

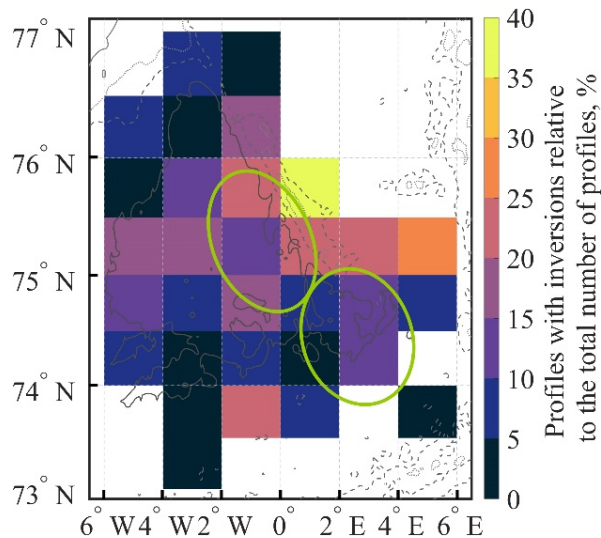








small vertical extent compared to the deep inversions, which have the same value of the density jump.



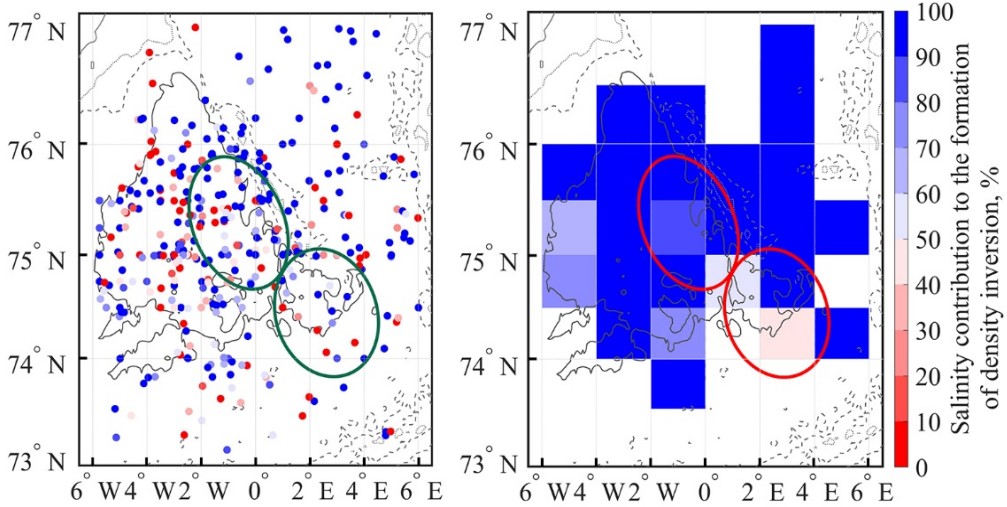
**Fig. 4.** Gridded spatial distribution of the percentage of profiles with inversions relative to the total number of profiles. The ellipses indicate the areas of the most frequent development of deep convection in the Greenland Sea. Only the grid cells in which the overall number of the profiles with 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

$$\sigma = \sigma_0 (-\alpha\Delta\theta + \beta\Delta S), \quad (1)$$

where  $\sigma$  is the potential density;  $\sigma_0$  is the reference potential density;  $\alpha$  is the coefficient of thermal expansion of the sea water;  $\beta$  is the coefficient of haline contraction of the sea water;  $\Delta\theta$  is the potential temperature difference and  $\Delta S$  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.



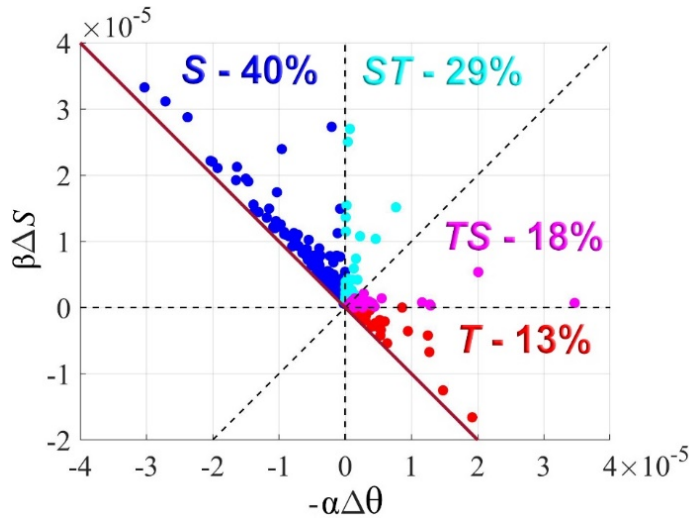
**Fig. 5.** Spatial distribution of the profiles with inversions in the Greenland Sea – *a* and salinity contribution to the density inversion in % – *b*. The ellipses indicate the areas of the most frequent development of deep convection in the Greenland Sea. Only the cells where the number of profiles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

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

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.



**Fig. 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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*The authors have read and approved the final manuscript.*

*The authors declare that they have no conflict of interest.*