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Original article

Thermoprofilemeter-Based Stationary Measuring System on the Oceanographic Platform for Determining Internal Wave Parameters: Testing Results

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Abstract
An experimental system for monitoring the dynamics of temperature changes in the coastal zone was tested at the oceanographic platform in the village of Katsiveli (Crimea) continuously for more than a year from 2021 to 2022. The created system was based on three distributed temperature sensors (thermoprofilemeters) identical in design and electronics (thermal copolymer), vertically installed on the spatial basis of an equilateral triangle with a side of 18 m. Continuous spatiotemporal data on vertical temperature profiles up to a depth of 19.5 m were obtained. Data correlation of simultaneous measurements of sensors with pronounced dynamics of temperature gradients allowed to calculate, in addition to the amplitude and period of oscillatory processes, the length, velocity and direction of internal wave propagation. Measurement data with pronounced time fronts of temperature changes made it possible to calculate the direction and velocity of transfer of water masses on horizons. Software algorithms for automatic calculation of specified parameters for correlated indicators of spatiotemporal displacement of calculating isotherms have been developed. The results of the experiments proved the possibility of using a system with the specified technical characteristics of thermoprofilemeters installed on a spatial basis limited by the dimensions of the oceanographic platform to measure the parameters of internal waves and temperature variability with pronounced fronts.

Keywords: distributed temperature sensor, thermoprofilemeter, isotherm, heat storage, thermocline, internal waves, temperature field, heat exchange, thermistor chain, oceanographic platform, temperature gradient

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Стационарная измерительная система на базе термопрофилемеров на океанографической платформе для определения параметров внутренних волн: результаты испытаний

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Аннотация
С июня 2021 по август 2022 г. на океанографической платформе в п. Кацивели непрерывно проводились испытания экспериментальной измерительной системы для мониторинга динамики температурных изменений в прибрежной зоне. Система построена на трех идентичных по конструкции и электронным компонентам распределенных датчиках температуры (термопрофилемерах), вертикально установленных на пространственном базисе равностороннего треугольника со стороной 18 м. Получены непрерывные пространственно-временные данные о вертикальных профилях температуры до глубины 19.5 м. Корреляция данных одновременных измерений датчиками при выраженной динамике градиентов температур позволила дополнительно к амплитуде и периоду колебательных процессов рассчитать длину, скорость и направление распространения внутренних волн. Данные измерений с выраженными временными фронтами изменения профилей температур позволили рассчитать направление и скорость переноса водных масс на горизонтах. Разработаны программные алгоритмы автоматического расчета указанных параметров для коррелированных показателей пространственно-временного смещения рассчитанных изотерм. Результаты экспериментов доказали возможность использования предложенной системы на базе термопрофилемеров с заданными техническими характеристиками, установленных на ограниченном габаритами океанографической платформы пространственном базисе, для определения параметров внутренних волн и температурной изменчивости с выраженными фронтами.

Ключевые слова: распределенный датчик температуры, термопрофилемер, изотерма, теплозапас, термоклин, внутренние волны, поле температуры, теплообмен, термокоса, океанографическая платформа, градиент температуры

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Introduction

Monitoring and studies of hydrodynamic processes in the coastal zone with pronounced water temperature gradients are impossible without spatiotemporal reference. Time-continuous measurements of vertical temperature profiles make it possible to observe small-scale variability in water temperature and determine the amplitude and period of subsurface wave processes [1–11]. A measuring system of temperature sensors spatially coordinated in a three-dimensional field is necessary to determine the direction of propagation, length and velocity of internal waves, as well as the direction and velocity of transfer of water masses accompanied by pronounced temperature fronts. Such sensors should show metrological characteristics identical in accuracy and inertia with a sufficiently high sampling frequency (at least 0.1 Hz). For long-term monitoring, mechanical probing with precision meters or creation of a network of analog point sensors is a complex and expensive solution that cannot ensure synchronous measurements. Therefore, chains of point digital sensors [12, 13] and thermistor chains based on analog sensors [7, 14–19] are often used for these purposes.

The DS18B20 digital sensors used do not always meet these requirements due to high inertia, slow sequential non-synchronous sampling (about 3 s per sensor in a chain) and limited accuracy (maximum digital 12-bit resolution 0.0625 °C and error without additional individual calibration up to 0.5 °C) [20]. Such shortcomings are often compensated by spatiotemporal averaging and smoothing of the measured temperature field which leads to the loss of high-frequency components in the measurements of the process under study. At the same time, it is necessary to increase the spatial basis (the distance among the chains) on the horizon in systems for monitoring the spatial transport of water masses and the propagation of internal waves.

Production of thermistor chains based on analog platinum resistance sensors [14–18] or a chain of thermistors [7, 17] with individual analog-to-digital converters is a labor-intensive and relatively expensive process. However, platinum sensors are characterized by greater metrological measurement accuracy (0.01 °C [14] and ±0.025 °C [17], respectively) and high stability.

In some cases, distributed thermal profilers [21, 22] made on the basis of copper conductors laid according to orthogonal functions continuously along the entire sensor profile can be an alternative. The resolution of each section ranging from a few centimeters to several meters in length is adapted to a specific task. This makes it possible to obtain a continuous smoothed profile with a reconstructed average temperature at each measurement section directly at the hardware level. Visual display of the dynamics of temperature changes in the form of isolines in telemetry mode 1) without any additional three-dimensional interpolation provides a quick solution to the problems of recording internal waves and determining their parameters. A system of thermoprofilemeters with identical metrological characteristics (inertia and accuracy) makes it possible to determine the temporal displacement in the phases of temperature oscillatory processes (short-period internal waves) and fronts on a smaller spatial basis for installing the meters in a more accurate way. Low overall dimensions of the system allow it to be placed on stationary objects (for example, on an oceanographic platform) avoiding technical difficulties during its installation and

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1) Gaisky, P.V., 2022. [*Program for Registration and Processing of Thermoprofilemeter Measurement Data "THERMOPROF"*]. Sevastopol: MHI. State Registration no. 2022611315

maintenance (surface waves, drift of buoys, autonomous power supply and data collection) and to monitor small-scale processes in the coastal zone with complex coastline and bottom topography as well as limited spatial localization.

The work aims at developing and testing a small-sized stationary automated system based on distributed thermoprofilemeters in order to determine the spatio-temporal parameters of the distribution in coastal waters of hydrological processes accompanied by changes in temperature gradients and analyzing the results obtained.

Instrumentation

Distributed thermoprofilemeters were created and installed on a stationary basis within the limits of the oceanographic platform in the village of Katsiveli (Crimea) as part of the development and testing of such a small-sized system [21, 22]. Structurally, thermoprofilemeters are copper conductors laid in orthogonal functions along the entire length of a distributed sensor. The number of conductors corresponds to the number of sections. The average temperature in each section of the profile is calculated using matrices of individual calibration coefficients obtained during metrological verification. The protective shell of the sensor part made from the outside in the form of a load-bearing polyamide tube was manufactured to meet the requirements for the same inertia (heat capacity) of the sensors. The metrological characteristics of the measuring channels with an instrumental resolution of 0.0026 °C were also the same. As a result, three 24-meter thermoprofilemeters with spatially distributed sections 1.5 m long, with 16 sensors in each, were produced.

It should be noted that earlier tests of thermoprofilemeters with increased profile resolution (sections of 20 cm in length) carried out on the oceanographic platform demonstrated no significant advantages in recording the primary parameters of the internal waves under study. The inertia of the meters in the liquid was about 30 s due to the protective load-bearing polyamide tube. The measurement error of the temperature averaged over the area is metrologically determined as ±0.1 °C. The sampling period for all 16 sensors (sections of the meter profile) was 0.5 s. Measurement data were received from all three meters simultaneously by the on-board computer linked to a single timer and in telemetry mode were displayed in the form of a gradient field and isotherms.

Fig. 1 shows general location and layout of the system. Since the bottom topography in the area of the platform location is characterized by an increase in depth in the southeast direction, the anchoring depth of the distributed sensors varied from 24 to 28 m (Fig. 2). Based on earlier geography-specific observations [11–13, 21, 22], the most suitable conditions for testing the system corresponded to the season of the formed thermocline and the manifestation of upwelling – downwelling (from May to August).

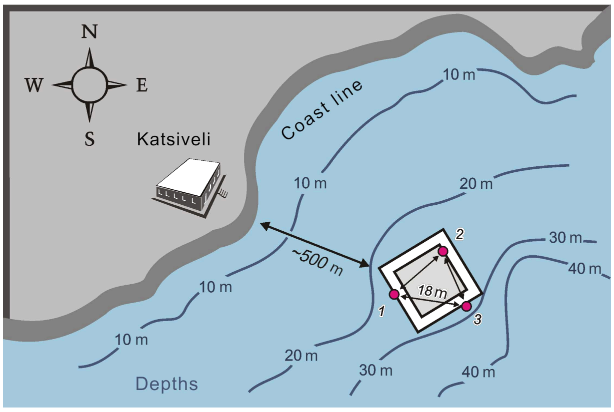

Fig. 1. Location and layout of a system of three thermoprofilemeters at the oceanographic platform. The red dots denote the installed thermoprofilemeters (*1*–*3*)

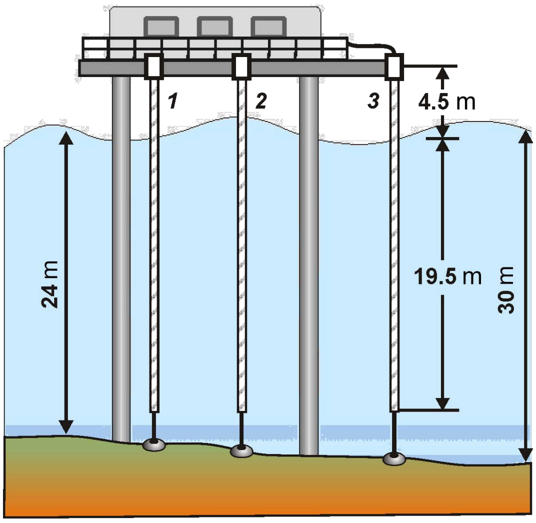

Fig. 2. Depth profile at the installation site of the system and vertical placement of the thermoprofilemeters (*1*–*3*)

The created system of three thermoprofilemeters was tested for more than a year (from June 2021 to August 2022), which made it possible to analyze the data for two indicated seasonal periods. Almost all recorded significant changes in the depth of the pronounced thermocline were accompanied by wave processes reflected in vertical temperature profiles. Visualization (with a pronounced periodicity of at least five consecutive frequency components) and possibility of interpretation made it possible to determine about 10 manifestations of short-period internal waves lasting from 1 to 4 hours in one season. Such waves showed their average period of 10–12 minutes and amplitude of 2.5–3 m. Fig. 3 shows the examples of data display on the monitor screen during processing by the program in telemetric measurement mode.

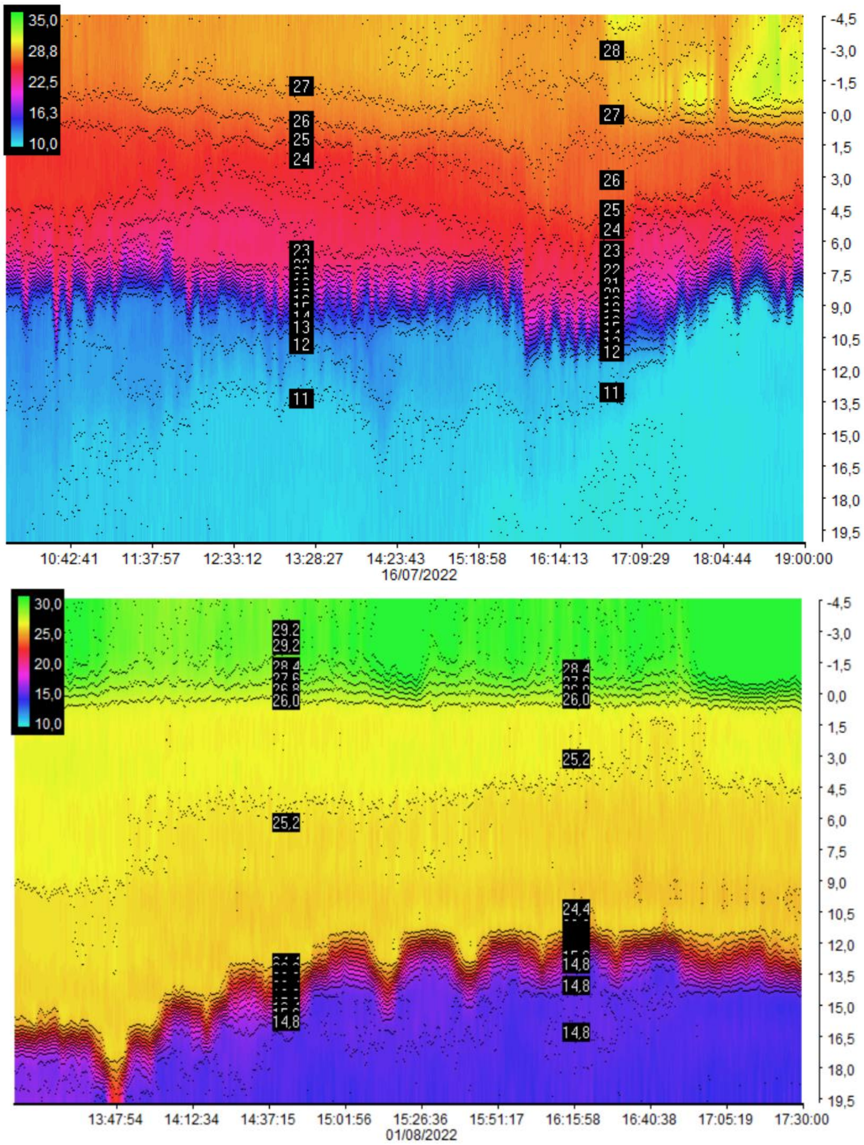

Fig. 3. Examples of a record of short-period internal waves made by one of the thermoprofilemeters

Results

The results of calculations of parameters for observed short-period internal waves are presented as examples of the system operation. This system makes it possible to determine the directions (horizontal and vertical) and velocities of displacement or propagation of internal waves only in the presence of pronounced temperature fronts, based on which we can correlate sensor data and calculate time delays. Coordinate system and geographic location references allow us to further determine the desired dynamic parameters of the observed process.

The calculated spatiotemporal displacements of isotherms in the pycnocline on the temperature profiles obtained by each of the thermoprofilemeters were used as data for synchronous referencing. The calculation of spatial displacements of isotherms was implemented algorithmically in software for each distributed sensor both in telemetry mode and during post-processing [2]. Algorithms for calculating the direction and velocity of front displacement were implemented in software using trigonometric formulas with updated reference to the spatial orientation and location of the sensors. Direct calculation of these parameters as part of the system tests was carried out in the mode of operator input of primary delays between the sensors (it is enough to enter t_{31} and t_{32} in this case, see Fig. 4) for given geometric parameters.

Fig. 4. Display of the results of data processing by the system on the monitor screen: temperature field with isotherm dynamics and temperature profile gradient – *a*, *d*, *g* (the white rectangle (*a*, *d*) and arrows (*g*) indicate the calculation area); correlated spatial displacements of the selected isotherm in the calculation area at the boundary of the temperature front and internal wave for three thermoprofilemeters (*1*, *2*, *3*) – *b*, *e*, *h*, *k* (the dashed lines mark on the graphs the selected boundaries of the isotherm spatial displacement in the time range for each sensor); results of program calculation of the dynamic characteristics of internal waves (*c*, *f*) based on the obtained time delays (t_{31}, t_{32}, t_{12}) and the velocity and direction of front displacement during upwelling (*j*) and downwelling (*l*)

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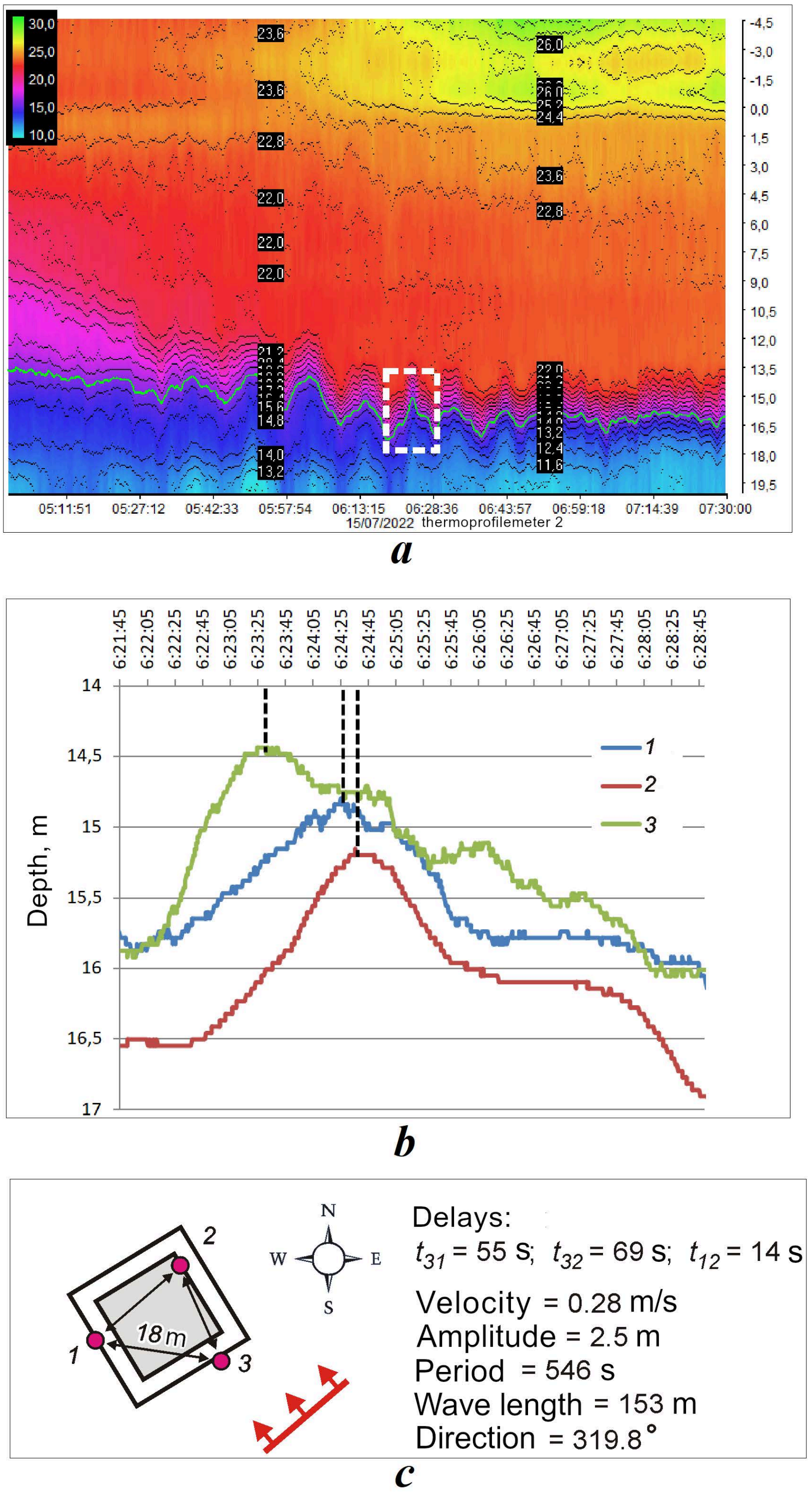
30,0
25,0
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06:59:18
07:14:39
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15/07/2022 thermoprofilemeter 2
-4,5
-3,0
-1,5
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3,0
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Depth, m
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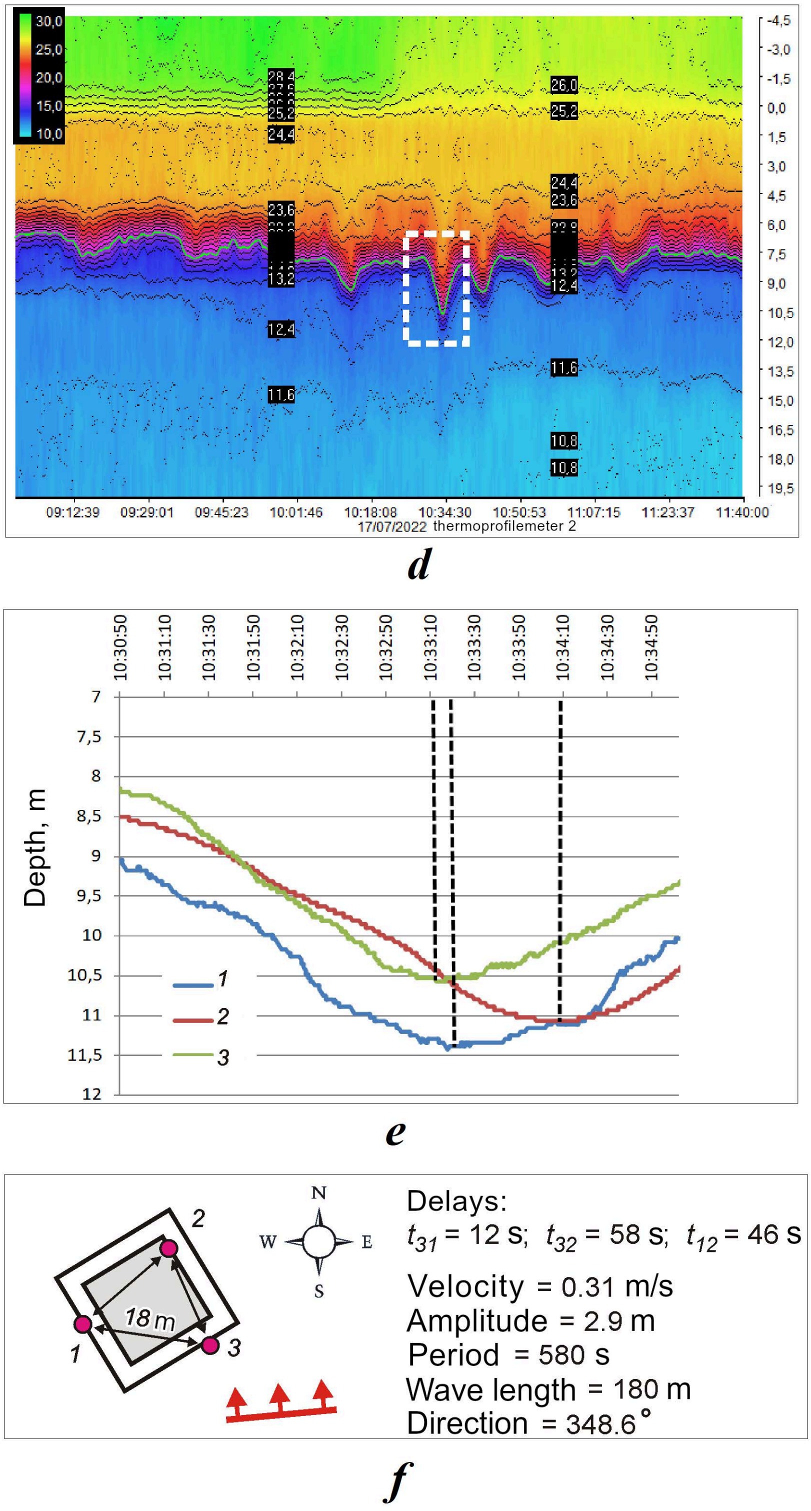
1
2
3
b
N
W
E
S
2
1
3
18 m
Delays:
t_{31} = 55 s; t_{32} = 69 s; t_{12} = 14 s
Velocity = 0.28 m/s
Amplitude = 2.5 m
Period = 546 s
Wave length = 153 m
Direction = 319.8°
c



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e

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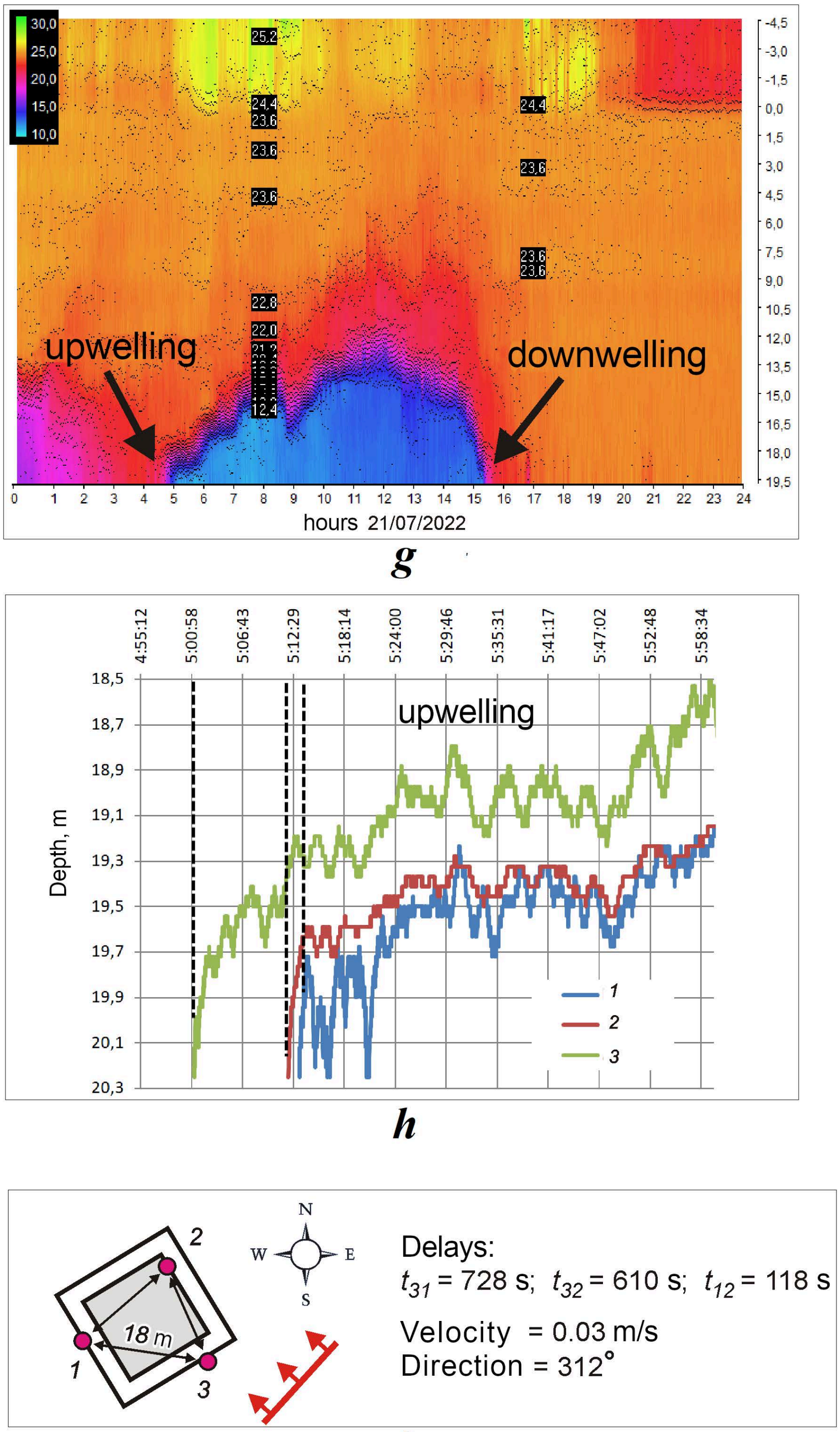
Fig. 4. Continued



g

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Fig. 4. Continued

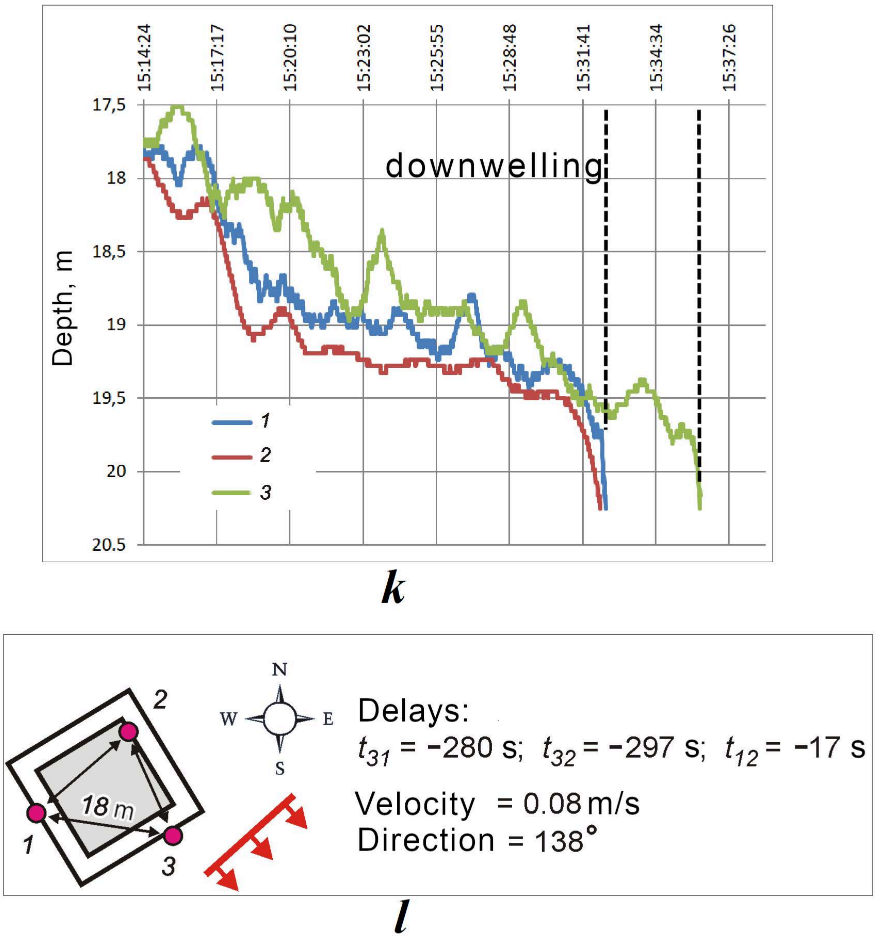

Fig. 4. End

Automatic collection of the characteristics of internal waves (amplitude, period, direction, velocity and wavelength) is complicated by a number of factors associated with non-stationary periodicity and complexity of automatic sampling of synchronized fronts of the oscillatory process in telemetric mode. Therefore, at the moment this problem is solved by an operator during visual assessment of events on the monitor screen or during subsequent processing of measurement information.

Figure 4 (*a* – *f*) shows the examples of displaying processing results on the monitor screen (parameters of short-period internal waves at the thermocline boundary). Figure 4 (*g* – *l*) shows calculations for a more time-scale transport of deep cold masses, for which the direction and horizontal velocity were calculated.

It should be noted that during turbulence [23–25] caused by currents and nearby pile structural supports of the platform, the low inertia of the sensors in the system affects negatively the comparison of correlated oscillatory processes associated with the passage of internal waves.

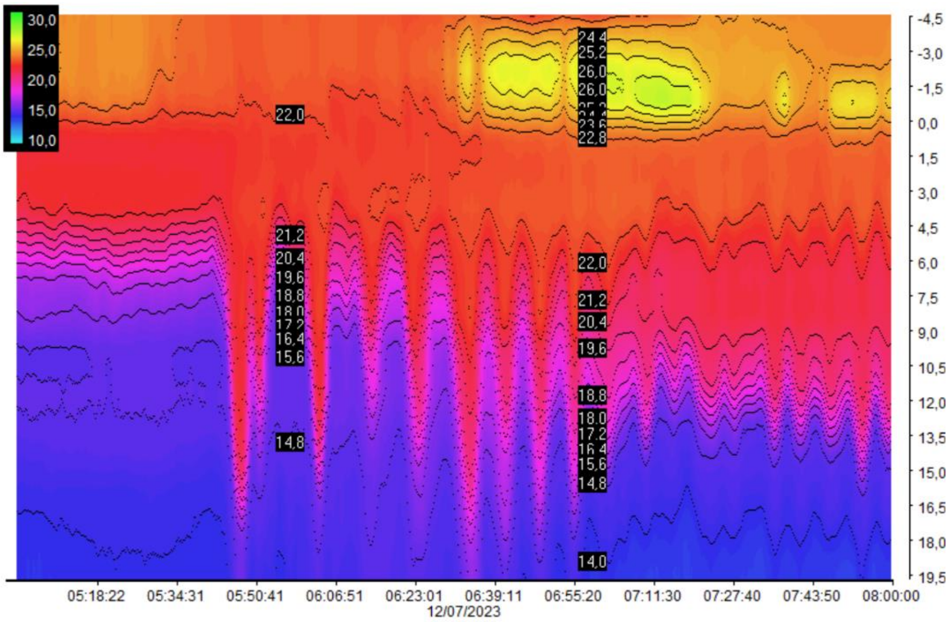

Fig. 5. Example of a record of intense internal waves with thermoprofilemeters near the oceanographic platform

When testing the system of three thermoprofilemeters, rather rare intense internal waves that had previously been recorded by thermoprofilemeters in the platform area up to three times a year and had had a large amplitude (more than 10 m), a period of about 12 minutes and a pronounced temperature front, were not observed (see Fig. 5).

Conclusion

Tests of the developed system based on distributed thermoprofilemeters showed its performance under conditions of pronounced temperature fronts. The correlation will obviously be clearer in a more laminar environment (relative to the spatial limits of the system installation), which will increase the reliability of automatic software calculations. Influenced by currents, indentation of coastal zone and heterogeneous bottom topography, an increase in the distance among the system sensors can lead to distortions in the synchrony of wave processes in the measured temperature profiles and consequently to difficulties in their comparison (correlation). In this case, installing such a system at a stationary facility is preferable from the point of view of cost and technical support, as well as due to the absence of such factors as drift of buoys and influence of surface waves on the spatial coordinates of the measuring system. Limited spatial localization in a bay or a strait can be ensured for a small-sized system.

The advantages and disadvantages of all types of sensors used to create such systems for determining the parameters of internal waves can be assessed not only by the metrological accuracy of the measuring channels, but also by long-term stability, cost and ease of maintenance. The final conclusion can be made after joint *in situ* tests at monitoring sites and intercalibration.

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