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Characteristics of Density Inversions in the Greenland Sea during the Cold Seasons in 1993–2019

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Purpose. The study aims at revealing spatial and temporal variability of the characteristics of density inversions in the Greenland Sea and at proposing the mechanisms of their formation during the cold seasons in 1993–2019. This helps further understanding the mechanisms which govern variation in the convection intensity in the sea.
Methods and Results. The *in-situ* temperature and salinity taken from the EN.4.2.1 dataset (Met Office Hadley Center Database) and casted during the cold season (November – April), are used in the study. The vertical profiles reveal a number of potential density inversions. The biggest vertical scale of a winter-mean inversion reached about 400 m and was recorded in the years of maximum convection intensity (2008, 2011 and 2013), and the largest value of density gradients were observed in the 1990s when convection was less intensive. Predominantly haline destabilization prevailed (about 70% of all the profiles with inversions) throughout the region; it was observed especially often in the northeastern part of the area under study. Exclusively haline destabilization accounts for 40% of all the profiles, exclusively thermal one – 13%, as for the rest of the profiles, both haline and thermal destabilizations are detected. In the 2010s, salinity contribution to the formation of inversions exceeds the one that had been observed in the mid-1990s.
Conclusions. The *in-situ* data confirm the leading role of winter salinity increase in formation of the water density inversions in the upper ocean, and, consequently, in the development of deep convection. This may indicate a significant role of potential instability in the development of convection in the region.

Keywords: convection, Atlantic Ocean, Greenland Sea, deep convection, density inversions, potential instability

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Introduction

Deep convection is an important element of dynamics of the Atlantic Meridional Overturning Circulation (AMOC) and, as a consequence, affects the entire climate system [1, 2]. Numerous studies have shown a relationship between variability of the AMOC intensity and that of the convection intensity [3, 4]. At the same time, the nature of the heat exchange between the ocean and the atmosphere in the North Atlantic and the adjacent part of the Arctic Ocean (AO) also changes [5, 6].

In [7], the main mechanisms of the AMOC variability were evaluated. It was noted that on a decadal timescale, the AMOC influences the deep convection development in the Greenland Sea, and not vice versa. This is possible as a result of the development of the potential instability in the water column [8] due to advection and subsequent cooling of the haline and warm Atlantic Water into the Greenland Sea [9].

Vertical mixing in the sea, including deep convection, can develop under the influence of various combinations of external factors. There are thermodynamic and dynamic mechanisms of vertical mixing [8], although they often work together.

Thermodynamic mechanisms include mechanisms (associated with the occurrence of gravitational instability) characterized by a formation of a higher density layer relative to the underlying one. Examples of such mixing are cooling or salinification of the sea-surface as a result of ocean-atmosphere interactions, double diffusion, thermobaric instability and potential instability [8].

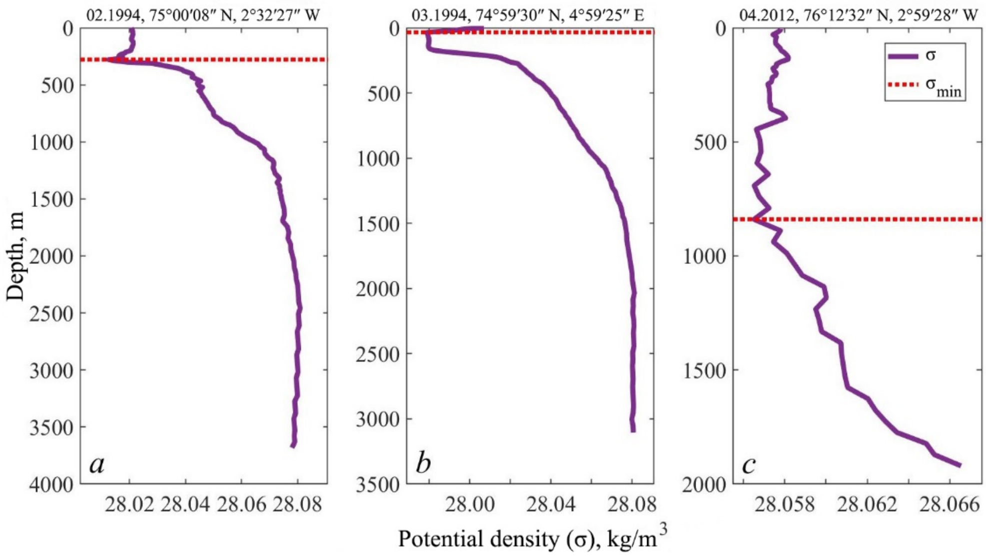
Due to cyclonic circulation in the Greenland Basin, cold intermediate waters rise to the sea surface in the center of the basin. At the same time, sharp gradients of temperature, salinity and water density are destroyed during intense winter convection at depths at least down to 200 m [10]. The relatively small thickness of the upper stratified layer in the center of the Greenland Sea favors, during the cold season, convection to reach and penetrate into the waters below the pycnocline with the weak stratification which occasionally can form very deep upper mixed layer (sometimes over 2000 m depth).

In addition to the cyclonic circulation, the deep convection development is also pre-conditioned during the preceding period [11]. Interaction with the atmosphere and oceanic advection during the warm season can both enhance or weaken the stratification of the layer above the cold-water dome by the beginning of the cold period, which, ceteris paribus, can lead to an increase or decrease of spring-winter convection [12, 13].

The observed significant increase in the intensity of deep convection in the Greenland Sea since the early 2000s compared to the 1990s [14] was explained by the considerable intensification of salt advection with the recirculating Atlantic waters [9, 15]. These conclusions were made based on the observed variability of heat and salt balances of the upper central Greenland Sea. In the present paper, for the first time the variability of the characteristics of density inversions in the Greenland Sea based on the data of *in-situ* temperature and salinity profiles are analyzed. An investigation of the mechanisms of formation of these inversions during the cold season creates the basis for further understanding of the interannual variability of convective processes.

Data and methods

In this paper we use data of *in-situ* observations of temperature and salinity profiles of the EN.4.2.1 database of the Met Office Hadley Center. This array includes data from various ocean vertical profiling instruments. The main source of these data is the World Ocean Database, which is complemented by data collected during various projects and expeditions (ASBO, NPEO, NABOS and CABOS) and the Global Temperature and Salinity Profile Programme (GTSPP). The data undergo strict quality control and duplicate profiles are excluded [16].



F i g. 1. Examples of potential density (σ) profiles with inversions. Red dotted lines indicate the depths of the minimum density in the profiles (σ_{min})

Density inversion is understood as a decrease in potential density with depth (Fig. 1). To identify profiles with inversions, the difference between the potential density values at the surface and at the minimum density depth was used. If the difference between these values exceeded the selected threshold of 0.001 kg/m^3, the profile was classified as the one with an inversion. Next, the profiles were visually examined to eliminate possible errors of the automatic algorithm.

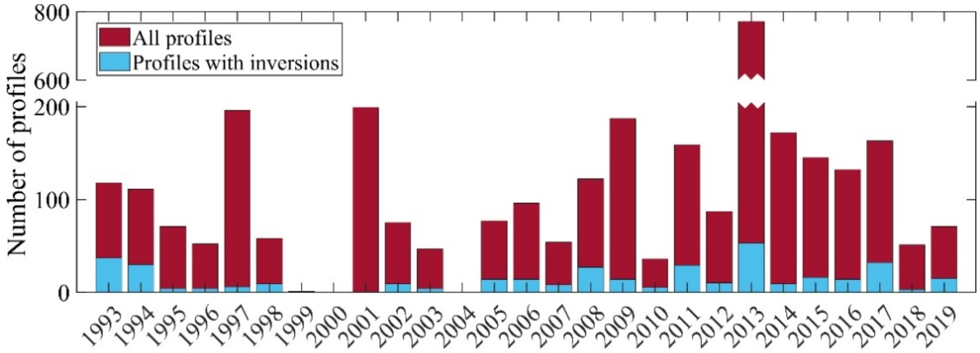
Results

In this paper, density inversions are considered, as an indicator of further development of convection. The upper mixed layer of the Greenland Sea begins to deepen in October – November, the active development of convection is observed in January – April, and the largest number of events of deep convection is recorded in April [17, 18]. Therefore, the November – April period was chosen here for the analysis of inversions.

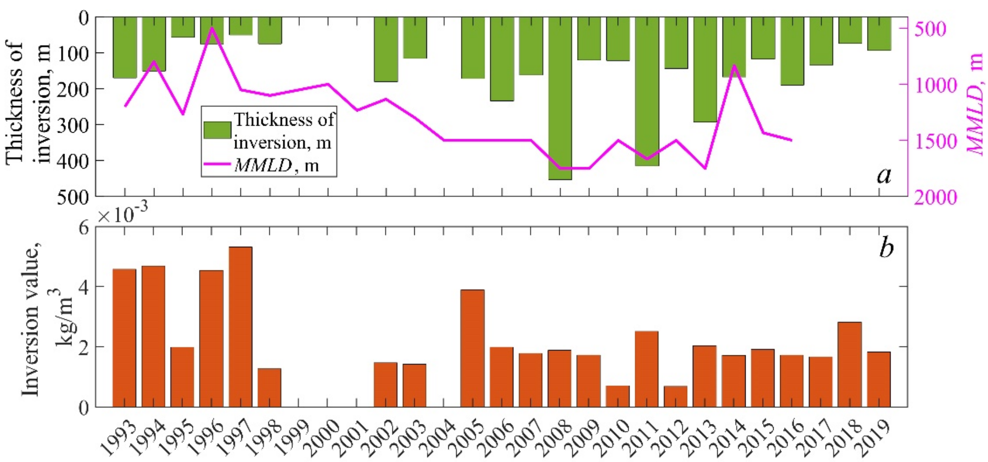
The largest number of profiles with inversions was registered in 2013, in 1993, 1994, 2008, 2011 and 2017 they are also distinguished. The median values over the entire interval of observations are 96 profiles performed per cold period, of which 14 profiles were with density inversions. An unprecedented maximum in the number of the profiles is noted in 2013 (more than 700, 23% of the total number for all the years of observations) is associated with a very high frequency of vertical casting of several profiling floats in the study region.

Since the dependence of the number of profiles with inversions on the total number of vertical casts was detected (the correlation of two time series reaches 0.7 and is significant for *p*-level < 0.01), it makes sense to study the time series of the percentage of profiles with inversions from the total number of casts performed. The largest number of profiles with inversions was recorded in 1993

(31%) and 1994 (27%), while a relatively high number of inversions was also recorded in 2008 (22%) and 2011 (18%).

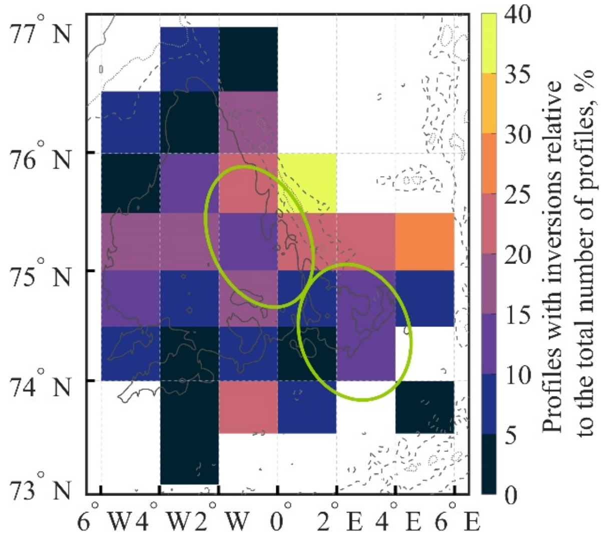


F i g. 2. Interannual variability in the number of all the available profiles and those with inversions



F i g. 3. Interannual variability of the vertical thickness of density inversions – *a* and the density jump in an inversion – *b*. The *MMLD* (maximum mixed layer depth over the cold season) values are given according to [9]

Over the past 30 years, the most intense convection in the Greenland Sea has been observed since the early 2000s (Fig. 3, *a*), and its maximum depths were recorded in 2008, 2009, 2011 and 2013 [9]. In the same years, except 2009, the largest average thickness of the vertical inversions was recorded. The correlation between the thickness of the winter-average inversion and the maximum mixed layer depth reaches 0.6 (p-level < 0.05). The largest values of the density jump in the inversions, on the contrary, was observed in the 1990s, years with the low intensity of convection. This is probably due to a smaller amount of the available potential energy for mixing in the inversions of relatively small vertical extent compared to the deep inversions, which have the same value of the density jump.



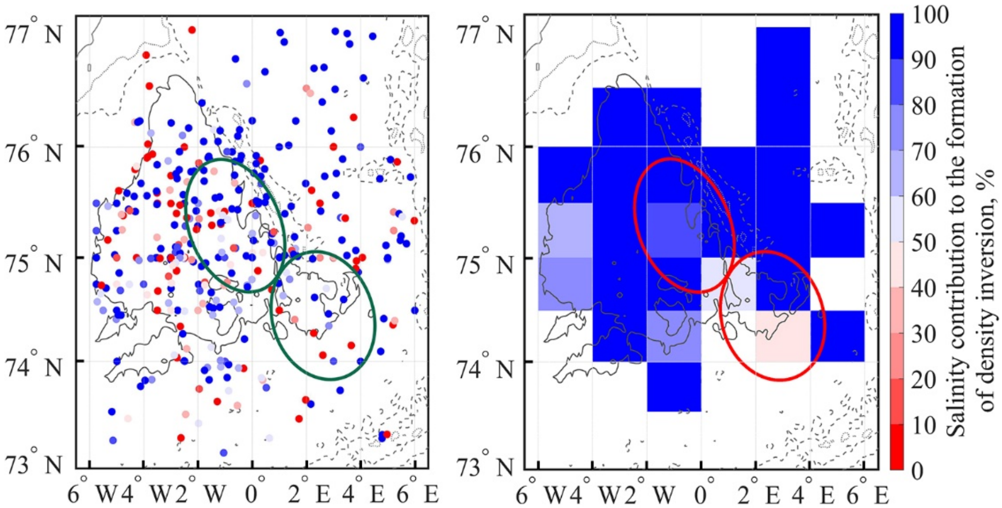
F i g. 4. Gridded spatial distribution of the percentage of profiles with inversions relative to the total number of profiles. The ellipses indicate the areas of the most frequent development of deep convection in the Greenland Sea. Only the grid cells in which the overall number of the profiles with inversions exceeding 30 are shown.

The highest recurrence of the profiles with density inversions is observed in the deep part of the northern Greenland Sea. The lowest number of the profiles is observed in the southern (with more stable thermal stratification) and northwestern (ice covered and with more stable haline stratification) parts of the region.

Using the equation of state of the sea water

$$\sigma = \sigma_0 \left(-\alpha\Delta\theta + \beta\Delta S\right), \tag{1}$$

where σ is the potential density; σ_0 is the reference potential density; α is the coefficient of thermal expansion of the sea water; β is the coefficient of haline contraction of the sea water; $\Delta\theta$ is the potential temperature difference and ΔS is the salinity difference between the sea surface and the depth of the minimum potential density, respectively. Using formula (1), the density inversions can be divided into the predominantly thermal ones ($\alpha\Delta\theta$ dominates the instability) and the predominantly haline ones ($\beta\Delta S$ dominates the instability), which, accordingly, leads to the development of predominantly thermal or predominantly haline convection. Profiles with both predominantly thermal and predominantly haline contributions to the instability of the water column almost uniformly cover the entire water area (Fig. 5, *a*). Profiles with more than 50% of the haline contribution make up 69% of the total number of profiles with inversions. The inversions with an almost 100% salinity contribution are concentrated in the northeastern part of the study region.



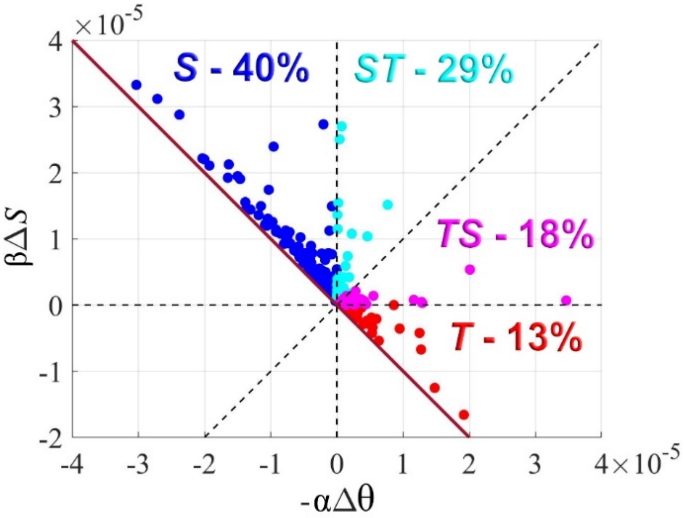
F i g. 5. Spatial distribution of the profiles with inversions in the Greenland Sea – *a* and salinity contribution to the density inversion in % – *b*. The ellipses indicate the areas of the most frequent development of deep convection in the Greenland Sea. Only the cells where the number of profiles with inversions exceeds 5, were used

A contribution of salinity (*RS*) to formation of a density inversion can be numerically evaluated using the following formula

$$RS = \frac{\beta \Delta S}{\left(-\alpha \Delta \theta + \beta \Delta S\right)} 100\%. \quad (2)$$

Computation of the time averages on a regular grid (Fig. 5, *b*) shows that the profiles with a predominantly haline contribution dominate in almost the entire study area.

The scatterplot (Fig. 6) shows the relationship between the salinity and temperature contributions to density inversions. Casts with the parameter values situated below and to the left of the red straight line $\beta\Delta S = \alpha\Delta\theta$ are in the area of stable vertical density profiles, and those above and to the right are in the area of unstable density profiles which can be due to one of the parameters or both. The positive values of $\beta\Delta S$ and the negative values of $-\alpha\Delta\theta$ describe salinity destabilization and temperature stabilization and are called the haline inversions; the positive values of $-\alpha\Delta\theta$ and the negative values of $\beta\Delta S$ are the thermal inversions; the positive values of $-\alpha\Delta\theta$ and $\beta\Delta S$ are the mixed inversions, where an inversion is formed by both, temperature and salinity. The latter can be divided into the inversions, where the salinity contribution exceeds that of temperature and vice versa.



F i g. 6. Scatterplot of haline versus thermal terms of the equation of state of the seawater in the density inversions observed. Haline inversions are indicated in blue – *S* (warm and saline surface waters), cyan indicate the mixed thermal and haline inversions with a predominance of haline destabilization – *ST*, magenta is the mixed thermal and haline inversions with a predominance of thermal destabilization – *TS* (cold and saline surface waters), and red is the thermal inversions – *T* (cold and fresh surface water)

The number of purely haline inversions forms 40% of the total number of profiles, while the purely thermal ones form 13%. The number of the mixed inversions with a predominance of haline destabilization is 29%, and those with a predominance of thermal destabilization are 18%. The predominance of haline destabilization of the profiles is consistent with the results of [9], where it is stated that water salinity plays a leading role in the interannual variability in the upper layer density of the Greenland Sea.

Conclusions

It is believed that density inversions do not appear in ocean observations because the water column is almost instantly mixed. Such a scheme is also implemented in the vast majority of hydrodynamic models. However, the observations presented here show that density inversions exist in the ocean and are regularly recorded by oceanographic instruments. The study of the inversions makes it possible to characterize the conditions that precede convection and to build hypotheses about the main mechanisms leading to the convective mixing, including the development of deep convection.

In the present paper, the inversions in the Greenland Sea were divided into predominantly thermal and predominantly haline.

During the years with more intense deep convection (2008, 2011 and 2013), the vertical development of inversions reached the vertical extent of about 400 m. In these years, the average value of the density jump in the inversions was relatively small, in contrast to 1993–1998, when the vertical extent of the inversions was low, but the related density jump was the highest. We attribute this to the dependence of the potential energy available for convective mixing on the vertical extent of the inversion.

With a quite uniform distribution of profiles with inversions over the water area, a clear dominance of the predominantly haline inversions (almost 2/3 of their total number) was found, with 40% formed exclusively due to an increase in salinity towards the sea surface and only 13% formed exclusively due to a temperature decrease towards the sea surface. It was also found that the role of haline anomalies in formation of the density inversions of the upper ocean increased in the 2010s compared to the mid-1990s. The relative importance of various mechanisms which can form the density inversions is yet to be established.

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Contribution of the co-authors:

Anastasiia S. Kaledina – formal analysis, methodology, visualization, writing of the original draft

Igor L. Bashmachnikov – conceptualization, methodology, supervision, writing of the review and editing

The authors have read and approved the final manuscript.
The authors declare that they have no conflict of interest.