

Study of the Characteristics of Internal Waves in the Kara Sea and Their Influence on Turbulent Heat and Momentum Fluxes over the Sea Surface

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Abstract—This paper is devoted to the study of the characteristics of internal waves in the Kara Sea and their interaction with the atmosphere, in particular, their influence on the turbulent momentum and heat fluxes in the surface layer of the atmosphere. The direction and horizontal velocity of propagation of short-period internal waves in the Kara Gates Strait are calculated. Cross spectra of mesoscale fluctuations of water temperature at the sea surface, at depths of 10 and 20 m, and meteorological parameters at a height of 22 m are analyzed. Common spectral maxima at periods characteristic of the trapped internal gravity modes propagating in the thermocline layer and atmospheric gravity modes in the stably stratified layer of the lower troposphere are revealed. A possible mechanism of influence of the observed gravity modes in the thermocline layer on mesoscale fluctuations of meteorological parameters (with periods from 10 min to several hours) and turbulent fluxes of momentum and apparent and latent heat in the surface layer of the atmosphere is proposed.

Keywords: internal waves, turbulent fluxes, spectral analysis, generation mechanism, Kara Sea

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1. INTRODUCTION

Small-scale processes in the atmosphere and ocean with characteristic scales that are small when compared to the size of the numerical grid in global and regional climate change models play a key role in the processes of interaction between the atmosphere and the ocean in the polar regions (Vihma et al., 2013; Repina et al., 2019; Ivanov et al., 2019). To parameterize in climate change models the influence of these processes on the exchange of heat, momentum, and moisture between the atmosphere and the ocean in the polar regions, a more detailed study of these processes is necessary, in particular, the interaction of the atmosphere and the ocean, including in the presence of surface manifestations of internal waves, which play an important role in the dynamics of the Arctic seas (Morozov et al., 2019; Fine and Cole, 2022; Chanona and Waterman, 2020).

The main studies of internal waves in the Arctic region are carried out on the basis of field observations

from ships and buoy stations (Kozubskaya et al., 1999; Sabinin and Serebryany, 2007; Zimin, 2012; Fer et al., 2020). Satellite data obtained using synthetic aperture radars make it possible to study the characteristics of internal waves in more detail and collect a more complete annual and interannual picture of the variability of their characteristics (Svergun et al., 2018; Kozlov et al., 2015; Kopyshov et al., 2023).

In work (Morozov et al., 2017), based on data from buoy stations, modeling of the main flow from the Barents Sea to the Kara Sea was carried out. Using numerical modeling, in (Li et al., 2019) it was shown that the formation of short-period internal waves occurs mainly due to the interaction of the semidiurnal tide (with a period of 12.4 h) with bottom topography. This conclusion is confirmed by experimental studies (Morozov et al., 2003; Sabinin and Serebryany, 2007; Kozlov et al., 2023). The strait called the Kara Gates (Kozlov et al., 2015), areas along the eastern coast of the Novaya Zemlya archipelago (Svergun

et al., 2018; Kozlov et al., 2015), and east of Cape Zhelaniya (Kozlov et al., 2015) are zones for generating internal waves, or so-called “hot spots” (Sabinin and Serebryany, 2007), in the Kara Sea.

Other possible sources of generation of internal waves in the Kara Sea are also being considered. In particular, internal waves can be generated by the katabatic front (Svergun et al., 2018), which is located along the eastern coast of the Novaya Zemlya archipelago and can change its position depending on the decade by 50–100 km. In the same work, based on data for 2007, it is noted that internal waves most often form in the summer–autumn period, and the highest frequency of formation is observed in August.

There is also a known assumption about the influence of changes in atmospheric pressure, including those associated with atmospheric fronts, on the generation of internal waves in the ocean (Bondur et al., 2019; Bukatov et al., 2021; Lappo, 1979; Dotsenko and Miklashevskaya, 2009; Lavrova et al., 2015; Kozlov et al., 2015). In (Dotsenko and Miklashevskaya, 2009), using the example of the Black Sea, the passage of a pressure front over the basin was simulated, as a result of which barotropic and baroclinic oscillations of the liquid were generated. In (Lavrova et al., 2015), using satellite images, the formation of internal waves near the atmospheric front in the Caspian Sea was studied. In (Miropolsky 2001), the mechanism of generation of internal waves by random fluctuations of atmospheric pressure is discussed, which takes into account the presence in the spacetime spectrum of spectral components that resonantly excite internal gravity waves in the oceanic waveguide.

Internal waves and near-inertial waves modulate shears in current velocity, leading to certain temporal and spatial spectra of variations in these shears (Pinkel 2008; Rohrs 2023). The slow modulation of vertical gradients of current velocity in time (compared to the scale of changes in turbulent pulsations of velocity and temperature) leads to a corresponding modulation of vertical turbulent momentum fluxes, and modulation of vertical temperature gradients affects vertical turbulent heat fluxes.

In the surface layer of the atmosphere, under conditions of its stable stratification, the influence of internal waves on wind speed shears (measured using sodar and the acoustic tomography method) and vertical turbulent momentum fluxes (measured using sonic anemometers and thermometers on the mast) was observed (Chunchuzov et al., 2009). Based on the above results of observation and modeling of internal waves in the ocean and the surface layer of the atmosphere, we assume that internal waves influence the turbulent fluxes of momentum and heat near the sea surface.

Despite the significant progress achieved to date in studying the characteristics of internal waves in the Arctic seas using satellite and insitu methods (Lavrenov

and Morozov, 2002; Svergun et al., 2018; Kozubskaya et al., 1999; Sabinin and Stanovoy, 2002; Zimin, 2012; Morozov et al., 2003; Bukatov et al., 2021; Kozlov et al., 2022), the influence of internal waves on the processes of exchange of heat and momentum between the atmosphere and the ocean, as far as we know, has not been studied. In this work, such a study will be carried out based on the analysis of data from contact measurements of water temperature at different depths of the Kara Sea (according to temperature sensors), sea surface temperature (SST) (according to an IR radiometer on board the vessel), and standard meteorological measurements carried out on the *Akademik Ioffe* research vessel during the Floating University expedition (Kozlov et al., 2023).

Section 2 describes the measurement instruments and methodology. In Section 3, using the method of coherent analysis of temperature fluctuations at a depth of 18 m, measured simultaneously on August 12 (station 3911) by three horizontally spaced thermistor chains (measurement systems of temperature sensors for determining vertical temperature profiles), the direction and speed of propagation of short-period internal waves (SPIW) are determined during the ship’s drift in the Kara Gates Strait on August 12, 2021. To assess the influence of internal waves in the Kara Sea on mesoscale fluctuations of meteorological fields near the sea surface (periods from several minutes to several hours), Section 4 analyzes cross spectra between fluctuations of meteorological parameters and temperature fluctuations at different sea depths. The spectra of mesoscale variations of vertical turbulent heat and momentum fluxes near the surface of the Kara Sea and the possible connection of these fluctuations with internal waves in the lower troposphere will be investigated in Section 5.

2. INSTRUMENTS AND MEASUREMENT METHODS

In August 2021, the Floating University of the Institute of Oceanology, Russian Academy of Sciences—Moscow Institute of Physics and Technology expedition was carried out in the Kara Sea on the research vessel *Akademik Ioffe*. An infrared (IR) radiometer HEITRONICS KT19 II was installed on board the vessel, the measurement accuracy of which was 0.1°C, and the measurement frequency was 1 Hz. The device was located on the direction-finding deck on the starboard side of the vessel at an angle of 30° to the sea surface. The methodology for calibrating and calculating the surface temperature is described in (Bulatov et al., 2003). Along the vessel’s route for 26 days, almost continuous data on the sea surface temperature (SST) were accumulated with a measurement resolution of 1 s. In the IR range, the emissivity of water is close to unity and depends little on the state of the surface. At the same time, the influence of the atmo-

sphere in the IR range is significant and requires its correct consideration (Volkov et al., 2004).

To measure temperature profiles in the upper layer of the sea up to a depth of 100 m, different systems of temperature sensors for measuring temperature profiles, called thermistor chains, were used. One of them, TPArctic, is a thermoprofiler developed at the Marine Hydrophysical Institute of the Russian Academy of Sciences. It had a measuring cable length of 48 m (32 continuous measuring sections of 1.5 m each), and also included a power/communication cable 100 m in length and two pressure sensors at the lower and upper sections of the line (Gaisky and Kozlov, 2023). Water temperature measurements were conducted with an accuracy of 0.1°C at depth intervals of 1.5 m and a sampling rate of 1 Hz.

Two other thermistor chains consisted of chains of temperature sensors (6–10 thermistors produced by Starmon StarOddi, Gardabaer, Iceland) for measuring temperature and pressure sensors (DST centi TD) designed to determine the depth of temperature sensors and linear correction of the thermistor chain's deviation from the vertical position (Silvestrova et al., 2023). The accuracy of the instruments measuring temperature with a time step of 1 s was $\pm 0.025^{\circ}\text{C}$. During measurement periods, either two separate thermistor chains with 10–11 sensors placed near the bow winch and amidships or data from the TPArctic thermistor chain 48 m in length with 32 measuring sections were used. On average, the duration of measurements varied from 30 to 40 min, with a maximum duration reaching 2 h.

To measure meteorological parameters (wind speed, atmospheric pressure, humidity, and air temperature), the ship's AIRMAR 220 ws weather station located on the direction-finding deck was used. With its help, air temperature measurements were carried out in steps of 1 s in the range from 40 to 80°C with an accuracy of $\pm 1.1^{\circ}\text{C}$ at 20°C and resolution of 0.1°C . The wind speed measurement range was from 0 to 40 m/s with a resolution of 0.1 m/s, and its directions from 0° to 360° with a resolution of 0.1° . Atmospheric pressure was measured by a weather station in the range from 300 to 1100 hPa with an accuracy of ± 0.5 hPa at 25°C (and higher) and with a resolution of 1 hPa.

3. DETERMINATION OF THE DIRECTION OF PROPAGATION AND SPEED OF SHORT-PERIOD INTERNAL WAVES OBSERVED DURING THE SHIP'S DRIFT ON AUGUST 12, 2021 (STATION 3911)

A detailed analysis of temperature variations at different depths (up to 50 m), measured using thermistor chains located in different parts of the Kara Gates Strait, was conducted in (Kozlov et al., 2023). Using three thermistor chains forming a triangle, vertical oscillations of the thermocline up to a 40 m height

were detected, caused by the propagation of short-period nonlinear internal waves generated by the flow of a time-varying (with the main period caused by the tide) stably stratified current over the complex relief of the strait. The most intense waves were recorded during the weakening of the ebb tide.

The isotherm fluctuations (see Fig. 7 in (Kozlov et al., 2023)) occurred almost in phase in the near-surface marine layer to depths of 30–40 m. This indicated that lower (in number) modes of internal gravity waves propagated in the stable-stratified thermocline layer (Miropolsky, 2001). Therefore, to determine the speed and direction of propagation of almost in-phase oscillations to a depth of 30 m, it was enough to select one depth horizon, for example 18 m, but at three points spaced horizontally.

During the ship's drift on August 12, 2021, at station 3911, water temperature measurements were conducted at different depths using three thermistor chains located at the ship's bow (thermistor chain 1), the stern of the starboard side (thermistor chain 2), and the port side (thermistor chain 3) (Silvestrova et al., 2023; Kozlov et al., 2023). The horizontal distance between adjacent thermistor chains was 51, 24, and 40 m.

Temperature records from the thermistor sensors of chains 1, 2, and 3, located at a depth of 18 m, are shown in Fig. 1a, while the mutual coherence functions of temperature fluctuations between sensor pairs 1-2 and 1-3 are shown in Figs. 1b and Fig. 1c, respectively. The simultaneous operation time of all three chains was only 22 min, which was caused by a malfunction in the measurement of two out of three thermistor chains after 22 min. High levels of coherence were observed in relatively narrow frequency bands across the entire considered range of periods from 10 to 160 s. Coherence reached maximum values in the period range of 40–160 s during specific time intervals: 600–700 s for pair 1-2 and 850–950 s for pair 1-3.

To further process the records of temperature fluctuations, they were filtered in the period range of 40–160 s, where the paired coherence functions are maximum (Fig. 1a). Then, using the cross correlation of these fluctuations with a sliding window length of Hamming analysis of 834 s, the differences in wave arrival times (delays) were measured for three pairs of temperature sensors. Using the delays, within the framework of the plane wave model, the propagation directions and horizontal phase (apparent) propagation velocities of internal waves were calculated. To detect precisely wave processes, we used the fact that, if a plane wave front passes through the sensors, then the sum of the differences in the arrival times of this front between sensors 1-2, 2-3, and 3-1 should be close to zero. In general, the similar detection of wave signals against a background of noise is used in the Progressive Multi-Channel Correlation (PMCC) method, widely used for locating infrasound sources in the atmosphere and seismic (Le Pichon and Cansi

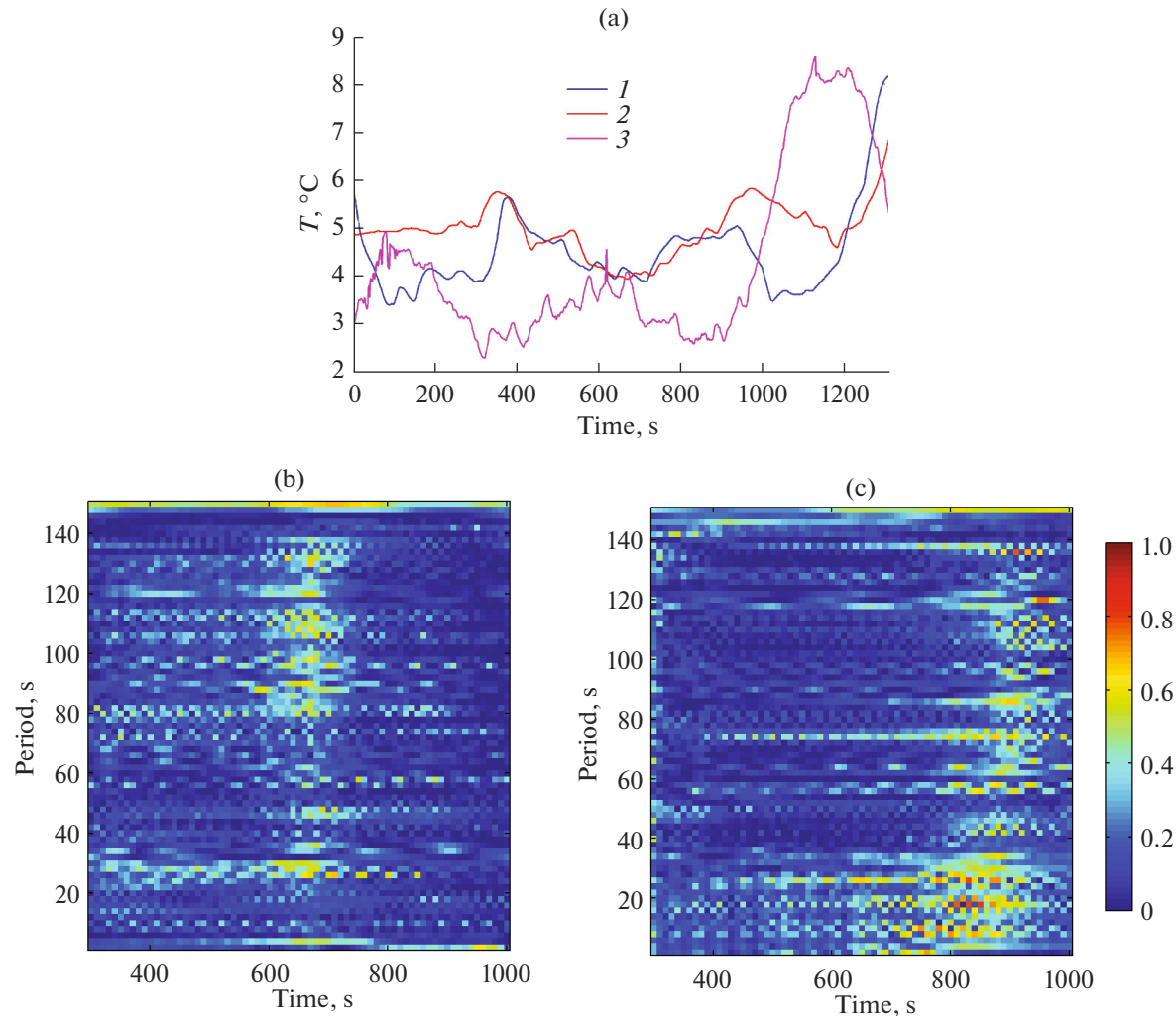


Fig. 1. Temperature measured on August 12, 2021, at a depth of 18 m on three thermistor chains (station 3911) (a) and mutual coherence functions of temperature fluctuations obtained for pairs of streamer sensors 1 and 2 (b) and 1 and 3 (c). Time on the horizontal axis is measured from 12:29 UTC. The recording length is approximately 22 min with a sampling rate of 1 Hz. The coherence calculation interval was 600 s with a sliding window of 150 s and an offset step of 10 s.

2003). The method was also used to determine the parameters of internal waves in the ocean (Serebryany et al., 2020).

Figure 2a shows temperature fluctuations filtered in the period range of 40–160 s, and Figs. 2b and 2c show the backazimuth (the angle between the direction from the receiver to the wave source and the direction of the ship's axis from stern to bow) and horizontal phase wave speed versus time, respectively. These parameters change slightly in the time interval from 400 to 700 s and are approximately equal to 108° and 0.15 m/s, respectively.

The direction and speed of the ship's drift during the time period of 400–700 s, when the direction and speed of wave propagation were determined in Fig. 2b and Fig. 2c (i.e., within 300 s), are shown in Figs. 3a and 3b, respectively. Schematically in Fig. 3c, the

direction of the ship's axis from stern to bow; the direction of its drift with speed $\vec{V}_{\text{dr}}$ with an azimuth of approximately 36° in the time interval from 400 to 500 s; and the horizontal phase velocity of the waves $\vec{C}$ relative to a drifting vessel, extending from northeast to southwest with an azimuth of approximately 234° , are also shown.

Considering that the dependence of the phase velocity of waves C on frequency is very weak both in the interval of periods 40–160 s and at shorter periods of 20–40 s, wave dispersion can be neglected and the group velocity can be considered close to the phase velocity C . Then the group velocity of the waves relative to the stationary earth $\vec{C}_{\text{gr}} = \vec{C} + \vec{V}_{\text{dr}}$ and at $C = 0.15$ m/s and $V_{\text{dr}} = 0.6$ m/s will be equal to 0.46 m/s and directed to the NE at an angle of 30° , as is shown in Fig. 3c.

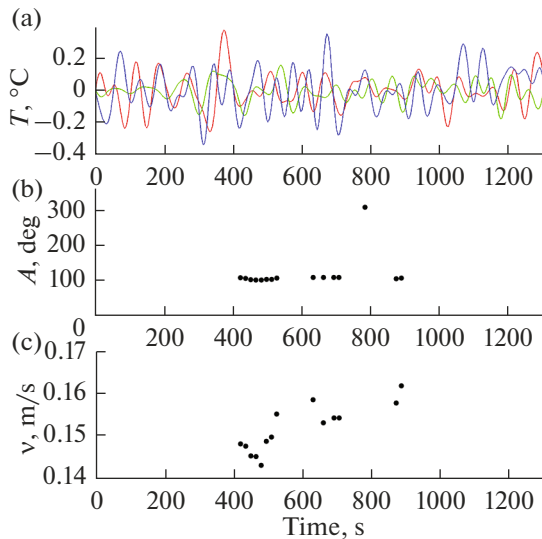


Fig. 2. Temperature fluctuations measured at a depth of 18 m using three thermistor chains labeled 1, 2, and 3, and filtered in the range of periods 40–160 s (a), back azimuth of propagation relative to the stern-bow axis of the vessel (b), and horizontal phase velocities of internal waves (c) relative to the vessel. Time is measured relative to the moment as 12:29 UTC.

It should be noted that the ship drifted at an average wind speed of 5–6 m/s and root-mean-square values of its fluctuations of the order of 1 m/s. At the same time, the surface roughness of the sea and the rocking of the vessel caused movement of the temperature sensors relative to the thermocline. Due to the motion, periodic vertical displacements of the sensors of the order of 0.5–1 m occurred with periods of several seconds. However, the temperature fluctuations and their spectra that we analyzed (see below) had significantly longer periods, from 40 s to 1 h. As the period increases, the amplitude of the spectrum of temperature fluctuations increases, and the vertical displacements of the isotherms corresponding to these fluctuations amounted to tens of meters (i.e., they were significantly higher than the displacements of the sensors during short-period pumping), so the influence of the rocking on such a long-period part of the spectrum can be neglected.

The source of the highly nonlinear internal waves observed on August 12, 2021, were tidal stable-stratified currents flowing around a complex bottom topography in the Kara Gates Strait (Kozlov et al., 2023). The internal wave packets recorded at stations 3911, 3913, and 3915 contained almost solitary strongly nonlinear internal waves (solitons). They propagated to the NE, but at a higher speed (0.8–0.9 m/s) compared to our above estimate of the speed of the high-frequency components of the wave packet.

Above, we discovered, using a coherent analysis of a short time interval (lasting ~22 min) of temperature variations at three points, the presence in wave packets of very short waves with periods of 40–160 s, lying

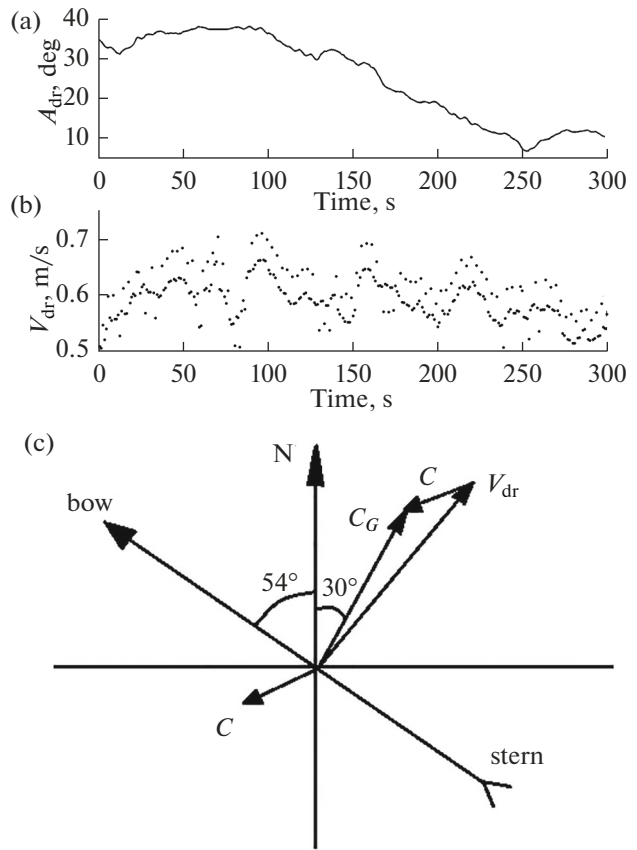


Fig. 3. Direction (a) and speed of the ship's drift (b), depending on time over a period of time of 400–700 s (i.e., within 300 s), when the direction and speed of wave propagation were determined in (b–c). The drift speed has an azimuth of approximately 36° relative to the direction to the north in the time interval from 400 to 500 s. The horizontal phase velocity of the waves relative to the ship is 0.15 m/s, and the azimuth is 234° . Group velocity C_G is also shown relative to the stationary earth.

below the minimum Brunt–Väisälä (BV) period (about 3.5 min) in the thermocline layer. The vertical frequency profile $N(z)$ shown in Fig. 6 from (Kozlov et al., 2023) at station 3911 had a maximum at a depth of 8–10 m and was approximately 17 cycles/h, and the corresponding minimum BV period was about 3.5 min. The horizontal speed of propagation of short waves was 0.45 m/s, with direction of propagation to the northeast. Such short internal waves with frequencies above the BV frequency ($\omega > N$) are high-frequency harmonics of internal waves having frequencies below the BV frequency and are generated as a result of nonlinear nonresonant interactions of these waves (Chunchuzov and Kulichkov, 2020). The interaction of internal waves is caused by the advection of these waves by an alternating current induced by the total field of internal waves. It leads to the generation of high-frequency harmonics with frequencies $\omega > N$, whose spectral density decreases with increasing frequency ω , as ω^{-3} (Chunchuzov and Kulichkov, Sec-

tion 4, 2020). The presence of such a steep section ($\sim \omega^{-3}$) in the experimental frequency spectrum at $\omega > N$ was noted in (Sandven and Johannessen, 1987).

4. CROSS SPECTRA BETWEEN FLUCTUATIONS OF WATER TEMPERATURE (THERMISTOR CHAIN), SST, AND FLUCTUATIONS OF METEOROLOGICAL PARAMETERS IN THE NEAR-SURFACE ATMOSPHERIC LAYER

In the previous section, characteristics (propagation speeds and directions) of short-period internal waves were obtained during a brief time interval on August 12, 2021, when simultaneous measurements were conducted on the ship using three thermistor chains. These waves were only short-period components of the entire wave packet of nonlinear internal waves observed on August 12, 2021, in the Kara Gates Strait (Kozlov et al., 2023). Along with the main source of these waves, associated with the flow of stratified tidal currents over the bottom topography of the Kara Gates Strait, fluctuations in atmospheric pressure and wind speed also contribute to the generation of internal waves in the ocean (Miropolsky, 2001, Chapter 6).

In order to identify the possible inverse influence of observed internal waves in the Kara Sea on mesoscale fluctuations of meteorological fields near the sea surface (periods from several minutes to several hours) and vertical turbulent flows of heat and momentum through the sea surface, in this section we will analyze measurement data of meteorological fluctuations parameters: atmospheric pressure, humidity, wind speed, and air temperature. Fluctuations in atmospheric pressure, wind speed, and air temperature were measured using an AIRMAR 220 mobile weather station located at an altitude of approximately 22 m above sea level with measurement steps of 1 s. The main characteristics of the measuring equipment of this weather station are given in Section 2.

Figure 4 shows variations in sea water temperature measured on August 12, 2021, over a period of 1.9 h from 11:00 UTC at depths of 10 and 20 m using thermistor chains at station 3911 (measurement discreteness of 1 s) and SST using an IR radiometer, simultaneously with variations in air temperature, atmospheric pressure, humidity, wind speed, and direction. The mutual amplitude cross spectra between these fluctuations (except for humidity) are shown in Fig. 5.

Common spectral maxima are found at periods close to 4, 10, 18, and 35 min (indicated by vertical arrows) in the mutual cross spectra (Fig. 5a) between fluctuations in water temperature at a depth of 10 m (T_{10m}) and fluctuations in atmospheric pressure (P), temperature T_{10m} and wind speed (V), temperature T_{10m} and SST T_{IR} , and temperature T_{10m} and air temperature (T_{air}), obtained for realizations of fluctua-

tions with a length of 1.9 h. Almost the same periods are characteristic of the maxima of the cross spectra between fluctuations in water temperature at a depth of 20 m (T_{20m}) and fluctuations in meteorological parameters (Fig. 5b), as well as between fluctuations in water temperature at depths of 10 m (T_{10m}) and 20 m (T_{20m}) (dotted line).

For the measurement period of August 12, 2021, the vertical profiles of temperature, salinity, and BV frequency are shown in Fig. 6. BV frequency profile analysis $N(z)$, given in (Kozlov et al., 2023), shows that in the layer to a depth of 20 m, the frequency $N(z)/(2\pi)$ in its vertical profile reaches a maximum at a depth of 8–10 m and is approximately 17 cycles/h, and the corresponding minimum BV period is about 3.5 min. As the depth increases to 20 m, the frequency $N(z)/(2\pi)$ drops to its minimum value of 4–5 cycles/h, which corresponds to a maximum BV period of 12–15 min. On the contrary, when the depth decreases to the depth of the upper thin mixed layer, the stratification within this layer becomes almost neutral ($N^2(z) = 0$).

In a stable stratified layer down to a depth of 25 m, waveguide propagation of high-frequency linear internal gravity modes with periods lying between 12 min (maximum BV period in the layer) and 3.5 min (minimum BV period in the layer) is possible. Below 25 m in profile $N(z)$, a second maximum of about 12 cycles/h (period 5 min) is observed at a depth of about 33 m, and at a depth of 47 m a minimum of about 4 cycles/h (period 15 min) is reached. Therefore, the 25–47 m layer can also capture high-frequency waves with periods between 5 and 15 min. Waves with periods of more than 15 min are captured by the entire stable stratified layer to a depth of approximately 50 m, below which the bottom topography disturbs the stratified tidal currents.

The periods of isotherm oscillations of 4 and 10 min, which correspond to the spectral maxima in Fig. 5, are included in the range of periods of 3.5–15 min of captured high-frequency internal waves in a layer up to a depth of 50 m. Short-period nonlinear internal waves were observed on August 12, 2021, in (Kozlov et al., 2023). In particular, high-frequency oscillations of isotherms with frequencies of 11–12 cycles/h (periods of 5–5.5 min) and periods of 10 and 15 min were observed on thermistor chains spaced apart from each other. Lower frequency oscillations of isotherms with periods of about 30 min were also detected. Based on the time delay in the arrival of these oscillations on different thermistor chains, their horizontal velocities and directions of propagation relative to the drifting vessel and in a fixed coordinate system were estimated. These velocities (~ 0.8 – 0.9 m/s) and the above periods of isotherm oscillations were caused by the observed nonlinear short-period waves (Kozlov et al., 2023). They are also typical for internal waves propagating in the thermocline layer (Sandven and Johannessen, 1987; Brekhovskikh and Goncharov, 1997; Svergun et al., 2020).

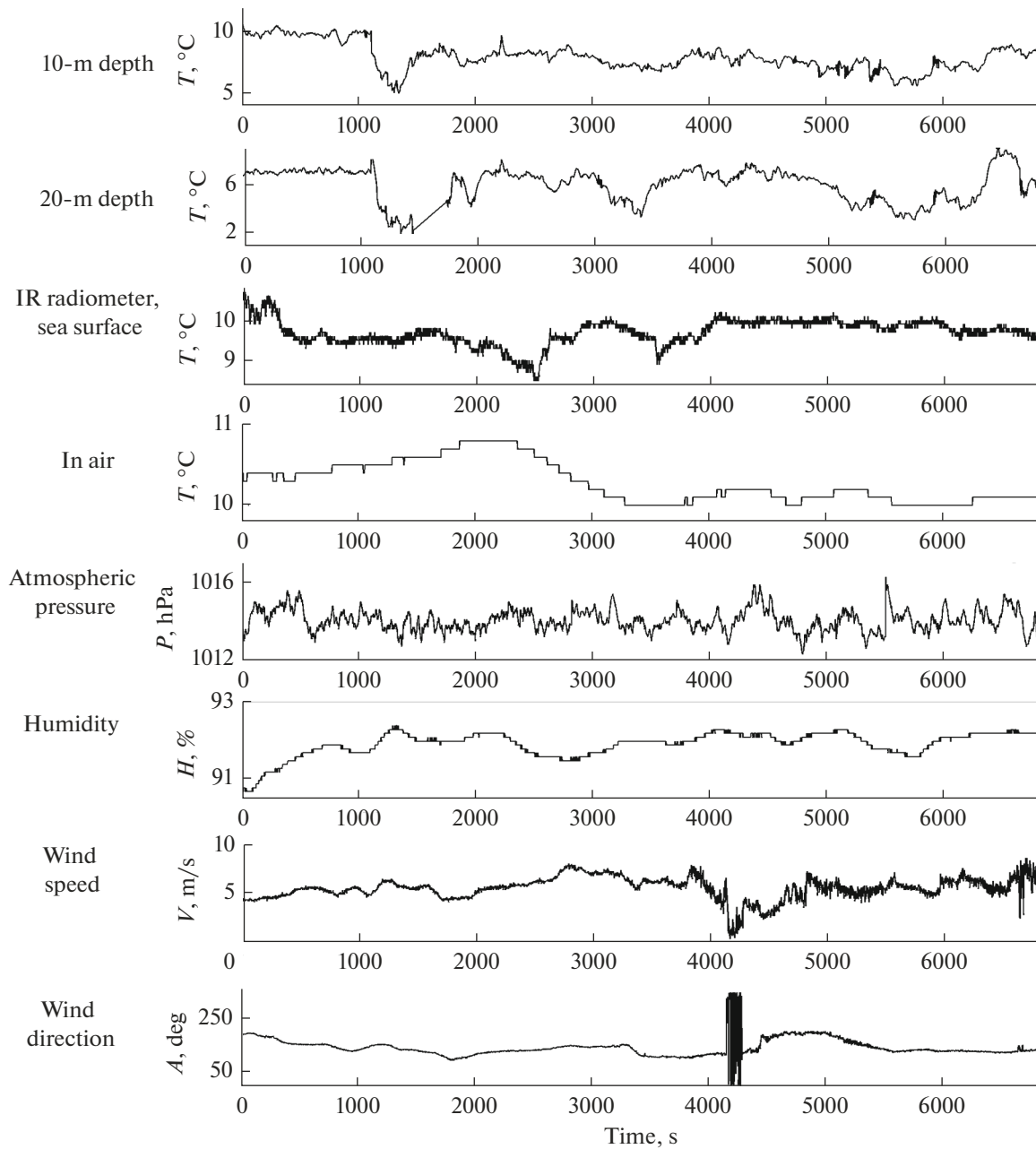


Fig. 4. Fluctuations in seawater temperature at depths of 10 and 20 m, SST according to the IR radiometer, atmospheric pressure, wind speed, humidity, and air temperature at an altitude of approximately 22 m above sea level, measured August 12, 2021, within 1.9 h from 11:00 UT.

From the presence of common periods in the cross spectra between fluctuations in water temperature at different depths and fluctuations in various meteorological parameters at an altitude of 22 m, we assume that internal waves propagating in the thermocline layer generated, at these same periods, certain spectral components of fluctuations in atmospheric pressure and wind speed and temperatures in the surface layer of the atmosphere. This generation is due to the fact that vertical displacements of particles of the medium caused by internal waves in the thermocline layer cause fluctuations in atmospheric pressure near the water–air

interface. Vertical speed connection $w(\vec{x}, z, t)$ in the field of internal waves of small amplitude propagating in a stable stratified layer of the ocean, where $\vec{x} = (x, y)$ is horizontal coordinates and z is the vertical coordinate, and fluctuations of atmospheric pressure $p_a(\vec{x}, t)$ near the undisturbed ocean surface $z = 0$ are carried out through the boundary condition at $z = 0$ (Miropolsky, 2001, Chapter 6):

$$\rho \left(\frac{\partial^2}{\partial t^2} \frac{\partial w}{\partial z} + f^2 \frac{\partial w}{\partial z} - g \Delta_{\perp} w \right)_{z=0} = \frac{\partial \Delta_{\perp} p_a}{\partial t}, \quad (1)$$

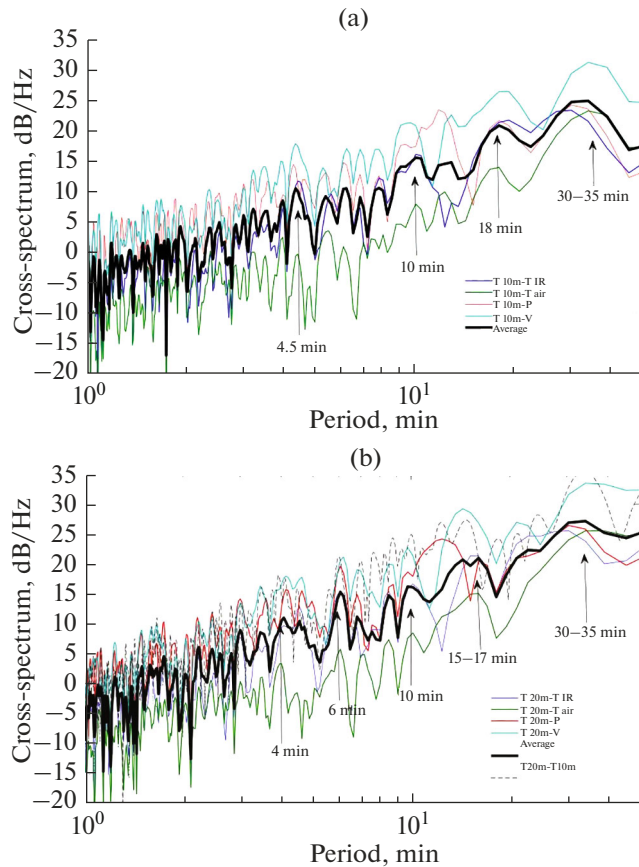


Fig. 5. Mutual amplitude cross spectra between water temperature fluctuations at a height of 10 m (T_{10}) and atmospheric pressure (P), temperature T_{10} and wind speed (V), temperature T_{10} and ocean surface temperature (T_{IR}), temperature T_{10} and air temperature (T_{air}), and the average cross spectrum for the above four cross spectra (thick black curve) (a); the same cross spectra as in Fig. 5a, only for water temperature at a depth of 20 m. The cross spectrum between water temperature fluctuations at depths of 10 and 20 m is also shown (dotted line).

where $\Delta_{\perp} = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$ is the Laplacian in the horizontal plane, f is the Coriolis parameter, and g is the acceleration of gravity.

The field of a separate gravity mode in the thermocline layer, propagating horizontally, can be represented as $w = W_0(z) \exp(-i\omega t + \vec{k}\vec{x})$, where ω and $\vec{k}$ are, respectively, the frequency and horizontal wave vector of the mode, related by the dispersion relation, and $W_0(z)$ is the amplitude of the mode, the dependence of which on depth z is determined by profile type $N(z)$ frequency BV.

In a wide frequency-wavenumber Fourier spectrum of atmospheric pressure fluctuations $p_a(\vec{x}, t)$, it is possible to isolate the spectral component $P_a(\omega, k) \exp(-i\omega t + \vec{k}\vec{x})$ with amplitude $|P_a(\omega, k)|$, associated by boundary condition (1) with the velocity

amplitude $W_0(z)$ in waveguide mode. If frequency ω and wave number $\vec{k}$ of this spectral component of fluctuations $p_a(\vec{x}, t)$ are close, respectively, to frequency ω and wave number $\vec{k}$ of the gravitational mode in the oceanic waveguide, then conditions arise for the resonant interaction of this mode with the above spectral component of atmospheric pressure fluctuations (Miropolsky, 2001, Chapter 6). Such a resonant connection is possible due to the fact that a significant contribution to the frequency-wavenumber spectrum of fluctuations in atmospheric pressure and wind speed is made by atmospheric gravity waves, in particular, high-frequency internal waves propagating horizontally in the lower stable stratified atmospheric boundary layer (ABL) (Chunchuzov et al., 2009). In such a layer, the temperature inversion forms a waveguide channel for high-frequency gravity waves with typical periods in the range from 3 to 11 min, which practically coincides with the range of periods of high-frequency internal waves in the thermocline layer. The horizontal phase velocities of atmospheric gravity modes of lower orders are low, amounting to 2–2.5 m/s, and decrease with increasing number of these modes so that these velocities for modes of sufficiently high numbers become close to the velocities of internal waves propagating in the thermocline layer. This indicates the possibility of fulfilling resonance conditions (coincidence of frequencies and horizontal phase velocities) for such slow high-frequency atmospheric gravity waves in a stable stratified ABL over the sea and internal waves in the thermocline layer.

5. ANALYSIS OF MESOSCALE VARIATIONS IN VERTICAL TURBULENT HEAT AND MOMENTUM FLUXES NEAR THE SURFACE OF THE KARA SEA

Internal waves in the atmosphere and ocean cause mesoscale variations in the vertical gradients of the velocity and temperature fields in these environments, leading to corresponding variations in the intensity of turbulent fluctuations of velocity and temperature (Finnigan et al., 1984), as well as vertical turbulent fluxes of momentum and heat near the ocean surface. The calculation of explicit turbulent fluxes (Q_L) and latent heat (Q_H) through the sea surface, as well as momentum flow and dynamic speed u^* , was carried out using the main provisions of the Monin–Obukhov theory of similarity (Repina, 2007; Timachev et al., 2008). These fluxes, determined by the covariance of the vertical velocity with the corresponding meteorological quantities measured in steps of 1 s, were averaged over a sliding time period of 10 min, which made it possible to study mesoscale temporal variations of turbulent fluxes with periods from tens of minutes to several hours. The calculation method for determining COARE flows was used (Fairall et al., 2003).

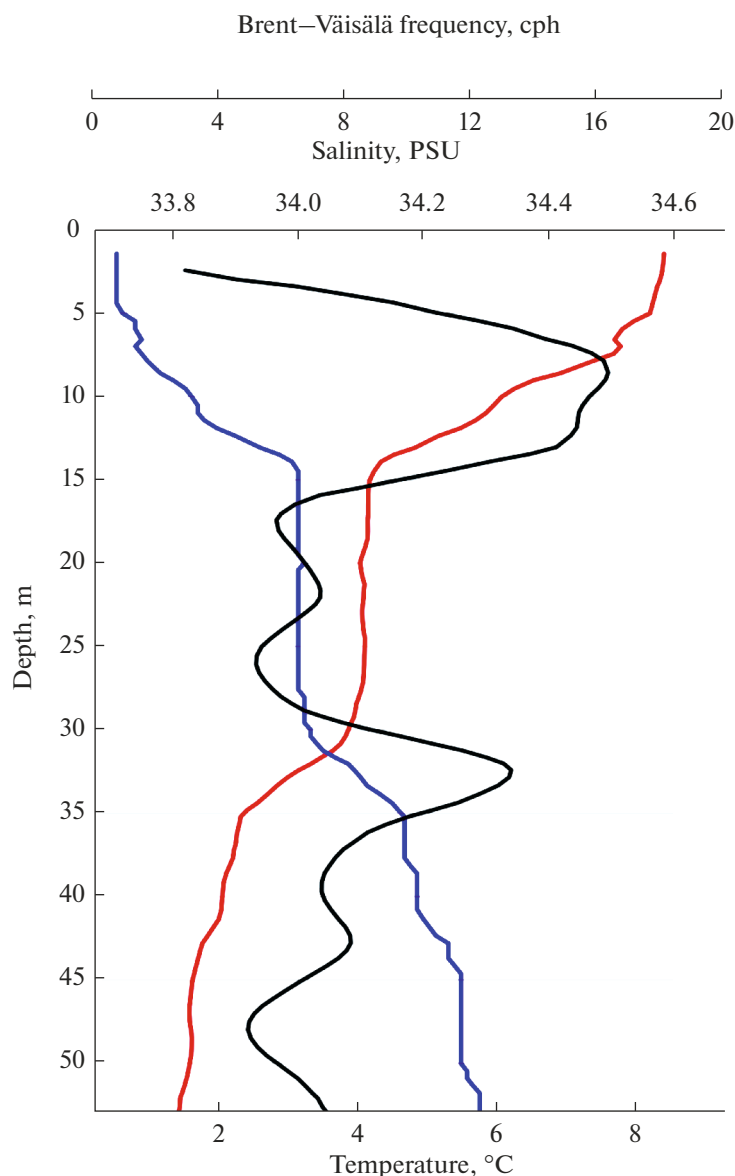


Fig. 6. Vertical profiles of temperature (red), salinity (blue), and frequency of Brunt–Väisälä (black) during the measurement period on August 12, 2021, at station 3911.

Before this section, we presented the results of spectral analysis of measurement data only for August 12, 2021. Short-period internal waves in the thermocline layer were observed on other days, in particular, on August 23, 2021, and August 24, 2021. For these days, we analyzed not only variations in meteorological parameters, as for August 12, 2021, but also studied their relationship with temporary variations in turbulent heat and momentum flows in the surface layer of the atmosphere.

Figure 7 shows mesoscale variations in turbulent fluxes of apparent (Q_H) obtained on August 23, 2021, for 14 h and latent heat (Q_L), dynamic speed u^* , as well as horizontal wind speed V , air temperature (temp), and difference between sea and air temperatures (delta) and

atmospheric pressure (P) averaged over 10 min obtained from weather station data. These variations are obtained relative to a moving vessel with an average speed on that day of approximately 1.5 knots, or 0.8 m/s.

Mesoscale variations of u^* , as can be seen from Fig. 7 (second and third panels from top), follow wind speed variations well at 22 m above sea level and, therefore, variations in the vertical gradient of wind speed in the surface layer of the atmosphere. From Fig. 7 one can also see the dependence of turbulent heat fluxes (first panel from the top) on the difference in sea and air temperatures (delta) (fourth panel from the top)

A similar influence of mesoscale variations in the vertical shear of wind speed and temperature difference (delta) on the dynamic speed u^* and vertical tur-

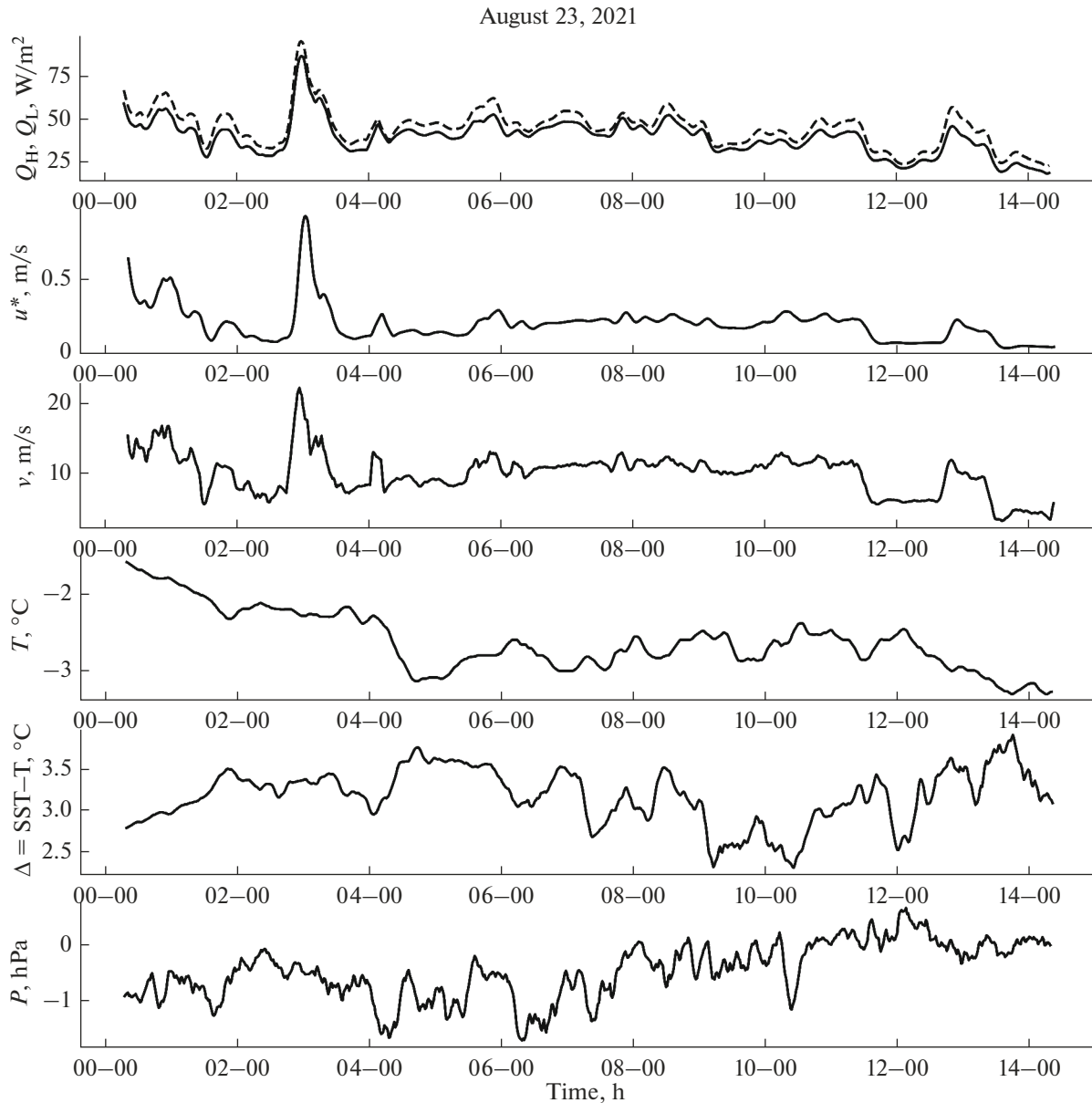


Fig. 7. Mesoscale variations over 14 h on August 23, 2021, in apparent turbulent fluxes (Q_H) and latent heat (Q_L), turbulent friction speeds u^* , as well as averaged over 10 min: horizontal speed V , air temperature (temp), temperature difference between ocean and air (Δ), and atmospheric pressure (P).

bulent heat fluxes, respectively, was also observed on August 24, 2021 (Fig. 8). The main periods of these mesoscale variations were determined from the time spectra of variations in the dynamic velocity u^* and turbulent heat fluxes Q_L received on August 23, 2021 (Fig. 9, left), and August 24, 2021 (Fig. 9, right), at night from 00:00 to 06:00 UTC.

The spectra contain spectral peaks at common periods of 20, 25, 35 min, 1, 3, and 4.7 h, at which the main contribution of oscillations in wind speed shears and temperature differences Δ to the time variations of vertical turbulent fluxes of momentum and

heat occurs, respectively. Such a discrete set of periods of oscillations of meteorological parameters was previously observed in the atmosphere when wave packets of atmospheric gravity waves, generated at different frequencies by regular and irregular sources in the atmosphere, such as the solar terminator, passed through the measuring network (Chunchuzov et al., 2021), natural vibrations of the earth (Shved et al., 2000), weather fronts, jet streams, unstable wind speed shears, etc. (Gossard and Hooke, 1975), along with numerous combinative harmonics (with sum and difference frequencies) of these waves generated as a result of their nonlinear interactions.

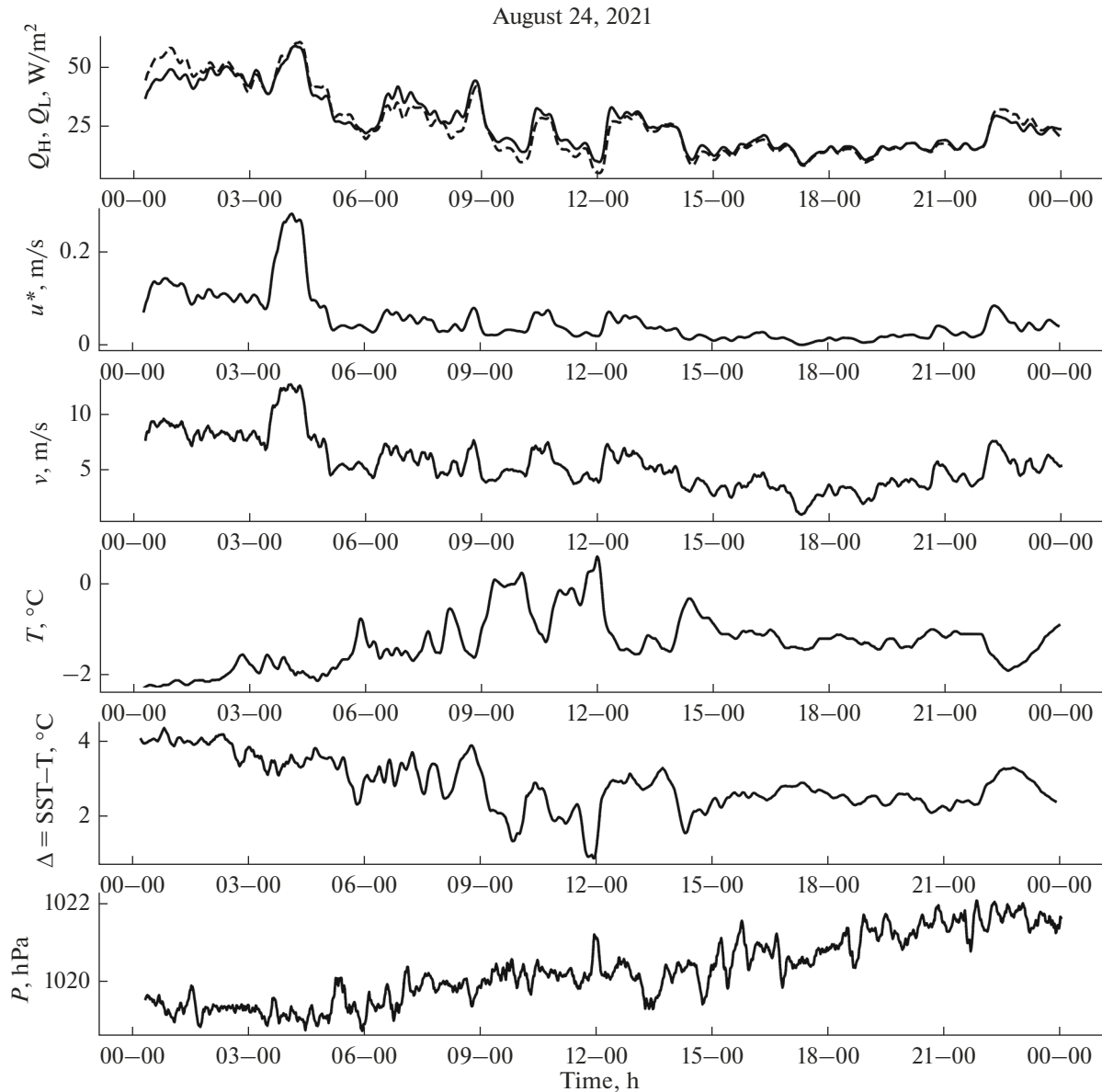


Fig. 8. Mesoscale variations of the same parameters as in Fig. 7, but received on August 24, 2021.

Based on the above results of observation and modeling of the influence of internal waves on shears in current speed in the ocean (Pinkel, 2008; Rohrs, 2023) and shears in wind speed in the surface layer of the atmosphere (Chunchuzov et al., 2009), we assume that internal waves of different periods influenced the turbulent fluxes of momentum and heat near the surface of the Kara Sea.

6. CONCLUSIONS

This paper analyzes data from insitu measurements of sea water temperature at different depths of the Kara Gates Strait (based on three thermistor chains), SST (using an IR radiometer), and meteorological parameters above the sea surface obtained during an expedi-

tion to the Kara Sea on the research vessel *Akademik Ioffe* in August 2021.

Using the method of coherent analysis of temporary fluctuations in sea water temperature at a depth of 18 m, measured simultaneously on August 12, 2021 (station 3911), by three horizontally spaced temperature sensors within a short period of time of 22 min, the direction and horizontal phase velocity of the propagation of SPIW to the drifting vessel in the range periods 40–160 s. The propagation speeds of these waves relative to the ship were 0.14–0.16 m/s and, relative to the stationary earth (taking into account the drift of the ship), the waves propagated northeast with a group velocity of approximately 0.46 m/s. This direction of the SPIW is close to the direction of propagation (to the northeast) of solitary nonlinear inter-

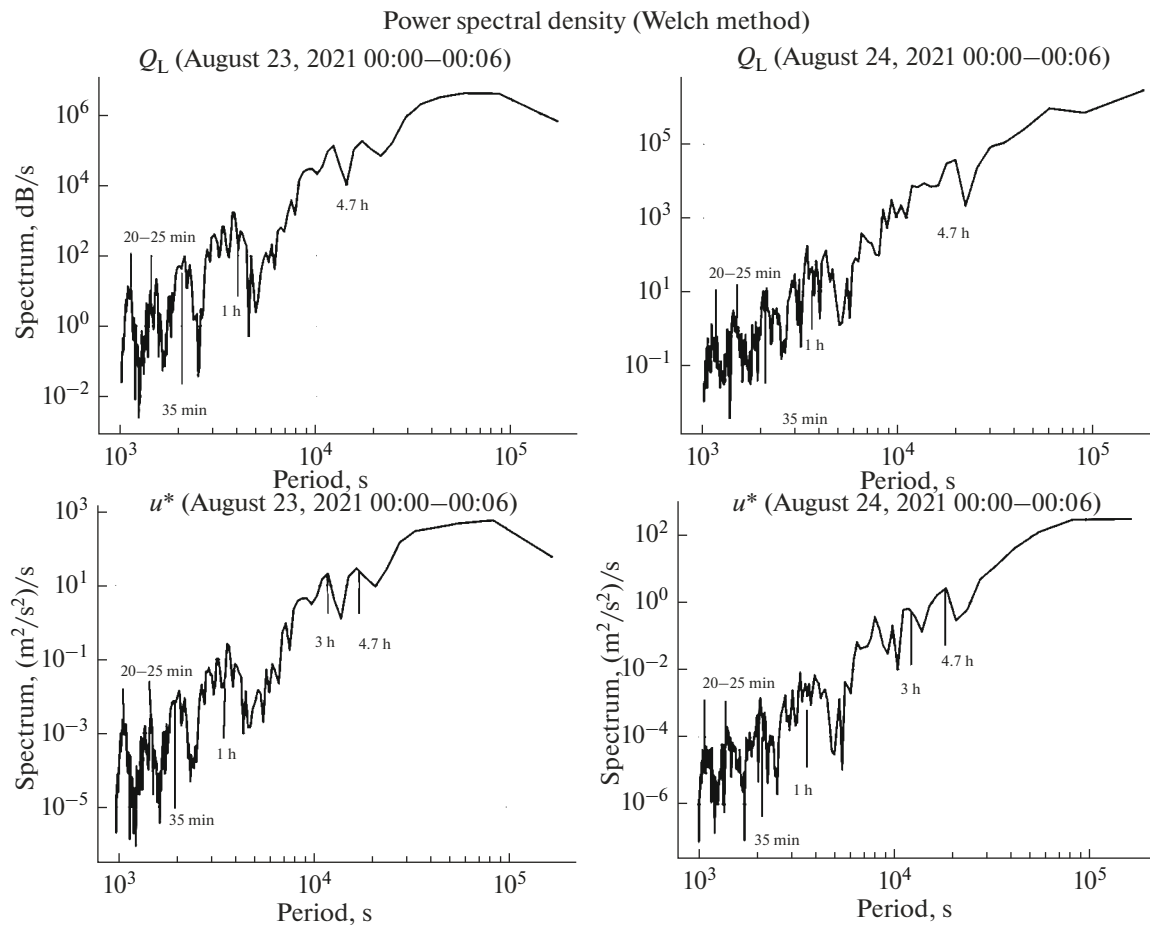


Fig. 9. Time spectra of variations in dynamic velocity u^* and turbulent heat fluxes Q_L , received on August 23 (left) and August 24 (right) 2021 from 00:00 until 06:00 UTC.

nal waves (solitons) observed on August 12 in the Kara Gates Strait (Kozlov et al., 2023) and propagating at a speed of 0.8–0.9 m/s, which suggests that high-frequency internal waves and the soliton were different components of a single wave packet. The main source of generation of this wave packet there were tidal stable stratified currents flowing around the bottom topography in the Kara Gates Strait (Kozlov et al., 2023).

By analyzing cross spectra of mesoscale fluctuations in SST using an IR radiometer, at depths of 10 and 20 m, using thermistor chains and meteorological parameters at an altitude of 22 m, the influence of observed internal waves in the Kara Sea on mesoscale (periods from several minutes to several hours) fluctuations of meteorological fields near the sea surface and vertical turbulent flows of heat and momentum through the sea surface into the surface layer of the atmosphere has been studied.

In the cross spectra of fluctuations, common spectral maxima were found at periods lying between the minimum BV period (~ 3.5 min) and the maximum BV period (15 min) in the sea layer to a depth of 25 m. These periods are typical for trapped internal gravity waves propagating both in layer of the oceanic ther-

mocline and for atmospheric gravity modes in the stable stratified layer of the lower troposphere. When in the spatiotemporal spectrum of atmospheric pressure pulsations there is a set of frequencies and wave numbers that satisfy the dispersion relations of trapped internal gravity modes in the thermocline layer, a resonant connection of these modes with the selected atmospheric pressure pulsations occurs. This resonant connection, which occurs when frequencies and horizontal wave numbers (or horizontal phase velocities) of waveguide modes in the ocean and atmosphere coincide, explains the presence of common spectral maxima in cross spectra between fluctuations in water temperature at different depths and on the sea surface and meteorological parameters of the atmosphere. However, the mechanism proposed here for the mutual influence of the fields of atmospheric and oceanic gravity modes requires further theoretical study and experimental justification.

The influence of mesoscale variations in wind speed at an altitude of 22 m above sea level and the difference in surface water and air temperatures (ΔT) (with periods from 10 min to several h) on variations in turbulent fluxes of apparent momentum (Q_H) and

latent heat (Q_1) near the sea surface was studied. Based on the time spectra of variations in turbulent flows, it is shown that the main influence on these variations is exerted by a discrete set of oscillations of the temperature difference (ΔT) and wind speed with a certain discrete set of periods (20, 25, 35 min, 1, 3, and 4.7 h) relative to the ship. These periods are typical for the atmospheric gravity waves of different scales, propagating in the stable-stratified lower layer of the troposphere and modulating vertical gradients of temperature and wind speed, as well as turbulent flows of heat and momentum during these periods.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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