Original paper

Frontal Zones as Boundaries of Areas with Different Range of Sea Surface Temperature Seasonal Variability in the North Atlantic

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Abstract
The paper analyses the position of the oceanic temperature frontal zones in comparison with the spatial distribution of the amplitude of the seasonal variability of water temperature and gradients of amplitude in the North Atlantic. The paper also considers the change in the amplitude of the water temperature seasonal variability along meridional surface transects through the Gulf Stream front, Subtropical and Arctic Fronts. The authors use data on the potential water temperature at 0.5 m depth of the ORAS5 ocean reanalysis (1958–2021). The position of frontal zones is determined based on the calculation of horizontal water temperature gradients. The amplitude of the water temperature seasonal variability is calculated as half of the difference between the maximum and minimum temperature in the mean annual cycle. It is noted that high values of the amplitude of water temperature seasonal variations are observed in the mid-latitudes, decreasing in the northern and southern directions. In the equatorial zone, Tropical Atlantic and Arctic, the range of water temperature seasonal variability is minimal. The extended areas with a sharp change in the amplitude of the water temperature seasonal variations were found to coincide with the position of temperature frontal zones. The correlation coefficient between the spatial distribution of temperature gradients and gradients of its seasonal variation amplitude was 0.93. The Gulf Stream front bordering the waters of the Labrador Current separates the regions with the largest difference in the water temperature seasonal variability. The difference in the amplitude of the water temperature seasonal variations in the areas located on both sides of the Gulf Stream, Subtropical and Arctic fronts was mainly due to the winter temperature difference. The obtained results show that the frontal zones in the ocean separate regions not only with different thermohaline characteristics, but also with different amplitudes of the seasonal variability of surface water temperature.

Keywords: water temperature, frontal zones, amplitude of water temperature annual variations, temperature gradient, seasonal variability, North Atlantic

Acknowledgements: The work was carried out under state assignment of MHI RAS no. FNNN-2024-0014 “Fundamental studies of interaction processes in the sea–air system that form the physical state variability of the marine environment at various spatial and temporal scales”.

For citation: Shokurova, I.G., Nikolsky, N.V. and Chernyshova, E.D., 2025. Frontal Zones as Boundaries of Areas with Different Range of Sea Surface Temperature Seasonal Variability in the North Atlantic. *Ecological Safety of Coastal and Shelf Zones of Sea*, (2), pp. 6–18.

Фронтальные зоны как границы областей с разным диапазоном сезонной изменчивости поверхностной температуры воды в Северной Атлантике

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Аннотация
Анализируется положение среднемноголетних океанических температурных фронтальных зон в сравнении с пространственным распределением амплитуды сезонной изменчивости температуры воды и градиентов амплитуды в Северной Атлантике. Рассматривается изменение амплитуды сезонного хода температуры воды вдоль меридиональных поверхностных разрезов через фронт Гольфстрима, Субтропический и Арктический фронты. Используются данные о потенциальной температуре воды на глубине 0.5 м океанического реанализа *ORAS*5 (1958–2021 гг.). Положение фронтальных зон определяется на основе расчета горизонтальных градиентов температуры воды. Амплитуда сезонной изменчивости температуры воды вычисляется как половина разницы между максимальной и минимальной температурой в климатическом годовом ходе. Отмечается, что высокие значения амплитуды сезонного хода температуры воды наблюдаются в средних широтах, уменьшаясь в северном и южном направлениях. В экваториальной зоне, в Тропической Атлантике и в Арктике диапазон сезонной изменчивости температуры воды минимальный. Получено, что протяженные области, на которых происходит резкое изменение амплитуды сезонного хода температуры воды, совпадают с положением температурных фронтальных зон. Коэффициент корреляции между пространственным распределением градиентов поверхностной температуры воды и градиентов амплитуды ее сезонного хода равен 0.93. Фронт Гольфстрима, граничащий с водами Лабрадорского течения, разделяет области с наибольшей разницей в сезонной изменчивости температуры воды. Различие амплитуд сезонного хода температуры воды в областях, расположенных с двух сторон фронта Гольфстрима, Субтропического и Арктического фронтов, в основном обусловливается зимней разницей температуры. Полученные результаты показывают, что фронтальные зоны в океане разделяют области не только с разными термохалинными характеристиками, но и с разной амплитудой сезонной изменчивости поверхностной температуры воды.

Ключевые слова: температура воды, фронтальные зоны, амплитуда годового хода температуры воды, градиент температуры, сезонная изменчивость, Северная Атлантика

Благодарности: работа выполнена в рамках темы государственного задания ФГБУН ФИЦ МГИ FNNN-2024-0014 «Фундаментальные исследования процессов взаимодействия в системе океан-атмосфера, формирующих изменчивость физического состояния морской среды на различных пространственно-временных масштабах».

Для цитирования: *Шокурова И. Г., Никольский Н. В., Чернышова Е. Д.* Фронтальные зоны как границы областей с разным диапазоном сезонной изменчивости поверхностной температуры воды в Северной Атлантике // Экологическая безопасность прибрежной и шельфовой зон моря. 2025. № 2. С. 6–18. EDN AEMNOT.

Introduction

Extended areas of high temperature and salinity gradients at the ocean surface indicate the presence of ocean fronts, i. e. boundaries of water masses with different thermohaline characteristics [1]. The areas within which the front position changes on daily, seasonal and interannual time scales are defined as frontal zones. The study of processes in frontal zones is connected with many branches of oceanological science such as physical, biological, climate, etc. Fronts play an important role in the processes of vertical mixing in the ocean and eddy formation [1, 2], atmosphere and ocean interaction [3]. Marine frontal zones are areas of high bioproductivity. They are important for both fisheries and nature conservation, which determines the applied importance of their study [4–8]. Long-term changes in the characteristics of frontal zones can be used to monitor and predict climatic changes in the ocean [9].

Presently, the study of fronts is the most intensive research domain, with investigations being conducted in various scientific disciplines and on different spatial and temporal scales. This is due to the emergence of multi-year series of satellite data and reanalyses on a regular grid with high spatial resolution. In our study, we address general issues related to ocean fronts, such as the position of large-scale temperature frontal zones, gradient values, and consider the distinctive properties of areas separated by frontal zones in the North Atlantic.

Large-scale fronts of various types are present in this region. They include fronts at the boundaries of the Gulf Stream, North Atlantic, Labrador, East Greenland and Norwegian currents carrying water with characteristics different from those of the surrounding waters; fronts in the areas of equatorial and coastal upwelling near West Africa. The subtropical front is that characterised by the interaction of colder waters transported from the north by Ekman transport and influenced by westerly winds, and warmer waters transported from the south by trade winds. The Arctic Front, located in the Atlantic sector of the Arctic, serves to delineate the boundary between the Atlantic and Arctic waters. The polar front of the ice zone boundary, otherwise known as the East Greenland Polar Front, and estuarine saline fronts, such as the Amazon River outflow front, are also of significance [2].

The position of the temperature fronts in the North Atlantic, as determined by calculations of surface temperature gradients, is outlined in [2, 10–13]. In the Atlantic sector of the Arctic, temperature fronts have been the focus in [14–16] and numerous other works. The highest recorded horizontal gradients of surface temperature are observed in the frontal zone of the Gulf Stream. A significant seasonal variability of temperature gradients is also noted here [13]. It has been observed that the area under discussion also exhibits the highest amplitude of seasonal variability in surface water temperature [17, 18]. The question of interest is whether the spatial variation in the amplitude of the seasonal cycle is related to the position of frontal zones. Temperature fronts along large-scale currents are present throughout the year, and the difference in the characteristics of the annual temperature variations in the surrounding waters is not obvious.

The aim of this work is to compare the spatial distribution of the amplitude of the seasonal temperature cycle with the position of frontal zones, and to analyse the change in amplitude at the crossing of frontal zones in the North Atlantic.

Research data and methods

Monthly averaged data from the ocean reanalysis ORAS5 on potential temperature θ (°C) at 0.5 m depth with a spatial resolution of about 0.25° (decreasing to 9 km in polar regions) for 1958–2021 were used in the work [19].

To determine the position of frontal zones, the absolute values of potential temperature horizontal gradients $\nabla\theta = \left(\frac{\partial\theta}{\partial x}, \frac{\partial\theta}{\partial y}\right)$ (°C/100 km) were calculated:

$$|\nabla\theta| = \sqrt{\left(\frac{\partial\theta}{\partial x}\right)^2 + \left(\frac{\partial\theta}{\partial y}\right)^2}.$$

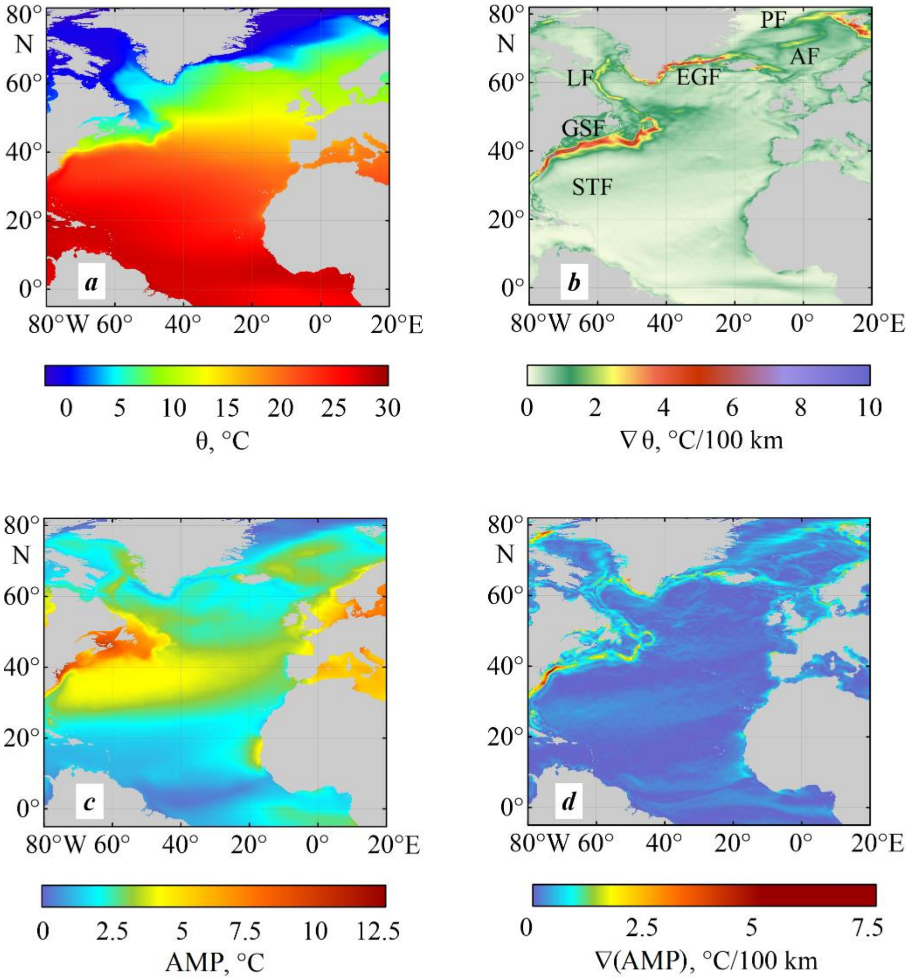
Gradient vector components were calculated using the central difference scheme. When calculating gradients, the latitude of the place was taken into account.

The amplitude of water temperature seasonal variability (AMP) was calculated as half of the difference between the maximum and minimum temperature values in the long-term mean annual variations for each grid node. In order to analyse changes in amplitude by space quantitatively, its horizontal gradients were calculated. Areas with high values of gradients were defined as boundaries between areas with different amplitudes of seasonal variability.

The spatial variability of the amplitude of the annual variations of water temperature and temperature gradients was considered on the examples of meridional surface transects crossing the frontal zones of the Subtropical Front, the Gulf Stream Front and the Arctic Front.

Results

Temperature gradients in large-scale temperature fronts in the North Atlantic. Large-scale temperature fronts are located in areas with extreme changes in water temperature (Fig. 1, *a*) which is manifested in high values of horizontal gradients (Fig. 1, *b*). According to long-term mean data, the highest temperature gradients exceeding 1°C/100 km are observed in the frontal zones of large-scale currents, e.g., the current systems of the Gulf Stream, the North Atlantic and



F i g . 1 . Long-term mean potential temperature θ at a depth of 0.5 m (*a*), its gradients (*b*), amplitude of the seasonal variations AMP (*c*) and its gradients (*d*). Notations: GSF – Gulf Stream Front, LF – Labrador Current Front, EGF – East-Greenland Current Front, AF – Arctic Front, PF – Polar Front, STF – Subtropical Front

the Norwegian currents, transporting warm water from more southern latitudes to northern ones, and northern – the East Greenland, West Greenland and Labrador – currents which carry cold water from the Arctic Ocean to the Atlantic Ocean. Fronts along these currents are present throughout the year. The maximum values of gradients are observed in the Gulf Stream front [13]. Here, the average annual gradient values range from 4 to 10°C/100 km (Fig. 1, *b*).

In the areas of coastal upwelling along the African coast and equatorial upwelling in the eastern part of the equator, the mean annual gradients in the frontal zones are about 1°C/100 km. In the subtropical front, the gradients do not exceed 1°C/100 km. In the Atlantic sector of the Arctic, in the Polar Front mainly manifested in summer during the period of ice melting, the mean annual gradient values are 1–2°C/100 km and in the Arctic Front (Jan Mayen – Mohns Ridge), they are 2–2.5°C/100 km. It should be taken into account that the real values may be higher than those obtained from the reanalysis data, which are rather smooth.

Amplitude of water temperature seasonal variability. The spatial distribution of the amplitude of seasonal variations in surface water temperature exhibits distinct zonality (Fig. 1, *c*). High values of the amplitude of the seasonal temperature variations are observed in the middle latitudes, decreasing in the northern and southern directions. The amplitude of the annual temperature variations is minimal in the equatorial zone, Tropical Atlantic and Arctic.

At the same time, the zonal direction shows pronounced features in the amplitude distribution. The region with the highest amplitude of seasonal temperature changes exceeding 3°C is located in the western part of the ocean between 25° and 55° N, narrowing to the east to 30°–50° N (Fig. 1, *c*). The largest amplitude reaching 10°C is located in the area of the Labrador Current branch spreading southward along the coast of Canada and the USA and bordering the Gulf Stream.

An extensive area with an amplitude of seasonal temperature variability exceeding 3°C is located in the Atlantic sector of the Arctic. The Polar and Arctic fronts are adjacent to this area. A high range of seasonal temperature variations is also observed off the coast of Africa in the area of the Canary upwelling and the equatorial upwelling. The results obtained correspond to the data given in [18].

Spatial gradients of the amplitude of water temperature seasonal variability. In order to determine the position of the areas of sharp changes in the amplitude of the annual variation of water temperature more precisely, the amplitude gradients were calculated (Fig. 1, *d*). The delineation of areas exhibiting divergent ranges of seasonal variability is facilitated by elevated gradient values. A comparison of the position of the gradients of the seasonal variability amplitude with the distribution of temperature gradients demonstrates that the areas with a sharp change in the amplitude of seasonal variability correspond to the position of large-scale temperature fronts. The spatial correlation was found to be 0.93.

Thus, frontal zones are located in places with a sharp transition from the area with a high range of seasonal temperature variability to the area with a low range. The obtained result can be defined as a property of frontal zones – they are the boundaries of areas with different ranges of seasonal variability.

The highest values of the gradients of the seasonal variation amplitude are observed in the areas of frontal zones of narrow western currents, including the Gulf Stream, the Labrador Current and the coastal branches of the West Greenland and East Greenland Currents (Fig. 1, *d*). In the subtropical and tropical zones, the amplitude gradients are minimal, as are the amplitude values themselves (Fig. 1, *c*, *d*).

Changes in the amplitude of the annual variations of water temperature along transects through the frontal zone of the Gulf Stream, Subtropical and Arctic fronts. As examples, let us consider changes in the amplitude of seasonal water temperature variability and temperature gradients on meridional transects through the subtropical frontal zone at 55° W, the Gulf Stream frontal zone at 61° W, and the Arctic front at 0° W (Fig. 2, *a* – *c*). Temperature values pre-averaged along the transect within ±0.5° of the selected longitude were used for the amplitude calculations.

Subtropical Front. The Subtropical Front (STF) or Subtropical Convergence Zone (STCz) crosses the subtropical gyre in a broad band, shifting northwards in the eastern part of the ocean (Fig. 1, *b*). The front occurs at the boundary between colder waters transported from the north by Ekman transport under the influence of westerly winds and warmer waters transported from the south under the influence of trade winds [11].

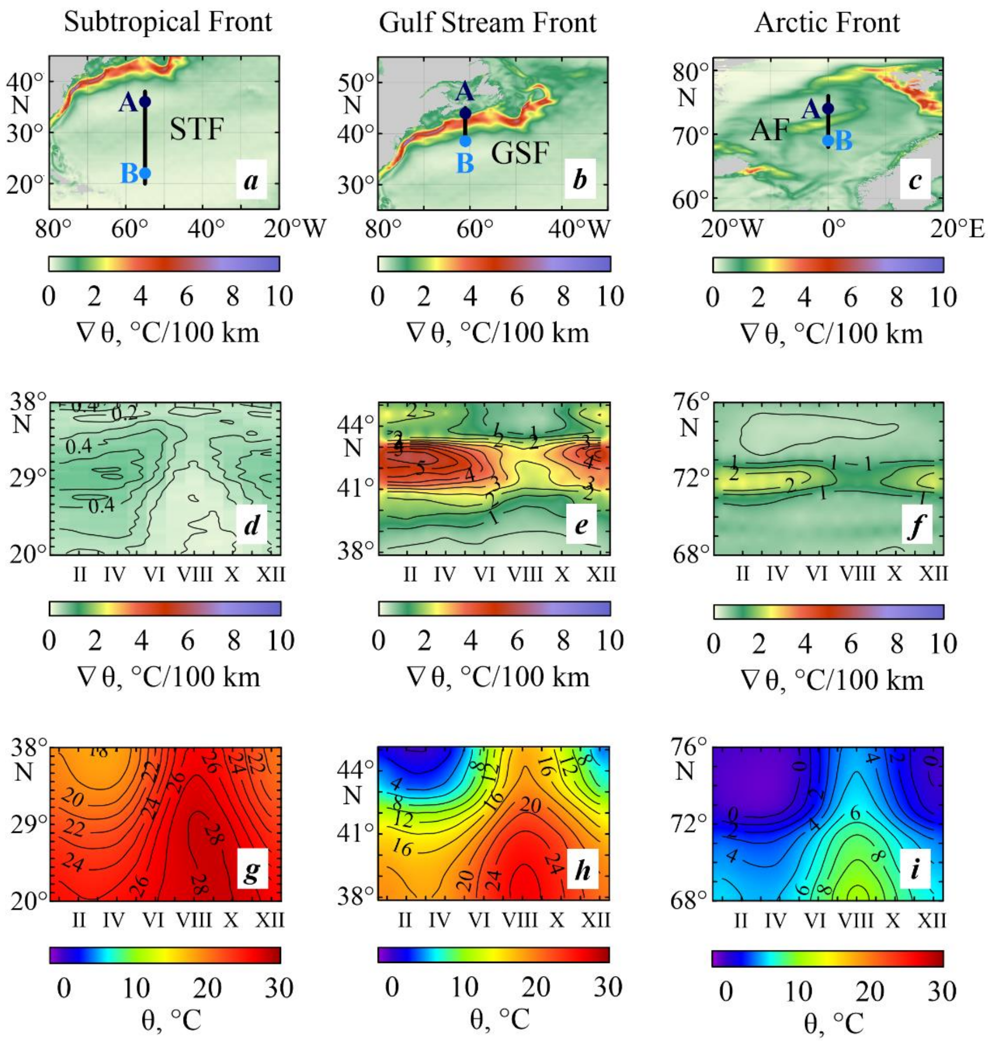
Temperature gradients in the front in the transect area are low and do not exceed 0.5°C/100 km on average (Fig. 1, *a*). From winter to spring, gradients increase reaching a maximum in spring (Fig. 2, *d*). In summer, as a result of water warming, the front weakens, narrows and the zone of increased gradients shifts northwards (Fig. 2, *d*, *g*) [11, 13].

Across the front (along the meridional transect at 55° W), the amplitude of the seasonal variations of surface water temperature changes insignificantly. North of the front, the amplitude at point A (36° N) is 4.2°C, and south of the front, at point B (22° N), it is 1.8°C (Fig. 3, *a*, *d*). Between points A and B, the change in amplitude is small, about 0.2°C per 1° latitude.

Gulf Stream Front. The Gulf Stream Front (GSF) has the highest horizontal temperature gradients in the North Atlantic due to high temperature difference between the warm waters of the Gulf Stream and the cold waters of the Labrador Current (Figs. 1, *a*, *b*; 2, *b*). In the region of the meridional transect at 61° W, the temperature gradients in the front increase in winter (January – March) up to 6°C/100 km and decrease in summer (July – August) (Fig. 2, *e*) up to 3°C/100 km due to summer warming (Fig. 2, *h*).

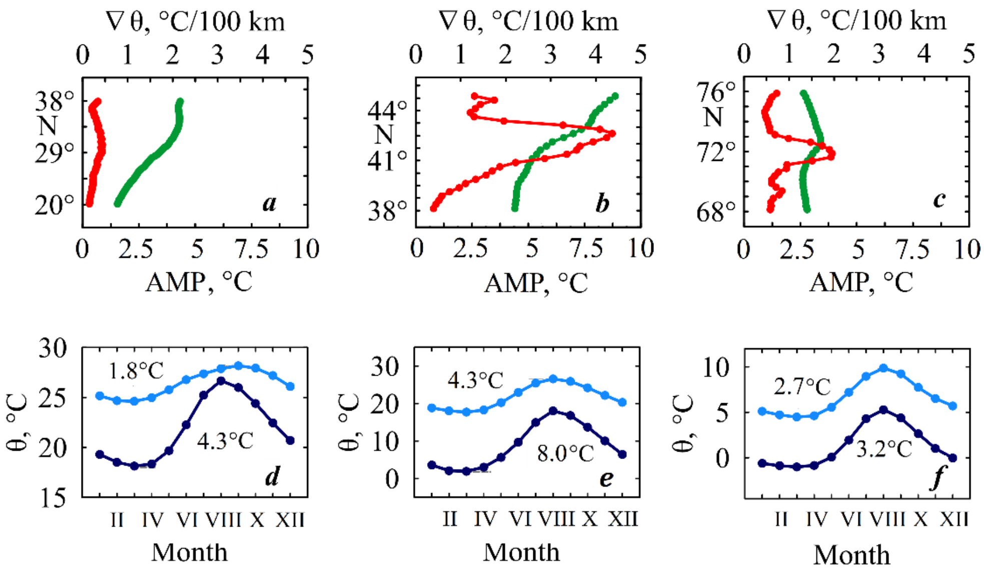
The amplitude of seasonal temperature variability along the transect decreases southwards. At point A (44° N), located in the cold waters of the Labrador Current, it is 8.0°C, and at point B (38.5° N) south of the front, the amplitude is 4.3°C (Fig. 3, *b*, *e*). The change of the amplitude relative to the distance between the points is 0.7°C per 1° latitude.

Arctic Front. The Arctic Front (AF) is located between the deep-water basins of the Norwegian and Greenland Seas (see Fig. 1, *b*), in the area of the Jan Mayen, Mohns Ridge, Knipovich Ridge submarine ridges [15, 16, 20].



F i g . 2 . Position of surface meridional transects through the frontal zones of the Subtropical Front (*a*), Gulf Stream (*b*), Arctic Front (*c*), seasonal variations of horizontal gradients of water temperature (*d* – *f*) and temperature (*g* – *i*) along the transects. Roman numerals denote months

This front is often divided into separate elements – frontal zones: the Jan Mayen zone, the zones of Mohns Ridge, Greenland and Norwegian Seas [14]. The front separates the warmer salty Atlantic waters of the Norwegian Atlantic Front Current (one of the branches of the continuation of the North Atlantic Current) and colder, fresher waters of the East Greenland Current mixed with the return Atlantic waters carried by the West Spitsbergen Current [15, 21].



F i g . 3 . Amplitude of seasonal variability (green curves) and gradient (red curves) of water temperature (*a* – *c*), annual variations of water temperature at points A and B on the cold (dark blue curves) and warm (light blue curves) sides of the front (*d* – *f*) along meridional transects through the frontal zones of the Subtropical Front (*a*, *d*), Gulf Stream (*b*, *e*), and Arctic Front (*c*, *f*). The figures indicate the amplitude at points A and B (see Fig. 2)

Water temperature gradients in the frontal zone in the area of the 0° W meridional transect increase to 3°C/100 km in winter and decrease to 1.5–2°C/100 km by summer (see Fig. 2, *f*). The minimum value is reached in August with a maximum water temperature of 6°C (see Fig. 2, *i*).

When crossing this front, the amplitude of the annual variations of water temperature decreases from 3.2°C at point A located on the cold side of the front (74° N) to 2.7°C at point B (69° N) south of the front (Fig. 3, *c*, *f*). The change in amplitude with respect to the distance between A and B is about 0.1°C per 1° latitude.

The northern boundary of the front (73° N) is characterized by a local maximum of the seasonal temperature variations and the southern side – by a local minimum (Fig. 3, *c*). In winter, water temperatures decrease on the northern side of the front, while the warm Atlantic waters continue to arrive on the southern side of the front, resulting in a strengthening of the front (see Fig. 2, *f*). In summer, the water warms up and the front weakens. The higher difference in water temperature between the cold and warm sides of the front in winter is accompanied by a difference in the magnitude of the seasonal temperature variations.

The analysed examples demonstrate that the most significant alterations in the amplitude of the seasonal variability of water temperature are observed in the frontal zone of the Gulf Stream at the boundary between warm water originating from low latitudes and cold water arriving with the Labrador Current from the Arctic. The highest water temperature gradients are also observed here (see Fig. 2). The Subtropical and Arctic fronts separate waters with a smaller difference in seasonal temperature variations compared to the Gulf Stream Front (Figs. 2, 3).

The greatest difference between water temperature on the cold and warm sides of the front is achieved in winter when the temperature on the cold side of the front decreases more than on the warm side, which, in turn, is accompanied by an increase in gradients. In summer, due to seasonal warming, the difference between the water temperature on both sides of the front decreases and contributes less to the difference in the seasonal variations. In addition, summer warming is accompanied by a decrease of gradients in the frontal zones. Thus, the cases under consideration show that the difference in the amplitude of the seasonal variations on both sides of the front is mainly related to the winter temperature difference between the cold and warm sides of the front.

Discussion

It is known that the formation of ocean fronts is the result of complex interaction of various physical and dynamic processes, such as wind forcing leading to currents, vertical rise and fall of water, spatial and temporal variability of heat fluxes on the ocean surface, ice melting, river runoff and ocean mixing processes [1, 2, 22]. Different regions have their own predominant processes leading to the emergence of temperature and salinity fronts.

Seasonal variability of these factors can lead to strengthening, weakening or complete disappearance of fronts. Summer heating weakens all temperature fronts, including those along the stationary large-scale currents. Weakening of westerly winds and trade winds in summer leads to weakening of the Subtropical Front, its narrowing and shift to the north.

These factors and their variability, heat reserve in the mixed layer [22] and proximity of coasts influence the temperature conditions on each side of the front. Thus, high seasonal range of water temperature on the cold side of the Gulf Stream Front corresponds to high seasonal range of air temperature along the coast of Nova Scotia [18]. It should be taken into account that the nearby continental regions have continental climate with low temperatures in winter and high temperatures in summer [23]. Moving away from temperate latitudes to the north and south, the amplitude of the seasonal variations decreases [17, 18]. Furthermore, the difference between the amplitude on both sides of the front decreases, as can be observed in the Arctic and Subtropical fronts.

Another aspect of the considered issue is the relative isolation of the areas separated by frontal zones. Thus, it is noted in [1] that frontal partitions are elements of the complex three-dimensional structure of ocean waters associated with local closure of individual elements of the general circulation. The difference not only in temperature values but also in its seasonal variations emphasizes the isolation of the areas on the cold and warm sides of the front.

An important manifestation of the isolation of the areas on both sides of the front are different hydrological and hydrochemical conditions of marine organisms, species composition and different indicators of water productivity [24–27]. An increase in the amplitude of the seasonal variations generally indicates lower winter temperatures on the cold side of the ocean front (Fig. 3, *d* – *f*), which can be accompanied by the predominance of cold-water marine species in this area [28].

Conclusion

Based on the ORAS5 ocean reanalysis data on the temperature at 0.5 m depth, the spatial position of temperature fronts and the distribution of the amplitude of the annual variations of surface water temperature were compared. It was obtained that the mean annual temperature fronts, which by definition are bands with high gradients of sea water temperature, were also the boundaries of areas with different ranges of seasonal variability of water temperature. The division of the ocean into areas with different amplitudes of seasonal variations can be characterised as one of the properties of frontal zones. The difference in the ranges of seasonal temperature variability emphasizes the local closure of the areas in the ocean separated by frontal zones.

The largest difference between the amplitudes of the seasonal variability of surface water temperature is noted in the areas located on both sides of the Gulf Stream frontal zone. In the subpolar, subtropical and tropical zones, the fronts separate areas with a smaller difference in the amplitudes of the annual temperature variations.

The difference in the amplitudes of the seasonal variations of water temperature on both sides of the Gulf Stream, Subtropical and Arctic fronts is mainly stipulated by the difference in temperature values on the cold and warm sides of the front in winter. At this time, the difference between the water temperature on the northern cold and southern warm sides of the front increases. In summer, due to seasonal warming, the difference between the water temperature values on both sides of the front decreases and contributes less to the magnitude of the annual variations.

The results obtained can be taken into account in climate studies, in marine biology, in the analysis of meteorological conditions in different regions of the ocean.

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Submitted 15.10.2024; accepted after review 19.01.2025;
revised 25.03.2025; published 30.06.2025

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All the authors have read and approved the final manuscript.