The Black Sea Cold Intermediate Layer disappearance observed from Argo autonomous profilers

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Introduction

Water masses give a very robust representation of the thermohaline state of the ocean and ocean circulation. Analysis of their formation and transformation enables us to identify the dominant processes controlling the climate and regional oceanographic characteristics. [1] The Cold Intermediate Layer (CIL) is considered a permanent feature in the Black Sea vertical stratification and is classified as a water mass. The positions of the 8°C isotherms have traditionally been considered the lower and upper boundaries of the CIL. [2]

Data

From 2005 to present, 38 Argo floats have been deployed in the Black Sea. In some periods, more than 10 floats have operated at the same time, which is impressive for this small basin. The northwestern shelf of the Black Sea is very shallow in depth and therefore not visited by the Argo floats.

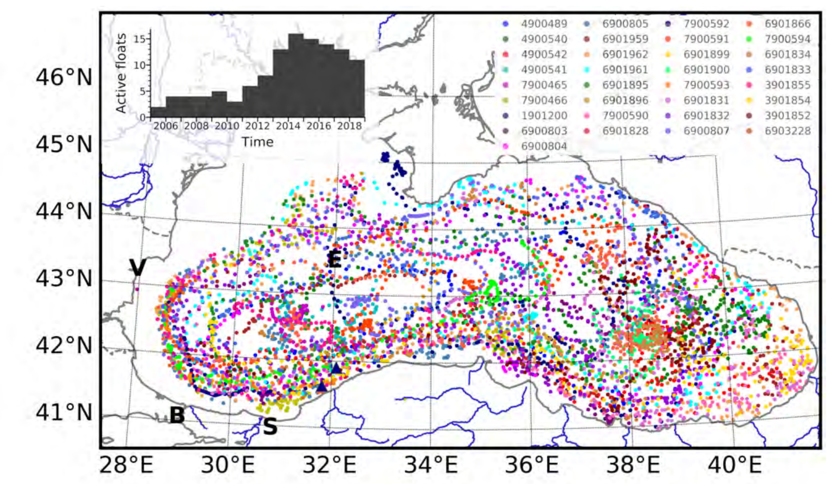

Figure 1: Sampling positions of Argo floats operating from March 2005 to December 2018. Different colours correspond to individual floats. The bar chart shows the number of simultaneously operating floats. [1]

In the present study, data form **33 floats** is used, which measured a total of **5884 profiles**. The sampling positions of these profiles are shown in Figure 1, together with the count of operational profilers for each year. Five floats are not included in the analysis because they operated for a very short time or did not operate properly.

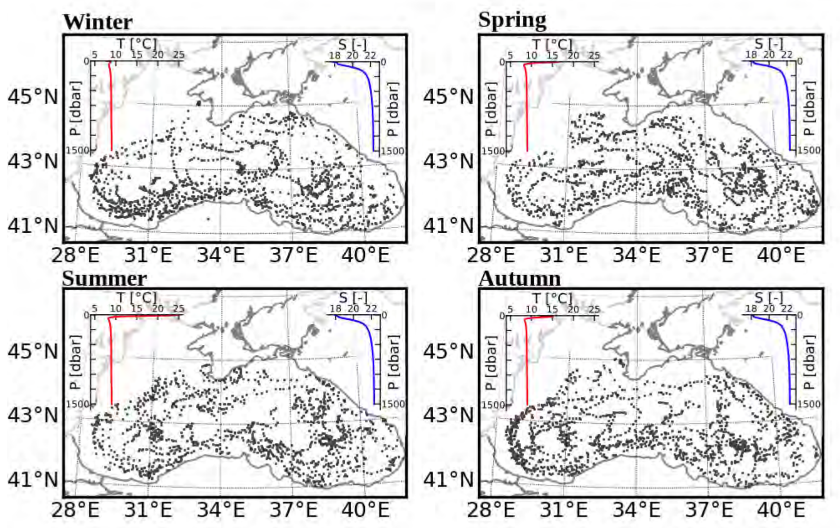

Figure 2: Seasonal distribution of Argo sampling positions and corresponding mean profiles. [1]

Compared with historical observations, most of which were performed during the warm part of the year, the sampling provided by the Argo missions is rather uniform during the individual seasons (Figure 2). The vertical distribution of seasonal mean profiles (insets in Figure 2) demonstrates a well-known vertical structure: a two-layer system with the main pycnocline at approximately 100-300 m, a strong seasonal thermocline, and a CIL at the upper part of the halocline.

Vertical Structure of the Upper Layers

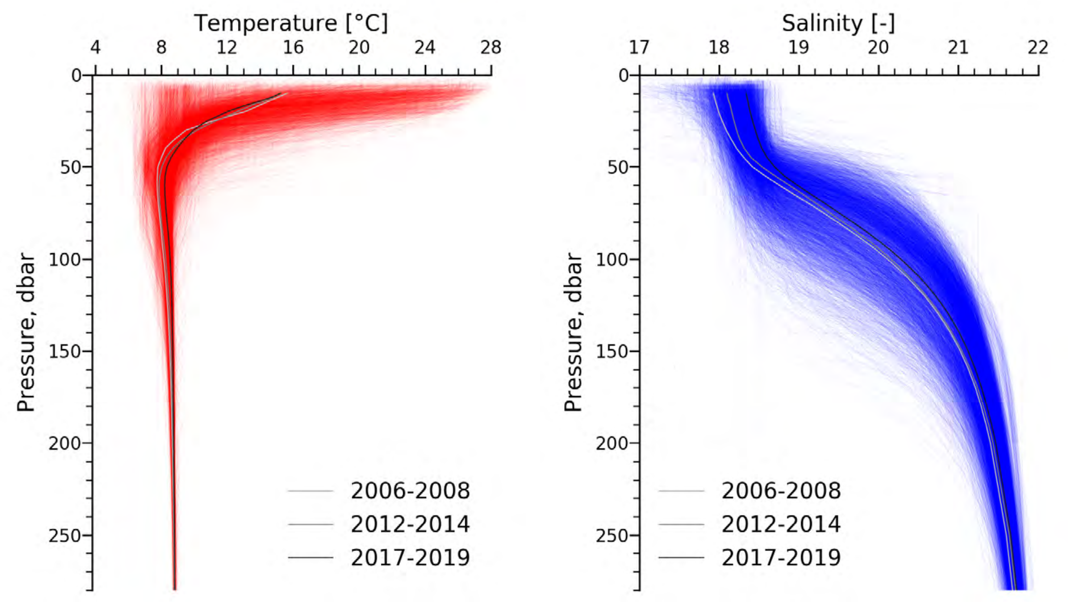

Figure 3: Vertical profiles of temperature, salinity and density in the upper parts of the Black Sea. [1]

In the upper mixed layer, the high surface temperatures in summer led to clear decreases in density. The individual vertical profiles in this layer in the low-temperature interval between 6 and 9°C illustrate separate convection events. The convergence of density profiles at 40 m appeared to be a fundamental feature in the density distribution, forming a **"density constriction"** around density values of σ **14-14.5**. This depth is approximately the bottom of the upper layer subject to convective mixing. Above this depth, salinity showed a rather homogeneous vertical profile with salinity values between 17.5 and 18.5 psu.

The homogeneity in salinity is explained as [1]:

1. a result of the **intense circulation** and mixing in the upper layers
2. a consequence of the distribution of **fresh waters from rivers** over large shelf areas, thus diminishing the signature of the low-salinity source.

The large spread of salinity profiles in the main halocline (between 50 and 250 m) represents the fact that the cyclonic circulation tended to displace the isohaline surfaces in the basin interior to shallower depths. [3]

The Black Sea

The **Black Sea** is an inland basin with a surface area of about $\mathbf{4,2.10^5 km^2}$ and a maximum **depth of 2210 m**. The large river runoff from three of the biggest European rivers **Danube, Dnepr and Dnestr** and the high salinity input of **Mediterranean water** through the Bosporus Strait form strong stratification with expressed halocline at 100-200 m depth. Consequently, the winter convection is limited to ~100 m depth and a **Cold Intermediate Layer** (CIL) is formed, showing significant seasonal and interannual variability [4, 5].

Temporal Variability of Water Mass Formation

The almost synchronous response of the upper 150 m layer to changes in atmospheric forcing is illustrated in Figure 4 by the rhythmic change in vertical profiles of temperature. The continuous trend of increasing temperatures in the core of the CIL appears to be the basic change in the cold water mass. Higher temperatures in the surface layers represented by the 20°C isoline show a quasiperiodic seasonal signal. The 8.7°C isoline is chosen to represent the boundaries of the CIL.

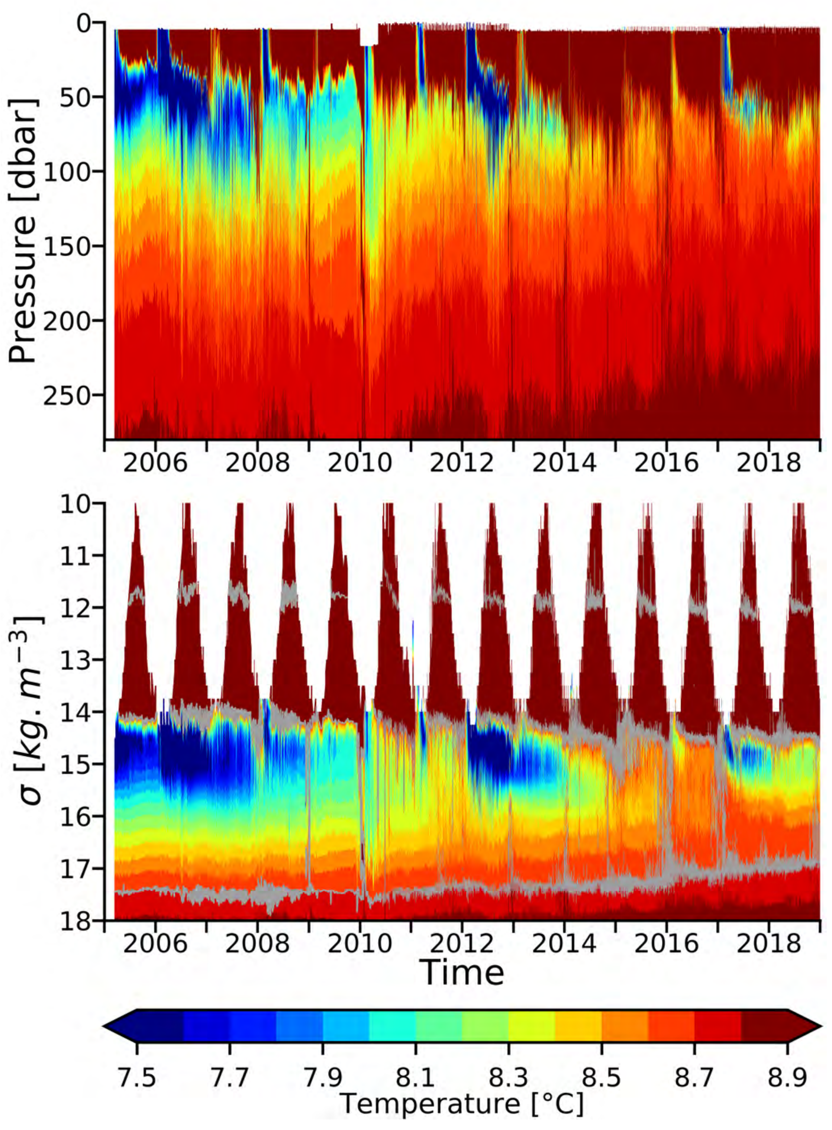

Figure 4: Time versus depth (top) and versus density (bottom) diagrams of temperature. The gray isolines correspond to isotherms 8.7 and 20°C. [1]

The reduction of the cold water content in the CIL was manifested not only by the **warming of its core** but also by **displacement of its boundaries**. The last 14-year period was characterized by only three major cold water formation events; each one much weaker than the previous. The chimney-like events during 2015-2017, in which the 8.7°C isotherm extended from the surface to 200 m depth, mark the periods when the CIL **almost disappeared basin-wide**. [1]

The presentation of the salinity anomaly in density coordinates clearly illustrates the vertical propagation (**diapycnic mixing**), which in recent years appeared as positive salinity-anomaly signals, crossing layers between σ 15 and 17 and propagating below the axis of the CIL - compare Figure 4 (bottom) with Figure 5.

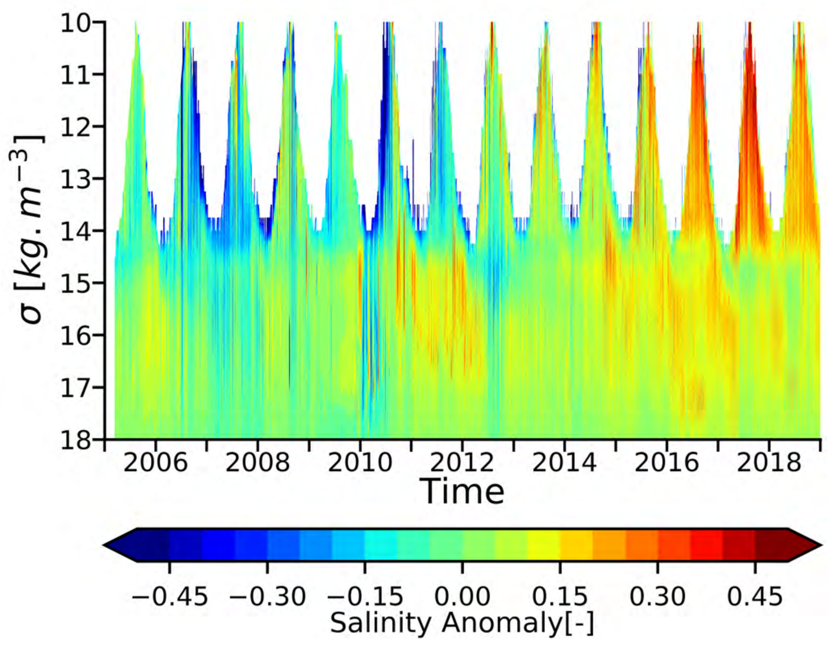

Figure 5: Time versus density diagram of salinity anomaly. [1]

Conclusion

The analysis of the vertical structure and temporal variability led to the following conclusions:

- There is a tendency towards disappearance of cold water masses in the Black Sea due to climate change.
- The warming trend is accelerated in the last 14 years; the most dramatic changes occured after 2010.
- The observed increases in both temperature and salinity were mostly due to diapycnic mixing with deeper layers.

These results are published in [1].

A presentation of the temporal evolution of the thermohaline state of the Black Sea is given in Figure 6.

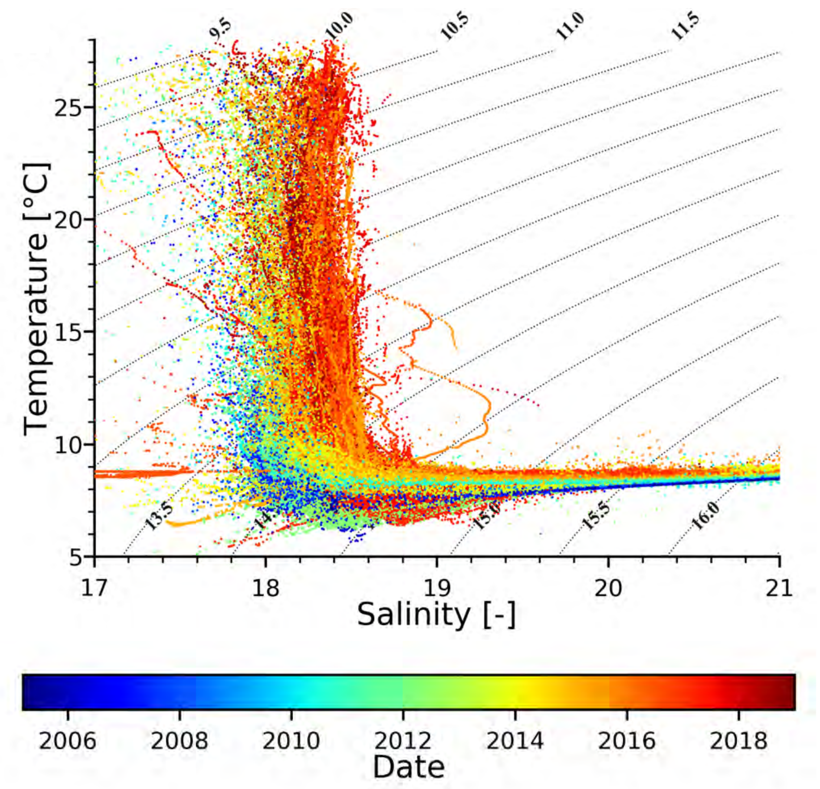

Figure 6: T-S diagram with data from Argo floats. The corresponding times of observations are shown with colors. [1]

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