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RESEARCH ARTICLE

Vertical distribution of mucilage typology in the water column after a massive mucilage formation in the surface waters of the Sea of Marmara

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Abstract

The vertical distribution of mucilage aggregates is described for the Sea of Marmara in July 2021. In order to understand the vertical distribution of mucilage aggregates, CTD measurements and underwater video records were obtained from 10 stations in the Sea of Marmara. Nine different types of mucilage aggregates were observed during this study. Flocs were observed in the entire surface waters of the Sea of Marmara. The biggest type of mucilage aggregates in terms of size was clouds. Vertical distribution of mucilage in the water column had a distinct distribution for different types and this distribution was same for all regions. Even though it was not possible to monitor the deep basin, this study confirms that mucilage aggregates passed the halocline and were recorded up to 60 m depth in the water column.

Keywords: Mucilage typology, mucilage aggregates, Sea of Marmara, underwater video

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Introduction

Formation of mucilage is a phenomenon known for nutrient-rich waters in the world oceans as a kind of population bloom of a variety of organisms in marine ecosystems (Lancelot 1995; Otero *et al*. 2003). Under special environmental and trophic conditions, especially various marine microorganisms produce large amounts of extracellular organic substances that result with mucilage formation in the seas (Innamorati *et al.* 2001; Mecozzi *et al*. 2001; Taş *et al*. 2016). Previous studies mentioned the formation, distribution and effects of mucilage phenomenon (Syrski 1872; Lancelot 1995; Degobbis *et al.* 1999; Najdek *et al.* 2002; McKenzie *et al.* 2002; Najdek *et al.* 2005; Schiaparelli *et al.* 2007; Nikolaidis *et al.* 2008; Fukao *et al.* 2009; Misic *et al.* 2011; Fernandes and Frassão-Santos 2011). The first mucilage event in the Sea of Marmara is well studied by number of articles (Aktan *et al.* 2008; Tüfekçi *et al.* 2010; Altuğ *et al.* 2010; Balkıs *et al.* 2011; Çiftçi Türetken *et al.* 2016; Taş *et al.* 2016; Ergul *et al.* 2018; Keleş *et al.* 2020; Terbıyık Kurt *et al.* 2020; Toklu-Alicli *et al.* 2020).

The Sea of Marmara is a semi-enclosed and internal sea of Turkey and has a coast of 240 km in length, the surface area of 11,500 km^2, connecting the Black Sea to the Mediterranean via two shallow and narrow straits. Large nutrient inputs from the Black Sea and direct wastewater discharges mainly from the major cities of the Marmara Region in recent years have severely deteriorated the marine habitat (Tugrul and Polat 1995; Ergul *et al.* 2018). The Sea of Marmara has been polluted by municipal and industrial inputs from its drainage basin, together with nutrients, organic inputs from the Black Sea since 1970's (Orhon *et al.* 1994). Previous studies focused on nutrient levels and physicochemical variables of the water column and annual fluxes of nutrients and organic carbon based on water flux in the Sea of Marmara (Tugrul *et al.* 1995; Polat and Tugrul 1995; Polat *et al.* 1998; Balkıs 2007; Balcı *et al.* 2014; Tugrul *et al.* 2015). There is a permanent halocline formed between 15-30 m depth that displays seasonal and regional variations due to two considerably different water masses (Ünlüata *et al.* 1990; Beşiktepe *et al.* 1994). The upper layer is dominated by the Istanbul Strait (Bosphorus) inflow carrying the brackish surface water of the Black Sea. This layer limits vertical mixing, thus, ventilation of the salty deep waters of the Mediterranean (Tugrul and Polat 1995). In the thorough review by Beşiktepe *et al.* (1994), the upper layer salinity was suggested in a range of 23 ±2 psu, reaching a maximum in winter. For the lower layer of the Marmara Sea that comes from the Aegean Sea via Strait of Çanakkale, the properties were defined as relatively constant with a potential temperature of 14.5°C, salinity of 38.5 psu, and density of 28.6 σ_θ (sigma-theta).

Intensity of phytoplankton production in the Sea of Marmara is determined by changes in environmental and hydrographic conditions (Ediger *et al.* 2016). Enhanced nutrient inputs with the appropriate meteorological conditions has led to red tides, mucilage formation and increased jelly organism blooms in the recent years (Tüfekçi *et al.* 2010; Ediger *et al.* 2016; İşinibilir and Yılmaz 2016; Taş *et al.* 2016).

Stachowitsch *et al.* (1990) defined different formation types of mucilage in the water column as, macroflocs (few centimeters), stringers, clouds (few meters), false bottom and creamy surface layers. Precali *et al.* (2005) studied the typology and distribution of mucilage aggregates in the northern Adriatic Sea (Table1).

Table 1. Types of macroaggregates (according to Precali *et al.* 2005)

Type	Description	Size
1) Flocs	Aggregates of small dimensions	0.5 mm - 1 cm
2) Macroflocs	Spherical or irregular aggregates	1-5 cm
3) Stringers	Elongated aggregates, typically in a shape of a comet; generally whitish	>25 cm; few millimeters thick
4) Ribbons	Elongated aggregates, generally from white to yellow	10-20 cm to over 1 m; few centimeters thick
5) Cobweb	Web-like aggregates formed from stringers, generally whitish	few meters vertically and tens of meters horizontally
6) Clouds	Huge aggregates, lengthened shape with one "head" and one or more "tails"; generally yellow	0.5 to 3-4 m
7) False bottom	Dense layer formed of stringers and macroflocs; usually positioned at the pycnocline	thick from few millimeters to tens of centimeters
8) Blanket	Layer of combined aggregates, covering uniformly cliffs and benthic organisms; from yellow to brown colour	
9) Creamy surface layer	Superficial layer of creamy consistency; formed from stringers or free flocs; float at or directly below surface	up to 15 cm thick
10) Gelatinous surface layer	Compact layer of spongy aspect, floating on the surface, mostly yellowish or brown	wide up to few hundred meters with long bands stretching tens of kilometers

A massive mucilage event was observed in the Sea of Marmara in 2021, for which some studies have already been published (Özalp 2021; Balkıs-Özdelice *et al.* 2021; Savun-Hekimoğlu and Gazioğlu 2021; Yüksek 2021). However, there has been no study on its status in the water column yet after the massive mucilage formation in the Sea of Marmara.

The aim of this study is to describe the distribution and the typology of mucilage aggregates occured in the spring of 2021 and present their spatial and vertical distribution in the Sea of Marmara.

Materials and Methods

In order to understand the vertical distribution of mucilage aggregates, both CTD measurements and underwater footages were obtained from 10 stations in the Sea of Marmara in the summer of 2021 (Figure 1). These stations were chosen due to their characteristic features. D7 (Çanakkale Strait-72 m) represents the exit from the Marmara to the Çanakkale Strait; MD101 (deep basin 1110 m), DTM3 (400 m), and MD18 (149 m) represent the deep and central basin; GD3 (37 m) and MD22 (100 m) represent the shallow and, inner parts of bays. BC1 (50 m) and MD4A (79 m) represent the northern section of the Sea of Marmara. MD10A (63 m) represents the transition zone between the Çanakkale Strait and the center of the Sea of Marmara, while MD19A (45 m) represents the southern section of the Marmara Sea.

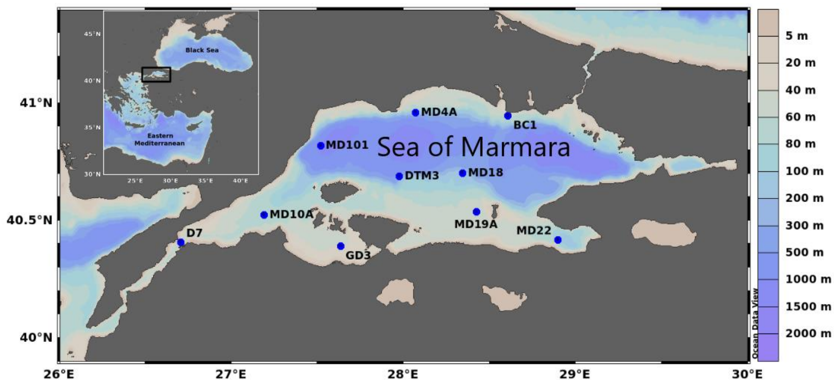


Figure 1. Sampling stations in the Sea of Marmara in July, 2021

The dataset of *in situ* salinity and temperature were collected by RV TUBITAK Marmara of the TUBITAK Marmara Research Center (MRC), within the framework of the "Integrated Marine Pollution Monitoring 2020–2022 Program" by the Turkish Ministry of Environment and Urbanization and TUBITAK-MRC. Conductivity, temperature, and depth measurements were obtained by using CTD: SeaBird SBE 25Plus from the surface up to the sea bottom at the predefined same 100 stations at the speed of 16 Hz in the 2021 summer scientific expedition to define the physical properties of the water column. Thus, the relationship between the vertical distribution of the types of aggregates and the layers of the Sea of Marmara could be investigated through the water column.

After quality control, the dense data were averaged to 1 m bin size during the post-processing for later use. For this study, 10 of the stations which had better image quality among the others to understand spatial distribution were selected and rewatched several times to determine the type of mucilage aggregates listed in Table 1.

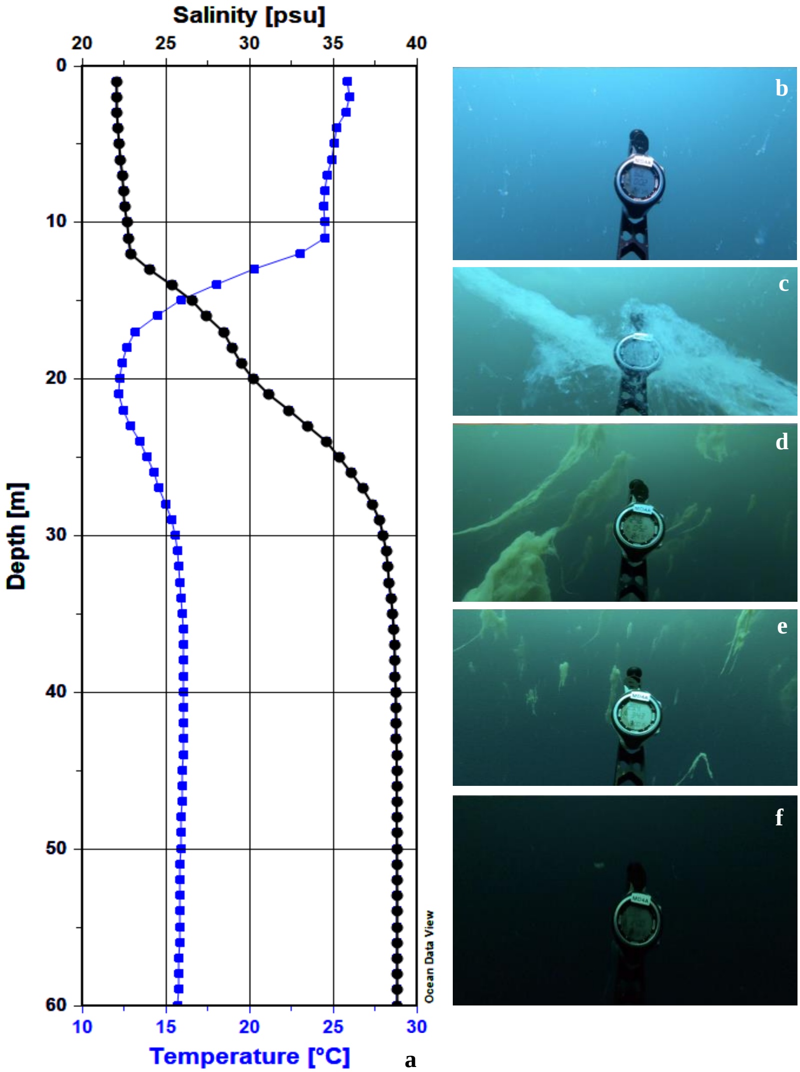
Underwater video images were obtained with two methods. An underwater camera (GoPro 8 Black) attached to the SeaBird Carousel sampling system was used for the stations shallower than 65 m. For the stations deeper than 65 m the camera was attached to a floating frame (Figure 2). For both systems, in order to estimate the depth, a dive watch was also attached with a station label on it.

Figure 2. Underwater video camera system with a floating frame for stations deeper than 65 m

Results and Discussion

Underwater video records of 10 stations (Figure 1) were examined and the vertical distribution of mucilage aggregates are presented with salinity and temperature. Three of them as representative of all types of mucilage aggregates were given in Figures 3-5 and others are presented in complementary section. Screenshots of different types of mucilage aggregates (Table 1) were taken at each station. In this study, nine types of mucilage aggregates, described in Table 1 were seen. Even though the creamy surface layer was not observed in this summer expedition, it was seen in the spring expedition in April 2021 (Figure 6).

Flocs were seen in all the surface waters in the Sea of Marmara, with macroflocs beneath it in the first 8-10 m. This type of mucilage aggregates was abundant in all stations. Stringers and ribbons were also seen in almost every station. These formations were accumulated between 8-10 to 15 m in each station. Under stringers and ribbons, another mucilage aggregation type, cobwebs were identified in 15 m and this depth was almost same for the stations.



F**igure 3 a:** Temperature and salinity profiles of MD4A station; **b:** Flocs and macroflocs at 6 m depth (σ_θ=13.79); **c:** Cobwebs at 15 m depth (σ_θ=19.29); **d:** Clouds at 24 m depth (σ_θ=26); **e:** Clouds & teardrops at 29 m depth (σ_θ=28.03); **f:** Teardrops at 53 m depth (σ_θ=28.73).

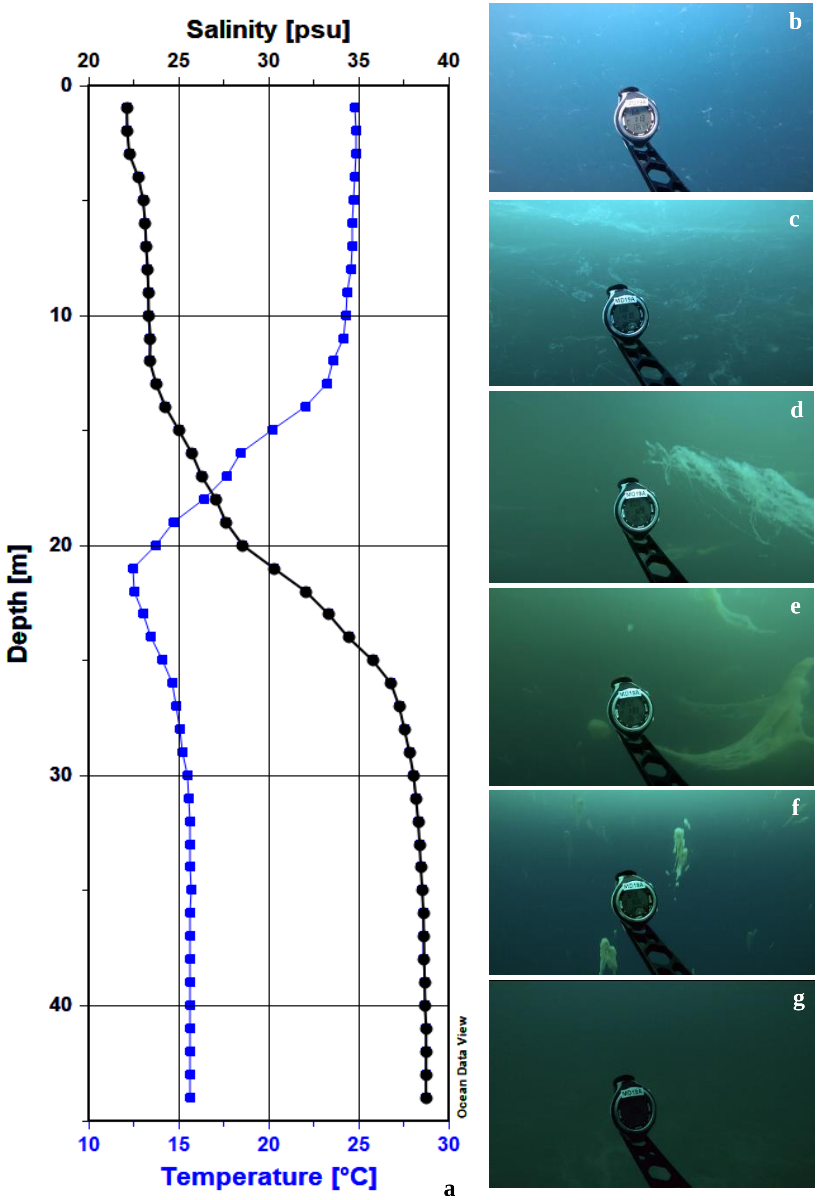


Figure 4 a: Temperature and salinity profiles of MD19A station; **b:** Flocs & Macroflocs at 6 m depth (σ_θ=14.5); **c:** Stringers & False bottom at 14 m depth (σ_θ=16.07); **d:** Ribbons & Cobwebs at 17 m depth (σ_θ=18.69); **e:** Clouds at 21 m depth (σ_θ=22.87); **f:** Clouds at 32 m depth (σ_θ=28.38); **g:** Blanket at the sea bottom (Depth = 45 m, σ_θ=28.71).

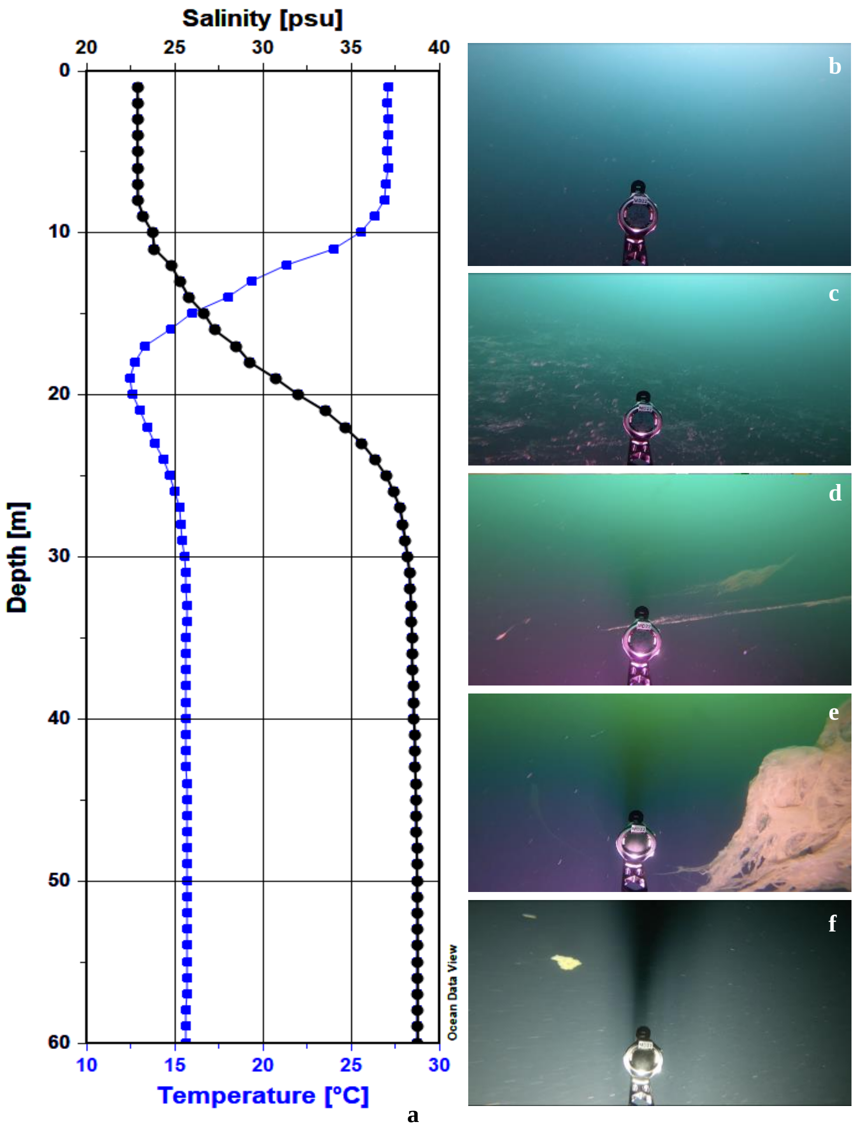


Figure 5 a: Temperature and salinity profiles of MD22 station **b:** Flocs at the surface (σ_θ=13.6) **c:** Macroflocs, stringers & False bottom at 10 m depth (σ_θ=14.69) **d:** Clouds at 17 m depth (σ_θ=21.3) **e:** Clouds at 23 m depth (σ_θ=26.69) **f:** Clouds & Teardrops at 60 m depth (σ_θ=28.74)

The biggest type of mucilage aggregates in terms of size was clouds. Clouds were also seen at each station, starting from 20 m up to 60 m depth. The permanent halocline was observed at 20 m, thus almost all the biggest mucilage aggregates were accumulated in this water layer. Unfortunately, it was not possible to record any images from deeper depths due to the lack of equipment and light.

Figure 6. Creamy surface layer in the Sea of Marmara (April, 2021)

As Stachowitsch *et al.* (1990) and Precali *et al.* (2005) stated, a false bottom that is positioned at the pycnocline observed at almost all the stations. This layer (false bottom) was seen as the bottom of the sea and formed by small mucilage aggregates such as stringers and macroflocs. An example of false bottom type of mucilage aggregation can be seen in Figure 7.

Figure 7. False bottom layer in MD19A

According to Table 1, the type of mucilage aggregates in the seafloor is called 'blanket'. Different types of blanket were observed during this study. At some stations, big aggregates were accumulated at the bottom, its colour ranged from whitish to yellow. Brownish mucilage layer was also observed at the bottom. Screenshots of different types of sea bottom can be seen in Figure 8.

For the surface waters, even though the creamy layer was not observed, the gelatinous layer was seen. The color of this layer ranged from brownish to yellow depending on the station.

There was another type of mucilage aggregates in this study named 'teardrops'. Teardrops started just below clouds. They can be considered as small pieces disattached from clouds in the shape of an inverted 'teardrop'. This layer always started at 28-30 m depth in the water column. These pieces have one "head" and one tail. "Teardrops" are shown in Figures 3f, 4f and 5f.

For each station, underwater video records were examined in detail. Different types of mucilage aggregates were identified and presented in Table 2 with their surrounding seawater densities.

As shown in Table 2, flocs and clouds were seen at 10 stations. Macroflocs and cobwebs were the second most sighted groups, followed by teardrops, stringers, ribbons and blanket.

Table 2. Mucilage aggregation types observed at 10 stations with their surrounding seawater densities as sigma-theta (σ_θ)

Stations	**BC1**	**MD 4A**	**MD 101**	**DTM3**	**MD 18**	**MD 19A**	**D7**	**MD 10A**	**GD3**	**MD 22**
Date	**29 Jul**	**31 Jul**	**01 Aug**	**30 Jul**	**30 Jul**	**04 Aug**	**02 Aug**	**02 Aug**	**03 Aug**	**05 Aug**
Flocs	13.54	13.79	13.95	13.71	13.95	14.5	14.29	14.19	14.8	13.6
Macroflocs	13.54	13.79	-	13.71	-	14.5	14.29	17.34	14.8	14.69
Stringers	-	-	-	13.71	14.78	16.07	14.29	17.34	-	14.69
Ribbons	14.83	-	-	-	16.4	18.69	16.06	-	-	-
Cobweb	-	19.29	14.97	14.7	18.31	18.69	18.85	-	15.89	17.78
Clouds	23.35 - 28.36	26 - 28.03	26.59 - 28.6	23.49 - 27.82	23.38 - 28.58	22.87	28.59	26.04 - 28.52	25.77	21.3 - 26.69
Teardrops	-	28.73	27.6	28.69	-	28.38	28.76	28.7	-	28.74
Blanket	-	-	-	-	-	28.71	-	-	28.61	-

Mainly three types of water masses were detected in the 2021 summer cruise. As expected, the upper layer (< 15 σ_θ) had the warmest (~25 °C) and the least saline (~23 psu) waters due to the seasonal warming and calm weather conditions (Figure 9). As shown in Tables 2 and 3, flocs and macroflocs were seen in the upper layer. The lower layer (> 28.5 σ_θ) had the potential temperature (θ) and salinity values of ~14.6 °C and ~38.7 psu. Clouds and teardrops were observed in the water layer with > 28.5 σ_θ density. If the total depth of a station shallower than 60 m and the sigma-theta > 28.5 σ_θ, blanket was the third type of mucilage aggregates observed in the lower layer. The pycnocline located in between the two layers and also contained the residual Cold Intermediate Layer (CIL) with the pot. temperature, salinity and pot. density values of ~12 °C, ~30 psu and ~23.5 σ_θ, respectively. Generally clouds were observed in the sub-halocline. The incoming waters from the Çanakkale Strait via lower layer current noticed from θ-S diagram. Mild (θ=16.8 °C) but the most saline waters (S=39.1 psu) were beneath the 30 m depth of the D7 station (Figure 9). All types of mucilage aggregates except blanket (Table 2) were observed in different depths of the water column.

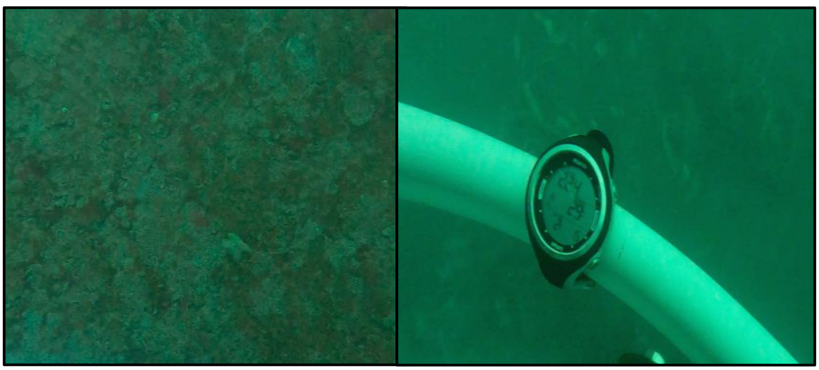


Figure 8. Different types of mucilage aggregation at the sea bottom

In terms of sea water density, all types of mucilage aggregates were seen in the water column with different density levels (Table 3). Small type aggregates were observed at a low density level. False bottom type was in the range of 14.95-16.07 density surfaces which coincided with pycnocline.

Table 3. Mucilage aggregates type and the water density ranges (in σ_θ)

Mucilage aggregates	Seawater density range
Flocs	13.54-14.50
Macroflocs	13.54-17.34
Stringers	13.71-17.34
False bottom	14.69-16.07
Ribbons	13.54-18.69
Cobwebs	14.97-19.29
Clouds	21.30-28.76
Teardrops	27.82-28.76
Blanket at the sea bottom	28.61-28.71

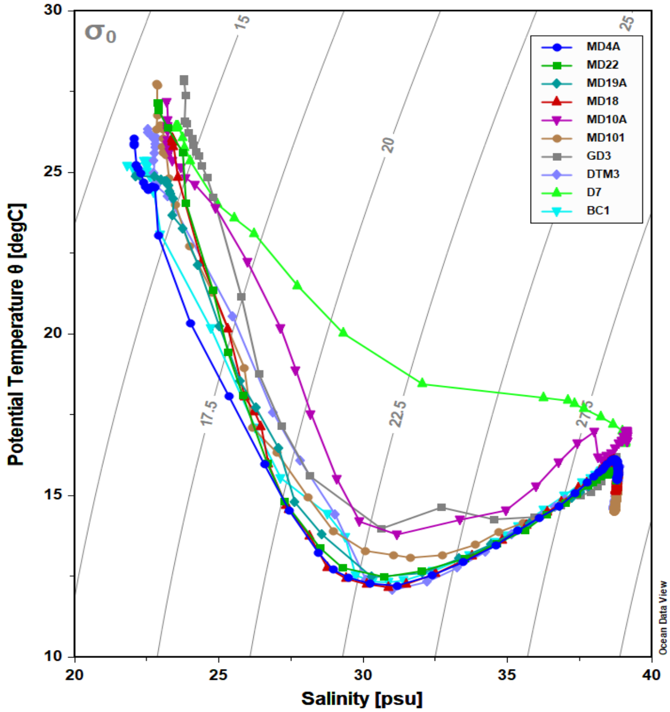


Figure 9. The θ-S diagrams of the stations

One of the important results of this study is the observation of the distinct distribution for different types, and this order of mucilage aggregates in the water column was the same in all studied stations. Vertical distribution of mucilage aggregates effected by their size, density, and physical, biological and chemical properties of the water column.

Another important result is the finding of large mucilage aggregates already sinking to the deeper layer. As mentioned above, there are two different water layers in the Sea of Marmara and they are separated with a permanent halocline. It was noticed that sea bottom was covered with sunk mucilage aggregates at the shallow stations (Figure 4g), however, even though the sea bottom below 60 m depth was not monitored, there were mucilage aggregates in the form of clouds or teardrops in the lower layer (sub-halocline waters). Thus, it is highly expected the teardrops to sink and mucilage aggregates to cover the sea bottom in time.

Many blooms occurred in the Sea of Marmara during recent years, not just those of phytoplankton but also of gelatinous organisms (Öztürk and Sümen 2020). Benthic species such as *Pinna nobilis* is another marine organism under threat with mass mortality in the Turkish Straits System (Özalp and Kersting 2020).

Blooms, mucilage formation, mass mortalities in benthic species underline the unhealthy conditions of the Sea of Marmara. Detailed examination of trophic status of the Sea of Marmara indicates that generally moderate to bad trophic conditions appeared due to anthropogenic and natural inputs (Ediger *et al.* 2016). In addition to trophic status, climate change affects the ecosystem of the Sea of Marmara via changes in sea surface temperature. Altıok *et al.* (2021) stated a temperature increase of 0.07°C observed during 1996-2010 for the Sea of Marmara.

For the ecosystem to recover to its previous state, IUU (Illegal, Unreported, Unregulated) fishing should be prevented and marine protected areas should be established. Marine spatial planning is crucial for better management in the Marmara Region. Monitoring studies are always important to understand the ongoing dynamics and the changes in marine ecosystems. However, for such an inland sea, long-term monitoring studies with the special attention to the relation between the Black Sea and the Aegean Sea are also crucial.

Acknowledgement

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Marmara Denizi yüzey sularında yoğun deniz salyası oluşumunu takiben deniz salyası tiplerinin su kolonunda dikey dağılımı

Öz

Marmara Denizi'nde deniz salyası (musilaj) kümelerinin 2021 Temmuz ayında dikey dağılımı bu çalışmada incelenmiştir. Dikey dağılımı görebilmek ve anlayabilmek adına, Marmara Denizi'ndeki 10 istasyonda sualtı video kayıtları ve CTD verisi alınmıştır. Müsilaj kümelerinin dokuz farklı tipi bu çalışmada tanımlanmıştır. Bu tiplerden flocs tüm Marmara Denizi yüzey sularında görülmüştür. Boyut olarak en büyük tip, cloud adı verilen bulut şeklindeki kümelerdir. Müsilaj tiplerinin dikey dağılımı farklı olup, bu dağılım tüm Marmara Denizi için aynıdır. Bu çalışmada derin basen görüntülenememişse de musilaj kümelerinin haloklinin altına geçip, alt tabaka suyuna ulaştığı görülmüştür.

Anahtar kelimeler: Musilaj tipleri, musilaj kümeleri, deniz salyası, Marmara Denizi, su altı videosu

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