Original article

Seasonal Variability of Horizontal Gradients in the North Atlantic Large-Scale Thermohaline Frontal Zones

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Abstract

The paper examines seasonal variability in the spatial distribution and magnitude of horizontal gradients of temperature, salinity and density in large-scale surface frontal zones in the North Atlantic Ocean. Monthly average temperature and salinity data at the 0.5 m horizon from the ORAS5 oceanic reanalysis (1958–2021) are used. High gradients of temperature exceeding 2 °C/100 km, those of salinity exceeding 1 PSU/100 km, and those of density exceeding 1 kg·m^{-3}/100 km were observed in the subpolar and temperate regions in fronts along large-scale currents carrying warm salty waters from the southern latitudes (Gulf Stream, North Atlantic Current) and cold waters with low salinity from the Arctic regions (Labrador Current, East Greenland Current). These fronts occur throughout the year. High salinity and density gradients are also observed in the tropical summer in the front at the edge of the Amazon River plume, resulting from seasonal river flow. In these five frontal zones, areas were identified for which quantitative estimates of seasonal variability of gradients are provided. In the subpolar and temperate latitudes, maximum temperature gradients are observed in winter. Warming up of water in the summer season is accompanied by a decrease in gradients. The greatest range of seasonal variability of temperature gradients was noted in the frontal zones of the Gulf Stream and the East Greenland Current. In summer, in the fronts of subpolar regions, salinity gradients increase due to the melting of Arctic and continental ice and an increase in the influx of waters with low salinity. In the frontal zone of the East Greenland Current, as well as at the boundary of the Amazon River plume, the highest range of seasonal changes in salinity and density gradients was noted. In these areas, the contribution of salinity to seasonal changes in density at the ocean surface increases.

Keywords: frontal zone, horizontal gradients, temperature gradient, salinity gradient, density gradient, seasonal variability, Atlantic Ocean

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Сезонная изменчивость горизонтальных градиентов в крупномасштабных термохалинных фронтальных зонах в Северной Атлантике

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Аннотация
Рассматривается сезонная изменчивость пространственного распределения и величины горизонтальных градиентов температуры, солености и плотности в крупномасштабных поверхностных фронтальных зонах в северной части Атлантического океана. Используются среднемесячные данные о температуре и солености на горизонте 0.5 м океанического реанализа ORAS5 (1958–2021 гг.). Получено, что высокие градиенты температуры, превышающие 2 °C/100 км, солености – 1 ЕПС/100 км, плотности – 1 кг·м$^{-3}$/100 км, наблюдаются в субполярной и умеренной зонах во фронтах вдоль крупномасштабных течений, переносящих теплые соленые воды из южных широт (Гольфстрим, Северо-Атлантическое течение) и холодные воды с низкой соленостью из арктических районов (Лабрадорское течение, Восточно-Гренландское течение). Эти фронты выделяются в течение всего года. Высокие градиенты солености и плотности также отмечаются летом в тропической зоне во фронте на границе плюма Амазонки, возникающего в результате сезонного стока реки. В указанных пяти фронтальных зонах были выделены области, для которых приводятся количественные оценки сезонной изменчивости градиентов. В субполярной и умеренной зонах максимальные градиенты температуры отмечаются в зимнее время. Прогрев воды в летний сезон сопровождается уменьшением градиентов. Наибольший размах сезонной изменчивости градиентов температуры наблюдается во фронтальных зонах Гольфстрима и Восточно-Гренландского течения. Летом во фронтах субполярных районов происходит повышение градиентов солености вследствие таяния арктических и материковых льдов и увеличения поступления вод с пониженной соленостью. Во фронтальной зоне Восточно-Гренландского течения, а также на границе плюма реки Амазонки отмечается наиболее высокий размах сезонных изменений градиентов солености и плотности. В этих районах возрастает вклад солености в сезонные изменения плотности на поверхности океана.

Ключевые слова: фронтальные зоны, горизонтальные градиенты, градиент температуры, градиент солености, градиент плотности, сезонная изменчивость, Атлантический океан

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Introduction

Frontal zones are areas in the ocean where water masses with different physical, chemical and biological properties are encountered as a result of water transport by currents, river flow, upwellings and other dynamic processes [1, 2]. Boundaries between water masses are characterized by high horizontal gradients of temperature, salinity, density and other characteristics which makes it possible to determine the position of fronts [1]. Frontal zones are areas of high biodiversity, while oceanic frontal interface separate zones with different habitat conditions for marine organisms, that is why the analysis of changes in frontal characteristics is important for marine biology [2–4]. The greatest number of studies of surface frontal zones are currently being conducted in this field. What is more, long-term changes in the characteristics of frontal zones can serve as indicators of climate change in the ocean, which manifests itself differently in different seasons, which determines the importance of studying them [1, 5, 6].

The study of processes in frontal zones began in the mid-20th century [1, 7], but the emergence of satellite data, drifting buoy data and creation of modern ocean reanalyses at the end of the century expanded the possibilities for studying fronts in the ocean [8]. These data made it possible to study fronts on various time and spatial scales [1, 6, 9].

Currently, the characteristics of frontal zones are analyzed based on satellite data on ocean surface temperature [10–12], salinity [13, 14], sea level [15, 16]. Modern ocean reanalyses with high spatial resolution make it possible to consider spatiotemporal changes in temperature and salinity frontal zones comprehensively.

The features of the seasonal course of the North Atlantic Ocean have been studied most closely for temperature frontal zones [17–22]. Therefore, it is of interest to consider the seasonal variability of the characteristics of frontal zones in the salinity and density fields. This paper examines the seasonal variability of climatic frontal zones associated with large-scale movements in the ocean. The position of the fronts is determined based on calculations of horizontal gradients of temperature, salinity and density.

The work aims at a comprehensive study of seasonal variability of horizontal gradients in the fields of temperature, salinity and density in large-scale frontal zones in the North Atlantic Ocean.

Research data and methods

Monthly average data from the ORAS5 ocean reanalysis for 1958–2021 on potential temperature θ (°C) and salinity *S* (PSU) at a depth of 0.5 m on a grid with a spatial resolution of about 0.25° (up to 9 km in polar regions) were used in this paper [23]. The potential density anomaly was calculated based on salinity and potential temperature values according to the algorithms of the international equation of seawater (TEOS-10) [1)].

[1)] UNESCO, 2010. *The International Thermodynamic Equation of Seawater – 2010: Calculation and Use of Thermodynamic Properties*. UNESCO, 196 p.

To determine the position and characteristics of frontal zones, horizontal gradients of potential temperature $\nabla\theta$ (°C/100 km), salinity ∇S (PSU/100 km) and potential density anomaly $\nabla\sigma_\theta$ (kg·m^{-3}/100 km) were calculated for each month of all the years:

$$\nabla\varphi = \left(\frac{\partial\varphi}{\partial x}, \frac{\partial\varphi}{\partial y}\right), \qquad |\nabla\varphi| = \sqrt{\left(\frac{\partial\varphi}{\partial x}\right)^2 + \left(\frac{\partial\varphi}{\partial y}\right)^2},$$

where φ is potential temperature θ, salinity S or potential density anomaly σ_θ. The gradient vector components were calculated using the method of central finite differences. When calculating, the local latitude was taken into account.

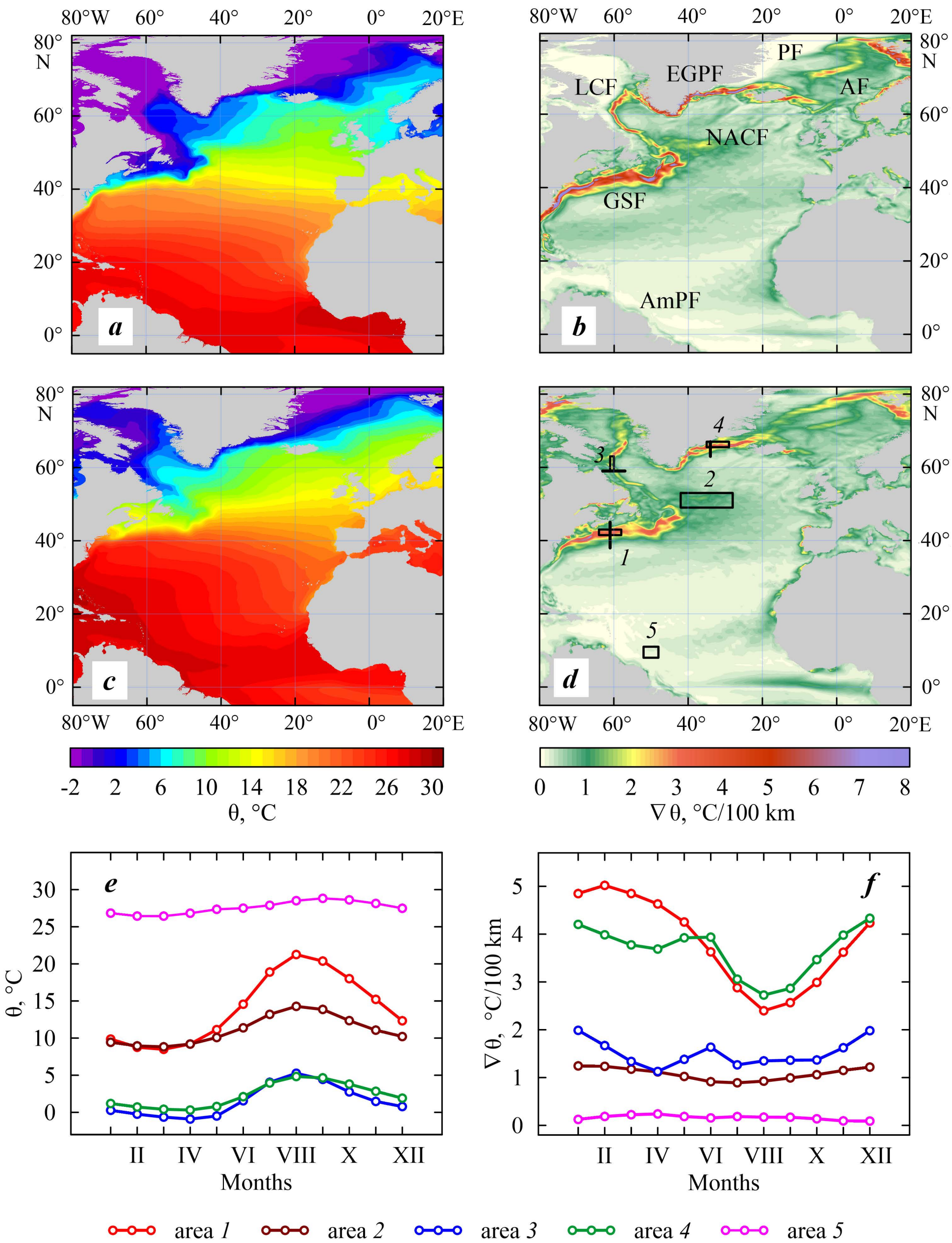
Spatial distribution of thermohaline fields and their gradients is presented for winter (December–February) and summer (June–August). Quantitative evaluation of seasonal variability of temperature, salinity and density gradients was performed for frontal zones with the gradients of temperature exceeding 2 °C/100 km, salinity – 1 PSU/100 km, density – 1 kg·m^{-3}/100 km. The calculations were carried out for five separate areas identified in frontal zones along large-scale currents and at the edge of the Amazon River plume. Area *1* was identified in the frontal zone of the Gulf Stream (41.5°–43° N, 58°–64° W); area *2* – of the North Atlantic Current (49°–53° N, 28°–42° W); area *3* – of the Labrador Current (59°–63° N, 60°–61° W); area *4* – of the East Greenland Coastal Current (65.5°–67° N, 29°–35° W); and area *5* – of the Amazon River plume (8°–11° N, 48°–52° W) (Fig. 1, *d*). Thermohaline characteristics were averaged within the area edges.

An analysis of the seasonal variability of the frontal zone position and size was carried out for areas *1*, *3* and *4*. Meridional sections were identified along 61° and 34° W, respectively, in the zonally oriented areas of the frontal zones of the Gulf Stream and the East Greenland Current. A zonal section along 59° N was identified on the meridionally oriented section of the Labrador Current frontal zone (Fig. 1, *d*). In this case, the gradient values were pre-averaged with a step of 0.25° along the section in areas with a finer grid.

Results and discussion

Temperature frontal zones

Waters with different thermohaline characteristics enter the North Atlantic with ocean currents, which determines the presence of oceanic fronts at their boundaries [1]. The temperature frontal zones are observed on the ocean surface in the vicinity of all such large-scale currents as the Gulf Stream, Labrador, West Greenland, East Greenland, Norwegian Currents, as well as in the area of coastal upwelling off the western coast of Africa and in summer in the eastern part of the equatorial region due to equatorial upwelling (Fig. 1).



F i g . 1 . Spatial distribution of potential temperature θ (*a*, *c*) and its horizontal gradients ∇θ (*b*, *d*) at a depth of 0.5 m in winter (*a*, *b*) and summer (*c*, *d*); seasonal variability of mean values θ (*e*) and ∇θ (*f*) in areas *1*–*5*. Frontal zones: GSF – Gulf Stream, NACF – North Atlantic Current, LCF – Labrador Current, EGCF – East Greenland Current, AmPF – Amazon River plume, PF – East Greenland Polar Front, AF – Arctic Front

The temperature frontal zone along the Gulf Stream is observed throughout the year. It separates the warm waters carried by the Gulf Stream from the southern latitudes and the cold waters of the Labrador Current off the Nova Scotia coast (Fig. 1, *a – d*) [24, 25]. Temperature gradients reach 13 °C/100 km in this frontal zone. Mean temperature gradients in area 1 in winter are 4 °C/100 km with their maxima up to 6.5 °C/100 km. (Fig. 1, *b*, *f*; Table). By summer, this front weakens due to the seasonal increase in water temperature in the surrounding waters and the gradients decrease, but remain quite high exceeding 2 °C/100 km (Fig. 1, *c*, *d*, *f*; Table).

Statistical characteristics of frontal zone gradients in areas *1–5*

Value	Area *1*	Area *2*	Area *3*	Area *4*	Area *5*
			$\nabla\theta$, *°C/100 km*		
Mean	3.8	1.0	1.5	3.7	0.16
Maximum	5.0	1.2	2.0	4.3	0.2
Minimum	2.4	0.9	1.1	2.7	0.09
Range	2.6	0.3	0.9	1.6	0.11
			∇S, *PSU/100 km*		
Mean	1.8	0.22	1.0	1.3	0.8
Maximum	2.0	0.24	1.6	2.3	1.7
Minimum	1.6	0.19	0.7	0.9	0.2
Range	0.4	0.05	0.9	1.4	1.5
			$\nabla\sigma_\theta$, *kg·m^{-3}/100 km*		
Mean	0.8	0.15	0.8	0.8	0.6
Maximum	1.0	0.22	1.1	1.6	1.3
Minimum	0.7	0.1	0.5	0.5	0.2
Range	0.3	0.12	0.6	1.1	1.1

The mean gradients do not exceed 1 °C/100 km in area *2* of the North Atlantic Current frontal zone. They increase in winter and decrease in summer. Low gradient values can be associated with the branching of the current and the seasonal displacement of branches [18].

The Labrador and East Greenland Currents transport cold waters into the North Atlantic from the Arctic Ocean. The frontal zones of the Labrador and East Greenland Coastal Currents are present in all seasons. The winter decrease in temperature lasts until April in these areas, with temperatures increasing towards summer, with its maximum in August (Fig. 1, *e*). Maximum gradients in areas *3* and *4* are observed in December and January, then they decrease from winter to summer (Fig. 1, *f*; Table). The local minimum in April corresponds to the minimum water temperature in the seasonal cycle. The local maximum in June is observed at the beginning of the summer warming, when the difference between the water temperature in the coastal and sea areas is still large.

Summer ice edge retreat in the Atlantic sector of the Arctic leads to the East Greenland Polar Temperature Front strengthening [26]. Here, the maximum gradients reach 4 °C/100 km in summer. The Arctic Front (Jan Mayen – Mohns Ridge [27]) extending from Iceland to Svalbard intensifies in winter and weakens in summer. Maximum temperature gradients are observed in the frontal area in winter and spring reaching 3 °C/100 km (Fig. 1, *b*, *d*). In summer, gradients decrease and do not exceed 2 °C/100 km.

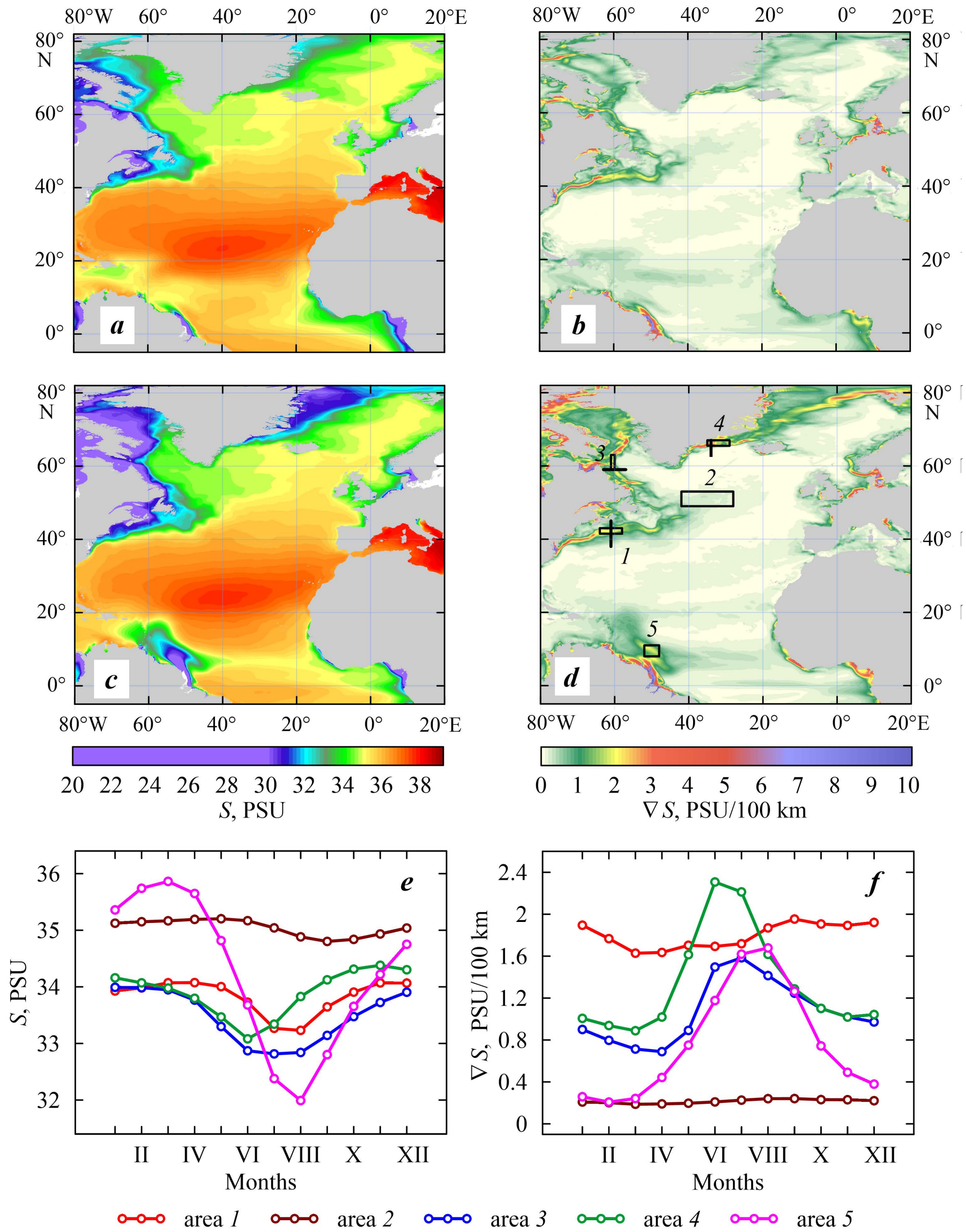
Along the African coast, the upwelling frontal zone is present south of 20° N in winter and spring and north of 20° N in summer and autumn, which is associated with seasonal changes in the wind regime [21]. Gradients in the equatorial upwelling frontal zone increase in summer and autumn (Fig. 1, *b*, *d*).

The obtained position of large-scale temperature frontal zones and seasonal variability of gradients are in good agreement with the results of previous studies conducted using different types of data: satellite data on the surface temperature of the entire World Ocean [2, 19], the North Atlantic subtropical zone [28], the Gulf Stream front [6, 20], *in situ* measurement hydrological data [17, 27] and satellite altimetry data for the North Atlantic [22].

Salinity frontal zones

The salinity frontal zones with gradients exceeding 1 PSU/100 km are located in the areas of the Gulf Stream, Labradorand East Greenland Currents, as well as of the Polar Front and at the edge of the Amazon River plume (Fig. 2).

In the Gulf Stream frontal zone, the maximum salinity gradients are found in the area of the Gulf Stream North Wall throughout the year [29] (Fig. 2, *b*, *d*). Their values reach 5 PSU/100 km in winter and 4 PSU/100 km in summer. In area *1*, maximum salinity is observed in spring [30] and gradients are minimum at this time (Fig. 2, *e*, *f*). High salinity gradients are observed in autumn and winter, when seasonal intensification of transport of



F i g . 2 . Spatial distribution of salinity S (a, c) and horizontal salinity gradients ∇S (b, d) at a depth of 0.5 m in winter (a, b) and summer (c, d); seasonal variability of mean values S (e) and ∇S (f) in areas 1–5 the Labrador Current and its branch spreading along the Nova Scotia coast occur [24, 31, 32]. The influence of fresh water flow from the Gulf of St. Lawrence and the salinity of the Gulf Stream water are also important [33].

Despite the fact that the Labrador Current intensifies in autumn and winter [31], and the East Greenland Current – in winter and spring [34], the gradients in the frontal zones of these currents (areas *3* and *4*) increase in summer, which is associated with the seasonal melting of the Arctic ice and removal of freshened water from the Arctic Ocean, as well as with the melting of coastal and continental ice. Minimum gradients are observed in March and April at minimum temperature, after which gradient values increase and reach their maximum at the beginning of summer (Fig. 2, *f*; Table).

In the Atlantic sector of the Arctic, the East Greenland Polar Salinity Front is significantly strengthened in summer. This is also stipulated by the Arctic ice melting and influx of freshened waters, the salinity of which is significantly lower than that of the subpolar regions [26]. The maximum values of horizontal salinity gradients in summer are 3.5 PSU/100 km.

In the tropical Atlantic Ocean, an extensive salinity frontal zone is located at the edge of the Amazon River plume [35]. Freshened waters are distributed by the North Brazil Current to the north to 15° N in spring and summer. Salinity decreases in area *5* from March (36 PSU) to August (32 PSU) and gradients increase from 0.2 to 1.7 PSU/100 km.

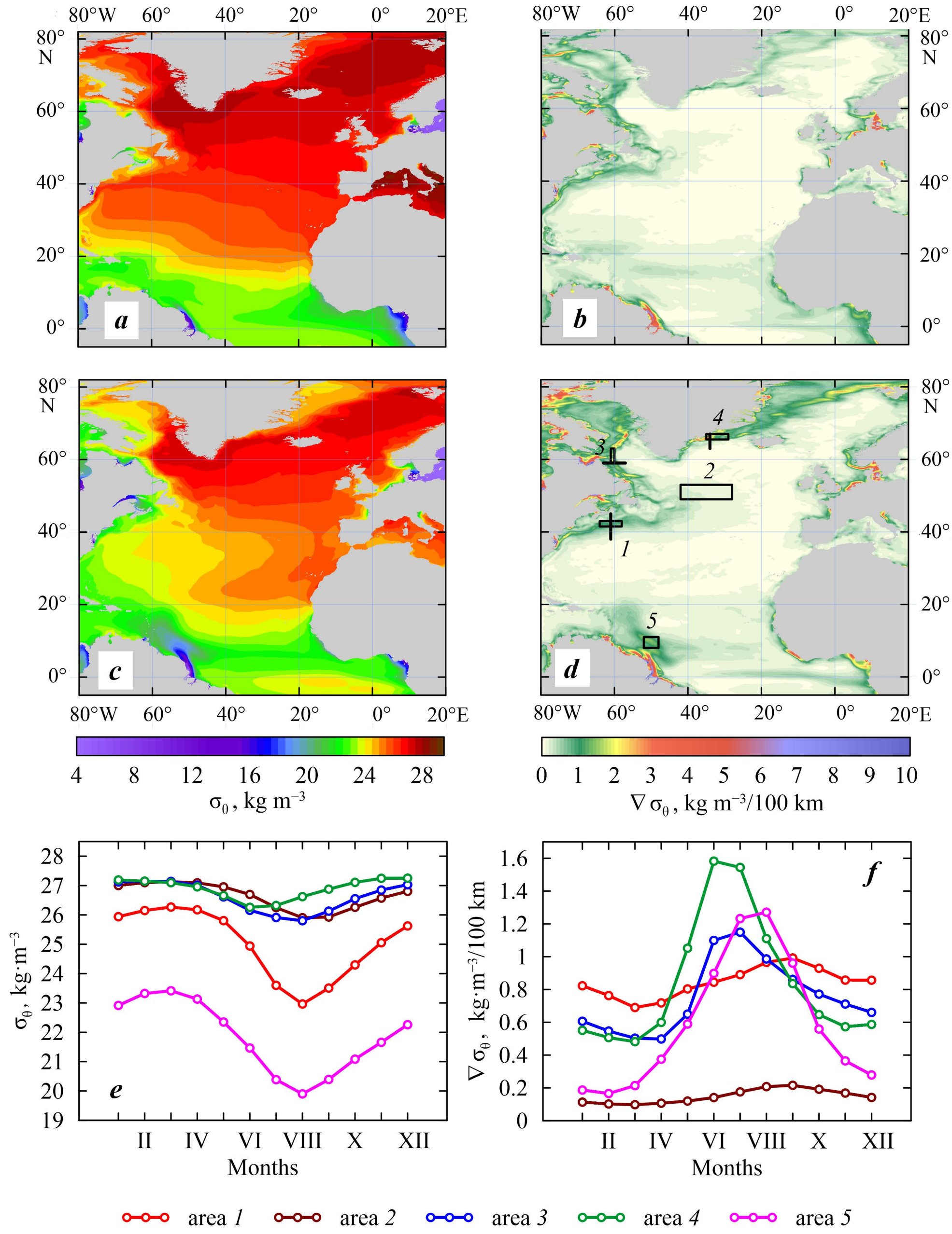
Density frontal zones

The density frontal zones with gradients exceeding 1 kg·m^{-3}/100 km are located in the areas of the Gulf Stream, Labrador, East Greenland Currents (Fig. 3, *b, d*). In summer, a large estuarine frontal zone is observed in the Amazon River plume area (Fig. 3, *c*, *d*). In summer, a frontal zone associated with equatorial upwelling also occurs along the equator.

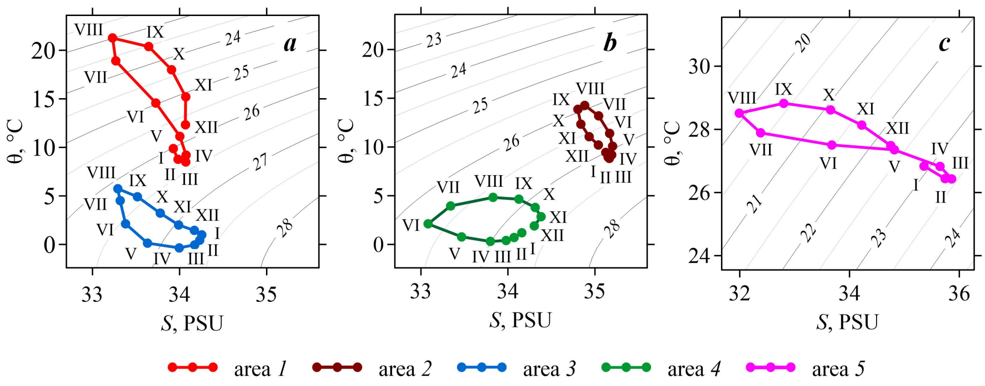
The density in areas *1–4* decreases in summer, while the density gradients increase at this time (Fig. 3, *e*, *f*). Gradients exceeding 4 kg·m^{-3}/100 km are observed locally in certain areas of the frontal zones of the Labrador Current in the Davis Strait, the East Greenland Coastal Current, the Polar Front and in the Amazon estuarine zone (Fig. 3, *b*, *d*).

Minimum density gradients in areas *1–4* of the North Atlantic frontal zones are observed in March. The minimum density gradient in the frontal zone of the Amazon River plume (area *5*) is observed in February.

In areas *1* (the Gulf Stream frontal zone) and *2* (the North Atlantic Current frontal zone), the minimum and maximum density in the seasonal cycle are observed at the maximum and minimum temperatures, respectively (Fig. 4, *a*, *b*). Here (in the open ocean), the contribution of temperature exceeds the contribution of salinity to seasonal density changes.



F i g. 3. Spatial distribution of potential density anomaly σ_θ (*a*, *c*) and horizontal potential density gradients $\nabla\sigma_\theta$ (*b*, *d*) at a depth of 0.5 m in winter (*a*, *b*) and summer (*c*, *d*) seasons; seasonal variability of mean values σ_θ (*e*) and $\nabla\sigma_\theta$ (*f*) in areas *1–5*



F i g . 4 . TS diagrams of seasonal variability of temperature and salinity at a depth of 0.5 m in areas *1*, *3* (*a*), *2*, *4* (*b*), *5* (*c*)

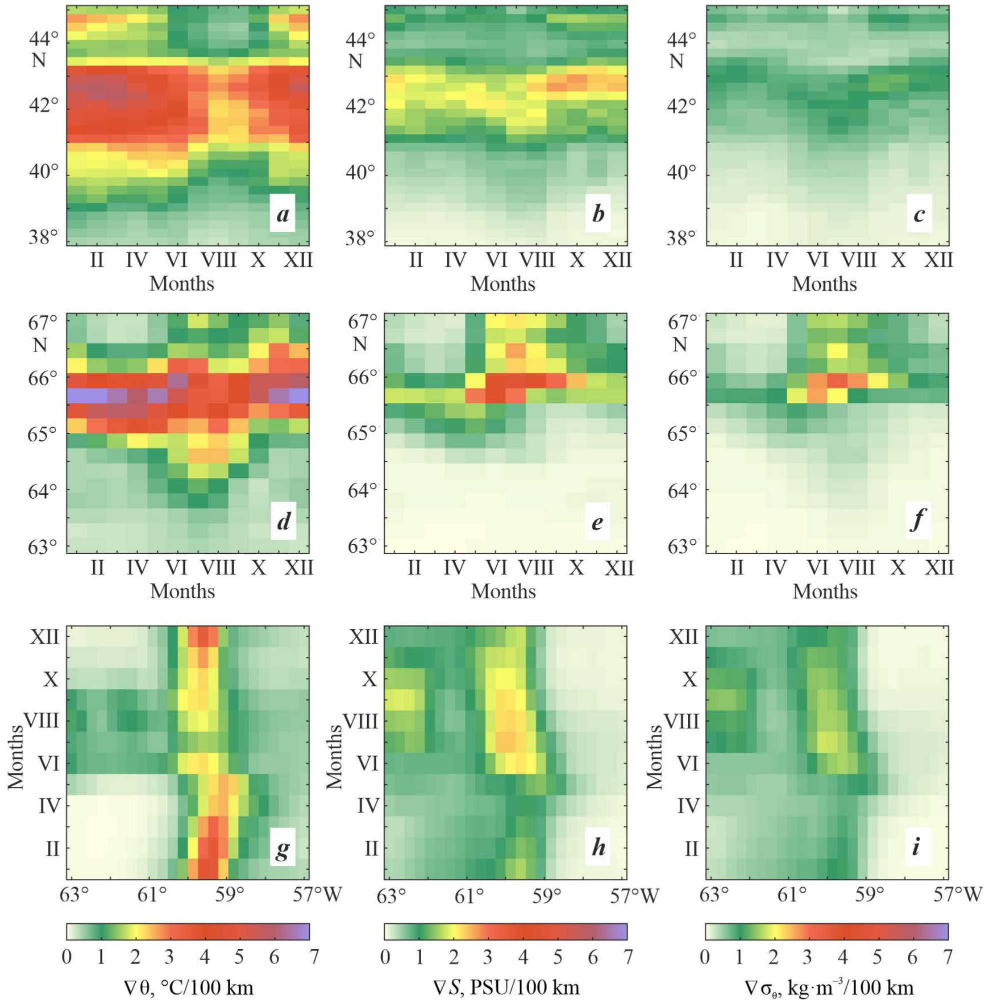
In areas where less saline waters flow from the Arctic Ocean (the Labrador and East Greenland Currents) and in the area of the Amazon River flow, the contribution of salinity to seasonal density changes increases. This is clearly illustrated by density changes in the frontal zone of the East Greenland Coastal Current (area *4*). Here, the lowest density is achieved in June with the lowest salinity, rather than with the maximum temperature, which is observed in August (Fig. 4, *b*). The maximum density is observed in November and December with high salinity. The minimum temperature in this area is observed in April. In the frontal zone of the Labrador Current (area *3*), the maximum density is observed in February and March, while the minimum temperature is in April.

In area *5* of the Amazon River plume frontal zone, the maximum temperature is observed in September [36], while the minimum density is obtained for August, when the salinity is minimum (Fig. 4, *c*).

Seasonal variability of the size of frontal zones

Seasonal temperature and salinity changes in currents and surrounding waters, as well as changes in river flow, can lead to shifts in the edges or changes in the size of the frontal zone. Thus, the salinity and density frontal zones of the Amazon River plume (Figs. 2, 3) are observed only during the increase in seasonal flow in spring and summer, not in the winter months.

The seasonal variability of the position and magnitude of gradients along the meridional section crossing the Gulf Stream frontal zone at 61° W (area *1*) is well expressed. Here, the front with temperature gradients exceeding 2 °C/100 km narrows in August and September with the decrease of gradients (Fig. 5, *a*). The zone of high salinity gradients (more than 2 PSU/100 km) shifts southward from winter to summer and back northward in autumn (Fig. 5, *b*). The zone of high density gradients shifts in a similar manner (Fig. 5, *c*). It should be noted that the change in the width of frontal zones obtained from average long-term data for individual seasons can be associated with the shifts of these zones in separate years.



F i g . 5 . Seasonal variability of gradients of potential temperature $\nabla\theta$ (*a*, *d*, *g*), salinity ∇S (*b*, *e*, *h*) and potential density anomaly $\nabla\sigma_\theta$ (*c*, *f*, *i*) on meridional sections along 61° W in area *1* of the northern section of the Gulf Stream frontal zone (*a*, *b*, *c*), along 34° W in area *4* of the East Greenland Coastal Current (*d*, *e*, *f*) and on the zonal section along 59° N in area *3* of the Labrador Current frontal zone (*g*, *h*, *i*)

In area *4* of the East Greenland Coastal Current frontal zone, the meridional section along 34° W was chosen. The meridional size of the temperature frontal zone expands southward in July and August and northward in October and December (Fig. 5, *d*). The width of the salinity and density frontal zones increases in summer due to the increase of gradients at the northern edge (Fig. 5, *e, f*).

In the meridional section of the Labrador Current frontal zone (area *3*), the zonal section along 59° N was considered. In this area, the zone of high gradients (more than 2 °C/100 km) shifts eastward from January to April. In May, the gradients decrease and the zone shifts westward (Fig. 5, *g*). The gradients in the salinity (Fig. 5, *f*) and density (Fig. 5, *i*) frontal zones increase in summer and early autumn. At the same time, the zones shift westward.

Conclusion

This paper gives a comprehensive understanding of the position of large-scale surface thermal, salinity and density frontal zones in the North Atlantic Ocean and seasonal variability of their gradients based on the use of ORAS5 ocean reanalysis data on temperature and salinity at the 0.5 m horizon. Quantitative evaluation of seasonal variability of gradients in frontal zones in individual areas of large-scale currents and at the edge of the Amazon River plume is provided.

The analysis of seasonal variability of spatial distribution and magnitudes of horizontal gradients in thermohaline frontal zones showed the following. Frontal zones on the ocean surface located along such large-scale currents as the Gulf Stream, North Atlantic, Labrador and East Greenland Currents, which carry waters differing in temperature and salinity from the surrounding waters, are observed throughout the year. Temperature gradients in these zones decrease from winter to summer due to seasonal warming of the waters. The maximum range of seasonal changes in temperature gradients is observed in the regions of the Gulf Stream and the East Greenland Current.

Significant seasonal variability of salinity and density gradients is observed in the frontal zones of the Labrador and East Greenland Currents. Minimum gradients are observed in late winter and early spring at minimum temperatures. Gradients increase in summer due to the melting of coastal, continental and Arctic ice.

In the Tropical Atlantic, high intra-annual variability of salinity and density gradients is observed in the Amazon River frontal zone. Here, maximum gradients are observed in summer at the edge of the plume that occurs due to the seasonal increase in river flow. No frontal zone is observed in winter.

The obtained magnitudes of seasonal changes in gradients in frontal zones can be used when studying the biological productivity of marine waters. They can also be taken into account in climate studies since as a rule, the amplitude of the seasonal cycle of the ocean surface layer characteristics exceeds interannual changes.

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