Oceanology, Vol. 43, Suppl. 1, 2003, pp. S26–S31.

MARINE PHYSICS

Mixing Processes in the Gorlo Strait of the White Sea

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Received February 27, 2003

Abstract—Mixing processes were studied in the southwest area of the Gorlo Strait, which has an important role in water mass exchange between the Barents Sea and the White Sea. A dense grid of CTD measurements in June 2000 revealed four contacting water masses: the well mixed Gorlo Strait Water (GSW), the warmer White Sea Surface Water (WSSW), the warm and fresher Dvina Bay Water (DBW), and the colder and more saline White Sea Intermediate Water (WSIW). The high vertical and horizontal resolution of temperature and salinity measurements showed the spatial structure of these water masses, different aspects of mixing, and the main characteristics of the resulting quasi-homogeneous mixed layers. A thermal front was evident in the southwest part of the Gorlo Strait that resulted in the formation of an intrusion of colder GSW into the White Sea basin. This intrusion was facilitated by Terskii Coastal Current and cyclonic Dvina Bay gyre. East of the front, a mesoscale "lens" of WSSW was observed in the near-surface layer. The intensity of mixing caused by bottom friction and/or intra-thermocline shear was judged by the degree of reduction of the core of the identified water masses. T-S diagrams and vertical profiles of temperature fluctuations have therefore clearly shown the relation between the nature of mixing between core water masses and the resultant quasi-homogeneous layers.

INTRODUCTION

The White Sea is a semi-enclosed basin, which is connected to the adjacent Barents Sea via the Gorlo Strait and Voronka region. The Gorlo Strait is 50–60 km wide, 150 km long and typically 40 m deep. The surface area of the Gorlo Strait is about 10% of that of the White Sea. The Voronka region is known to have very strong tidal waves, which come from the Barents Sea and are enhanced by the funnel-like shape of the Voronka and Mezen' Bay. However, most of the tidal energy is reflected back at the entrance to the Gorlo Strait, so only 20% of the incoming tidal energy enters the Gorlo Strait, and only 6% enters the White Sea basin. Tidal currents in the Gorlo Strait are not strong and the maximum velocity is about 150–180 cm/s, which is mainly observed along the Terskii coast.

In the summer there are five water masses in the White Sea and Gorlo Strait which are involved in the mixing process. These are the well mixed Gorlo Strait Water (GSW), a thin layer (about 10 to 20 m) of White Sea Surface Water (WSSW), fresher Bay Waters, colder White Sea Intermediate Water (WSIW), which generally has the temperature $T = -0.2$ to -0.9°C, and the White Sea Deep Water (WSDW) below 100m.

Despite some progress achieved in previous studies, which analyzed the mixing process in the White Sea, this process is still not well understood due to its complex nature. Standard hydrographic sections have been carried out across the Voronka and Gorlo Strait [1], mainly obtained with Nansen bottles. The analysis of data from these sections at various seasons revealed the following features of the mixing processes. Traditionally, it has been thought [1] that the waters in the Voronka and the Gorlo Strait are well mixed from the bottom to the surface, excluding the period after the spring river flood, when low salinity waters enter the Gorlo from Dvina Bay. We will show below that this concept is not relevant to the southwestern part of the Gorlo Strait. A "belt" of maximum salinity gradients (i.e., the salinity front) was found to be located in the southern part of the Voronka [3], where salinity changes from 34 to 30 psu. Waters with a salinity of about 30 psu and a temperature of about –1.5° penetrate into the southern part of the Gorlo only during the second half of winter to renew bottom waters in the deep basin of the White Sea. The Gorlo Strait is the only route for water exchange between the Barents and White Seas. Derjugin [2] and later Timonov [4] suggested that there are two major steady currents: the outgoing current along the Winter coast, which removes the fresher White Sea waters, and the incoming current along the Terskii Coast, which maintains the salinity balance. Timonov [5] estimated the renewal time for the White Sea to be about two years, which is a rapid exchange rate compared to other semi-enclosed seas. However, there has been some concern about the accuracy of this estimate. This paper presents an analysis of mixing processes in the Gorlo Strait, based on recent observations using modern oceanographic technology.

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MATERIALS AND METHODS

A CTD survey was carried out from June 17 to 21, 2000, over a rectangular area in the Gorlo Strait and adjacent shallow regions of the White Sea Basin and Dvina Bay (Fig. 1), in order to study water mass distribution and mixing. The measurements were taken in a region where water masses from the Basin, Dvina Bay, and the Gorlo Strait come into contact. The mixing process is intensified by strong tides and the shallow and ragged bottom topography. The survey consisted of 50 stations and it was part of a multidisciplinary EU-INTAS project, entitled Mesoscale Physical and Biogeochemical Processes in Coastal Waters of the Russian Arctic. Measurements were taken using the research vessel Kartesh, with typical distances between stations of 3–6 km. Vertical profiles of temperature and salinity were obtained with the CTD probe SBE–19 from Sea Bird Electronics, with a vertical resolution of about 0.3 m. Both down- and up-casts were recorded to monitor any changes in the water properties due to the ship drift caused by tidal currents during the period of measurements at a station (about 10 minutes). Throughout the survey, the weather was calm, with wind speeds never exceeding force 2 on the Beaufort scale. The study includes a comprehensive analysis of the 3D water mass structure, and it is based on horizontal charts of temperature and salinity distribution at various depths, vertical cross sections along and across the Gorlo Strait, temperature-salinity diagrams, vertical profiles at individual stations, and an analysis of temperature and salinity fluctuations in the areas of strong mixing. The results of the analysis are presented in the following section and are supported by a selection of plots, which reveal the mesoscale horizontal and small-scale vertical structure of water masses.

RESULTS

Generally, the large-scale distribution of hydrographic parameters in the White Sea was typical for early summer conditions [1]. However, the dense grid of stations and the high vertical resolution of the newly obtained data allowed us to study the water mass distribution and mixing in greater detail. The chart of temperature distributions (Fig. 1) at a depth of 5 m clearly shows the spatial structure of water masses in the near-surface layer. The northern and northeastern parts of the study area are occupied by the modified Gorlo Strait

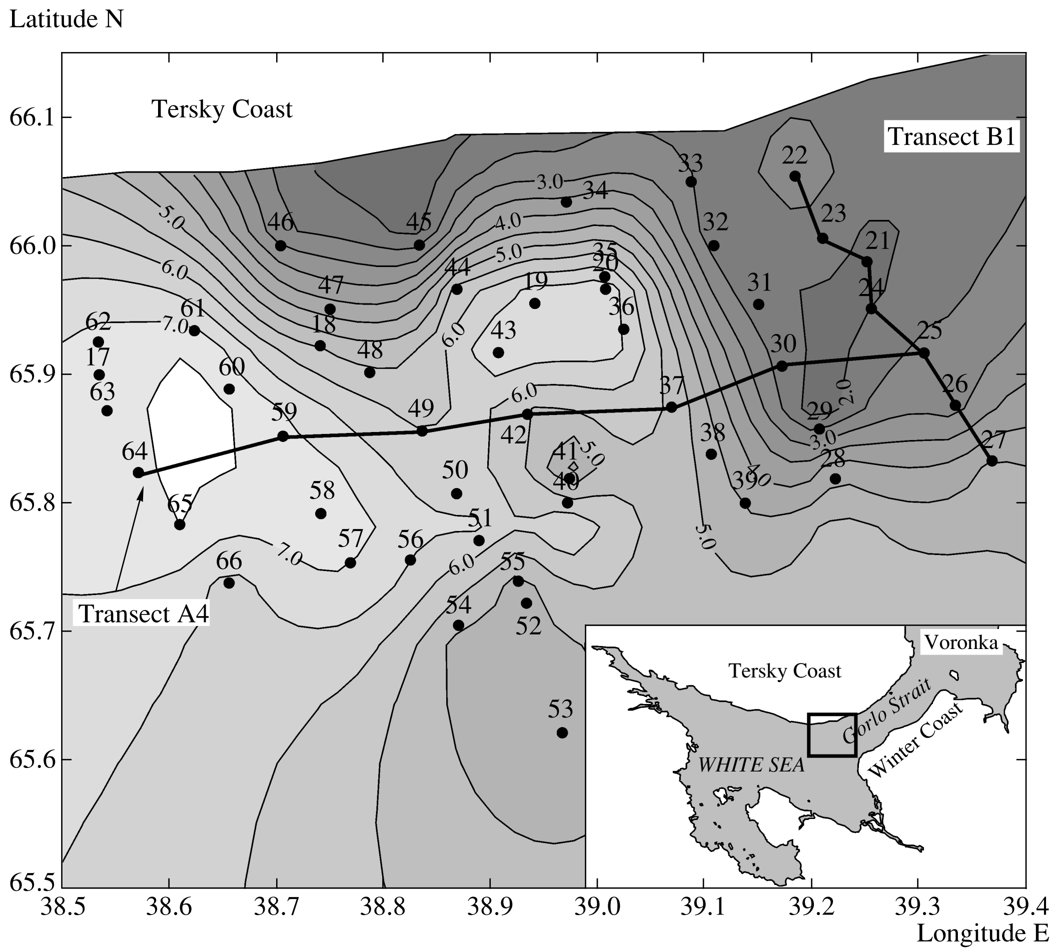

Fig. 1. Temperature distribution at a depth of 5 m in the mixing area at the southwestern end of the Gorlo Strait, June 2000.

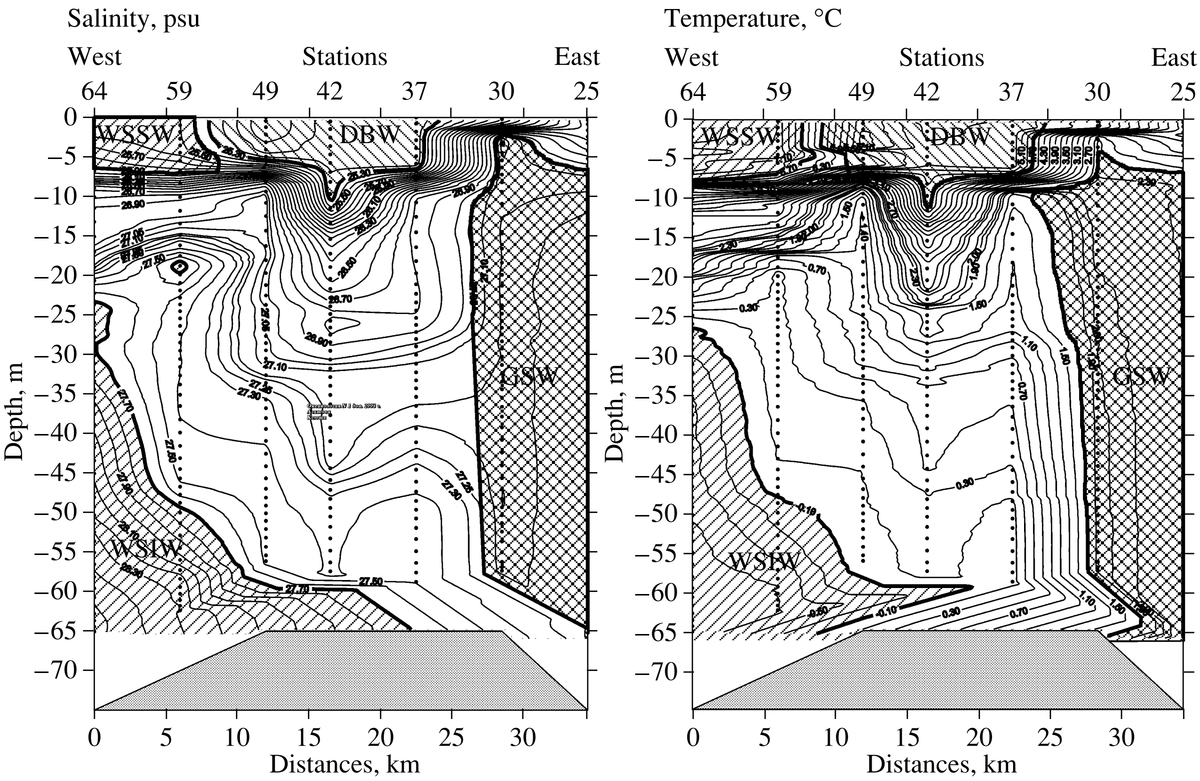

Fig. 2. Temperature and salinity on a cross-section (Transect A4) along the southwest end of the Gorlo Strait, June 2000.

Water (GSW, 1.9–2.4°C, 27.05–27.25 psu). The "source current" [1] brings waters from the Voronka into the Gorlo Strait, where it is well mixed due to intensive tidal mixing. The warmest was the White Sea Surface Water (WSSW; 6.7–8°C; 25.5–25.9 psu), which occupied the western side, whilst the fresher and slightly colder Dvina Bay Water (DBW, 4.8–6.1°C; 24.8–25.3 psu) was advected from the south, probably by the cyclonic Dvina Bay gyre [5, 8]. The influence of this gyre and the adjacent Terskii Coastal Current [1] is evident from the intrusion of colder GSW into the western end of the Gorlo Strait along the Tersky Coast in the north.

In the central part of the area studied, the measurements reveal a mesoscale patch (lens) of WSSW, which is surrounded by colder GSW from the north and a mixture of GSW and DBW in the south. Despite having a diameter of only 7–8 km and a thickness of 8–10 m, the lens core is well defined and occupied four adjacent CTD stations. The lens is separated by a sharp thermocline (a drop in temperature by 6°C at a 5-m depth) from the underlying water. This thermohaline feature is indicative of the initial stages of an anticyclonic mesoscale eddy formation, a process well observed in various parts of the World Ocean (e.g., [6, 7]) but which has not been reported in the White Sea before. Formation of the lens might be forced by the baroclinic instability of the thermohaline front and the associated current, or, alternatively, by the intensification of the Dvina Bay gyre due to the increase of fresh water discharge. South of this lens, there is a small patch of surface Dvina Bay Water; however, it was only evident at station 41, and we were not able to resolve its horizontal structure.

Contours of salinity and temperature in Transect B1 (see Fig. 1) clearly show the incoming Gorlo Sea Water. This water mass is present in Transect B1 (not shown here) through the entire water column and at the bottom, with the exception of fresh surface water—probably already mixed—from a depth of 10 m to the surface. The contours of salinity 27.05 and temperature 2.4°C show the parameters for the Gorlo Strait Water, which are separated from fresher and warmer water in the surface layers.

Moving closer to the White Sea Basin from the Gorlo Strait, the "core" of the Gorlo Strait Water is considerably reduced across the strait, due to mixing caused by the surrounding water masses. Here we note the presence at stations 28 and 29 (i.e., at the southernmost location) of the Dvina surface water, with a maximum salinity of 25.3 and minimum temperature of 4.8°C. In the thin surface layer (5–10, approximately 15 m below the surface) at stations 29–30, sharp gradients of temperature and salinity show a region of mixing between the Dvina surface water and the Gorlo Sea Water. In the shallow areas close to the Terskii shore (stations 32–33), the water is well mixed with water that is fresher compared to that of the Gorlo Strait Water. This probably implies topographic stirring near

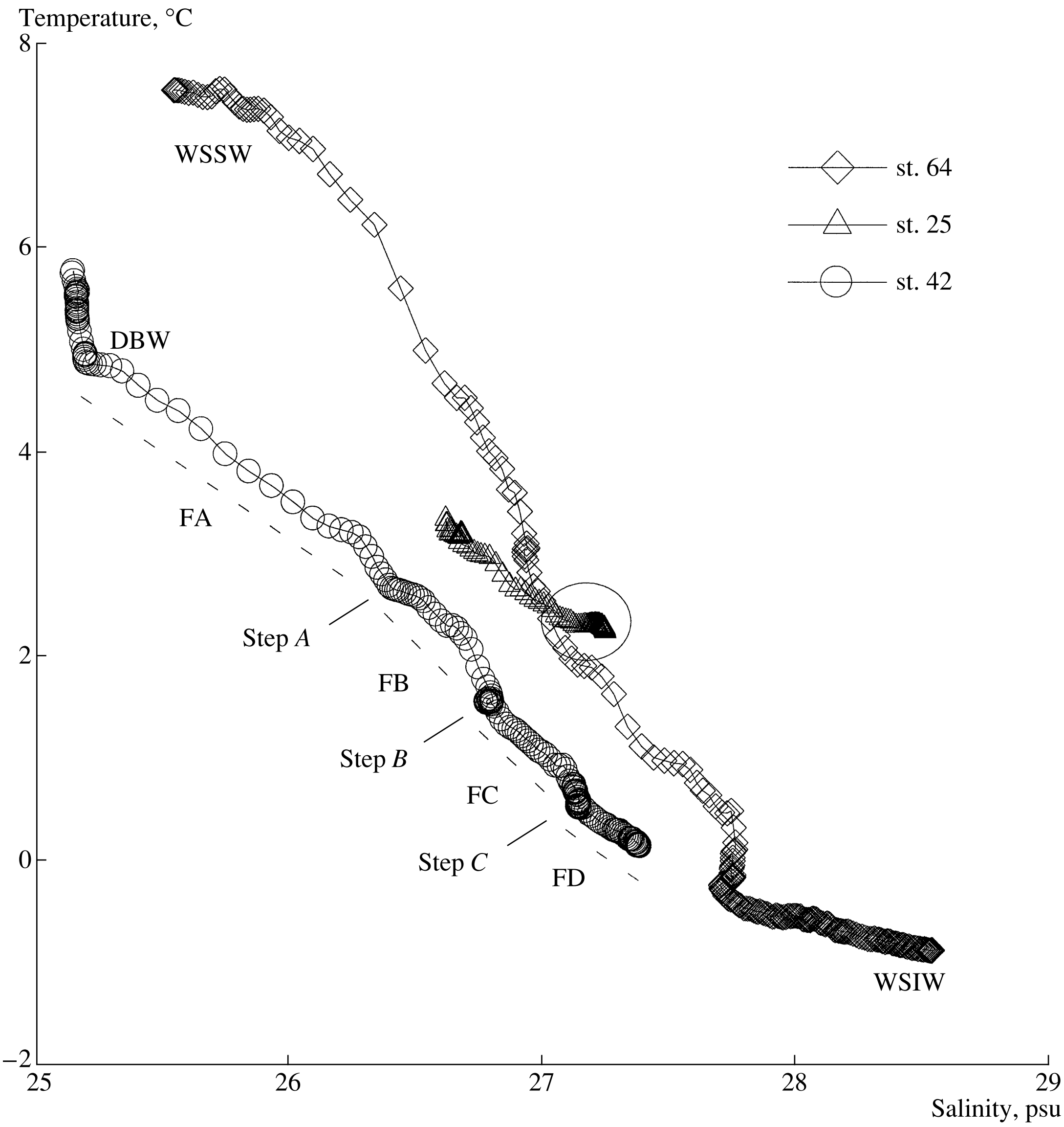

Fig. 3. TS Diagram of selected stations from Transect A4 showing the contacting water masses and different aspects of mixing in the southwestern part of the Gorlo Strait.

the bottom (25–30 m) and mixing with fresher and warmer WSSW coming from the basin with local circulation gyres.

Therefore, it is interesting to analyze along shore cross sections in order to identify the area where bottom mixing occurs more intensively. One could expect that areas of strong mixing should be separated from the source water masses by a sharp front. The temperature and salinity for transect A4, across the thermal front, is shown in Fig. 2. This transect avoids the warm mesoscale patch and it clearly shows four water masses and their interaction in the southwestern end of the Gorlo Strait. In addition to the three water masses described above, this transect reveals the cold and saline White Sea Intermediate Waters (WSIW, –0.1 to –1°C and below, 27.7 to 28.5 psu and more). This water mass occupies a depth range below 25 m, and it is believed to be formed by the previous winter's cooling and salinization due to the incoming current from the Gorlo Strait along the Terskii Coast. The current brings more saline Barents Sea waters, modified through stirring and mixing in Voronka Bay.

Gorlo Strait Water on the eastern side of the transect is well mixed below 5–7 m, and it is covered by a duvet of warmer surface water, which could be attributed to summer heating. Surface waters from the Basin (in the western end of the transect) and Dvina Bay (in the center) occupy a thin layer, penetrating no deeper than 8–10 m. The mixing area between WSSW and DBW is concentrated in a narrow band not exceeding 5 km. The temperature front between warmer GSW and colder WSIW occupies the water column from 15–25 m down

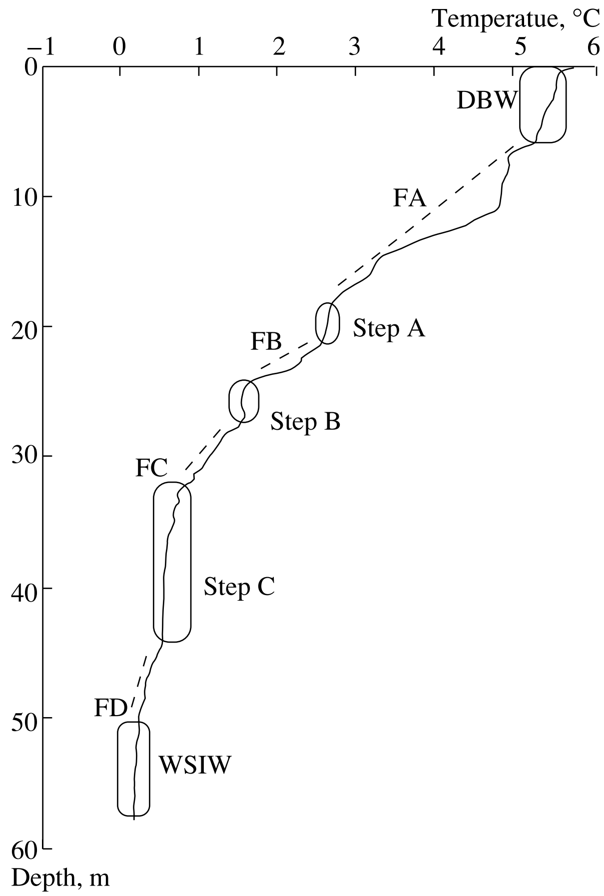

Fig. 4. Temperature profile at station 42, showing the mixing region marked as anomaly fluctuations FA, FB, FC, and FD, and identified water masses along with previously mixed water from observed quasi-homogeneous layers (Steps A, B, and C).

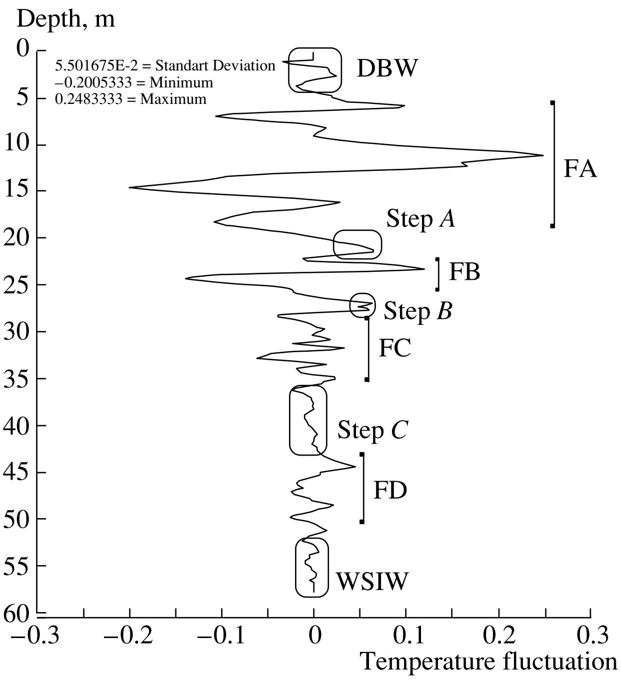

Fig. 5. Temperature fluctuation derived at station 42 using a running filter with a 15-point averaging window. Water masses and mixed layers (steps) are marked with the fluctuations FA, FB, FC, and FD, showing different aspects of mixing through the water columns.

to the seabed. Frontal mixing takes place in a strip between 20 and 25 km wide, coinciding with the shallowest area on the transect. The resultant water mass leaks into the White Sea as a thin intrusion at a depth of 15–25 m. Along its way, the water mixes with the overlying DBW and WSSW, producing well developed temperature and salinity inversions, as well as quasi-homogeneous layers (Steps).

Tidal currents occupy the whole water column from the bottom to the surface, although the shear stress caused by bottom friction is expected to be stronger than near the thermocline. Within the stratified layers, the intensity of mixing is controlled by the balance of production of turbulent energy by baroclinic shear currents, which facilitates mixing, and the hydrostatic stability of the water column, which suppresses mixing. We can also judge the intensity of mixing by the degree of reduction of the “core” of the identified water masses. Therefore, T-S diagrams are a useful tool to clearly determine the “core” of water masses, and to identify the mixed waters that result from these different mixing processes.

Core water masses and their mixtures are seen on the T-S diagrams shown in Fig. 3. In order to keep the figure clear, only three stations from the transect A4 are plotted, with stations 25, 42, and 64 representing the eastern end, the center and the western end of the transect, respectively. The diagram shows individual data records using nonconnected symbols, so that core waters and quasi-homogeneous layers are seen as the darker parts of the curve, while stratified waters are represented by lighter areas. Station 25 reveals the most uniform water, although two clusters—i.e., the colder GSW and warmer surface water—are easily identified. Station 64 incorporates the three main water masses—cold and saline WSIW, warm and less saline WSSW, and a small amount of GSW—penetrating into the Basin at a depth of 15–20 m in the form of a quasi-homogeneous layer.

The most complex picture of the mixing process was observed from station 42. This was obtained by subtracting the averaged profile from the original high-resolution profile. Smoothing was performed by a running mean method with an averaging window of 15 data points. There, the top of the water column is occupied by modified DBW from the sea surface down to 6 m, marked DBW in Fig. 4. Beneath it there is a sharply stratified pycnocline (marked FA), which ends at depth of 17 m. Further down we see a 4-m thick homogeneous layer (Step A), which contains the mixture of DBW, GSW, and WSIW. Beneath that, the stratified layers FB and FC connect the temperature inversion (Step B, 24–28 m) and the deep homogeneous layer (Step C, 36–44 m). Mixed water with a strong contribution of WSIW occupies the near bottom layer.

Temperature fluctuations are shown in Fig. 4. The most intensive oscillations, up to 0.25°C, relate to the thermocline (marked as FA) that separates surface DBW from the modified waters of Step A. Strong fluctuations are evident near the bottom, despite the fact that the layer is already nearly homogeneous.

CONCLUSION

The study area was located in the southwestern part of the Gorlo Strait, where four water masses come into contact. The measurements were carried out soon after the maximal intrusion of the Dvina Bay Waters into the Gorlo area. A high-resolution CTD survey revealed the mechanism of mixing of different water masses in the Gorlo Strait of the White Sea. Water masses in contact with each other were separated either by a sharp thermocline or by hydrographic fronts. At the time of measurements, the incoming waters from Voronka Bay were warmer and saltier than the home waters of the White Sea. Mixing processes included vertical stirring and horizontal exchanges through interleaving at the thermal and salinity fronts. The formation of mesoscale eddies, apparently due to baroclinic instability, extends the length of the boundary that separates differing water masses and hence facilitates horizontal mixing. Vertical mixing is highly enhanced by strong tides in the Gorlo Strait. The resultant mixed water is advected into the White Sea basin along the Terskii Coast.

ACKNOWLEDGEMENTS

The study was partially supported by the EU through grant INTAS–97–1881 and by the Higher Education Funding Council for England (HEFCE) through QR funding. The authors wish to thank Prof. Geoff Millward for his helpful comments.

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