China Geology 9 (2026) 445−455

China Geology

Journal homepage: http://chinageology.cgs.cn
https://www.sciencedirect.com/journal/china-geology

Special Review

Upper boundary variation of the gas hydrate stability zone in the Sea of Okhotsk: Error assessment and climate change scenarios based on 131286 oceanographic stations (1929–2020)

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ARTICLE INFO

Article history:
Received 31 October 2025
Received in revised form 11 February 2026
Accepted 16 March 2026
Available online 9 June 2026

Keywords:
Methane hydrates
Combustible ice
Upper boundary of stability zone
Oceanographic conditions
Climate change
Greenhouse effect
Atmospheric CO_2 rise
Methodological errors
Sea of Okhotsk

ABSTRACT

Gas hydrate (GH) dissociation and its interaction with global warming represent a critical yet poorly constrained climate feedback. This study aims to quantify the instrumental and methodological errors in estimating the upper boundary of the gas hydrate stability zone (GHSZ) in the Sea of Okhotsk and to assess how this boundary shifts under various global warming scenarios, thereby evaluating the thermal stability of known GH accumulations in the region. A total of 131286 oceanographic stations (1929–2020) from multiple data centers were compiled and quality-controlled; the upper GHSZ boundary was computed using the Dickens GR and Quinby-Hunt MS phase equilibrium equation for a pure methane–seawater system (100% CH_4, S = 33.5‰) on a 0.35°×0.55° trapezoidal grid, with comprehensive observational errors quantified as three standard deviations within each grid cell, and five warming scenarios (1°C–5°C) applied to full-depth temperature profiles at 22 representative deep-water nodes. The total observational error in upper GHSZ boundary depth is approximately ±25 m, distributed randomly with no dependence on data density or location; each 1°C of warming causes a downward shift of about 40 m, and the boundary of the zone lacking thermobaric conditions for GH formation extends to a maximum isobath of about 170 m under the most extreme scenario considered. Critically, known GH accumulations in the Sea of Okhotsk are not threatened by thermal dissociation even under a conservative 1°C/100 a warming sustained for 300 years or a rapid 3°C warming over 100 years, consistent with global simulations and regional vessel-based observations. These findings provide essential GHSZ boundary constraints for numerical modeling of hydrate–climate interactions, support quantitative assessment of GH sensitivity to environmental changes, and inform hydrate exploration and methane seep monitoring across marginal seas of the western Pacific.

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1. Introduction

Exploration of fields of natural gas hydrates (GH), which are a potential hydrocarbon resource, is important for addressing a variety of environmental and climatic issues. An increase in the near-bottom water temperature leads to a reduction in the thickness of the gas hydrate stability zone (GHSZ), which eventually can cause GH dissociation and release of methane (Dickens GR and Quinby-Hunt MS, 1994; Reagan MT et al., 2011; Giustiniani M et al., 2013; Bogoyavlensky VI et al., 2018a, 2018b). The major part of GHs, which are subject to dissociation due to ocean warming, is located in sediments of the upper parts of continental slopes (Reagan MT and Moridis GJ, 2007; Westbrook GK et al., 2009; Reagan MT et al., 2011). Consequently, variations in the temperature of intermediate ocean waters can affect the stability of these sediments and, as a result, pose a potential threat associated with global warming (Kretschmer K et al., 2015; Marín-Moreno H et al., 2015; Ruppel CD and Kessler JD, 2017). This is also evidenced by the results of vessel-based studies during the last two to three decades which have shown an increase in methane flux from seafloor sediments (Westbrook GK et al., 2009; Shakhova N et al., 2010;

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Literary editor: Xi-jie Chen
doi:10.31035/cg2025305
2096-5192/© 2026 China Geology Editorial Office.

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Obzhirov AI and Shakirov RB, 2013; Obzhirov AI, 2018; Shakirova MV et al., 2020).

GH dissociation is sometimes considered not only a consequence of warming but also a factor that potentially amplifies global warming (if methane released from GHs reaches the atmosphere). Thus, the gas liberated during the decomposition of hydrates enters the near-bottom waters and migrates into the atmosphere by bubble transport, increasing the greenhouse effect (Eliseev AV, 2018; Bondur VG et al. 2022). Such a dual role of GH dissociation—subject to the effect of global warming and a possible contribution to it—caused a number of scientists to suggest catastrophic impacts from the interaction of the climate system with GH deposits (Whiteman G et al., 2013; Ruppel CD and Kessler JD, 2017). Methane, a potent greenhouse gas with a radiative forcing effects 28–34 times that of CO_2, can have serious climatic consequences when emitted into the atmosphere (Biastoch A et al., 2011; Reagan MT et al., 2011; Smyshlyaev SP et al., 2015; Bogoyavlensky VI et al., 2018a, 2018b). It should be noted, however, that only shallow GH deposits are considered in this study.

Two scenarios of further transformation are known for methane entering the near-bottom layer of water. First, dissolved methane can be utilized by bacteria through aerobic oxidation (Valentine DL et al., 2001). As a result, methane is converted into CO_2, which ultimately influences pH of the ocean water. The variations in pH caused by GH-derived methane can spread to the 100-m near-bottom layer within the following 100 a (Biastoch A et al., 2011). It is also known that the GH decomposition and the dissolution of methane in water can lead to ocean acidification and a decrease in oxygen content of the water column (Biastoch A et al., 2011; Giustiniani M et al., 2013; Ruppel CD and Kessler JD, 2017). Second, methane rising from sediments as free gas can bypass the benthic methane filter (Knittel K and Boetius A, 2009) and, depending on depth and dynamics of waters, reach the near-surface water layer and/or the atmosphere (McGinnis DF et al., 2006; Kretschmer K et al., 2015; Ruppel CD and Kessler JD, 2017; Eliseev AV, 2018). The currently used models that consider GH degradation in the context of the climate system are usually divided into two types. The first one addresses the effect of climate change on GH deposits (Reagan MT and Moridis GJ, 2007; Reagan MT et al., 2011; Biastoch A et al., 2011; Marín-Moreno H et al., 2015). According to the second, climate changes are studied that may occur after the release of methane into the ocean and/or atmosphere from dissociating GH deposits (Isaksen ISA et al., 2011; Shakhova N et al., 2015). However, many numerical models for the climate–GH interaction face a number of challenges, such as heterogeneous gas composition of hydrates, availability of data on heat flux and thermal gradient, estimated size of GH source, insufficient consideration of methane sinks, and oversimplification of oceanographic conditions, which may result in overestimated amounts of methane released through GH decomposition and, consequently, to unrealistic catastrophic scenarios (Ruppel CD and Kessler JD, 2017). As the study by Hunter SJ et al. (2013) showed, even significant variations in sea level (up to +20 mm/a) will not cause substantial changes in world's GH reserves. Therefore, stability of GHs depends on variations in water temperature rather than in pressure. Berndt C et al. (2014), after simulating the response of sediments temperature to variations in bottom-water temperature off western Svalbard (where observations were conducted continuously for almost two years), concluded that the currently observed methane seepage may depend also on seasonal bottom-water temperature variations. The actual depth of the upper GHSZ boundary (with its probable shifts) is required for calculation in numerical models (Reagan MT et al., 2011; Biastoch A et al., 2011; Giustiniani M et al., 2013), estimation of GH's sensitivity to variations in environmental parameters (Reagan MT et al., 2007), and for planning surveys to find GHs (Obzhirov AI and Shakirov RB, 2013; Minami H et al., 2016; Obzhirov AI, 2018; Shakirova MV et al., 2020). Furthermore, many numerical models use simplifications that neglect the actual distribution of GHs, oceanographic parameters, and other factors, which leads to probable overestimation of methane emissions into the ocean–atmosphere system (Whiteman G et al., 2013; Kretschmer K et al., 2015; Ruppel CD and Kessler JD, 2017).

In the studies of Shakirov RB et al. (2024, 2025), based on all available oceanographic information (131286 stations sampled from 1929 to 2020), patterns of spatial distribution of the parameters for the upper boundary of the methane hydrate stability zone (water temperature, salinity, and depth of the upper boundary in the water column) were reported for the first time for the Sea of Okhotsk. An area was identified that lacked thermobaric conditions for methane hydrates to form and exist in the water column. However, these studies did not provide estimates of instrumental and methodological errors in calculating the depth of the upper GHSZ boundary in the Sea of Okhotsk waters, as well as changes in the position of the upper GHSZ boundary depending on various global warming scenarios. Based on the most comprehensive array of oceanographic data, this study aimed to estimate the instrumental and methodological errors in calculating the depth of the upper GHSZ boundary in the Sea of Okhotsk waters and to assess variations in this boundary depth depending on various global warming scenarios.

2. Materials and methods

For this study, the authors used data from 131286 oceanographic stations, including measurements of water temperature and salinity in Sea of Okhotsk waters for the period 1929–2020. To calculate the upper GHSZ boundary, this study used all available data from deep-sea oceanographic observations in the Sea of Okhotsk. The major part of the data was taken from historical oceanographic arrays provided by RIHMI-WDC (http://meteo.ru), TINRO (http://www.tinro.vniro.ru), and FERHRI (http://ferhri.org). Then, it was extended by the addition of available observation materials

from several data centers (National Centers for Environmental Information, https://www.ncei.noaa.gov), and POI FEB RAS (http://www.poi.dvo.ru). The generalized array of deep-sea observations included bathymetric data (bottle data, OSD), CTD-profiling, and data from drifting "ARGO" buoys. Bathythermographic observations, including Mechanical Bathythermograph (MBT) and Expendable Bathythermograph (XBT) data, were also used.

Using the Ocean Data View software (http://odv.awi.de, 2023), the authors removed unreliable values (taking into account the regional features of the thermohaline regime of the Sea of Okhotsk). Additionally, the authors developed computer programs to remove duplicates of stations, determine the upper boundary of the methane hydrate stability zone, and calculate statistical parameters at trapezoid nodes (see Tables S1, S2). These programs were written in the Microsoft Visual Studio environment using the C# programming language for the NET Framework platform. Using the Ocean Data View software, the authors carried out necessary sorting of the entire data array and also compiled the data arrays required for calculations. A detailed description of the database compilation and the method for calculating the upper GHSZ boundary was published by Shakirov RB et al. (2024, 2025). As was reported in a study of Shakirov RB et al. (2025), based on the average long-term monthly calculations of the statistical parameters of water temperature, the upper GHSZ boundary in the major part of the Sea of Okhotsk is located deeper than the lower boundary of the active layer (where the seasonal temperature variations are not statistically significant). However, an analysis of seasonal variations in water temperature and the upper GHSZ boundary depth (Shakirov RB et al., 2025) showed that their minimum values in the Sea of Okhotsk are recorded in May–June, and their maximum values are in November–December. Therefore, in this study, the authors assigned long-term average values of the upper GHSZ boundary depth and statistical parameters (the number of water temperature profiles used and standard deviations) during the periods May–June and November–December to each node of trapezoids 0.35° latitude × 0.55° longitude (Shakirov RB et al., 2025). The authors used two arrays of statistical parameters (number of observations in a trapezoid, mean value, and standard deviation) to estimate the error in calculation of the upper GHSZ boundary depth.

To assess the effect of climate change on the upper GHSZ boundary depth, the authors initially formed two long-term arrays (from the original array of oceanographic data for 1929–2020) for the periods May–June and November–December. Note that the most extensive array of oceanographic data that the authors used has some limitations. According to these data, the authors currently cannot, as is done in meteorological studies, use basic 30-year data sets to calculate initial climatic values because of the lack of regular observation series in the Sea of Okhotsk, even in small parts of the sea. This is mainly due to severe weather conditions and low air temperatures (in early spring and early winter) in most of the Sea of Okhotsk. Moreover, there has been reduction of sea-based oceanographic observations in recent decades. These are usually carried out to provide fishing, safety navigation, and oil and gas production. In these arrays, information on each water temperature profile was presented with 5-m intervals vertically. Then, in each trapezoid (0.35° latitude × 0.55° longitude), the average long-term water temperature values at each depth were calculated for the periods May–June and November–December. The authors assumed these arrays to be reference, characterizing the modern thermal structure of Sea of Okhotsk waters from the surface to the seafloor depths. Then, based on the known patterns of thermal regime and currents of the Sea of Okhotsk (Moroshkin KV, 1966; Luchin VA, 1987, 2007; Luchin VA and Zhigalov IA, 2006; Luchin VA et al., 2009; Kruts AA and Luchin VA, 2013; Belonenko TV et al., 2025) and on results of studies (Shakirov RB et al., 2024, 2025), the authors selected 22 nodes of the computational grid that relatively evenly represented the slope and deep-sea areas of the Sea of Okhotsk. The arrangement of the nodes is shown in Fig. 1 which also depicts a part of the Sea of Okhotsk that lacks thermobaric conditions in the water column for the formation/decomposition of GHs (Shakirov RB et al., 2024, 2025).

The estimate of the shift of the upper GHSZ boundary under the effect of possible climate change was based on the results of model calculations that used water temperature increments within a range of 1°C–5°C (Reagan MT and Moridis GJ, 2007; Reagan MT et al., 2011; Biastoch A et al., 2011; Giustiniani M et al., 2013), which resulted in a deeper upper boundary and brought the base of the GHSZ closer to the seafloor.

In the present paper, variations in the position of the upper GHSZ boundary are considered only in seawater. The processes of GH formation/decomposition in sediments are a separate and complex issue (Yin ZY et al., 2018; Bei KQ et al., 2022), which is also beyond the scope of this study. A wide range of parameters are required for the processes of GH formation and decomposition (geological structure of the region, thermobaric (T, P) conditions on the bottom, sediment composition and porosity, heat flux, salinity of pore waters, slope angles of strata, temperature gradient in sediments, etc.), which is noted in the studies (Makogon YF, 2003, 2010; Veselov OV et al., 2006; Reagan MT et al., 2011; Burov BA et al., 2018; Yin ZY et al., 2018; Bei KQ et al., 2022). No sea-based observations of this kind (that would determine the input parameters for modeling the GH formation and decomposition) were conducted in the Sea of Okhotsk.

In this paper, the authors carried out calculations of the upper GHSZ boundary for five scenarios. Thus, values from 1°C to 5°C with a discreteness of 1°C in the periods May–June and November–December were successively added to the basic profiles of water temperature at each depth for all 22 nodes of the computational grid (Fig. 1). Of course, this approach is substantially provisional. This option is used as a first approximation of climate change in the Sea of Okhotsk

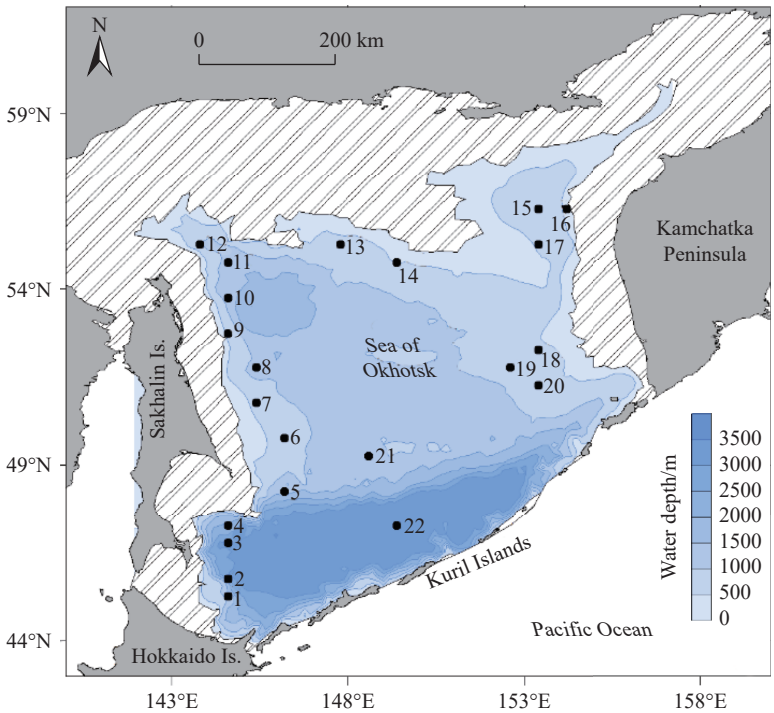

Fig. 1. Schematic map of the Sea of Okhotsk showing the water areas (diagonal shading) that lack thermobaric conditions in the water column for the formation/existence of GH (after Shakirov RB et al., 2025) and the grid nodes (black dots) for which this paper estimated shift of the upper GHSZ boundary depth under the effect of possible climate change.

basin. The application of a uniform temperature increase across the entire profile for all hypothesized scenarios has two objectives. The first is the possibility to correctly determine the upper GHSZ boundary in the water column of the sea. The second is the retention/continuation of the currently existing patterns of the vertical water temperature distribution from the sea surface to the near-bottom layer. The implemented scenarios of climate-driven GHSZ variations (e.g., Reagan MT and Moridis GJ, 2007; Reagan MT et al., 2011; Biastoch A et al., 2011; Giustiniani M et al., 2013) were based on discrete water temperature data at the upper GHSZ boundary or in the near-bottom layer. It should also be noted that there are no publications to date that would consider climate changes in the water column of the sea with good depth resolution and a time scale of 100 years and more. Use of numerical modeling data, such as a set of CMIP6 models available at https://cds.climate.copernicus.eu/datasets/projections-cmip6?tab=download, is beyond the scope of the present study. Then, as suggested in the studies (Shakirov RB et al., 2024, 2025), calculations of the upper GHSZ boundary were performed for all scenarios (including the baseline one) using the condition of methane hydrate stability for the pure methane–seawater system (100% CH_4, S = 33.5‰ for the phase equilibrium calculation was used, Eq. 1) (Dickens GR and Quinby-Hunt MS, 1994) :

$$\frac{1}{T} = 3.79\times10^{-3} - 2.83\times10^{-4}\left(\log P\right) \quad (1)$$

where T is temperature (K), and P is pressure (MPa).

The resulting difference in the upper GHSZ boundary depth between the basic calculations and the five calculations with successive water temperature increments indicates the shift of the upper GHSZ boundary depth under the effect of possible climate change.

3. Results and discussion

A step-by-step update of the boundary of the Sea of Okhotsk part where the water column lacks thermobaric (T, P) conditions for the formation and accumulation of GH can be performed if all consecutive sums of all possible errors are available: Inconsistent measurements of water temperature, methodological errors in estimation of the upper GHSZ boundary depth, or the effect of possible climate change.

3.1. Errors of instruments and observations during expeditions

The first block of errors was associated with the shortcomings of the instruments for measuring water temperature and depth. As known, modern sensors used in CTD observations over the past 20 years have errors in depth measurements of no more than 1–2 m and in water temperature measurements of up to 0.01°C–0.02°C. However, earlier depth and water temperature measurements, e.g., in arrays of bottle data (OSD) and Mechanical Bathythermograph Data (MBT), provided an accuracy of up to 5 m and up to 0.05°C–0.10°C, respectively.

The more significant errors in water temperature measurements (reaching 0.5°C–1.0°C) are associated with the dynamic processes in the Sea of Okhotsk: Effects of internal waves, thermal fronts (primarily at boundaries of currents), and vortex formations with different signs (Moroshkin KV,

1966; Luchin VA, 1987; Belonenko TV et al., 2025). The spatial and temporal heterogeneity of the original oceanological observations is also a substantial factor (Luchin VA et al., 1998), as well as insufficient consideration of year-to-year (including long-term climate trends) variations in oceanographic parameters (Luchin VA and Zhigalov IA, 2006; Luchin VA et al., 2009).

The summarized estimate of all errors related to the above-described first block can be found by calculating statistical parameters within 0.35° latitude × 0.55° longitude trapezoids and taking into account the increasing capture ratio of original data equal to 2.4, as assumed in this study. In each of the elementary trapezoids (667 for the May–June period and 401 for the November–December period), the authors used a value equal to three standard deviations (SD) as an error in our estimation of the upper GHSZ boundary depth (Tables S1, S2). This value, as a rule, reflects the full range of errors associated with the above-listed drawbacks in the original array of oceanographic observations.

The calculations showed the lack of relationship between the amount of original data in each trapezoid and the SD value. There was no any relationship between the SD values and their spatial localization in the Sea of Okhotsk as well. All these facts indicated the random origin of errors in estimation of the upper GHSZ boundary depth. Therefore, the average values (equal to 3 SDs) obtained through calculations at all nodes of the Sea of Okhotsk area were assumed to be the total error in estimation of the upper GHSZ boundary depth. These values (24.7 m for May–June and 21.5 m for November–December) reflected all the drawbacks in the original array of oceanographic observations.

3.2. Methodological errors in determining the upper GHSZ boundary

The second block of errors in estimation of the upper GHSZ boundary was associated with the multicomponent composition of GHs. In the present study, the authors assumed the following condition: 100% CH_4 and S = 33.5‰. However, the GHSZ depth is known to be influenced by the gas composition of hydrates. The presence of higher hydrocarbons (ethane, propane, etc.) even in small amounts shifts the phase boundary to the region of higher temperatures (at a constant pressure), and, consequently, the base of the GHSZ shifts deeper at such temperatures (Holder GD et al., 1987; Chen ZA et al., 2005; Sloan ED and Koh CA, 2008; Giustiniani M et al., 2013).

Moreover, as the results of model calculations showed (Chen ZA et al., 2005), methane in its pure form and a mixed gas differ in the GHSZ thickness. According to these authors, at a pressure of 5 MPa (which corresponds to a depth of about 510 m), a mixture of methane with 0.2% propane causes the stability temperature to increase by 1.49°C and the GHSZ to shift downward to a depth of 28 m. Accordingly, with 0.2% carbon dioxide in the mixture, the temperature will change by 0.03°C and the depth by 1 m; with 0.2% hydrogen sulfide, by 0.4°C and 14 m, respectively; with 0.2% ethane, by 0.13°C and 3 m, respectively.

All these results of model calculations (Holder GD et al., 1987; Chen ZA et al., 2005; Sloan ED and Koh CA, 2008; Giustiniani M et al., 2013) refer to GHSZ in the sediment layer. Since there are no instrumental and model data concerning shifts of the upper GHSZ boundary in the water column to assess the multicomponent composition of GHs, this study assumed relationships that reflect the change of the GHSZ in the sediment layer. According to the results of the studies (Holder GD et al., 1987; Chen ZA et al., 2005; Sloan ED and Koh CA, 2008; Giustiniani M et al., 2013), the presence of higher hydrocarbons (ethane, propane, etc.) even in small amounts causes an increase in the vertical extent of the GHSZ. Its upper boundary shifts to the sea surface, and the lower boundary deepens. All these factors lead to the stabilization of GHs in the sediment layer. It should also note that there is almost no published information available concerning the gas composition of hydrates in the Sea of Okhotsk. Only one study (Veselov OV et al., 2006) has shown that hydrates extracted from the Sea of Okhotsk contain 97.80% methane, 0.04% ethane, and 0.09% carbon dioxide. Based on the patterns of relationships presented in the studies (Holder GD et al., 1987; Chen ZA et al., 2005; Sloan ED and Koh CA, 2008; Giustiniani M et al., 2013), it is concluded that the errors associated with the multicomponent composition of GHs can be neglected in the present study.

3.3. Assessment of possible climate changes

In recent decades, the study of natural GHs and areas of their deposition has been considered from the aspect of environmental and climatic effects, because an increase in near-bottom water temperature can cause a reduction in the GHSZ thickness and GH dissociation (Dickens GR and Quinby-Hunt MS, 1994; Reagan MT et al., 2011; Giustiniani M et al., 2013). The environmental and climatic consequences of a shift in the upper GHSZ boundary in the Sea of Okhotsk can be evaluated using available information about trends in year-to-year water temperature variations based on oceanographic observations, results of previous model calculations, and possible climate change and its effect on the GH dissociation.

As evidenced by model calculations carried out by different authors (Reagan MT and Moridis GJ, 2007; Reagan MT et al., 2011; Biastoch A et al., 2011; Giustiniani M et al., 2013), an increase in the near-bottom temperature by 1°C–5°C causes the upper GHSZ boundary to shift downward and brings its base closer to the seafloor. Thus, the temperature increase was simulated either near the bottom (Biastoch A et al., 2011; Giustiniani M et al., 2013) or at the upper GHSZ boundary located in the water column (Reagan MT and Moridis GJ, 2007; Reagan MT et al., 2011) to represent variations in the near-bottom water temperature.

According to the study of Luchin VA et al. (2009), a significant linear trend of increasing water temperature in the

Sea of Okhotsk for the period from 1950 to 2003 was observed at a depth of 300 m. For the eastern part of the sea (warm sector), it was approximately 0.15°C/54 a. A more significant increase in water temperature at the 300-m depth (0.3°C/54 a) was recorded from the cold sector of the sea (east of Sakhalin Island). These values agree quite well (especially in sign) with the previously obtained model estimates (Reagan MT et al., 2011) under a conservative scenario of potential warming (1°C/100 a) for the Arctic region.

The authors assessed variations in the depth of the upper GHSZ boundary due to possible climate warming using data of vertical water temperature profiles at the grid nodes (Fig. 1). For this, water temperature increments at each depth were made sequentially from 1°C to 5°C according to the above-described method.

The resulting difference in the depth of the upper GHSZ boundary between the basic calculations (for the period from 1929 to 2020) and the five calculations with sequential water temperature increments is shown in Table 1. It indicates shifts in the upper GHSZ boundary depth under the effect of possible climate change for the periods May–June and November–December. Furthermore, Table 1 shows the average (Avg.) and median (Med.) values calculated at 22 nodes of the computational grid (Fig. 1). This study assumed these values to be possible errors related to various water warming scenarios all over the Sea of Okhotsk.

Note that the '-' symbol in the cells of Table 1 is not the result of missing observation data or incorrect calculations. The '-' symbol in the cells of Table 1 is explained by several factors. First, it is a consequence of the limited sea-based observations during expeditions (that were conducted in this local region but did not reach the near-bottom layer). Second, the vertical distributions of water temperature (from the surface to the near-bottom layer), as well as the values of near-bottom pressure in these local regions, indicate the lack of conditions in the water column of this part of the sea for the formation and stable state of gas hydrates.

The calculation results (Table 1) show that the values obtained (under certain scenarios) across the entire water area under consideration agree well with each other (with no any extremely large or extremely small values). It should also be noted that the values presented in Table 1 (under certain scenarios) do not have any geographical localization. In the water area under consideration, large/small values occur both in peripheral shallow waters and within the deep-sea basin of the Sea of Okhotsk.

It should be noted here that the estimates of variations in the upper GHSZ boundary depth presented in Table 1 are well consistent with the simulation results reported by Reagan MT et al. (2011). According to their data, after simple additional calculations, GHs decompose in the upper (near seafloor) sediment layer with a thickness of 65 m for 100 a, 122 m for 200 a, and 174 m for 300 a with a gradual temperature variation of 1°C/100 a. Under a rapid warming scenario (3°C/100 a), GHs in the upper sediment layer degrade to a depth of 131 m for 200 a.

Table 1. Downward shift of the upper GHSZ boundary (ΔH, m) for various scenarios of global warming in Sea of Okhotsk waters (compared to long-term average data for 1929–2020).

Node no.	ΔH (at T_w+1°C)	ΔH (at T_w+2°C)	ΔH (at T_w+3°C)	ΔH (at T_w+4°C)	ΔH (at T_w+5°C)
1	30/35	75/85	130/140	195/195	255/260
2	30/30	75/80	130/130	195/195	255/255
3	30/30	95/75	150/125	210/195	265/255
4	30/30	70/75	145/125	200/195	-/255
5	35/35	80/80	135/135	195/200	260/265
6	40/35	95/80	155/140	-**/195	-/-
7	40/30	90/75	160/120	-/-	-/-
8	45/40	95/85	155/150	-/210	-/275
9	35/35	85/80	140/150	200/215	-/280
10	35/30	80/75	145/150	200/210	265/280
11	40/40	85/85	150/150	205/210	265/270
12	40/35	90/85	150/150	210/210	270/275
13	40/40	85/85	150/150	210/205	275/270
14	40/40	85/85	145/150	205/205	270/-
15	40/40	80/85	135/135	185/190	240/235
16	40/40	80/85	135/135	185/190	240/240
17	40/35	80/75	135/125	-/170	-/-
18	40/40	-/85	-/140	-/-	-/-
19	35/40	85/85	145/145	205/-	270/-
20	40/40	85/85	145/150	205/205	270/270
21	40/40	85/90	-/155	-/-	-/270
22	35/35	80/85	135/140	200/205	255/260
Avg.	37/36	84/82	144/141	200/200	261/263
Med.	40/35	85/85	145/140	200/203	265/268

Notes: Values in numerator are estimates based on data for May–June; in denominator, for November–December. Minus sign (-) hereinafter means no data.

Using the obtained results of errors in calculating the upper GHSZ boundary depth and taking into account its downward shift under the effect of climatic change, the authors consistently updated the boundary of the Sea of Okhotsk region (Shakirov RB et al., 2024, 2025) that lacked the *T*, *P* conditions for the formation/accumulation of GHs in the water column. This study carried out these estimations of the shift of the upper GHSZ boundary based on the difference between the depth of the location at each calculation node and the updated values of the upper GHSZ boundary depth. Moreover, this study estimated possible changes in the upper GHSZ boundary depth only in the cases where the boundary shifted downward (which could lead to dissociation of GHs).

Afterwards, this paper evaluated the first correction of the boundaries of the Sea of Okhotsk region where the *T*, *P* conditions are not suitable for the formation/accumulation of GHs. For this, when calculating the upper GHSZ boundary depth, this study took into account only statistical errors which, as shown above, were 24.7 m for the May–June period and 21.5 m for November–December. Finally, this paper assumed the error related to instrument limitations, dynamic processes in the Sea of Okhotsk, spatial and temporal heterogeneity of original oceanological observations, and insufficient consideration of year-to-year variations in oceanographic parameters to be maximum (24.7 m). Taking into account this correction, this study updated the boundaries of the Sea of Okhotsk area that lacks *T, P* conditions for GH formation/accumulation in the water column (Figs. 2, 3). Compared to the authors' previous calculations, the boundary shifted to an isobath of approximately 25 m. These local areas of the sea are highlighted in yellow (Fig. 2).

Then the authors evaluated the following correction of the boundaries of the Sea of Okhotsk region where the thermobaric conditions are not suitable for GH formation/accumulation. For this, the authors took into account the following errors: The first error (equal to 25 m) and the errors leading to a downward shift of the upper GHSZ boundary under various scenarios of global warming of the sea water column (Table 1).

The first correction of the boundaries of the Sea of Okhotsk region (where the *T, P* conditions are not suitable for GH formation/accumulation) was associated with potential warming under a conservative scenario (with an increase in sea water temperature of 1°C/100 a). In this case, the updated area that lacks *T*, *P* conditions for the formation/accumulation of GH included two adjustments: The first is related to instrument limitations and dynamic processes in the sea (equal to 25 m), and the second is 40 m, the maximum value from Table 1 (at T_w+1°C). In Fig. 2 and Fig. 3, these local areas are highlighted in yellow and blue.

In the case of a conservative scenario where global warming lasts 300 a or the water temperature increases at a rate of 3°C/100 a, which corresponds to the rapid warming scenario (Westbrook GK et al., 2009; Reagan MT et al., 2011), the updated boundary of the Sea of Okhotsk region that lacks *T, P* conditions for GH formation/accumulation will additionally cover local areas highlighted in red (Figs. 2, 3), and its maximum distribution will match the position of the 170 m isobath. In the remaining (deeper) part of the Sea of Okhotsk, the upper sediment layer is not influenced by

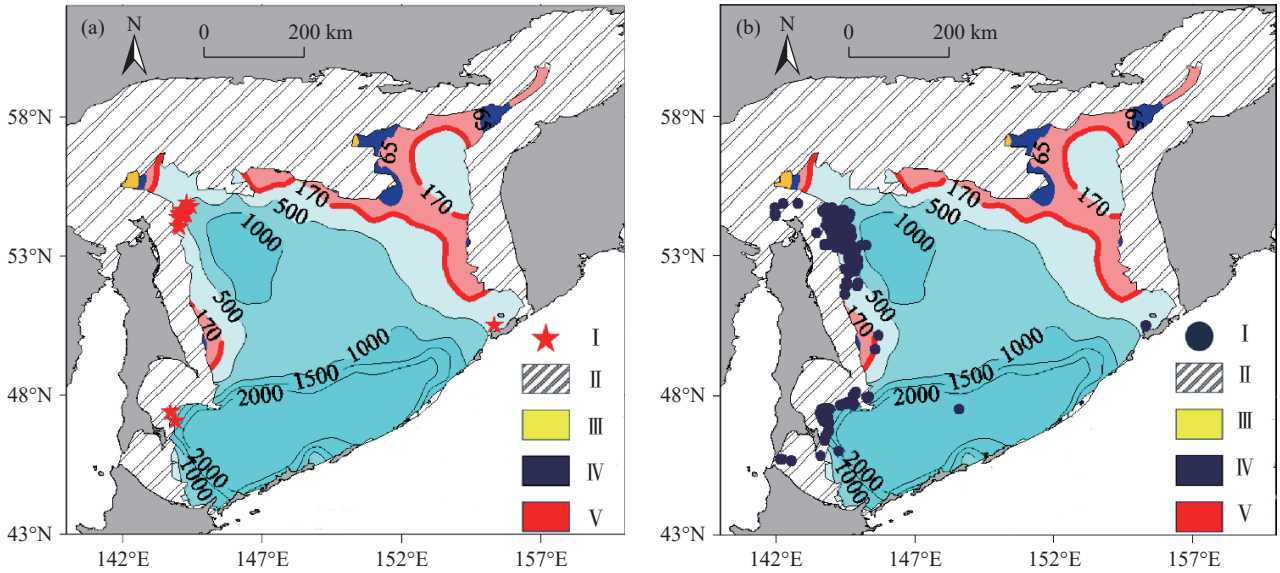

Fig. 2. Spatial distribution of differences in depth (m) between the upper GHSZ boundary and the seafloor in the Sea of Okhotsk in May–June. a–Known GH accumulations confirmed by direct methods: Ⅰ–GH confirmed by direct methods; Ⅱ–the area that lacks the *T*, *P* conditions for GH to formation in seawater; Ⅲ–correction of the area that lacks the *T*, *P* conditions for GH to formation in seawater (with statistical errors); Ⅳ–correction of the area that lacks the *T*, *P* conditions for GH to formation in seawater (with an increase in seawater temperature of 1°C/100 a). Ⅴ–correction of the area that lacks the *T*, *P* conditions for GH to formation in seawater (with an increase in seawater temperature of 3°C/100 a. b–Known methane flares: Ⅰ–Methane flares; Ⅱ–the area that lacks the *T*, *P* conditions for GH to formation in seawater; Ⅲ–correction of the area that lacks the *T*, *P* conditions for GH to formation in seawater (with statistical errors); Ⅳ–correction of the area that lacks the *T*, *P* conditions for GH to formation in seawater (with an increase in seawater temperature of 1°C/100 a); Ⅴ–correction of the area that lacks the *T*, *P* conditions for GH to formation in seawater (with an increase in seawater temperature of 3°C/100 a).

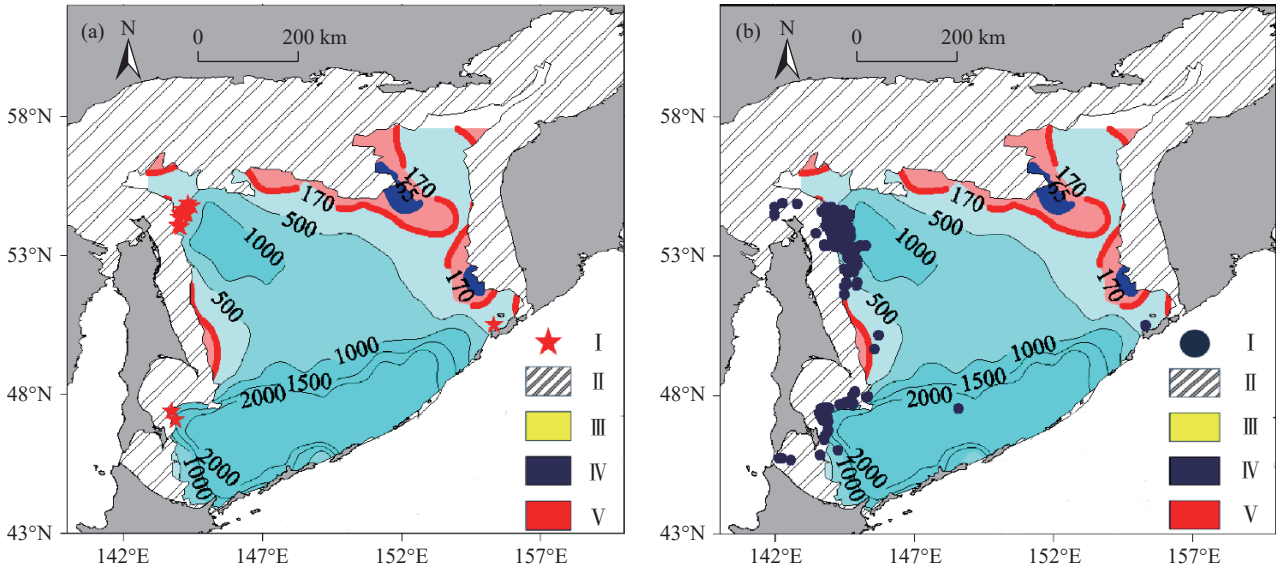

Fig. 3. Spatial distribution of differences in depth (m) between the upper GHSZ boundary and the seafloor in the Sea of Okhotsk in November–December. a–Known GH accumulations confirmed by direct methods: Ⅰ–GH confirmed by direct methods; Ⅱ–the area that lacks the *T*, *P* conditions for GH to formation in seawater; Ⅲ–correction of the area that lacks the *T*, *P* conditions for GH to formation in seawater (with statistical errors); Ⅳ–correction of the area that lacks the *T*, *P* conditions for GH to formation in seawater (with an increase in seawater temperature of 1°C/100 a). Ⅴ–correction of the area that lacks the *T*, *P* conditions for GH to formation in seawater (with an increase in seawater temperature of 3°C/100 a. b–Known methane flares: Ⅰ–Methane flares; Ⅱ–the area that lacks the *T*, *P* conditions for GH to formation in seawater; Ⅲ–correction of the area that lacks the *T*, *P* conditions for GH to formation in seawater (with statistical errors); Ⅳ–correction of the area that lacks the *T*, *P* conditions for GH to formation in seawater (with an increase in seawater temperature of 1°C/100 a); Ⅴ–correction of the area that lacks the *T*, *P* conditions for GH to formation in seawater (with an increase in seawater temperature of 3°C/100 a).

changes in the water column associated with errors in oceanographic observations and with possible climate change over the next 100–300 a according to a conservative forecast for global warming. The GH clusters shown in Fig. 2a and Fig. 3a are not under the threat of thermal dissociation even if the trend of global warming (1°C/100 a) persists for the next 300 a or the trend of climate warming remains 3°C for the next 100 a.

The estimates of the change in the upper GHSZ boundary in this study are confirmed by data from vessel-based observations in the Sea of Okhotsk conducted by researchers from the POI FEB RAS (Obzhirov AI and Shakirov RB, 2012, 2013; Obzhirov AI, 2018; Shakirov RB et al., 2024). As follows from Fig. 2a and 3a, known GH accumulations were found in areas of the sea where the upper GHSZ boundary ran in the water column. Therefore, the conclusion can be drawn that these waters have optimal thermobaric conditions in the upper sediment layer for the maintenance and accumulation of GH.

The methane flares shown in Fig. 2b and Fig. 3b are located not only in the zone with no *T*, *P* conditions for GH formation/accumulation in the water column but also in the deep-sea part. The existence of methane plumes in the shallow parts of the study area is associated, first, with the oil and gas deposits and active faults in the sediment layer. Here, in the water column (and probably in the upper sediment layer), there are no thermobaric conditions for the formation and existence of GHs that can act, by "cementing" bottom sediments, as a fluid-impermeable seal. Second, in these areas of the sea, the upper GHSZ boundary can run both near the seafloor and in the upper part of the sediment layer. Therefore, thermal conditions favorable for GH dissociation can form here. This can be evidenced by the well-known facts of both seasonal and year-to-year fluctuations in water temperature in the Sea of Okhotsk (Gladyshev S et al., 2003; Itoh M et al., 2003; Shcherbina AY et al., 2003; Luchin VA and Zhigalov IA, 2006; Luchin VA, 2007; Nakanowatari T et al., 2007; Ohshima KI et al., 2010; Figurkin AL, 2011).

The presence of methane seeps in the deep-sea part (Figs. 2, 3), where thermobaric conditions in the water column are favorable for GH formation and existence, can be explained by effects of the following factors. Here, disturbances in the structure of host sediments may occur due to seismic and tectonic processes (especially in fault zones), which may also cause gas emissions. As is known, episodes of seismic and volcanic/magmatic activity are currently observed in the Sea of Okhotsk region (Obzhirov AI and Shakirov RB, 2013; Obzhirov AI, 2018).

Another factor is apparently some additional sources in the form of accumulations of hydrocarbons, foci of post-magmatic processes, etc., which will be considered in subsequent publications.

4. Conclusions

(i) The use of all available oceanographic observation data for 1929–2020 allowed us to update the boundaries of the Sea of Okhotsk region that lacks *T, P* conditions for GH formation/accumulation in the water column. For this, this paper carried out calculations to clarify the upper GHSZ boundary depth taking into account the limitations of

instruments used, spatial and temporal heterogeneity of the original observation data, and insufficient consideration of year-to-year variations in water temperature.

(ii) With the identified errors and various scenarios of global warming, the estimates obtained in this study showed that GH accumulations in the Sea of Okhotsk are not under the threat of thermal dissociation even if the trend of global warming (1°C/100 a) persists for the following 300 a or the trend of climate warming remains 3°C for the following 100 a. The results are well consistent with data of vessel-based observations in the Sea of Okhotsk and previous studies (experimental observations and numerical simulation) in other regions of the world's oceans.

(iii) These findings are expected to be in demand for a numerical simulation of the response of methane hydrates to climate change, because the necessary conditions are the depth of the boundaries and the extent of GHSZ. This study will also be helpful when evaluating the sensitivity of GHs to changes in external environmental factors, with their dissociation and formation depending on the distance from the upper boundary to the seafloor. Moreover, the results of this study will allow assessment of the spatial and temporal scales of destabilization of GHs and their possible effect on the climate system, such as on ocean pH, atmospheric methane, and benthic fauna, in a numerical simulation of the interaction of climatic processes and GHs

CRediT authorship contribution statement

The authors made equal contributions at all stages of preparation of the paper (objective setting, calculations, analysis of results, and writing of text). All authors discussed the results obtained from the study and contributed to the final version of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

Acknowledgment

The authors are grateful to the reviewers for their constructive comments. The oceanography investigation was carried out within the framework of the state theme of the POI FEB RAS "Study of the Structure and Dynamics of World's Oceans Waters in Conditions of Current Climate Change" (124022100079-4). This article contributes to international multilateral projects WESTPAC "Methane Fluxes and their Impacts on Climate and Ecosystem in the Indo-Pacific Region (2025–2029)" and, GEOMIR (id 164) under the UN Decade of Ocean Sciences for Sustainable Development (2021–2030). The examination of gas hydrates and methane flares distribution in the Sea of Okhotsk was supported in part by the project of the Ministry of Science and Higher Education of the Russian Federation "Methane Fluxes and Vertical mixing and Their Effect on the Environment in Vietnam Waters and the Marginal Seas of the Western Pacific Ocean (2026–2028)" (075-15-2025-644).

Supplementary dataset

Supplementary data (Table S1 for Fig. 2 and Table S2 for Fig. 3) to this article can be found online at doi:10.31035/cg2025305.

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