

COASTAL-TRAPPED BAROCLINIC KELVIN WAVES IN MORDVINOVA BAY (SEA OF OKHOTSK)

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Abstract: Based on a multi-month observation time series with one-second temporal resolution of seawater temperature and sea level oscillations obtained in 2015–2025 off the southeastern coast of Sakhalin Island in Mordvinova Bay, low-frequency wave processes in the coastal zone were analyzed. A pronounced seasonal contrast in the amplitude of temperature oscillations was identified: during the autumn–winter period, temperature variations generally do not exceed 2 °C, whereas in the spring–summer season, beginning in May, large-amplitude oscillations develop, increasing with progressive water warming and reaching ~ 7 °C. Interannual comparison of the time series reveals a high degree of reproducibility in the temporal structure of the oscillations (correlation coefficients between the 2025 and 2020 and 2025 and 2022 records range from 0.76 to 0.82), indicating a common underlying generation mechanism. Spectral analysis identified a set of persistent peaks in the period range of 3–43 days, recurring in different years and partially coinciding with characteristic periods of atmospheric pressure and wind variability. The combination of the observed periods, their seasonal occurrence under stratified conditions, and the consistency of the basin spatial scales with the first baroclinic Rossby radius of deformation supports the interpretation of the temperature oscillations as manifestations of coastal-trapped baroclinic Kelvin waves. Analysis of the 2025 data shows that southerly winds prevail from mid-April to late August, coinciding with the period of intensified baroclinic temperature variability. Calculation of the absolute value of the transfer function for the wind–sea level and wind–temperature time series pairs confirms more efficient energy transfer from wind to baroclinic oscillations during the spring–summer season, indicating the leading role of southerly winds in generating the observed regime. Additional analysis of satellite-derived sea ice concentration shows that the decay of seasonal ice cover occurs by late March–early April, several weeks before the onset of high-amplitude oscillations. This indicates that sea ice processes play a secondary role and cannot explain the observed low-frequency variability.

Keywords: time series, seawater temperature, sea level, spectral analysis, baroclinic wave, Kelvin wave, Mordvinova Bay, wind speed

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REVIEW

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1. Introduction

Experimental research conducted by the Wave Dynamics and Coastal Currents Laboratory at the Institute of Marine Geology and Geophysics, Far Eastern Branch of the Russian Academy of Sciences, focuses on surface and internal (baroclinic) wave processes in the coastal zone of Sakhalin Island in the northwestern Pacific Ocean. Field observations are performed using autonomous bottom-mounted pressure and temperature recorders, complemented by a meteorological station deployed near the measurement sites. The resulting datasets enable analysis of both barotropic and baroclinic variability, which is essential for understanding coastal ocean dynamics and for addressing applied problems, including navigation safety and fisheries operations.

Long-period seawater temperature variability associated with baroclinic waves is of particular interest, as these processes constitute an integral component of stratified basin dynamics and contribute to large-scale ocean circulation [Müller *et al.*, 1986; Timmermann *et al.*, 1999]. For waves with periods of several days or longer, the Coriolis force becomes dynamically significant and must be explicitly accounted for in analyses of large-scale oceanic and atmospheric motions, climate variability modeling [Summerhayes and Thorpe, 1996], and weather prediction [Shindell and Schmidt, 2004].

One of the fundamental large-scale boundary-trapped wave types is the Kelvin wave, which exists at frequencies both above and below the local inertial frequency. In the Northern Hemisphere, Kelvin waves propagate with the coast on their right-hand side, whereas in the Southern Hemisphere the coast lies to the left of the direction of propagation. Their amplitude is maximal at the boundary and decays exponentially offshore [Efimov *et al.*, 1985]. The existence and dynamics of Kelvin waves are governed by the combined effects of gravity, stable stratification (permitting internal oscillations), a dynamically significant Coriolis parameter, and the presence of a vertical boundary or the equator [Ibragimov, 2012; Wang, 2002].

Baroclinic Kelvin waves represent the internal analogue of barotropic coastal oscillations [Efimov *et al.*, 1985] and are most clearly expressed in layers characterized by strong vertical density gradients. A typical example is the thermocline, a layer of rapid temperature change that separates a relatively warm surface layer, typically 50–200 m thick, from the colder deep ocean beneath [Ibragimov, 2012; Wang, 2002]. In the horizontal plane, a baroclinic Kelvin wave behaves similarly to a surface gravity wave; however, its amplitude and phase structure vary with depth, reflecting the internal nature of the motion.

A few studies have shown that one of the main causes of the generation of long coastal waves is wind action. For example, Gill and Schumann [1974], in their analysis of continental shelf waves—dynamically similar in many respects to Kelvin waves—showed that at mid-latitudes such waves are excited by the passage of cyclones and anticyclones across or along the shelf, with typical periods of several days. Similar conclusions were reached [in Chapman *et al.*, 1988], where it was shown that a substantial fraction of low-frequency (2–10 day) variability in alongshore currents, bottom pressure, and adjusted coastal sea level over continental shelves can be attributed to both local and remote wind forcing. In this context, assessing the relationship between the low-frequency baroclinic oscillations identified in the present study and variability in surface wind forcing is crucial.

Despite the extensive body of work on coastal-trapped waves and their wind-driven generation, the seasonal expression of low-frequency baroclinic temperature variability in specific semi-enclosed coastal basins—particularly those whose dimensions are comparable to the first baroclinic Rossby radius of deformation—remains insufficiently explored. In particular, the manner in which seasonal stratification and changes in the wind regime modulate the amplification or suppression of such processes in individual coastal environments is not yet fully understood. Mordvinova Bay, located along the southeastern coast of Sakhalin Island, represents a coastal basin whose geometric configuration and hydrographic conditions are potentially favorable for the formation of baroclinic coastal trapped waves. The objective of this study is to identify robust seasonal and interannual patterns of low-frequency seawater temperature variability in Mordvinova Bay, to determine their characteristic time scales, and to provide a physical interpretation of the observed processes in terms of wind-driven excitation of coastal baroclinic waves.

2. Materials and Methods

Field observations were conducted in the coastal zone (within 10 km from the shoreline) using autonomous digital bottom-mounted recorders (ARV-14K) that measure near-bottom hydrostatic pressure fluctuations and seawater temperature. Pressure records were converted to sea-level variations, accounting for the depth-dependent attenuation of short-period surface waves. The specified full-scale accuracy of bottom pressure measurements is 0.06% of the measurement range, with a resolution of $\pm 0.0008\%$ of full scale. The

temperature sensor resolution is 0.01 °C, with an absolute accuracy of ± 0.15 °C (± 0.5 °C for a subset of instruments). Both sea-level and temperature measurements were sampled at 1 s intervals. Concurrent atmospheric pressure and wind speed data were obtained from a Vantage Pro2™ weather station and supplemented with records from open-access meteorological archives (<https://rp5.ru>).

The observational layout within Mordvinova Bay (southeastern Sakhalin Island) is shown in Figure 1. The map indicates instrument deployment sites and the corresponding observation periods at each location. At station 1, the instruments were recovered annually for battery replacement.

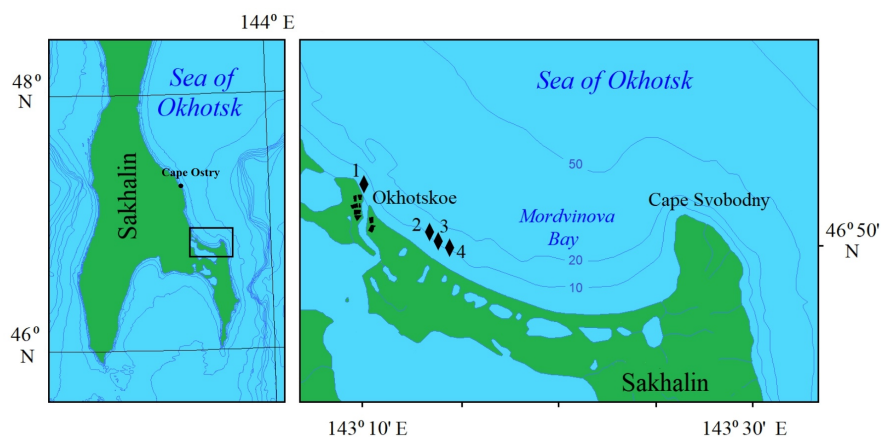


Figure 1. Map of the study area and instrument deployment locations near the settlement of Okhotskoye (southeastern Sakhalin Island). Diamond symbols indicate the positions of bottom-mounted wave recorders. Instruments were deployed at station 1 in 2015–2017, at station 2 in 2020–2021, at station 3 in 2019–2020, and at station 4 in 2024–2025.

The study area is located in the Sea of Okhotsk, a marginal sea situated on the eastern shelf of the Eurasian continent and separated from the western Pacific Ocean by the Kamchatka Peninsula and the Kuril Island chain [Kurkina *et al.*, 2017]. The islands of Hokkaido and Sakhalin separate the Sea of Japan from the Sea of Okhotsk. The Sea of Okhotsk has a surface area of approximately 1,583,000 km² and a mean depth of about 851 m. The substantial freshwater discharge from the Amur River contributes to an elevated freezing point and promotes the formation of seasonal sea ice during winter [Kurkina *et al.*, 2017].

The field experiments yielded multi-month records of sea-level fluctuations and seawater temperature sampled at 1 s intervals at several locations within the study area (record lengths of 5–10 months), including both open-water and ice-covered periods. Data processing and visualization were performed using the Kyma software package [Kovalev, 2018; Plekhanov and Kovalev, 2016].

To quantify the interannual similarity of temperature time series, the Pearson linear correlation coefficient was applied. Correlation analysis was carried out for the 2025 and 2020 and 2025 and 2022 datasets to assess the consistency of low-frequency variability across different years. The correlation coefficient was calculated using the standard expression:

$$r_{x,y} = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}},$$

where n is the sample size, x_i and y_i are the values of the compared time series at time index i , and $\bar{x}$ and $\bar{y}$ denote their respective sample means. The use of correlation analysis makes it possible to quantify the degree of consistency in the seasonal and intraseasonal structure of temperature variability across different years.

To examine the dynamical relationship between wind variability and the response of the coastal basin (sea level and water temperature), the magnitude of the transfer function was applied, following the approach adopted in our previous studies [Kovalev and Squire, 2020]. In practice, the analysis involved computation of the frequency response function (Bode plot), but for consistency, the more general term transfer function is used throughout the paper. This approach is widely employed in studies of linear relationships between two time series, where one process is treated as an external forcing and the other as the system response [Bendat and Piersol, 2010; Yaffee and McGee, 2000]. The transfer function is defined as a complex function of frequency, $K(j\omega) = K(\omega)e^{-j\varphi(\omega)}$ where the modulus $K(\omega)$ describes the amplification (or attenuation) of harmonic components and the phase $\varphi(\omega)$ characterizes their phase shift under the action of a linear operator [Marple, 1987]. Application of this method makes it possible to identify the frequency bands in which energy transfer from wind variability to sea-level and temperature oscillations is most efficient.

3. Results and Discussion

Figure 2 presents the time series of near-bottom water temperature obtained during different observation years in Mordvinova Bay. The records span both the autumn–winter and spring–summer seasons, allowing comparison of the seasonal structure of temperature variability across different years.

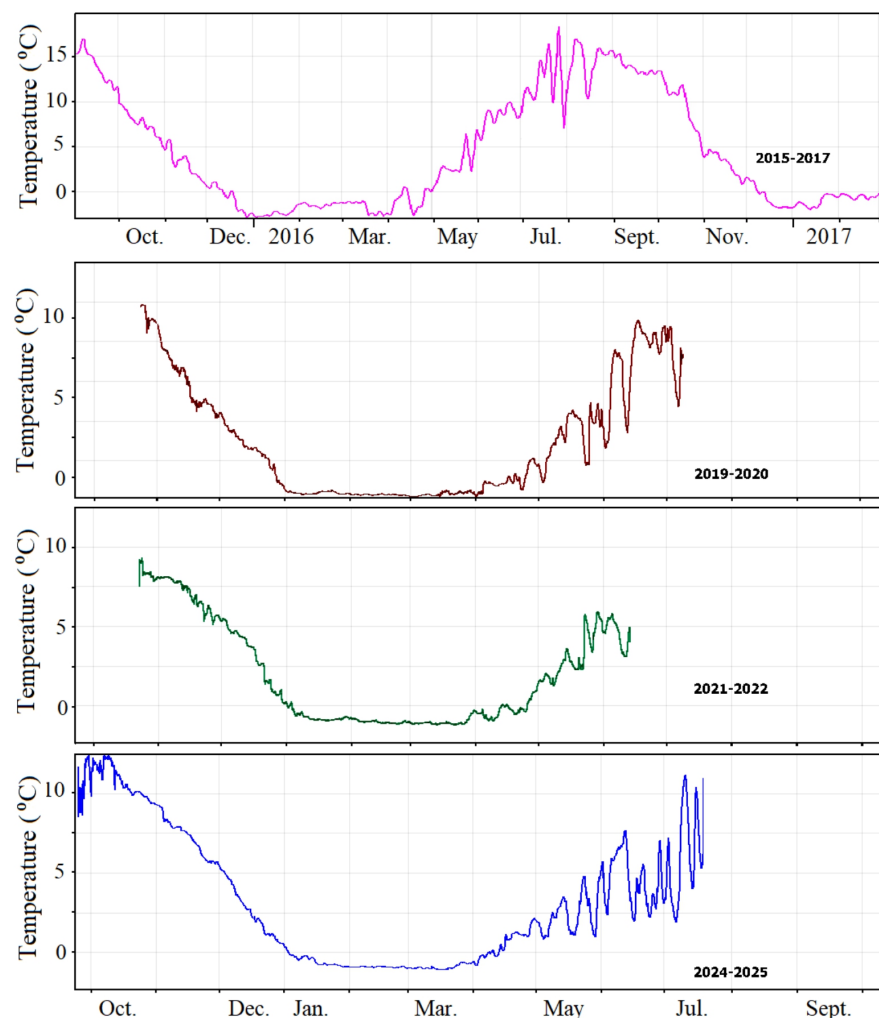


Figure 2. Time series of temperature fluctuations in Mordvinova Bay.

Analysis of the temperature time series reveals a consistent pattern of seasonal evolution. During autumn, temperature decreases gradually until mid-January, when seasonal ice cover typically forms. Throughout the ice-covered period, temperature variability is weak and remains relatively stable until early April, when ice breakup occurs, and the bay becomes ice-free. To quantify the timing of ice cover decay and its interannual variability, satellite-derived sea ice concentration data were analyzed for the study area. Figure 3 shows the seasonal evolution of mean sea ice concentration (Mean SIC) for representative observation years [Spreen *et al.*, 2008]. Following ice retreat, a steady increase in temperature is observed. Because the instruments were generally deployed in late September–October, the 2019–2025 records do not include the late summer period, when warming ceases and autumnal cooling begins. To illustrate the complete seasonal cycle, the 2015–2017 record, which encompasses this interval, is additionally presented.

Importantly, the onset of high-amplitude quasi-periodic temperature oscillations occurs several weeks after the complete decay of the ice cover. This temporal offset indicates that the observed oscillations are not directly associated with ice-related thermodynamic processes.

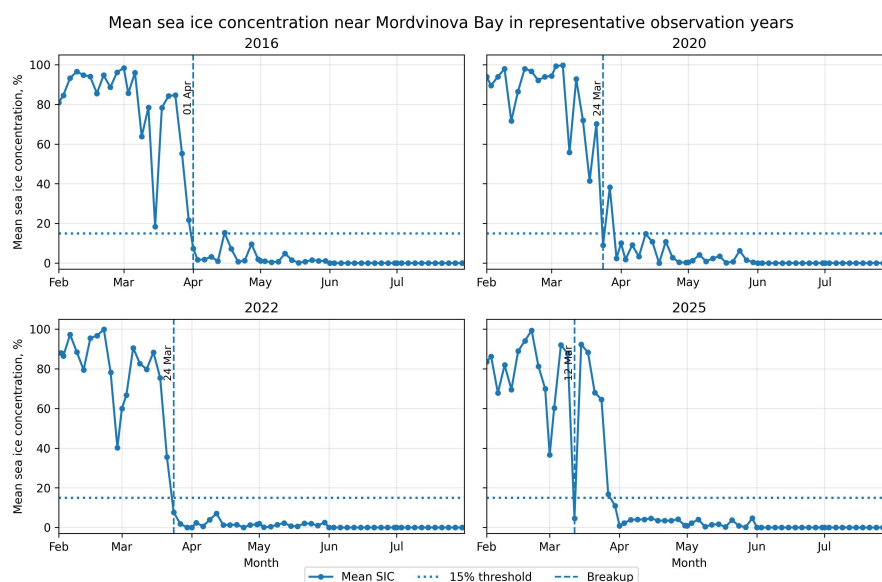


Figure 3. Seasonal evolution of mean sea ice concentration (Mean SIC) in the nearshore region of Mordvinova Bay for representative observation years (2016, 2020, 2022, 2025). The dashed horizontal line indicates the 15% threshold commonly used to define the presence of sea ice. Vertical dashed lines mark the estimated dates of ice breakup, defined as the transition of mean SIC below 15%. The results demonstrate that the study area becomes effectively ice-free by late March–early April in all years.

The analysis reveals a consistent pattern of seasonal ice decay. In all considered years, the transition from ice-covered to ice-free conditions occurs between mid-March and early April. After this period, mean sea ice concentration rapidly decreases below 10%, indicating the absence of continuous ice cover in the study area.

A distinctive feature of the spring–summer season is the emergence of pronounced quasi-periodic temperature oscillations that are absent during the cold season. In autumn and winter, temperature variability remains comparatively smooth, whereas beginning in May the amplitude of intraseasonal fluctuations increases with progressive warming and, in some years, reaches up to 7 °C. For a more detailed examination of the structure of these oscillations, selected segments of the time series corresponding to the period of rapid temperature increase are shown in Figure 4. A third record is not displayed due to graphical limitations but exhibits similar behavior.

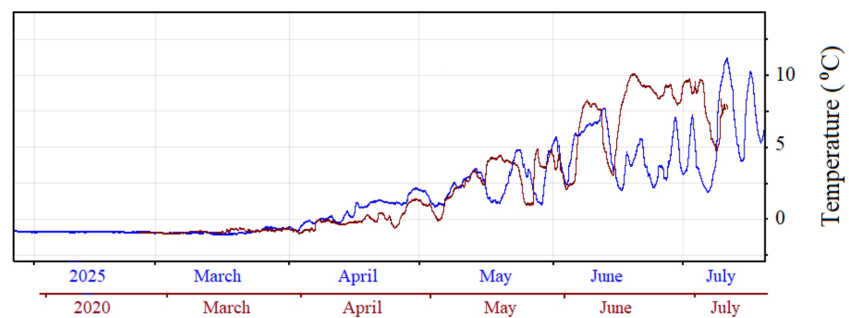


Figure 4. Time series of temperature fluctuations during the spring warming period in Mordvinova Bay.

Figure 4 demonstrates a clear consistency in the phase structure of temperature oscillations across different years, particularly the alignment of temperature maxima in April–May. A quantitative assessment of interannual similarity was performed using the Pearson correlation coefficient for selected segments of the hourly time series beginning on 05 April 2025 and 01 April 2020 (sample size $n = 1849$), and on 05 April 2025 and 05 April 2022 ($n = 1675$). The resulting correlation coefficients are 0.82 and 0.76, respectively. According to the commonly accepted interpretation of the Pearson coefficient, these values fall within the range of strong correlation ($|r| = 0.70\text{--}0.89$). The corresponding coefficients of determination (r^2) are 0.67 and 0.58, indicating that a substantial fraction of the variance is shared between the series and confirming the reproducibility of the intraseasonal temperature oscillations across different years.

For the analyzed time series, time–frequency diagrams were constructed and are shown in Figure 5b and Figure 5d. The distribution of spectral energy density reveals several pronounced peaks within the period range of 4–50 days. A characteristic feature is the seasonal amplification of energy beginning in March and reaching a maximum during the spring–summer season, followed by a gradual weakening of low-frequency variability from September onward.

Based on the computed power spectral densities, which allowed refinement of the characteristic time scales of variability, Table 1 was compiled to summarize the periods identified in different years that are close in magnitude. It should be noted that for the shorter time series of 2020 and 2022, reliable identification of spectral peaks with periods exceeding 10 days is limited by the finite record length. Nevertheless, comparison of the dominant spectral peaks reveals a consistent recurrence of characteristic temperature periods across different years, as well as partial correspondence with variability periods of atmospheric pressure and wind speed.

Table 1. Periods of dominant peaks in the power spectral densities of seawater temperature time series (2016–2025), atmospheric pressure, and wind speed

2025	2022	2020	2016	Atmospheric pressure	Wind speed
3.08	3.08	3.03	3.04	3.08	3.04
4.42	4.41	4.38	4.38	4.50	4.80
6.25	6.13	6.12	6.25	–	6.25
7.83	7.63	7.87	7.91	–	–
10.63	10.50	10.13	–	–	10.13
–	–	–	–	–	15.50
–	–	–	34.04	–	34.50
41.38	–	–	41.42	41.38	–

The identified temperature oscillations exhibit a pronounced wave-like character and develop under stratified conditions, allowing them to be interpreted as baroclinic

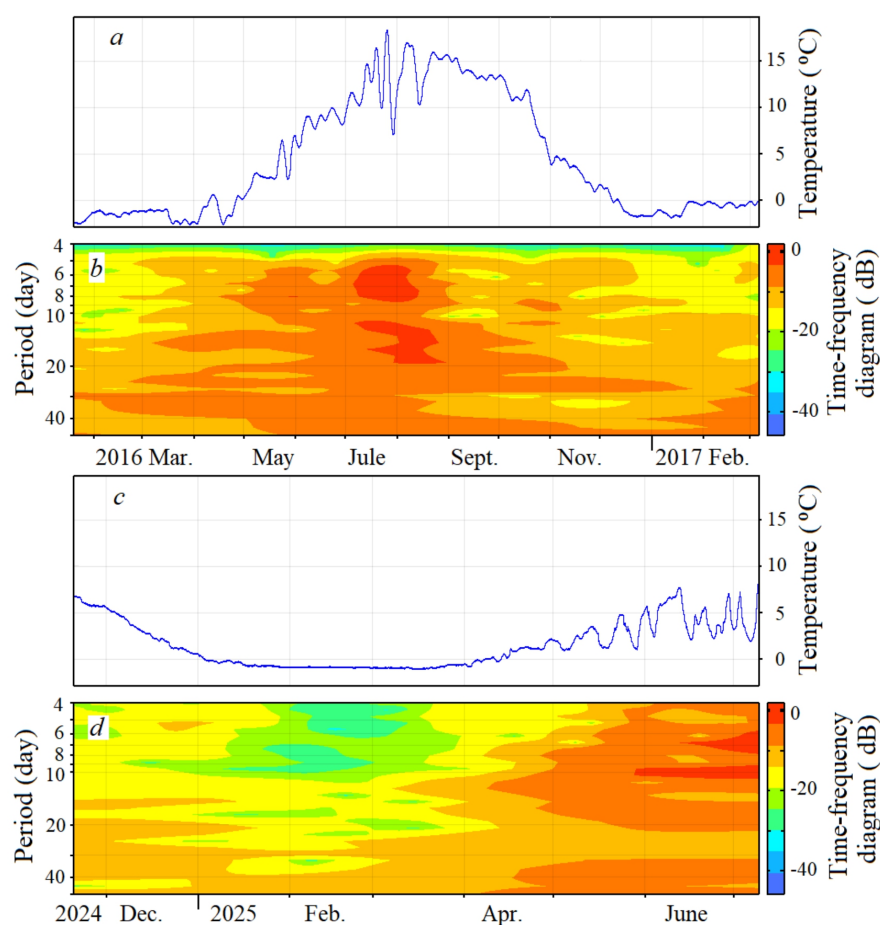


Figure 5. Time series of water temperature (*a*, *c*) and corresponding time–frequency diagrams of temperature variability (*b*, *d*). Spectral amplitudes are normalized to the maximum value.

processes. To assess their characteristic spatial scales, particular attention must be given to the internal (baroclinic) Rossby radius of deformation – a fundamental parameter that defines the scale at which rotational effects become comparable to buoyancy forces [Gill, 1982]. The baroclinic Rossby radius is a key quantity in the analysis of mesoscale and synoptic dynamics in both the ocean and the atmosphere, including eddy structures, wave motions, frontal systems, and upwelling processes [Novoselova et al., 2020].

To estimate the first baroclinic Rossby radius of deformation (R_1), we use the expression derived from the quasi-geostrophic potential vorticity equations [Pedlosky, 1987]. At latitudes $|\theta| \geq 5^\circ$, R_1 can be determined from the relation [Chelton et al., 1998]:

$$R_1 = \frac{c_1}{f} \quad (1)$$

where $f = 2\Omega \sin \theta$ is the Coriolis parameter, Ω is the Earth's angular velocity, and c_1 is the phase speed of the first baroclinic gravity mode. In contrast to the barotropic case, baroclinic dynamics is characterized by the presence of multiple vertical modes and the associated modal interactions [Majda et al., 1999].

Using representative values of the phase speed of the first baroclinic mode for the nearshore zone of the Sea of Okhotsk ($c_1 \approx 0.2\text{--}0.5\text{ m s}^{-1}$) and the Coriolis parameter at the latitude of the study area ($f \approx 1.1 \times 10^{-4}\text{ s}^{-1}$), equation (1) yields an estimate of the first baroclinic Rossby radius R_1 on the order of 2–5 km. The adopted range of c_1 is based on previously published estimates for the Sea of Okhotsk derived from seasonal stratification data and solutions of the vertical modal problem [Kurkina et al., 2017] and reflects the expected variability in stratification and depth conditions in the nearshore zone, including

seasonal changes in the vertical density structure and effective layer thickness. It should therefore be regarded as a regionally representative approximation rather than a site-specific value. The magnitude of R_1 depends strongly on the vertical stratification and local depth. According to calculations for the Sea of Okhotsk based on hydrographic data and numerical solutions of the vertical eigenvalue problem [Kurkin *et al.*, 2020; Stepanov, 2017], the first baroclinic Rossby radius in the nearshore zone of southeastern Sakhalin, at depths of approximately 10–20 m, is about 2–6 km. The width of Mordvinova Bay between its entrance capes is approximately 25 km, which substantially exceeds R_1 . The ratio of bay width to Rossby radius is therefore on the order of 4–12, consistent with conditions favorable for the existence of coastal-trapped waves whose horizontal structure is confined to a coastal zone with a cross-shore scale comparable to the Rossby radius of deformation. These estimates define the characteristic horizontal scale of baroclinic processes in the study area and provide a physical basis for interpreting the observed temperature oscillations as manifestations of coastal-trapped waves.

Analysis of the temperature time series shows a pronounced increase in oscillation energy from May through September across a broad range of periods. The dominant timescales identified from spectral maxima are similar from year to year, indicating a stable and recurrent structure of variability. The persistence of these periods, together with their consistency with spatial scales comparable to the estimated R_1 , supports a baroclinic interpretation of the observed low-frequency oscillations and allows them to be considered within the framework of coastal-trapped waves.

4. Identification of baroclinic waves

The results obtained indicate the presence of baroclinic oscillations in Mordvinova Bay with periods ranging from several days to several tens of days. This raises the question of their physical identification. It is well established that most topographically trapped baroclinic waves represent internal counterparts of their barotropic analogues. They typically exhibit weak surface signatures, while their maximum amplitude is concentrated within layers of strong vertical density gradients, particularly in the thermocline [Efimov *et al.*, 1985]. Given the characteristic temporal scales and the coastal setting of the study area, the most plausible dynamical mechanisms include coastal-trapped baroclinic waves of either Rossby or Kelvin type.

According to published estimates, the minimum periods of barotropic Rossby waves at these latitudes are on the order of several days, whereas baroclinic modes are characterized by substantially longer periods that may approach annual timescales (<https://www.who.edu>). Previous studies further indicate that freely propagating baroclinic Rossby waves in mid-latitudes rarely exhibit periods shorter than several months. Since the oscillations observed in Mordvinova Bay fall within the range of several to several tens of days, their interpretation within the framework of classical baroclinic Rossby wave theory appears unlikely. Accordingly, the subsequent analysis focuses on the alternative hypothesis of coastal-trapped baroclinic Kelvin waves.

A Kelvin wave is a coastal or equatorial wave mode first described by W. Thomson (*Lord Kelvin*) [1880]. Coastal Kelvin waves propagate unidirectionally along a boundary under the influence of the Coriolis force; in the Northern Hemisphere, the wave travels such that the coast remains on its right-hand side. The wave amplitude attains its maximum at the boundary and decays exponentially offshore. In a stratified ocean, the baroclinic Kelvin wave corresponds to a set of vertical modes, each characterized by its own phase speed determined by the stratification and vertical density structure, with the first baroclinic mode typically providing the dominant contribution to the observed variability.

Baroclinic (internal) Kelvin waves exhibit horizontal behavior similar to their surface counterparts, but their vertical structure is governed by stratification, resulting in depth-dependent variations in amplitude and phase [Ibragimov, 2012]. These waves are most strongly expressed in the vicinity of stable density interfaces or within layers characterized by pronounced vertical density gradients [Wang, 2002]. The phase speed of a baroclinic

Kelvin wave is controlled by stratification, and depends on the effective reduced gravity and vertical density gradients in the water column, and is substantially lower than that of surface gravity waves. At mid-latitudes, it is typically on the order of 1 ms^{-1} , corresponding to a baroclinic deformation radius of roughly 10 km [Ibragimov, 2012; Wang, 2002], although in shallow nearshore regions it may be significantly lower due to a decrease in both effective stratification and water depth, consistent with the range adopted in this study.

In terms of vertical structure, baroclinic Kelvin waves are characterized by a modal distribution of velocity and density perturbations. For the first baroclinic mode, horizontal velocity typically changes sign across the thermocline, with opposite flow directions in the upper and lower layers, while the amplitude reaches a maximum in the region of strongest stratification. The phase speed of the first baroclinic mode may be estimated in the framework of a reduced-gravity approximation as $\approx \sqrt{g'h}$, where g' is the reduced gravity and h is the effective thickness of the stratified layer. This vertical structure reflects the internal nature of the wave and distinguishes it from barotropic coastal oscillations, which exhibit nearly depth-uniform velocity profiles. A detailed reconstruction of the vertical current structure would require direct velocity profile measurements and density stratification data, which are beyond the scope of the present dataset. Coastal baroclinic Kelvin waves along the eastern boundary of the Pacific Ocean have been documented using sea-level and temperature observations from the nearshore zone [Ibragimov, 2012; Wang, 2002]. These studies demonstrate that such waves may be generated by time-varying wind forcing, particularly through coastal upwelling and downwelling mechanisms. Alongshore winds induce Ekman transport, which redistributes water masses within the coastal zone and perturbs the density structure. These perturbations can then propagate along the boundary as coastal-trapped baroclinic Kelvin waves [Ibragimov, 2012].

According to Donnet *et al.* [2025], stratified embayments whose width is comparable to or exceeds the internal Rossby radius of deformation, and whose coastal bathymetric slopes are sufficiently steep, may support motions dynamically similar to baroclinic Kelvin waves and other forms of coastal-trapped waves [Gill and Clarke, 1974].

Mordvinova Bay is approximately 25 km wide between its entrance headlands and about 8 km long. In view of the previously established estimates of the first baroclinic Rossby radius of deformation in the nearshore zone off southeastern Sakhalin Island [Kurkin *et al.*, 2020; Stepanov, 2017], the basin geometry satisfies the conditions for the existence of coastal-trapped baroclinic waves. Under such conditions, the horizontal structure of the motions is confined to a nearshore zone with a cross-shore scale comparable to the Rossby radius of deformation. This geometric configuration is therefore consistent with the potential formation of baroclinic Kelvin waves within the bay.

The dispersion relation for long baroclinic Kelvin waves is given, for example, [in Firing, 2011] and can be written as:

$$\frac{\omega}{k} = \sqrt{gh_j} = c_j \quad (2)$$

where ω is the wave frequency, k is the wavenumber, h_j is the equivalent depth of the j -th vertical mode, and c_j is the corresponding phase speed. The cited study provides estimates of the equivalent depths for the first three baroclinic modes: $h_1 \approx 1 \text{ m}$, $h_2 \approx 0.3 \text{ m}$, and $h_3 \approx 0.1 \text{ m}$. These values make it possible to evaluate the horizontal propagation characteristics of each mode by treating it as a long gravity wave in a fluid layer of equivalent depth.

Based on relation (2), dispersion curves were calculated for the first three baroclinic modes and the corresponding dispersion relationships were constructed (Figure 6). For comparison with the spectral analysis of temperature oscillations, the dispersion curves are presented in period–wavelength coordinates. Comparison of the characteristic periods listed in Table 1 with the calculated dispersion curves shows that the observed time scales are consistent with the parameters of the first baroclinic modes derived from the dispersion relationship and adopted phase speed estimates, and the comparison between observed periods and theoretical dispersion curves supports their interpretation as coastal-

trapped baroclinic Kelvin waves. Taken together with the estimate of the first baroclinic Rossby radius of deformation and the inconsistency between the observed periods and the characteristic scales of baroclinic Rossby waves, this supports the interpretation of the recorded oscillations as coastal-trapped baroclinic Kelvin waves.

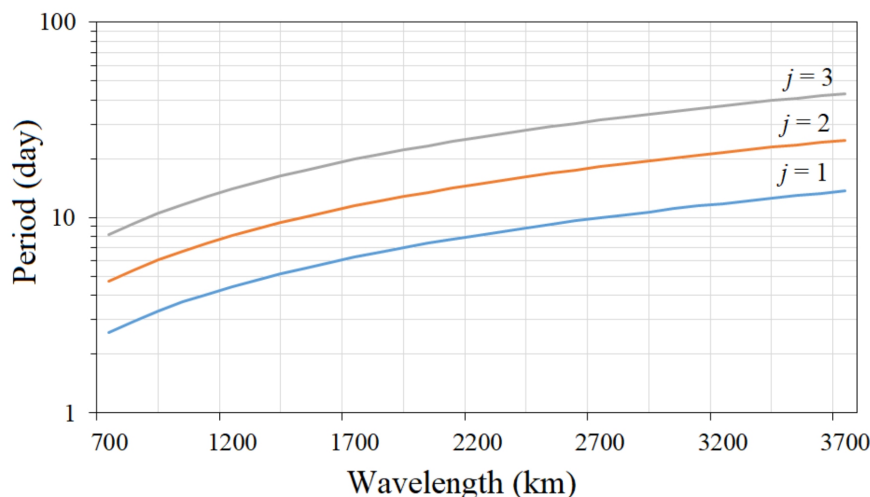


Figure 6. Dispersion curves for the first three modes of baroclinic Kelvin waves.

The proposed interpretation is based on linear coastal wave theory. According to [Smith, 1972], nonlinear effects become significant only at sufficiently large disturbance amplitudes and at specific spatial scales of evolution. In the present case, the characteristic temporal and spatial scales, together with the moderate amplitudes of the observed temperature oscillations, support the applicability of the linear approximation.

5. Role of wind forcing in the generation of baroclinic waves

In the literature, it has repeatedly been noted that coastal baroclinic trapped waves can be generated by wind forcing [Adams and Buchwald, 1969; Donnet et al., 2025; Gill and Clarke, 1974; Gill and Schumann, 1974]. According to these studies, the alongshore component of wind stress plays a key role, driving Ekman transport and creating favorable conditions for the generation of coastal waves. The characteristic periods of such waves are typically comparable to the temporal scales of atmospheric variability. For most mid-latitude regions, this corresponds to the frequency range $\omega < |f|$, where f is the Coriolis parameter. Baroclinic coastal Kelvin waves may likewise be excited by time-varying wind forcing [Ibragimov, 2012; Wang, 2002].

To assess the potential role of wind in the formation of the observed oscillations, variability in wind speed and direction was analyzed using data from 2025. Figure 7 presents the temporal evolution of wind speed magnitude and direction, together with the corresponding time–frequency diagram (spectrogram) of wind speed. Until mid-April, northerly winds prevail and are generally stronger. Beginning in the second half of April and continuing through late August, the frequency of southerly winds increases. This interval coincides with the onset of enhanced-amplitude oscillations in the temperature records. The predominance of northerly and southerly winds is likely related to the orographic features of southern Sakhalin Island, in particular the influence of the Susunai and Tonino-Aniva mountain ranges.

The time–frequency diagram of wind speed magnitude (Figure 7) reveals energetically pronounced variability over a broad range of periods. To quantify the relationship between wind forcing and the coastal response, the modulus of the transfer function was computed for the paired time series “wind speed – sea level” and “wind speed – water temperature.” The calculations were performed separately for the intervals 10 January–31 March and

10 April–15 July (limited by the availability of concurrent sea-level measurements). The results are presented in Figure 8.

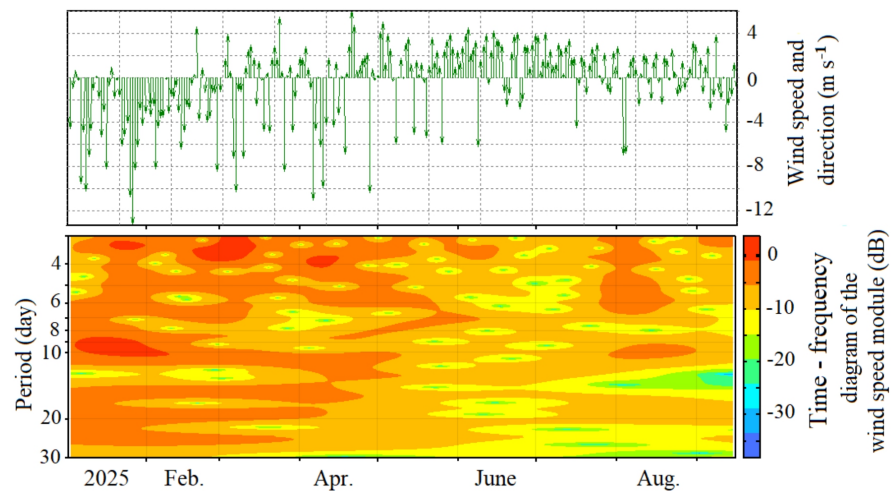


Figure 7. Temporal variations of wind speed and wind direction, and the time–frequency (spectrogram) diagram of wind speed magnitude.

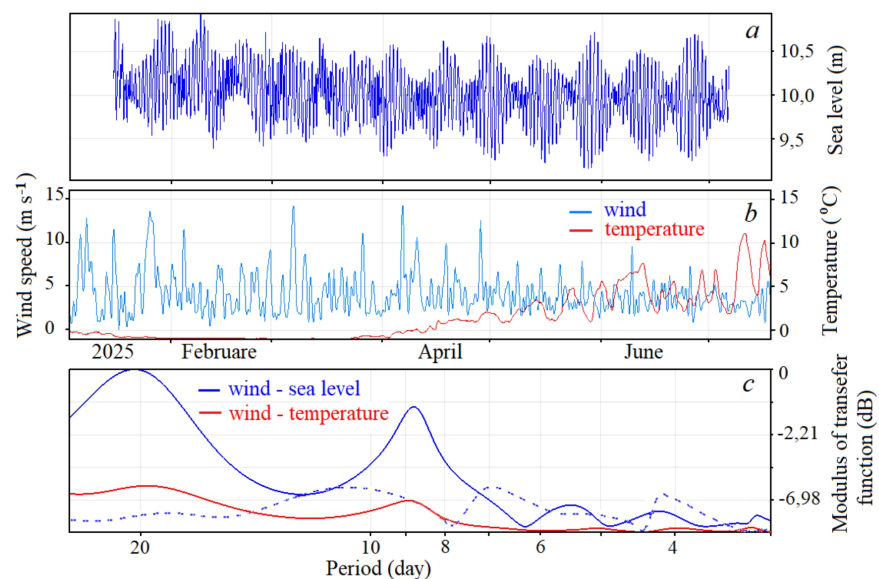


Figure 8. Time series of sea-level oscillations (a), wind speed and water temperature (b), and the magnitude of the transfer function for the time-series pairs (c): wind speed–sea level oscillations and wind speed–water temperature oscillations. Calculations are shown for the periods 10 January–31 March (dashed lines) and 10 April–15 July (solid lines).

Analysis of the transfer function magnitude (Figure 8c) indicates that during 10 April–15 July the transfer of energy from wind variability to sea-level and temperature oscillations is substantially more efficient than in the winter period (10 January–31 March). It is precisely during this spring–summer interval that an intensification of baroclinic temperature oscillations is observed. In contrast, during January–March the magnitude of the transfer function for the wind–temperature pair is markedly lower and approaches zero over the considered frequency range, indicating a weak dynamical coupling between wind variability and temperature fluctuations in winter.

One factor potentially affecting the efficiency of energy transfer from the wind to the water column is the presence of sea ice during winter. Satellite observations (Figure 3) show

that the study area becomes effectively ice-free by late March–early April in all considered years, whereas the intensification of temperature oscillations occurs later, beginning in May. This mismatch in timing indicates that the presence or decay of sea ice cannot be considered the primary driver of the observed baroclinic variability.

At the same time, comparison with Figure 5c, d shows that even in November–December, when the basin is ice-free, the amplitude of baroclinic oscillations remains relatively small. This suggests that the absence of ice alone is insufficient to produce the observed regime. Wind direction appears to play a substantial role as shown in Figure 7, the frequency of southerly winds increases during the spring–summer period, coinciding with the strengthening of baroclinic temperature variability. The relatively low correlation coefficients likely reflect the phase-dependent nature of the interaction and the fact that an instantaneous linear relationship does not fully capture the dynamics of energy transfer within the system.

An additional quantitative assessment was performed using the Pearson correlation coefficient between the wind speed and water temperature time series. For April–June, the correlation coefficient was $r = -0.21$, whereas for January–March it was $r = -0.06$. Although the spring–summer value formally corresponds to a weak linear relationship, its presence is consistent with the transfer function analysis and indicates a measurable dynamical coupling between wind variability and temperature fluctuations.

Taken together, the seasonal structure of the wind regime, the enhanced transfer function magnitude in the spring–summer period, and the reproducibility of the characteristic temporal scales support the interpretation that southerly winds represent a significant factor contributing to the generation of baroclinic waves with periods from several days to several tens of days in Mordvinova Bay.

6. Conclusion

Based on multi-year in situ observations with a sampling interval of 1 s (2015–2017, 2019–2020, 2021–2022, 2024–2025), a pronounced seasonal asymmetry in the low-frequency variability of near-bottom water temperature has been identified in Mordvinova Bay. During the autumn–winter period, temperature fluctuations remain relatively smooth and weakly modulated, whereas in the spring–summer season, beginning in May, quasi-periodic oscillations of substantial amplitude develop, reaching up to $\sim 7^\circ\text{C}$. This behavior is consistent with the presence of seasonal ice cover, which suppresses wind forcing and limits the development of dynamic variability. At the same time, satellite-derived sea ice concentration data show that the decay of ice cover occurs several weeks before the onset of high-amplitude oscillations, indicating that ice processes play a secondary rather than dominant role.

Spectral analysis reveals that the characteristic periods of temperature variability during the spring–summer season lie within the range of 3–43 days and are consistently reproduced in different years. Comparison of these periods with estimates of the first baroclinic Rossby radius of deformation ($R_1 \approx 2\text{--}6\text{ km}$), together with the dispersion properties of coastal waves, indicates that the observed oscillations are consistent with the first baroclinic modes of coastal-trapped Kelvin waves. The identified time scales are substantially shorter than those typical of baroclinic Rossby waves at mid-latitudes, making their interpretation within the classical Rossby-wave framework unlikely.

Analysis of the wind regime shows a seasonal shift toward increased recurrence of southerly winds during the spring–summer period, coinciding with the intensification of baroclinic temperature oscillations. Transfer-function analysis demonstrates more efficient energy transfer from wind variability to sea-level and temperature fluctuations during this interval, supporting the conclusion that wind forcing, particularly southerly winds, is a key factor in the generation of the observed baroclinic waves.

Overall, the results indicate that under conditions of seasonal stratification and a specific wind regime, Mordvinova Bay exhibits a recurrent and dynamically consistent pattern of coastal baroclinic oscillations that is reproducible from year to year.

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