Variation of the cold intermediate water in the Black Sea exit of the Strait of Istanbul (Bosphorus) and its transfer through the strait*

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Hüsne Altiok*
Halil İbrahim Sur
Hüseyin Yüce

Institute of Marine Science and Management,
Istanbul University,
Müşküle sk. 1, Vefa Istanbul, Turkey;

e-mail: altiokh@istanbul.edu.tr

*corresponding author

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Abstract

The cold intermediate water (CIW, T < 8°C) entering the Strait of Istanbul and its variation along the strait have been studied by using monthly conductivity-temperature-depth (CTD) data sets collected during the period from 1996 to 2000. In the northern exit of the strait, CIW is located between the seasonal thermocline and Mediterranean water originating from the lower layer of the Sea of Marmara. The thickness of CIW decreases from April to October. In the Strait of Istanbul, CIW is observed as a layer of temperature < 14°C. The thickness of this modified cold intermediate water flowing southwards with the upper layer decreases, while its temperature increases along the strait due to mixing with adjacent water. In the southern exit of the strait, the modified cold intermediate water is observed during the period from May to October. If CIW exists in the Black Sea exit region of the strait, modified cold water is found in the Marmara exit region during the

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same period. The distribution of CIW in the Strait of Istanbul contributes to our understanding of the dynamics of the strait, especially in the summer months.

1. Introduction

The Strait of Istanbul has a two-layered flow system between the Black Sea and the Sea of Marmara. The lower layer carries the more saline water to the subhalocline part of the Black Sea while the upper layer carries the less saline water to the Sea of Marmara. The upper layer (~ 18 PSU) originates from the Black Sea, the lower layer (~ 38 PSU) from the Sea of Marmara. Flow exchange is affected mainly by the hydraulic conditions generated by the geometry of the strait. One specific water mass through the strait is the cold intermediate water (CIW) observed below the seasonal thermocline in the Black Sea during the summer months (Tolmazin 1985, Stanev 1990). Part of CIW is found in the Strait of Istanbul and the Sea of Marmara. The warm and more saline lower layer, called Mediterranean water, flows to the Black Sea and extends as a salt wedge over the continental shelf and is controlled by a sill lying in the northern extension of the Bosphorus channel (Ünlüata et al. 1990, Yüce 1990, 1996a,b, Latif et al. 1991, Di Iorio & Yüce 1999). The Mediterranean water effluent mixes with CIW, and its temperature and salinity decrease in the shelf region of the Black Sea exit of the Strait of Istanbul (Özsoy et al. 1991, 2001, Oğuz & Rozman 1991, Gregg & Özsoy 1999). The influence of this water can be seen in the intermediate layer in the Black Sea (Buesseler et al. 1991, Özsoy et al. 1993). Tsimplis et al. (2004) analysed long term data and found a significant correlation between the salinity of the upper water of the Aegean Sea and the layer between 50 and 300 m in the Black Sea, indicating that the latter layer is a product of the Mediterranean inflow.

CIW is defined as water of temperature $< 8°$C located between the seasonal and permanent halocline in the Black Sea. In the central basin of the Black Sea, it lies at depths of 50–150 m (Tolmazin 1985, Stanev 1990). The main source of CIW is considered to be the cold north-western shelf waters during the winter months in the Black Sea (Tolmazin 1985). The other source of CIW is thought to be the centre of cyclonic eddies (Ovchinnikov & Popov 1987). Ivanov et al. (1997) claim that CIW is partly formed in coastal anticyclones. Its temperature and salinity characteristics provide evidence for its existence in different parts of the sea (Oğuz et al. 1998). Oğuz & Beşiktepe (1999) reported that CIW is formed in the north-western Black Sea and transported by the Rim Current along the shelf. Stanev et al. (2003) analysed CIW formation using the Modular Ocean Model (MOM) and in situ observations. They indicated that CIW is formed over the entire Black Sea and its residence time is ~ 5.5 years.

Neighbouring water masses can easily influence CIW, which itself is a dynamically passive layer (Stanev 1990). The CIW is advected by the Rim Current and entrapped by the associated eddy field (Oğuz et al. 1992). Cold water is observed in the shelf around the anticyclonic eddies (Andrianova & Kholoptsev 1992, Sur et al. 1996, Sur & Ilyin 1997). The thickness of CIW decreases on the shelf in conformation with the bathymetry and upward displacement (Trukhchev et al. 1985, Stanev 1990).

The Sea of Marmara, an inland basin between the Black Sea and the Aegean Sea, has a two-layered structure that is separated by a strong pycnocline at a depth of about 25 m. The upper layer consists of waters of Black Sea origin; its renewal time is estimated at 4–5 months (Ünlüata et al. 1990, Beşiktepe et al. 1994). A cold intermediate layer just above the halocline is observed in this sea during the summer months. This layer is thought to be partially formed within the Sea of Marmara in the winter months and partially advected from the Black Sea (Ünlüata et al. 1990). A temperature decrease in this layer is also observed in summer (Altıok et al. 2000).

The objective of this study is to discuss the transfer of CIW through the strait by monitoring monthly variations in temperature at both exits of the strait. First, the temporal and spatial variation of CIW in the Black Sea exit of the Strait of Istanbul is examined. The variation of the cold layer in the Black Sea exit is discussed using the term $(\mathrm{CIW})_8$, where 8 denotes

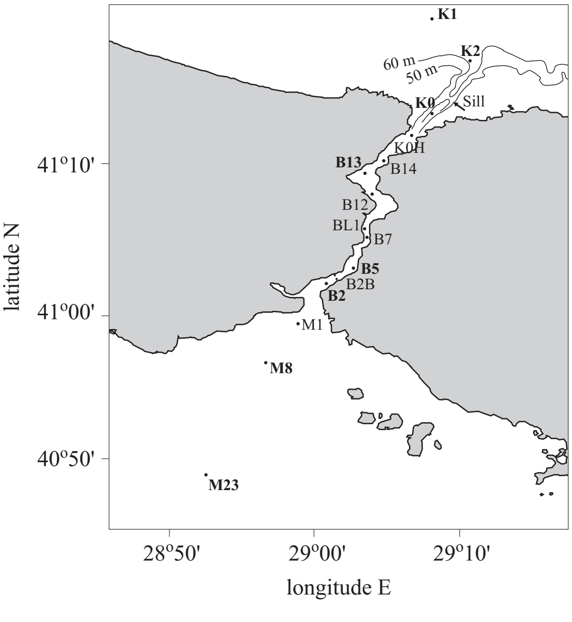

Figure 1. Location of stations (stations measured monthly are shown in bold)

the maximum temperature of this cold layer. This water is Black Sea CIW. Later, the transition of this layer through the Strait of Istanbul is explained using temperature transects. Finally, in the Sea of Marmara, the temporal variations of the cold layer are examined by using $(\mathrm{CIW})_{14}$, which denotes water with a maximum temperature of 14°C. This water is called modified Black Sea CIW.

This study is based on conductivity-temperature-depth (CTD) data collected in the Strait of Istanbul and at both exits of the strait during the period 1996–2000 by r/v 'Arar' of Istanbul University, Institute of Marine Science and Management (IMSM-IU) (Figure 1). CTD casts were made with SeaBird SBE-9 and SBE25 Sealogger (November 1997–May 1998) CTD systems. The temperature and salinity differences between the two instruments at the same station are 0.03°C and 0.014 PSU respectively (Altıok 2001). These small differences can be considered negligible.

2. Results and discussion

2.1. $(\mathrm{CIW})_8$ in the Black Sea exit of the Strait of Istanbul

After passing the Strait of Istanbul, the Mediterranean water flows into the Black Sea through a deep bottom canyon oriented along the strait's axis in a north-easterly direction. There is a sill ~ 5 km away from the strait's exit in this canyon (Figure 1). Monthly observations are made at stations K0 and K2, which are located on the upstream and downstream sides of the sill. Station K0 is located in close proximity to the exit of the strait at a depth of 71 m. Station K2, at a depth of 73 m, is located ~ 8 km from the strait exit after the sill. In order to characterize the regional distribution of water masses in the Black Sea exit of the Strait of Istanbul, the monthly salinity and temperature profiles and T-S diagrams in 1999 for stations K2 and K0 are given in Figure 2.

Danube-influenced water, cold intermediate water and Mediterranean water masses are easily visible on the temperature and salinity profiles. The Danube-influenced water is identified from the salinity values, which are < 17 PSU in the surface layer. The Black Sea cold intermediate water $(\mathrm{CIW})_8$ is distinguished from temperature profiles, especially during the summer months. Its salinity is usually in the range of 17.5–18.5 PSU. The thickness of the Black Sea CIW can change from several metres to 10 metres and its lower limit is generally defined by the Mediterranean water. The temperature and salinity characteristics of the Mediterranean water reflect the warm temperature and high salinity values at the bottom. In the T-S diagrams of the stations K2 and K0 these water masses can be clearly identified from temperature and salinity characteristics.

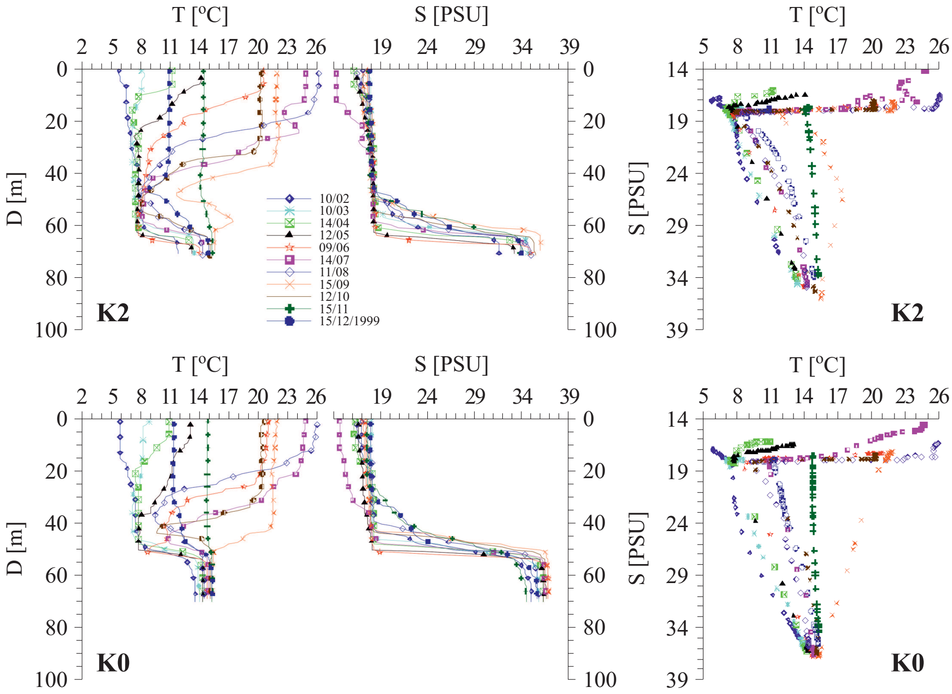

Figure 2. Monthly temperature and salinity profiles and T-S diagrams during 1999 at station K2, and at station K0

The halocline between the brackish Black Sea water and Mediterranean water is observed at ~ 50–65 m depth at station K2 and at 35–55 m depth at station K0. The sill located between these two stations is critical for the control of the Mediterranean flow through the Strait of Istanbul (Oğuz et al. 1990). Internal hydraulic adjustment of the lower layer flow induces intense vertical mixing downstream of the sill. There can therefore be a big difference in temperature and salinity characteristics between these two stations despite their being situated close to each other. The temperature and salinity profiles at station K2 indicate the existence of Mediterranean water below a depth of ~ 65 m. The temperature range is 12–16°C and the salinity range is 31.5–36 PSU. At station K0, the Mediterranean water layer is thicker (~ 20 m) and more saline (34.3–37 PSU). It is diluted and its thickness decreases along the path from station K0 to station K2 (Figure 2). The average salinity and thickness of the Mediterranean water layer is 35.65 PSU and 20 m at station K0, and 33.75 PSU and 15 m at station K2. The dilution is estimated at 29% from these values. The calculated dilution rate is in agreement with Özsoy et al. (1993), who found the ratio of entrainment flux over the shelf to the Mediterranean flux to be 3–6.

The salinity range of the upper layer is 14.3–18.0 PSU at station K2 and 14.5–18.0 PSU at station K0. Sur et al. (1994) reported that the mean surface salinity (upper 10 m) was 18 PSU in the south-western Black Sea during the period from 1985 to 1992. They also reported that the salinity decreases to 16–17 PSU when the Danubian influence is felt in the area from March to August each year. We made similar observations in the same area. Less saline waters (< 17 PSU) are recorded in February 1999 and during the period from April to August 1999. Our observations also show that the salinity of the upper layer is less than 15 PSU (14.3 PSU at station K2 and 14.5 PSU at station K0) in July 1999. The thickness of this water layer is ~ 40 m at station K0 and ~ 30 m at station K2. This rather thick and much diluted water mass clearly shows the strong influence of Danube water in the area (Sur et al. 1994, Sur & Ilyin 1997).

Temperature profiles indicate a two-layered stratification in the winter months but three layers in the summer months. The upper layer temperature range is ~ 6–26°C at both stations K2 and K0. The coldest surface water is observed in February (6°C). Its thickness is ~ 15 m at K0 and several metres at K2. Below this cold surface layer, the temperature increases slowly to ~ 8°C, then rises rapidly to 11°C in the interface depth. From March onwards, surface waters warm up as a result of atmospheric heating. The surface water temperature reaches a maximum in August at stations K0 and K2. When the surface temperature is > 8°C, the cold layer appears between the warm surface layer and the lower layer.

The surface water thickness increases while the CIW thickness decreases at both stations from March to October. However, this is not a regular feature. For example, in July when Danubian waters are observed in the area, the surface layer is rather thick and the amount of cold water is small compared to June and August. This can be explained by the 40 m thick layer of Danubian waters influencing the area. The mean discharge of the River Danube is 6550 $m^3\ s^{-1}$, the highest discharges are observed between March and July, and the lowest ones in August-November (Lampert et al. 2004). Sur et al. (1994) reported that Danube-influenced water can arrive in the vicinity of the Bosphorus within the space of 1–2 months, assuming a mean current speed of 10–20 cm s^{-1}. One other exception was observed in September 1999, when the surface layer was rather thick, and cold water (the minimum temperature was nearly 12°C) was observed only at station K2. The reason for the absence of cold water at station K0 could be explained by the strong Rim Current, flowing eastwards at station K2. One month later, in October 1999, the base of the surface layer was at a shallower depth, and CIW was thicker than in September. In November 1999, the water column had almost the same temperature ($\sim$ 15°C) and CIW disappeared.

In December 1999, the surface layer temperature was about 11°C at both stations, but there was a cold layer with a minimum temperature of 9°C below 40 m depth at station K2. In all cases (July 1999, September 1999 and November 1999), the diminishing or disappearing CIW was related to the Rim Current. The Rim Current advects CIW to the area in accordance with its dimensions and speed. There are many different spatial and temporal scales of the anticyclonic eddies on the right-hand side of the Rim Current in the south-western Black Sea (Oğuz et al. 1992, Sur & Ilyin 1997, Oğuz & Beşiktepe 1999). In the anticyclonic eddies CIW mixes with the upper layer as a result of a turbulent entrainment mechanism. Cold and warm temperature anomalies in the surface are commonly observed in this region (Sur & Ilyin 1997). The irregular thickness and temperature of the cold layer at stations K2 and K0 are related to these eddies instead of atmospheric heating/cooling.

Comparison of the temperature profiles of stations K2 and K0 for 1999 indicates that CIW at station K2 was thicker than the one at station K0. For some months, there was no cold water whatsoever at station K0, whereas CIW was observed at station K2 owing to the variable current pattern in the Black Sea exit of the strait. In September 1999, some warm water occurred in the halocline at station K2. Because of the absence of the cold layer at station K0 while the Mediterranean water was flowing to station K2, this was in direct contact with the overlying warm upper layer, and entrainment from that upper layer increased its temperature slightly. This feature was not observed in November 1999, because the temperature of the upper layer was close to that of the lower layer.

In order to show the annual and seasonal variation of the cold intermediate layer we need to distinguish CIW with a temperature < 8°C $(\mathrm{CIW})_8$ from other CIW having a higher temperature, as can be seen from the temperature profiles. The time series of $(\mathrm{CIW})_8$ together with the upper layer thickness and the Mediterranean water at stations K2 and K0 between 1996 and 2000 are given in Figure 3. The same figure also shows the minimum temperature and corresponding salinity values. The layers are distinguished according to temperature. If there is a cold water layer of temperature < 8°C, the upper layer thickness is defined as the starting depth of this layer. By definition, the lower layer lies below the cold layer. For 1996, measurements are available only in August and November at station K2. For 1997 and 1998, the measurements are available fortnightly during the summer period at station K0. $(\mathrm{CIW})_8$ is found between the warm upper layer and the Mediterranean water in varying thicknesses. The minimum temperature and $(\mathrm{CIW})_8$ thickness are also different between stations K2 and K0. Monthly and annual changes in the amount and minimum temperature of $(CIW)_8$ are observed in the region.

The minimum temperature of $(CIW)_8$ at station K2 is generally lower and its thickness greater than at station K0. During certain months, the $(CIW)_8$ is not observed at station K0, such as in November 1996, 1997, May and September 1998. The thickness of $(CIW)_8$ at station K2 is only a few metres during the same months.

$(CIW)_8$ is usually observed from March or May to October according to the upper layer temperature. The minimum temperature and salinity of $(CIW)_8$ is observed from March to May, indicating that this water is formed during the winter months in the region. On the other hand, the minimum temperature of $(CIW)_8$ decreases slightly in June 1997 and 1998. The reason for this temperature decrease is thought to be new cold water, advected to the region by the Rim Current (Oğuz et al. 1992, Sur & Ilyin 1997, Oğuz & Beşiktepe 1999). Because the temperatures of the layers above and below $(CIW)_8$ are higher than that of the cold intermediate layer, there is no source of cooling; the temperature decrease must therefore be due to advection. The $(CIW)_8$ thickness decreases and its depth increases from April to October due to atmospheric heating. However, this decrease in thickness is not a regular feature. In some months $(CIW)_8$ is not observed at all. But later on it appears again, as in November 1997. This feature can be explained by the existence of anticyclonic eddies in the region during the summer months (Sur & Ilyin 1997). The other effect is considered to be Danube-influenced water, which is advected by the Rim Current to the region. When the Rim Current is strong and close to the coast, Danubian water is observed in the exit of the Strait of Istanbul (Sur et al. 1994). Our observations show that $(CIW)_8$ has a weak signature at stations K0 and K2 in June and July 1999, when Danubian water is plentiful. The behaviour of the Rim Current and the existence of anticyclonic eddies in the region also influence the amount of $(CIW)_8$ in the exit region of the Strait of Istanbul annually and monthly.

The salinity of the minimum temperature depth may show the interaction of CIW with other water masses. A lower salinity indicates Danubian effects, whereas a higher salinity shows the effects of Mediterranean water. Although the upper and lower layer in the strait can easily change with meteorological conditions, seasonal variations of Mediterranean water in the exit of the strait show that the salinity of the lower layer at stations K2 and K0 increases during the autumn. Altıok (2001) reported that the mean salinity in the exit of the strait is 36 PSU (at station K0) and ranges between

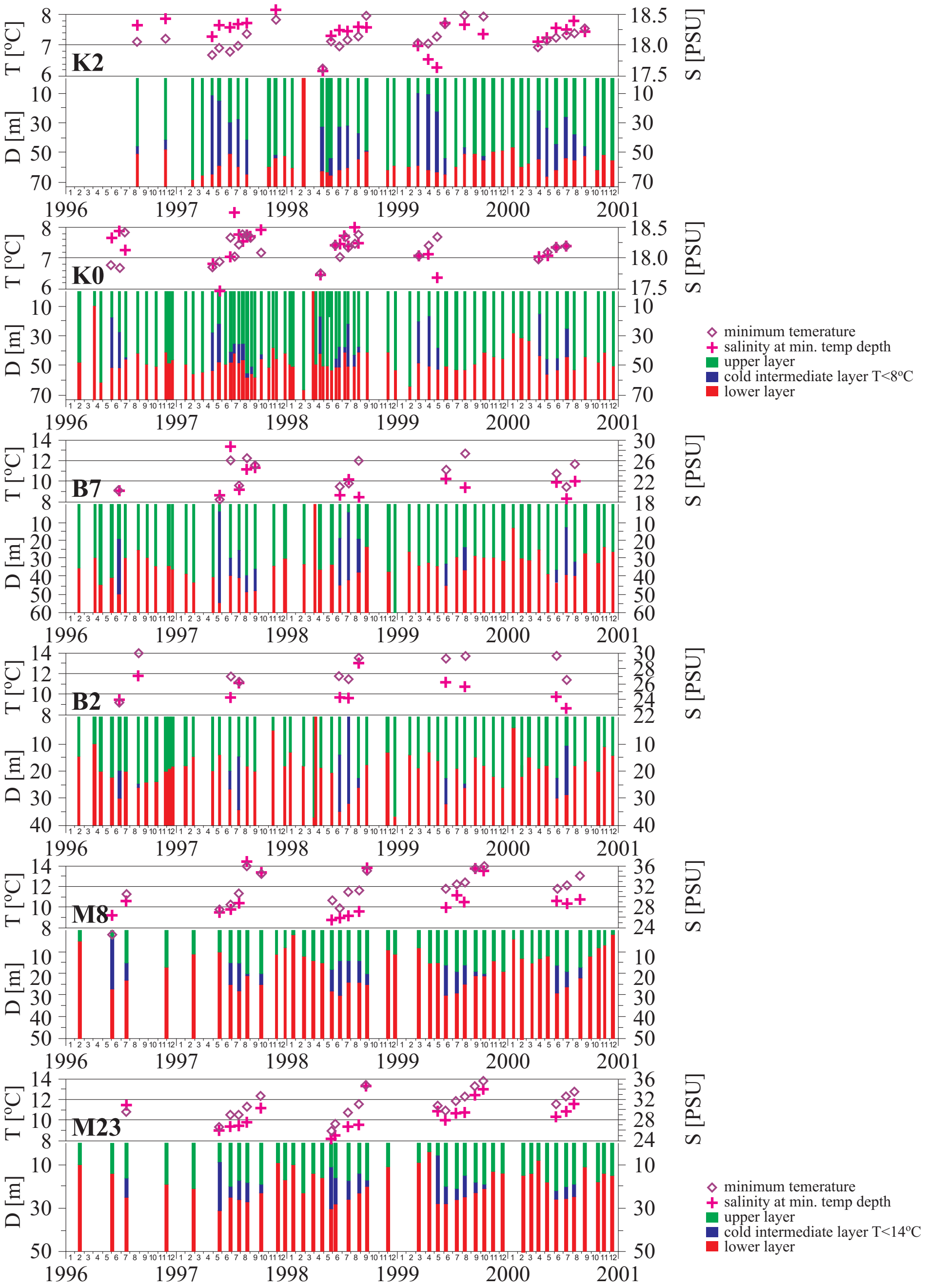

Figure 3. Minimum temperature and thickness of the layers at stations K2, K0, B7, B2, M8 and M23 between 1996 and 2000 (K2 measured monthly since August 1997)

31 and 38 PSU from an evaluation of monthly T-S data during the period 1996–2000. The maximum thickness and salinity of the Mediterranean water can be observed in the same season. On the other hand, due to atmospheric heating, the seasonal thermocline lies deeper during this season. The fact that the thickness of $(\mathrm{CIW})_8$ at station K2 decreases while that of Mediterranean water increases suggests that $(\mathrm{CIW})_8$ is influenced by the Mediterranean water. Thus we can say that the higher salinity at the minimum temperature depth indicates mixing with Mediterranean water (Figure 3).

The factors mentioned above affect the temperature and thickness of $(\mathrm{CIW})_8$ in the northern exit of the strait. The salinity at the minimum temperature depth is an indicator of the water's characteristics. A higher salinity (18.5 PSU) indicates more intense mixing with the lower layer of Mediterranean water. On the other hand, a lower salinity (17.5 PSU) indicates mixing with coastal waters originating from the north-west Black Sea. In June and July, when CIW is advected to the region, the minimum temperature of $(\mathrm{CIW})_8$ slowly decreases and the salinity at the minimum temperature depth increases. A thicker $(\mathrm{CIW})_8$ with the minimum temperature is observed in the region during those months when there are no anticyclonic eddies.

2.2. CIW in the Strait of Istanbul and the southern exit of the strait

$(\mathrm{CIW})_8$ was studied at two stations – B7 and B2 – in the Strait of Istanbul in 1999 (Figure 1), station B7 being chosen because of its location in the middle of the strait close to the channel contraction, and station B2 in the southern exit of the strait. The temperature, salinity profiles and T-S diagrams (Figure 4) at station B7 indicate that the depth of the interface varies in the range of 30–45 m. The upper layer temperature is between 6.2 and 25.1°C and its salinity changes between 15 and 23 PSU. The lower layer temperature is 14.2–15.8°C and the salinity 36.5–37.8 PSU. The Mediterranean water layer is more saline and thicker at station B7 than at station K0. The salinity of the upper layer is also slightly higher than at station K0. For example, the salinity of the upper layer increases from 14.6 PSU at station K0 to 15.4 PSU at station B7 in July 1999 when Danube-influenced water is observed in the Black Sea exit of the strait. The upper layer salinity is almost 23 PSU in November and December 1999 due to an Orkoz event. During this event, strong south-westerly winds oppose the surface flow in the strait and cause the upper layer of the Sea of Marmara to fill the strait (Latif et al. 1991).

Cold water is observed at station B7 only in June, July and August 1999, but this is not the original $(\mathrm{CIW})_8$, as the minimum temperature of this cold water is ~11°C in June 1999. The reason for the increase in temperature of the cold water is mixing with the warm surrounding waters along the strait. As can be seen from the T-S diagrams (Figure 4), the upper and lower layers at station B7 mix with each other because of entrainment along the strait (Oğuz et al. 1990). As a result of this mixing, the salinity and temperature of the cold water also increase, and it becomes located partly within the halocline.

The temperature, salinity profiles and T-S diagrams at station B2 in 1999 indicate that the interface is observed between 20 m and 35 m depth. The upper layer temperature shows seasonal variations in the range from 6.5 to 24.8°C, and its salinity changes in the 15.5–23 PSU range. The lower layer temperature ranges from 14.5 to 16°C, its salinity from 36.7 to 38.1 PSU. The cold layer is found at station B2 only in June and August 1999, and its minimum temperature is slightly less than 14°C during both months. The cold water coming from the Black Sea mixes with ambient water because of the hydraulic conditions of the strait. Therefore, the

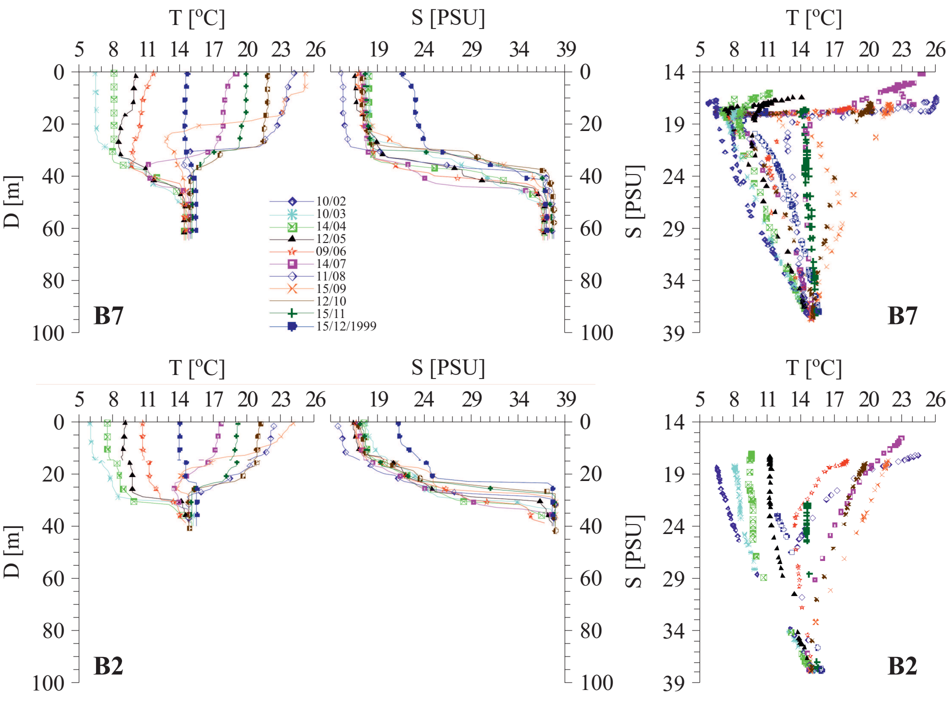

Figure 4. Monthly temperature and salinity profiles and T-S diagrams during 1999 at station B7, and at station B2

surface layer temperature at station B2 is slightly lower than at stations K0 and B7 in the summer months. There is also a temperature decrease in the lower layer (Mediterranean water) in the opposite direction (i.e. from station B2 to station B7 and K0) along the strait. The oppositely directed flow system in the Strait of Istanbul causes a decrease in the amount of cold intermediate water.

Further offshore from the Sea of Marmara exit of the Strait of Istanbul, the cold intermediate water is investigated by using temperature and salinity profiles at stations M8 and M23 in 1999 (Figure 5). At these stations, the surface and bottom layers of the Sea of Marmara are separated from each other by a thin interface layer that is found at varying depths in accordance with seasonal or meteorological events. The cold layer is located in the halocline. The upper layer temperature shows seasonal variations; its value ranges from 9 to 23.5°C at station M8 and from 8.5 to 24°C at station M23. The upper layer salinity also varies seasonally between 18 and 23 PSU at station M8, and between 20 and 23 PSU at station M23. On the other hand, the lower layer temperature and salinity indicate small seasonal changes. The minimum salinity of 18 PSU at station M8 is observed in July 1999,

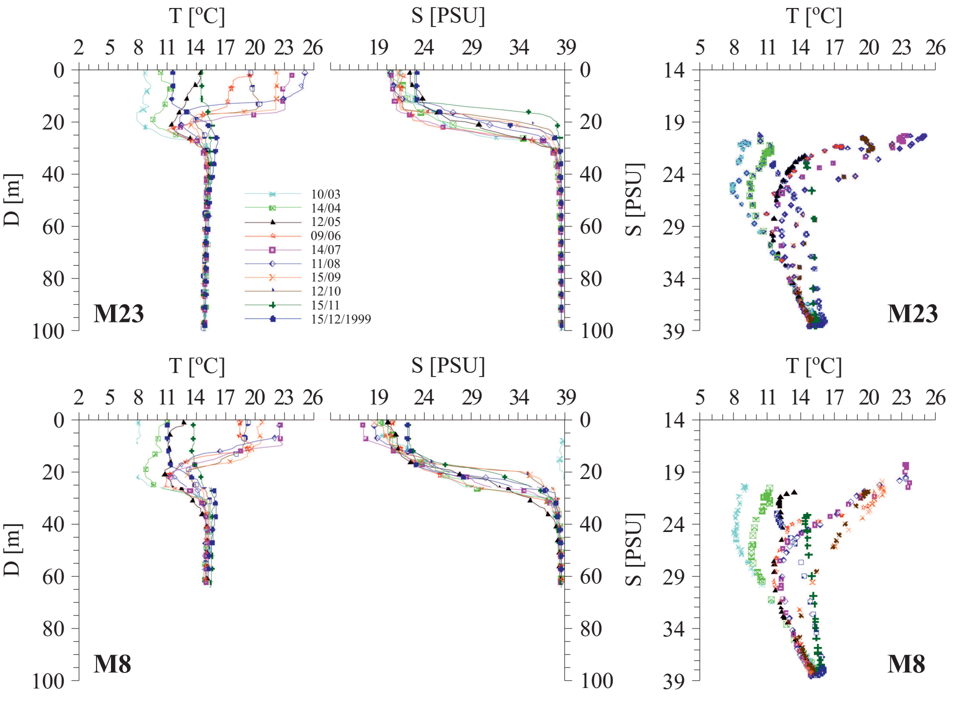

Figure 5. Monthly temperature and salinity profiles and T-S diagrams during 1999 at station M8, and at station M23

when Danube-influenced water is found in the exit of the strait (stations K2 and K0) and in the strait itself (stations B7 and B2). The upper layer temperature varies over a wide range as a result of atmospheric cooling and heating. Less saline water can be seen from the T-S diagrams over a wide temperature range (Figure 5). Station M8 is directly influenced by the strait flow, but station M23 possesses the characteristics of the Sea of Marmara. The upper layer temperature is lower at station M8, as at station B2 in the summer months. The upper layer of the strait reaches station M8 as a jet flow and changes its characteristics. The thickness of the cold intermediate layer at station M8 is less than that at station M23. The cold water coming from the strait to the Sea of Marmara (at station B2) is not as cold as at station M23, but surface temperatures at station B2 are always lower than those of the strait and the Sea of Marmara stations. The cold layer at stations M8 and M23 becomes thinner and warmer during the summer months.

The effects of atmospheric heating cause an increase in temperature starting at the surface, so the cold water formed in the winter months gradually disappears during the summer months. But the increase of the cold layer temperature and decrease of its thickness are irregular. For example, the minimum temperature is observed in June 1999 and the maximum thickness is observed in August 1999 at station M23. In June 1999 and in August 1999, the minimum temperature of the upper layer is almost 14°C at station B2. In addition, there is a cold water layer at station B2 in July 1999. The upper layer of water in the Sea of Marmara is replenished by this cold water from the Strait of Istanbul for approximately 3–4 months (Beşiktepe et al. 1994). The temperature increase due to atmospheric heating in the upper layer of the Sea of Marmara does not compensate for the temperature decrease caused by advection of the cold water into the upper layer.

2.3. Transfer through the strait

In the summer months, a cold intermediate layer identified as a tongue-shaped extension towards the south is generally observed in the Strait of Istanbul. Its temperature is about 11–12°C in the southern exit of the strait in June and July (Altıok et al. 2000). This cold layer is examined by the temperature transects through the strait shown in Figure 6 for July 1997–2000. The temperature transects in July can be a good explanatory plot for the transition of cold water through the strait, because the temperature difference is higher between the layers. In general, all the transects (Figure 6) show that there are three different water masses in the strait, as can be seen from the T-S diagrams.

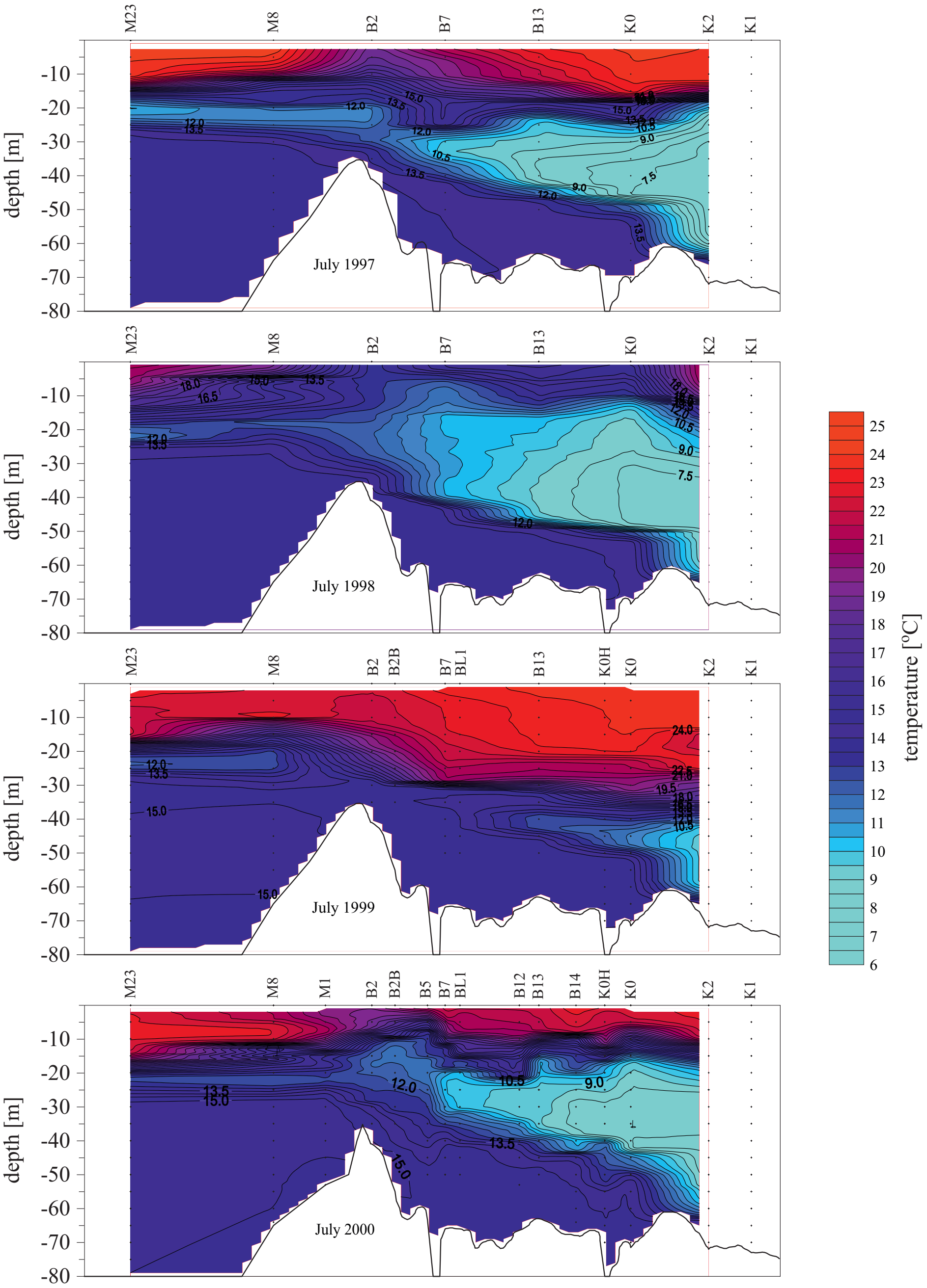

Figure 6. Longitudinal temperature transects through the strait during July between 1997 and 2000

The thickness of CIW and its temperature change every year. In 1997, cold intermediate water is observed along the strait below the warmer upper layer. On the south side of the strait (at station B2), the temperature of the upper layer decreases to 19°C but is 24°C on the north side (at station K0). Temperature transects show that the temperature of the upper layer suddenly decreases after the constricted part of the strait in the south. Owing to the geometry of the strait, the upper layer flows in three-dimensional circulations (Özsoy et al. 1998). This causes vertical mixing between the layers, and the temperature decreases.

In 1998, the warmer upper layer disappears along the strait. The upper depth limit of the 8°C isotherm at station K0 is shallower than the one at station K2 (Figure 6). There is also a significant difference in temperature between these two stations at the surface (20.5°C at station K2 and 14.5°C at station K0). This feature could be due to the anticyclonic eddy formation sometimes observed in the Black Sea exit of the strait (Sur et al. 1996). Eddy formation in the Black Sea exit of the strait generally causes a rise of CIW along the strait (Sur et al. 1994, Sur & Ilyin 1997). In this case, colder water entrains into the upper layer along the strait, as in July 1998.

In 1999, the amount of CIW is too small, so that a thick warmer upper layer is observed along the strait. CIW is observed only as a thin layer in the northern part of the strait. As mentioned above, the thick ($\sim$30 m) Danubian water layer most likely prevents the entrance of CIW into the strait. Due to the smaller amount of cold water in the strait, the temperature decrease of the surface layer is not fully observed after the contraction region in the south of the strait. But this is not an indication of less mixing in the region. According to the salinity profiles of stations B2 and B7 (Figure 4), the salinity at B2 is always 0.5 PSU higher than at station B7 as a result of mixing, except under extreme conditions. In July 1999, there is an almost 0.5 PSU salinity difference between two stations as an indication of this mixing.

In 2000, the tongue-shaped CIW is clearly identified in Figure 6. The distribution of the cold intermediate water from north to south gives an idea of the dynamics of the strait. The difference in upper layer temperature at the strait ends is 3.5°C (24.5°C at K0 and 21°C at B2).

Because of the mixing between the upper and CIW layers, the upper layer temperature decreases in the south of the strait. The extent of this decrease depends on the upper layer current velocity and the thickness of CIW. On the other hand, the amount of CIW entering the strait from the Black Sea is under the influence of Danubian water, as observed in 1999.

2.4. Temporal variation of cold intermediate water ($< 14°$C)

In order to examine the annual and seasonal variation of cold water in the Strait of Istanbul and in both exit regions, the minimum and average temperatures were recorded at stations M23, M8, B2, B7, B13, K0 and K2 during the period 1996–2000. The temperature transects for July reveal the need for a new definition of cold intermediate water in the strait. The Black Sea CIW entering the strait is exposed to mixing because of the strait dynamics. This mixing occurs between $(\mathrm{CIW})_8$ and the upper layer, as well as between $(\mathrm{CIW})_8$ and the Mediterranean water. Consequently this water mass has different properties than $(\mathrm{CIW})_8$. It is better to characterize this mixed water by its temperature. Although there is some disadvantage, the choice of 14°C appears suitable to distinguish it from Mediterranean water, the temperature of which is usually $> 14°$C. When the surface temperature is $> 14°$C, the thickness and average temperature of the cold layer are calculated from the temperature profiles. This cold layer is defined as modified CIW or $(\mathrm{CIW})_{14}$. The results are given in Table 1.

Figure 3 shows $(\mathrm{CIW})_8$ at stations K2 and K0 and $(\mathrm{CIW})_{14}$ at stations B2, B7, M8 and M23. In addition to the parameters in Table 1, the salinity at the minimum temperature depth is given in Figure 3. The variation of $(\mathrm{CIW})_{14}$ at the Marmara Sea exit of the strait has characteristics similar to those of the variation of $(\mathrm{CIW})_8$ at the Black Sea exit of the strait. On the other hand, the characteristics of $(\mathrm{CIW})_{14}$ at stations B7, B2 are different at both exits due to dynamic conditions along the strait.

In 1996, modified CIW is observed in June at stations B2, B7, B13 and K0. In July, it is found only at stations B13 and K0 because of the mixing of the layers in the strait. In August, modified CIW is observed at stations M8, B2 and K2, but in September only at station K0.

In 1997, $(\mathrm{CIW})_{14}$ is observed at stations B7, B13, K0 and K2 from May to September, but at station B2 only in June and July. In the Sea of Marmara (station M8), it is observed from June to September. In September 1997, the average and minimum temperatures of the modified cold water $(\mathrm{CIW})_{14}$ are lower than in August 1997 at station M8. In addition, the $(\mathrm{CIW})_{14}$ layer is thicker in September 1997. This indicates that the volume of $(\mathrm{CIW})_{14}$ has increased. This decrease of temperature and increase in thickness can be explained only if there is advection of cold water with the upper layer from the strait. Since the lower layer is colder in the spring months, the $(\mathrm{CIW})_{14}$ thickness (9–70 m) covers the lower layer at station K0 in May 1997.

In 1998, $(\mathrm{CIW})_{14}$ is observed from May to September at station K2, from May to August at stations K0, B13 and M8, and from June to August

Table 1. Thickness, average temperature and minimum temperature of $(\mathrm{CIW})_{14}$. D(m) – upper and lower limits of $(\mathrm{CIW})_{14}$; T(a) – average temperature in °C; T(m) – minimum temperature in °C. N/A – no measurement made; * – no cold layer present

Years	Months	M8			B2			B7		
		D(m)	T(a)	T(m)	D(m)	T(a)	T(m)	D(m)	T(a)	T(m)
1996	5	4–16	**11.1**	**8.0**	*	*	*	*	*	*
	6	N/A	N/A	N/A	20–30	**10.5**	**9.2**	20–50	11.6	6.8
	7	N/A	N/A	N/A	*	*	*	*	*	*
	8	15–20	11.7	11.2	25–26	13.9	13.9	*	*	*
	9	N/A	N/A	N/A	*	*	*	*	*	*
		B13			K0			K2		
		D(m)	T(a)	T(m)	D(m)	T(a)	T(m)	D(m)	T(a)	T(m)
	5	*	*	*	*	*	*	N/A	N/A	N/A
	6	30–50	**9.9**	**7.8**	17–68	**8.5**	**7.0**	N/A	N/A	N/A
	7	31–39	12.0	10.3	40–50	10.9	7.2	N/A	N/A	N/A
	8	*	*	*	*	*	*	36–55	**9.6**	**7.1**
	9	*	*	*	21–41	13.0	12.3	*	*	*
		M8			B2			B7		
		D(m)	T(a)	T(m)	D(m)	T(a)	T(m)	D(m)	T(a)	T(m)
1997	5	*	*	*	*	*	*	5–55	11.4	**8.3**
	6	15–25	**12.0**	**10.2**	20–27	12.7	11.7	30–40	12.1	12.0
	7	15–28	12.5	11.2	15–34	**12.5**	**11.3**	26–41	**11.2**	9.6
	8	20–21	13.9	13.9	*	*	*	40–49	13.2	12.2
	9	20–25	13.6	13.2	*	*	*	36–48	12.4	11.5
		B13			K0			K2		
		D(m)	T(a)	T(m)	D(m)	T(a)	T(m)	D(m)	T(a)	T(m)
	5	4–61	10.9	**7.4**	9–70	10.7	6.9	5–71	9.2	6.9
	6	20–45	10.4	8.3	20–55	10.9	7.7	20–72	9.6	**6.8**
	7	20–47	**9.9**	8.3	24–53	**9.5**	7.4	18–69	8.6	7.0
	8	29–56	10.8	9.1	38–57	9.7	**6.9**	32–72	**8.3**	7.4
	9	30–54	10.7	9.3	31–56	10.1	8.2	N/A	N/A	N/A
		M8			B2			B7		
		D(m)	T(a)	T(m)	D(m)	T(a)	T(m)	D(m)	T(a)	T(m)
1998	5	18–28	12.3	10.6	*	*	*	*	*	*
	6	14–30	**12.1**	9.9	15–32	**12.2**	11.8	19–45	11.6	**9.5**
	7	5–24	13.0	**8.3**	1–32	12.4	**11.5**	4–42	**10.6**	9.8
	8	14–24	12.4	11.6	23–26	13.7	13.6	19–38	13.1	12.0
	9	20–25	13.7	13.6	*	*	*	*	*	*
		B13			K0			K2		
		D(m)	T(a)	T(m)	D(m)	T(a)	T(m)	D(m)	T(a)	T(m)
	5	4–47	12.8	11.6	7–50	12.4	**6.9**	5–72	11.0	7.1
	6	20–51	10.0	8.5	20–54	9.7	7.0	18–72	9.4	**7.0**
	7	8–49	**9.9**	**8.4**	5–52	**8.9**	**6.9**	15–71	9.3	7.2

Table 1. (*continued*)

Years	Months	B13			K0			K2		
		D(m)	T(a)	T(m)	D(m)	T(a)	T(m)	D(m)	T(a)	T(m)
1998	8	21–42	11.6	9.8	24-49	10.1	7.7	23-64	**9.1**	7.4
	9	*	*	*	*	*	*	41–53	10.3	8.0
		M8			B2			B7		
		D(m)	T(a)	T(m)	D(m)	T(a)	T(m)	D(m)	T(a)	T(m)
1999	5	*	*	*	*	*	*	*	*	*
	6	16–30	**12.6**	**11.6**	23–32	13.7	13.5	34–45	**11.9**	**11.1**
	7	19–29	12.7	12.2	*	*	*	*	*	*
	8	16–25	13.0	12.4	25–26	13.8	13.7	24–37	13.3	12.7
	9	19–21	13.9	13.8		*	*	*	*	*
	10	20–21	13.9	13.9	*	*	*	*	*	*
		B13			K0			K2		
		D(m)	T(a)	T(m)	D(m)	T(a)	T(m)	D(m)	T(a)	T(m)
	5	*	*	*	*	*	*	7–71	9.0	7.3
	6	26–51	**10.5**	**9.1**	30–53	**11.0**	**867**	18–69	**9.2**	**7.7**
	7	36–45	12.9	12.1	38–50	12.1	10.9	38–65	9.6	8.1
	8	26–45	12.5	10.4	26–50	11.2	9.4	28–64	10.1	8.0
	9	*	*	*	*	*	*	44–51	12.4	11.6
	10	*	*	*	39–45	10.9	9.5	35–63	10.3	7.9
		M8			B2			B7		
		D(m)	T(a)	T(m)	D(m)	T(a)	T(m)	D(m)	T(a)	T(m)
2000	6	16–29	**12.8**	**11.8**	23–30	13.8	13.7	37–44	11.8	10.8
	7	19–26	12.8	12.1	11–29	**12.3**	**11.4**	13–39	**11.4**	**9.4**
	8	17–22	13.4	13.1	*	*	*	33–40	12.5	11.6
	9	*	*	*	*	*	*	*	*	*
	10	*	*	*	*	*	*	*	*	*
	11	*	*	*	*	*	*	*	*	*
		B13			K0			K2		
		D(m)	T(a)	T(m)	D(m)	T(a)	T(m)	D(m)	T(a)	T(m)
	6	27–50	**10.1**	**8.6**	34–53	10.2	**6.9**	27–71	9.5	**7.3**
	7	13–46	10.3	9.0	13–50	**8.9**	7.4	16–63	**8.6**	7.3
	8	28–46	10.7	9.8	31–51	10.7	8.5	29–64	8.8	7.4
	9	*	*	*	34–42	11.2	8.9	34–62	9.9	7.5
	10	*	*	*	*	*	*	*	*	*
	11	*	*	*	*	*	*	40–58	13.0	11.7

at stations B7 and B2. In July 1998, the upper layer is colder along the strait so that the temperature of the surface layer at station B2 is less than 13.0°C (Figure 6). For this reason, the $(\mathrm{CIW})_{14}$ layer starts at 1 m depth at station B2 (Table 1). On the other hand, at station M8, the $(\mathrm{CIW})_{14}$ layer is thicker in this month. Monthly fluctuations of the thickness of $(\mathrm{CIW})_{14}$ at station M8 indicate the entrance of cold water to the Sea of Marmara through the strait. In September, $(\mathrm{CIW})_{14}$ is very thin at station K2 and does not enter the strait.

In 1999, cold water $(\mathrm{CIW})_{14}$ is observed in the Black Sea exit of the strait (station K2) and in the Sea of Marmara (at station M8) from June to October. At station K2, excluding the upper 7 m, the temperature of the entire water column is less than 14°C in May 1999. The upper limit of the $(\mathrm{CIW})_{14}$ is found at 38 m depth in July at station K2 owing to Danubian-influenced water, as mentioned before (Figure 2). The thickness of $(\mathrm{CIW})_{14}$ increases in August 1999 at station K2. In September, the amount of $(\mathrm{CIW})_{14}$ decreases at station K2 and it does not enter the strait. On the other hand, in October 1999, the amount of $(\mathrm{CIW})_{14}$ increases compared to September and its minimum temperature is $\sim 7.9°\mathrm{C}$ compared to 11.6°C in September. This increase is thought to be due to the advection of CIW to the area by the Rim Current.

In 2000, the thickness of $(\mathrm{CIW})_{14}$ decreases in both exits of the strait. In the Black Sea exit of the strait, $(\mathrm{CIW})_{14}$ is not observed after July, and consequently, it is not observed at station M8 either.

Examination of $(\mathrm{CIW})_{14}$ indicates that the cold water existing in the Black Sea exit of the strait influences the cold water in the Sea of Marmara. The annual and monthly fluctuations in the amount of $(\mathrm{CIW})_{14}$ have similar characteristics in the Black Sea and the Sea of Marmara. This similarity leads to the consideration that the cold layer in the Sea of Marmara is mostly supported by the cold layer in the Black Sea.

3. Conclusions

Seasonal and spatial variations of $(\mathrm{CIW})_{14}$ (modified CIW) in the two exit regions of the Strait of Istanbul are studied. $(\mathrm{CIW})_{14}$ is usually observed from May to September in the Black Sea exit of the strait. In some years it is also observed in October or November. While the thickness of CIW increases as a result of the formation of anticyclonic eddies in the northern exit of the strait, it decreases when a large amount of Danubian water is observed in the area. Mediterranean water raises the temperature and salinity of the cold layer in the Black Sea exit region of the strait. The minimum temperature and salinity of the cold layer is observed in June and July, and the amount of CIW may change from one year to the next.

In the summer months, CIW is advected with the upper layer along the Strait of Istanbul. It lowers the upper layer temperature in the southern part of the strait in this season. The temperature difference between the two ends of the strait is about 3 to 5°C. Modified cold intermediate water $(\mathrm{CIW})_{14}$ is defined as cold water that has a temperature of $< 14°\mathrm{C}$. In the Strait of Istanbul and at both ends, the thickness together with the average and minimum temperature of $(\mathrm{CIW})_{14}$ layer are examined on the basis of monthly and annual data sets between 1996 and 2000. In the Strait of Istanbul, variations of $(\mathrm{CIW})_{14}$ are related to the amount of $(\mathrm{CIW})_{8}$ in the Black Sea exit of the strait. They are also dependent on the dynamics of the strait. Although the Sea of Marmara has its own cold intermediate water remaining from the winter months, $(\mathrm{CIW})_{14}$ is modified by the original CIW flowing through the Strait of Istanbul from the Black Sea during the summer months. It usually disappears after September or October.

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