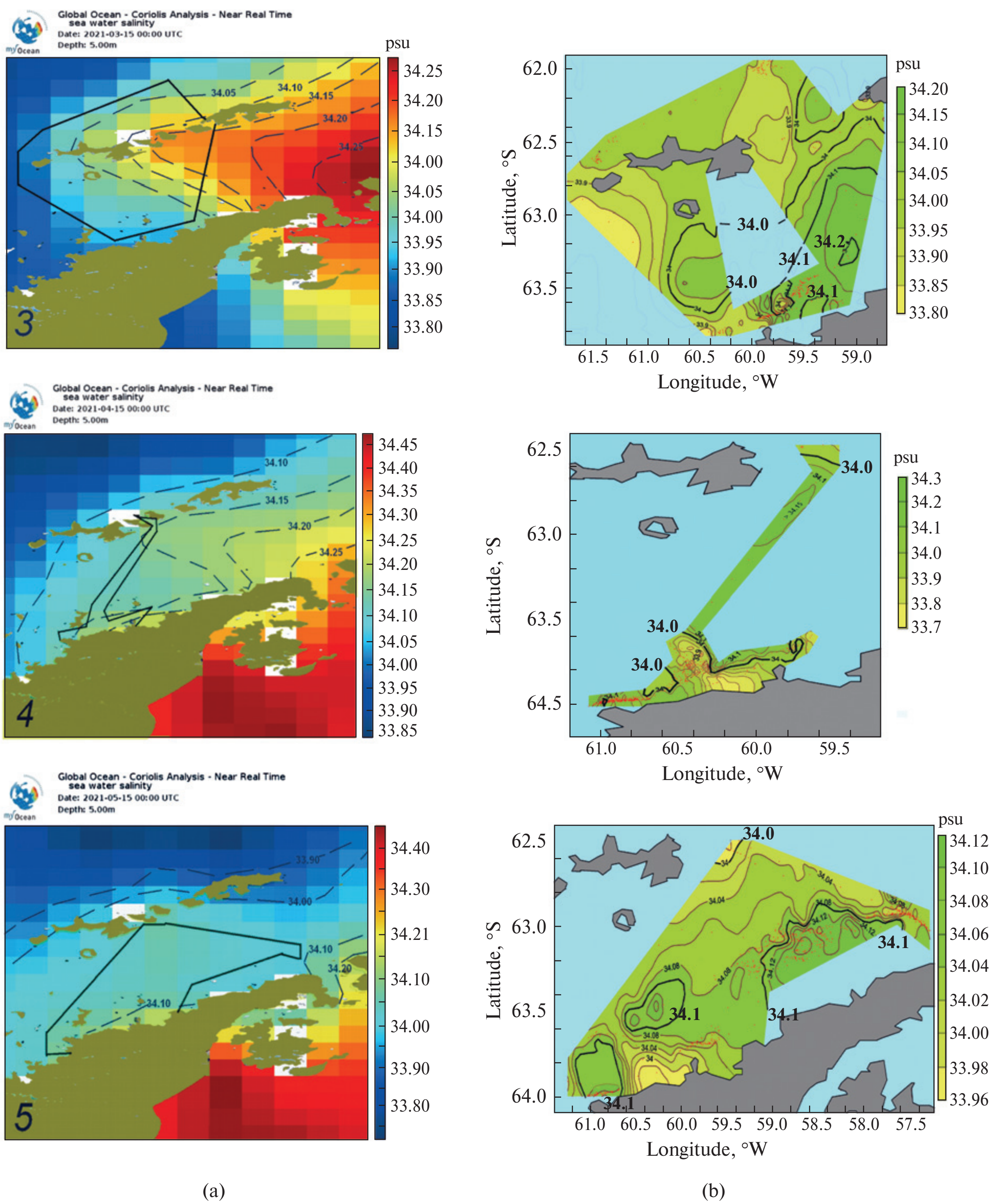

Figure 7. Combined distributions of near-surface average monthly water salinity (psu) in the Bransfield Strait in March 2021, (a) according to the CMEMS and (b) the FB measurements. Trawling sites for each month are marked with a black line in (a). The numbers in left bottom corners in (a) indicate the months March, April, May

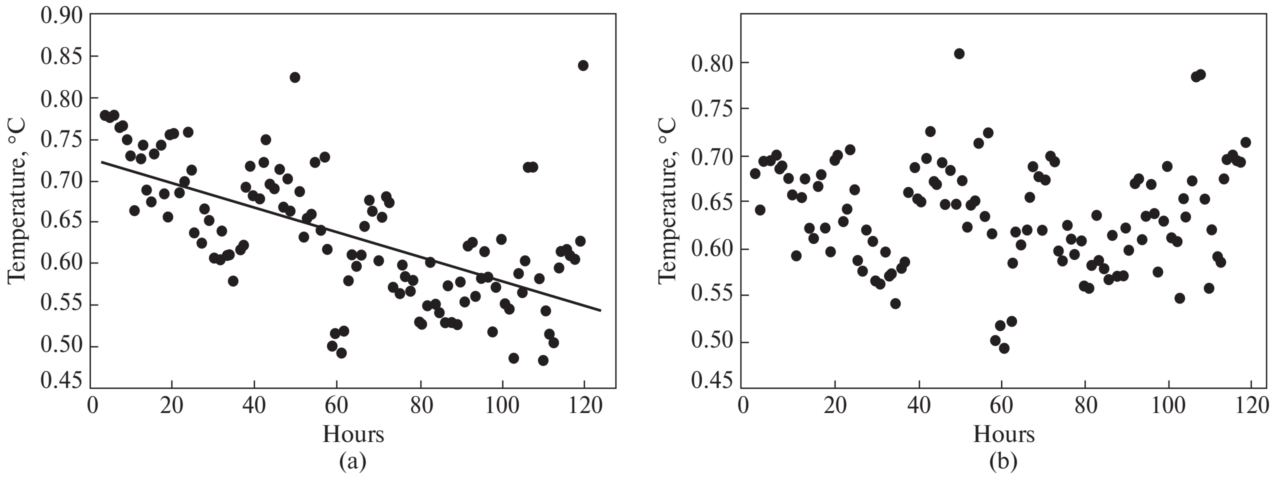

Figure 8. The initial series of seawater temperature (a) before the removal of the linear trend, and (b) after the removal of the linear trend

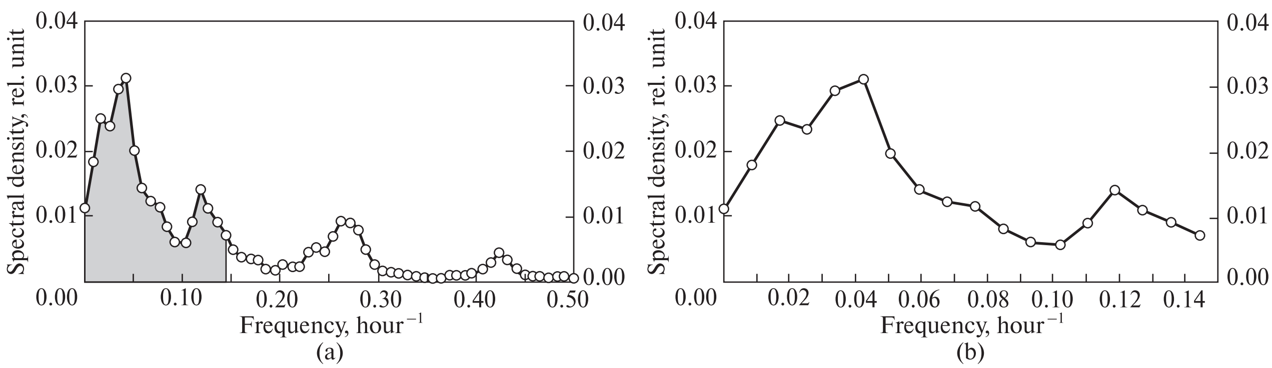

Figure 9. Spectral density of seawater temperature (a) and spectral density of seawater temperature with reduced frequency scale (b). In (a) the part of data shown in (b) is shaded

The temperature distribution suggests the most intense thermal fronts were located in the SW Bransfield Strait at the farthest intrusions of the Weddell Sea. In this part of the strait, the trawler was fishing in March and April 2021.

CMEMS salinity data put a somewhat different spin on the waters' thermal dynamics in the fall. In March, and to a lesser extent in April, there was indeed an intense invasion of high-salt waters (up to 34.35 psu) from the northern periphery of the Weddell Sea. In mid-May, the intensification of the inflow from the Weddell Sea declined sharply, and the average salinity of the waters in the strait was equalized within a small range of 34.0—34.1 psu. Distributions of salinity in April—May show an increase along the slope fronts in the SW part of the Bransfield Strait (Fig. 7a, b).

The spectral analysis is shown by the example of processing data obtained near the South Orkney Islands (Fig. 9). A continuous series of water temperature values from March 2 to 6, 2021 (120 hours total) was analyzed. Trawling took place in a rather limited area, which, in our opinion, reduced the influence of horizontal inhomogeneity of the temperature field. We use hourly average data to exclude the influence of small-scale and impulse processes. The temperature varied within 0.48—0.84 °C. Analysis of the graph in Figure 8 shows a linear trend in the initial series, the removal of which will allow a more accurate assessment of the periodic temperature changes.

A statistical filter was used to remove the linear trend, which allows for estimating the standard error of the slope of the trend line. Thus, the trend was considered statistically significant if the modulus of inclination exceeded 3σ (at 5% significance level) of the root mean square error. The modulus estimate of the time series trend was 0.00147 with its root mean square error 0.00015, indicating the linear trend's statistical significance in the original time series of seawater temperature. The graph of the transformed time series is shown in Figure 8b. After removing the linear trend, the Fourier transform was used to estimate periodic changes in seawater temperature using a smoothing Tukey-Hamming window (Privalsky, 1985). The graph of the spectral density of seawater temperature is shown in Figure 9a. For details, part of the data with a reduced frequency scale is shown in Figure 9b.

Analysis of the graphs shows that the spectral density maximum is observed at 0.041 hour^{-1} frequency that corresponds to a 24-hour periodicity. It indicates the presence of a daily variation of the temperature in the surface layer.

From the above examples, it is obvious that the adjusted series of the FB observations provide great opportunities for studying the spatial-temporal variability of oceanographic structures of the surface layer of seawater.

4 Conclusions

Analysis of the information obtained by the FerryBox complex during the Antarctic seasons 2018—2021 showed the reliability of the FB data to study various oceanographic parameters. The data allow identifying frontal areas and their hydrological structure, determining surface water masses and their variability, identifying significant temporal features of the measured parameters, studying the gas component, the ocean surface temperature. When the vessel was crossing the Southern Polar Front, the length of the frontal transect was 18 miles, the temperature of the upper water layer rose from 2.1 °C to 4.7 °C, and salinity was in the range of 33.76—33.88 psu. The front zone consisted of two "waves" of high-temperature gradients. The maximum gradient along the line of the vessel motion exceeded the temperature gradients of the nonfrontal area in 14 times. Trawling tackles in the Bransfield Strait ran along the coastline of the Antarctic Peninsula parallel to the thermal fronts. In transition from March to June, the water temperature dropped to negative values. The average seasonal decrease in the OST was 1.0—1.5 °C. The significant presence of daily variations in the high-frequency water temperature fluctuation was observed. Outliers in the data usually occurred when the measurements were interrupted which has happened in less than 0.1% of the total number of measurements. The comparison of the Copernicus Marine Environment Monitoring Service data with the results of the FB observations showed qualitative consistency.

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Conflict of Interest. The authors declare no conflict of interest.

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Мінливість океанографічних структур у Південному океані за даними автоматизованого комплексу «Ferry Box»

Реферат. Упродовж антарктичного літа у 2018—2021 роках проводилася безперервна реєстрація фізичних, хімічних і біологічних параметрів верхнього шару морської води за допомогою програмно-вимірювального комплексу «Ferry Box» (FB), встановленого на борту українського рибно-крилевого супертраулера «Море Содружества». За цей період на шляху прямування з порту Кейптаун до району основних робіт судно неодноразово перетинало основні гідрологічні фронти Південної Атлантики та Південного океану. У ході науково-дослідних робіт, спрямованих на виявлення та ідентифікацію океанічних структур, було виконано близько 800 тисяч щохвилинних вимірів FB. Мета статті — оцінка просторово-часової мінливості океанографічних параметрів поверхневого шару води у Південному океані на базі аналізу даних FB. У статті використані класичні методи аналізу гідрологічних структур, графічний, порівняльний і статистичний види аналізу натурних даних, а також даних Служби моніторингу морського середовища Копернікус (СММСК). Райони тралення розглядалися як гідрологічні полігони. В результаті проведених досліджень визначено, що від сезону до сезону в роботі FB спостерігається зниження загальної кількості пропусків у відсотковому відношенні, з 8.6% в сезон 2018—2019 рр. до 3.9 % в 2020—2021 рр. Аналіз якості інформації, отриманої FB, показав, що після коригування їх можна впевнено використовувати для вирішення різноманітних океанографічних завдань, наприклад, ідентифікувати фронтальні зони і деталізувати їхню гідрологічну структуру, визначати поверхневі водні маси, мінливість меж їх поширення, виділяти значущі цикли в часовому ході вимірюваних параметрів, досліджувати газову складову верхнього шару морської води та інші. Порівняльний аналіз результатів спостережень FB з даними СММСК показав їх якісну узгодженість.

Ключові слова: безперервні спостереження, гідрологічна структура, південний полярний фронт, поверхневі води