ISSN: 2148-9173 Vol: 9 Issue:3 September 2022

International Journal of Environment and Geoinformatics (IJEGEO) is an international, multidisciplinary, peer reviewed, open access journal.

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Abstracting and Indexing: TR DIZIN, DOAJ, Index Copernicus, OAJI, Scientific Indexing Services, International Scientific Indexing, Journal Factor, Google Scholar, Ulrich's Periodicals Directory, WorldCat, DRJI, ResearchBib, SOBIAD

IJEGEO

International Journal of Environment and Geoinformatics 9(3):126-145 (2022)

Research Article

An Analysis of Meteorological Conditions in Relation to Occurrence of the Mucilage Outbreaks in Sea of Marmara, March-June 2021

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Received 26.12.2021
Accepted 01.02.2022

How to cite: Kömüşcü, et al., (2022). An Analysis of Meteorological Conditions in Relation to Occurrence of the Mucilage Outbreaks in Sea of Marmara, March-June 2021. *International Journal of Environment and Geoinformatics (IJEGEO)*, 9(3): 126-145. doi. 10.30897/ijegeo. 1037842

Abstract

A severe mucilage problem appeared as a major environmental disaster in the Marmara Sea, Turkey, during March-May 2021 period, imposing significant implications for the fishing industry, marine life and tourism. The mucilage layers covered areas of hundreds of kilometers of coastline along the Marmara Sea. This study aimed to provide an insight into the mucilage outbreak observed in the Marmara Sea during March-May 2021 period by establishing some links between meteorological factors including SST anomalies and changes in wind speed and mucilage occurrence and puts some emphasis on the importance of monitoring variability of such parameters to assess mucilage outbreaks. For this purpose, mean and maximum SSTs and wind speed variability at several locations along the shores of Marmara and Black Seas are analyzed for the April-June period, when the mucilage problem peaked. Both surface and satellite data are used to identify the spatial and temporal extent of the SST anomalies. Furthermore, the relationship between turbidity in the Marmara Sea and the SSTs is sought as a contributing factor to mucilage formation and enhancement. The findings indicate that most of the stations are characterized by warming trends and positive SST anomalies, with a few stations indicating periodic warming and cooling. Moreover, the NOAA NCEP Optimum Interpolation SST (OISST) data supported the warming event especially in central and eastern parts of the Marmara Sea. The wind observations at different locations along the shores of Marmara and Black Seas indicate decreasing trends in the mean wind speed. The view taken in this paper is that both the increased SSTs and reduced wind speed generate a favorable environment both for the formation and enhancement of the mucilage episode over the Marmara Sea during the March-June 2021 period. Therefore, analysis of such meteorological parameters can provide a better understanding of mucilage aggregation in addition to other causative factors involved. The study also concluded that the modest turbidity conditions caused increase in the SSTs to some extent in addition to the climate change-related warming.

Keywords: mucilage, Marmara Sea, sea surface temperatures, wind speed, turbidity

Introduction

Mucilage is produced as a result of an overgrowth of microscopic algae called phytoplankton. When nutrients such as nitrogen and phosphorus content increase abundantly in the seawater, the phytoplankton grows excessively, leading to the formation of thick and slimy layers of organic matter, called mucilage (Precali, et al., 2005; Flander-Putrle and Malej, 2008). In other words, a large increase in phosphorus and other excessive nutrients cause the formation and growth of mucilage. Both domestic and industrial pollution is considered to be the main causative factor for phytoplankton overproduction, which releases an overabundance of mucus. Besides, prolonged warm temperatures and calm sea conditions associated with reduced wind speed also contribute to the formation of marine mucilage (De Lazzari, et al., 2008; Russo, et al., 2005; Fabio et al., 2014).

Turkey's Marmara Sea was impacted by the marine mucilage problem during the January-May period of 2021, disrupting the fishing industry, local economies and posing a significant threat to marine life (Savun-Hekimoğlu and Gazioğlu, 2021; Savun-Hekimoğlu et al., 2021; Gazioğlu, et al., 2022). It also caused considerable environmental impact and concerns for public health in settlements engulfing the Marmara Sea. The problem initially emerged in December of 2020, and it worsened in the spring of 2021 when the shores of the Marmara Sea were invaded by thick layers of mucilage. In a recent study by Acar et al. (2021), the distribution and spatial variation of the mucilage coverage were investigated for March-June 2021 period by remote sensing techniques. It was found that the mucilage formation was spotted in the Dardanelles Strait first in the early and mid-March and then spread towards the Gulf of İzmit and the Gulf of Gemlik. The same study found that the density of mucilage increased in the Dardanelles Strait, İzmit Gulf, Gemlik Gulf, Erdek, Kapıdağ Peninsula, and the north of the Marmara Island during May 2021. Between mid-May and the first week of June, it was observed that the mucilage coverage increased rapidly and the area covered by the sea surface reached 12,741.94 ha (Acar et al., 2021; Aksu et al., 2021; Balkis Ozdelice et al., 2021; Usluer, 2022). An immediate clean-up effort was initiated to remove the mucilage layers by the Ministry of Environment, Urbanization and Climate Change (MEUCC) with help of municipalities of cities littoral to the Marmara Sea as part of the "Marmara Sea Action Plan". Some layers of the mucilage also drifted towards the Aegean Sea, through Dardanelles Strait, in the southwest of Marmara with currents originating from the Black Sea in the north. The mucilage outbreaks are not new in the Marmara Sea, which has been experiencing such problems during the last two decades. The mucilage problem was first reported in 1997 in the Dardanelles Strait and the Marmara Sea and reappeared in 2007-2008 (Aktan et al., 2008). Yet the recent one was environmentally most damaging and covered greater sea surface area than those of the previous mucilage outbreaks. During the 2007-2008 periods, countries with coasts on the Adriatic Sea also tackled the mucilage problem (Precali et al., 2005; Flander-Putrle et al., 2008). The impact was felt more severely especially in coastal towns of Istanbul and Bursa provinces, where intense industrial activities pollute the Marmara Sea considerably through untreated waste discharged into the sea (Figure 1). Initially, the mucilage layers appeared on the sea surface and then they stretched 20-30 meters below the water surface. There were concerns among authorities if the mucilage layer settled on the seafloor, which would then pose a severe threat to all the aquatic life there by preventing oxygen transfer from upper parts of the sea surface. The problem became visible in the deep waters of the Marmara Sea to some extent, according to various reports (NewScientist, 2021; Wilcox, 2021). Invasion of the Marmara Sea by mucilage layer also caused some economic and health implications for the people living nearby the Marmara Sea (Bardvaid, 2021; Brackett, 2021). Many residents on the Marmara Sea coasts rely on fishing and tourism for their livelihood, and thus the sea snot caused some impact on the local economy. Some concerns were also raised about water-borne disease outbreaks like cholera in settlements at close proximity to the Marmara Sea if the mucilage problem persisted (BIA News Desk, 2021).

Partially treated wastewater dumped into the sea, coupled with climate change-related warming may have caused the recent mucilage outbreak that turned into an environmental disaster in the Marmara Sea. Household waste from main cities, including İstanbul, Kocaeli, and Tekirdağ, in the region also pollutes the Marmara Sea severely (Tüfekçi et al., 2010). The carbon-rich wastes of the petrochemical industry located in Kocaeli Bay are undeniably harmful to the Marmara Sea ecosystem. In addition, pollution from the tanker traffic causes an additional burden for the Marmara Sea ecosystem it is the only local and international maritime transit route for tankers crossing to and coming from the Black Sea. Contamination of the water with nutrients like nitrogen and phosphorus may lead s to more build-ups of sea snot over the Marmara Sea, particularly during an unseasonably warm spring of 2021. Moreover, the Marmara Sea has a unique environment that makes it particularly prone to large algal blooms (Aktan et al., 2008). Low salinity near the surface and saltier water near the bottom make it easier for small, plant-like organisms known as phytoplankton to grow. Tüfekçi et al. (2010) found that the intense mucous formations both in the surface and subsurface waters of the Sea of Marmara were the result of mucilage aggregates caused by direct, coagulated cellular exudates of phytoplankton and the presence of high dissolved organic carbon (DOC) content in the waters surrounding the aggregate. On the other hand, scientists believe that climatic factors, such as positive sea surface temperature anomalies and stable sea conditions from calm winds can generate a favorable environment for mucilage formation and enhancement (Deserti et al., 2005; Precali et al., 2005; De Lazzari et al., 2008; Danavaro et al, 2009). The spatial concentration of the mucilage layers can vary depending on wind speed and direction. During calm sea conditions, the layers can settle on the shores and pose threat to the coastal marine life and fishery (Russo et al, 2005). Danovaro et al. (2009) investigated the relationship between climate change and the frequency of mucilage in the Mediterranean Sea over the last 200 years and found that the number of mucilage outbreaks increased almost exponentially during the 1990-2009 period. They related the increasing frequency of mucilage outbreaks closely with the temperature anomalies. In another study, seasonal anomalies of temperature calculated as a spatial mean for the Po Valley area and North Adriatic Basin and anomalies of North Atlantic Oscillation (NAO) were compared with the historical record of mucilage outbreaks, and both climatic indices were found to be positively correlated with mucilage events (Deserti et al., 2005).

The mucilage problem led to a wide range of implications not only for marine life and fishing activities but also for the economy of the engulfing coastal towns. Many residents on the Marmara Sea coasts rely on fishing and tourism, and thus the mucilage problem created a major impact on the local economy. It prevented tourism activities by restricting the use of beaches along the shores of the Marmara Sea. It impacted the livelihoods of fishermen as they were not able to fish due to the sludge which got caught in their nets. Some concerns were also raised about water-borne disease outbreaks like cholera in settlements at close proximity to the Marmara Sea if the mucilage problem persisted. The scientist also further worried that the enhanced growth of sea snot through nutrient enrichment would disrupt the entire biogeochemical cycle not only in the Marmara Sea but also in the Aegean Sea as freshwater inflow from the Marmara Sea is crucial for the northern part of the Aegean Sea (Ilicak et al., 2021).

Motivated by the link between the meteorological factors and mucilage formation, this study aims to analyze the impact of increased sea surface temperatures and variability in wind speed, on the formation and enhancement of the mucilage over the Marmara Sea during March-May 2021 period. The goal also here is to provide some insight into the role of meteorological parameters, including the sea surface temperature and wind speed variability, as to how they are linked to occurrences of the mucilage problem in the Marmara Sea. That can help better identification of onset and progress of the mucilage outbreaks and provide some guidance to the authorities before they take any action. It also should be noted that the mucilage events affecting the Sea of Marmara have not been studied thoroughly from a meteorological perspective before although such events took place several times during the past two decades.

Study Area

The study focuses on the recent mucilage problem in the Marmara Sea and its relation to possible changes in the meteorological environment. The Sea of Marmara is a semi-enclosed basin with limited size connected through the Strait of Istanbul (also known as Bosporus Strait) to the Black Sea and through the Strait of Çanakkale (also known as Dardanelles Strait) to the Aegean Sea (Figure 1). The two-layer current systems exist in the straits and the Sea of Marmara, driven by the density and sea-level differences between the adjoining seas (Beşiktepe et al., 1999; Chiggiato, et al., 2012). The persistence of these two-layer structures is due to salinity differences. The two-layer structure restrains vertical mixing, generating stagnancy in the Marmara Sea. It was found that upwelling/downwelling dynamics of the current structure in the Marmara Sea were associated with north-easterly winds as well as flow from both Straits to some extent (Chiggiato, et al., 2012). Figure 2 illustrates upper and lower level current structures in the Marmara Sea and the aforementioned straits. Low salinity Black Sea waters (~18 PSU) flows into the Marmara Sea through the SOI and denser salty Aegean waters (~38.5 PSU) water flows into the Sea of Marmara through the SOC. Normally it is expected that the mucilage layers concentrated over the shores of the Marmara would be drifted by the surface currents from the Black Sea toward the Aegean Sea.

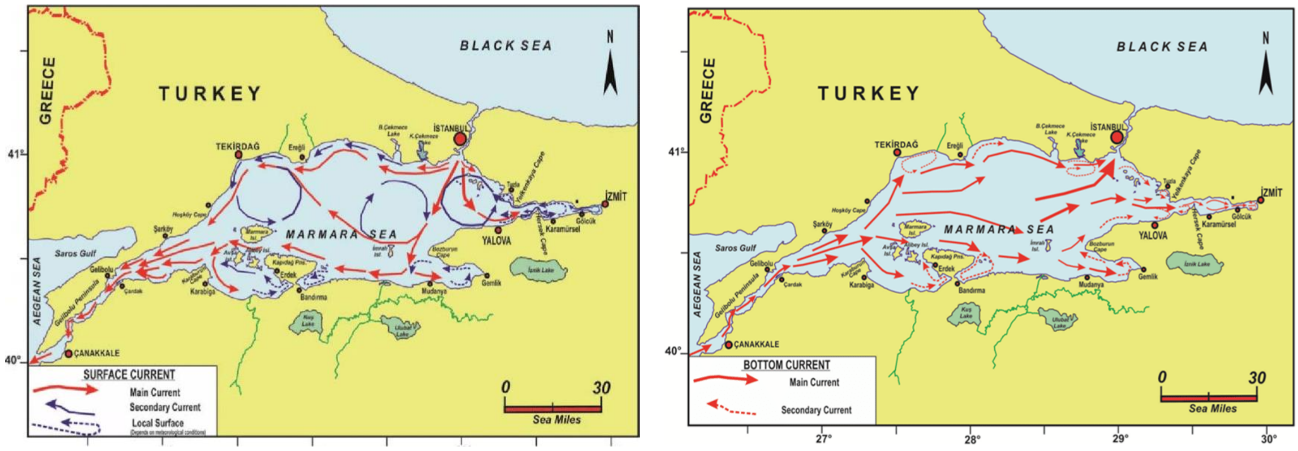


Fig. 1. Surface and bottom-level current structures in the Sea of Marmara and the connecting straits (From Engin et al.,2018).

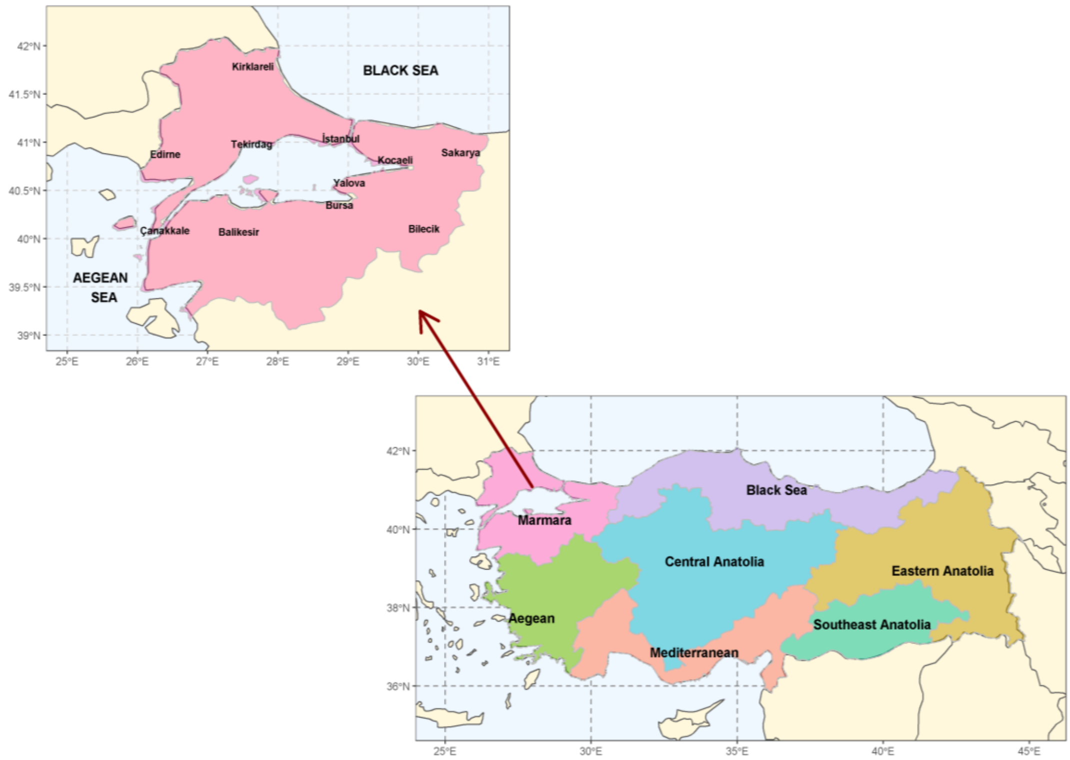


Fig. 2. Location of the Marmara region of Turkey

The Marmara Sea separates the European side of Turkey from the Asian side. A region that surrounds the Marmara Sea on both sides is also known as the Marmara region. It makes up 8.5 percent (approximately 67,000 square kilometers) of Turkey's surface area, with nearly 25 million people residing (Figure 2). It is the most populated region of Turkey and consists of coastal cities clustered around the Sea of Marmara. The region hosts many of the country's largest industrial facilities, which are specially situated on the Istanbul-Bursa-Kocaeli triangle. Automotive, textile, and petrochemical production are the main industrial activities in the region. Availability of land, sea, and air transportation networks, access to raw materials, easy and low-cost transportation and close proximity to the consumers attracted and facilitated the establishment and development of industrial facilities in the region. Istanbul is a major city of the region and has always been a center for business, culture, and education and acted as a hub for national and international transportation. The region has always been attractive for economic activities and employment which stimulated the migration of people from other parts of the country. Eventually, the Marmara Sea coastal zone began to suffer from severe industrial and domestic pollution as it receives the wastewater of more than 20 million people as well as industrial wastes. In addition, the pollution carried by the rivers from Europe and Russia, such as the Danube, Dnieper, and Rioni that confluence with the Black Sea flows into the Marmara Sea through the Strait of Istanbul (Bat et al., 2018). It is also likely that high amounts of phosphorus-rich detergent waters triggered the mucilage problem due to the pandemic conditions as people had to spend more time at home. Although there are decarbonization plants and advanced biological treatment plants in the region, they are not in sufficient numbers to meet the required demand.

Materials and Methods

In order to investigate the impact of the meteorological factors on the mucilage formation, mean and maximum sea surface temperatures at 27 locations and wind speed variability at 4 locations on the shores of Marmara and Black Seas are analyzed for the 1 April-6 June periods, when the mucilage problem developed (Figure 3). In addition, at 4 separate locations in the vicinity of Istanbul, seas surface temperatures (SST) variations are analyzed for the same period. Only one station (Sarıyer station) is located on the Black Sea shore, while the remaining 26 locations are located on the shores of the Marmara Sea. The SST analysis included both variabilities in the mean and maximum temperatures and their anomalies to detect cooling and warming trends in the SST records. In addition to the meteorological parameters, the relationship between the SSTs and water turbidity is also investigated as a factor that contributes to mucilage formation and enhancement.

The meteorological data used in the study were obtained from the database of Turkish State Meteorological Service (TSMS). The meteorological data were screened for quality control before used in the analysis. All the statistical analysis were performed using R Project for Statistical Computing tool at TSMS facilities.

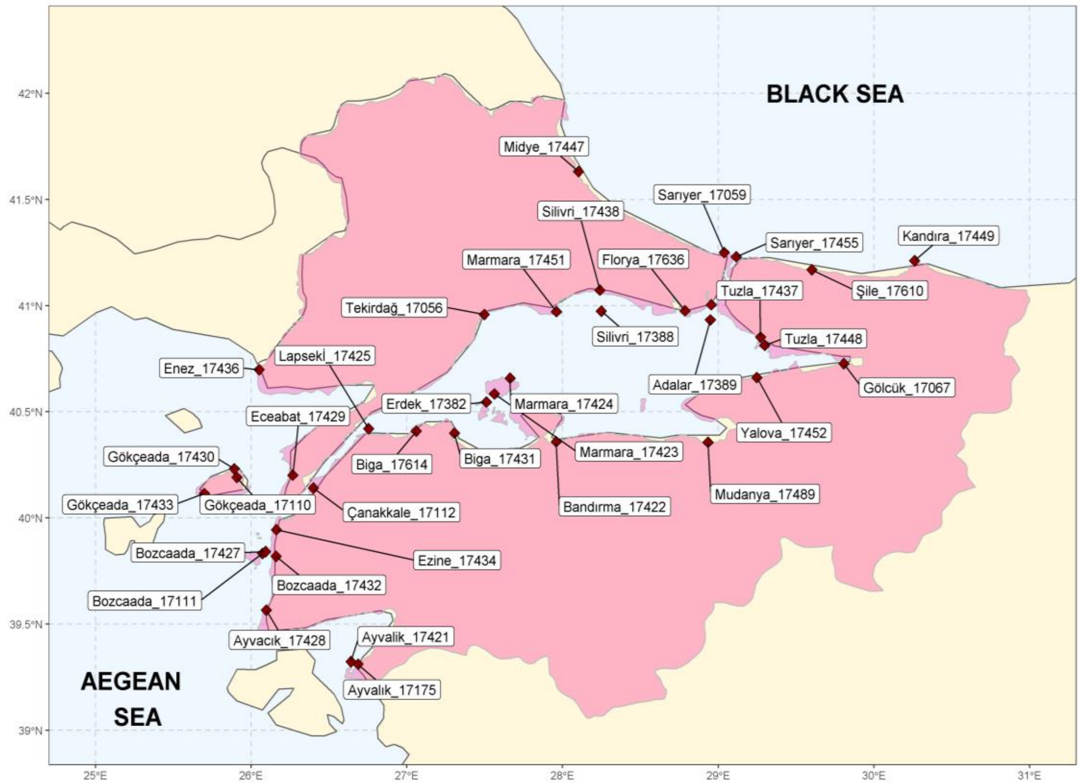


Fig. 3. Station selected for analysis of the SST and wind data across the Marmara Sea and the Black Sea coasts.

Analysis

Variability of Sea Surface Temperatures

When mean, minimum, and maximum sea surface temperatures are analyzed at 27 different locations on the shores of Marmara and Black seas, it is evident that they have increasing trends during the March-June period, and the increase is more apparent especially after mid-April (Figure 4). The highest increases in the SSTs are observed especially at Bozcaada, Gökçeada, Enez ve Çanakkale stations, which are located at southern parts of the Marmara Sea, reflecting latitudinal effect (Please see the Figure A1 and Figure A2 in the Appendix A section for the daily minimum and maximum SST graphs).

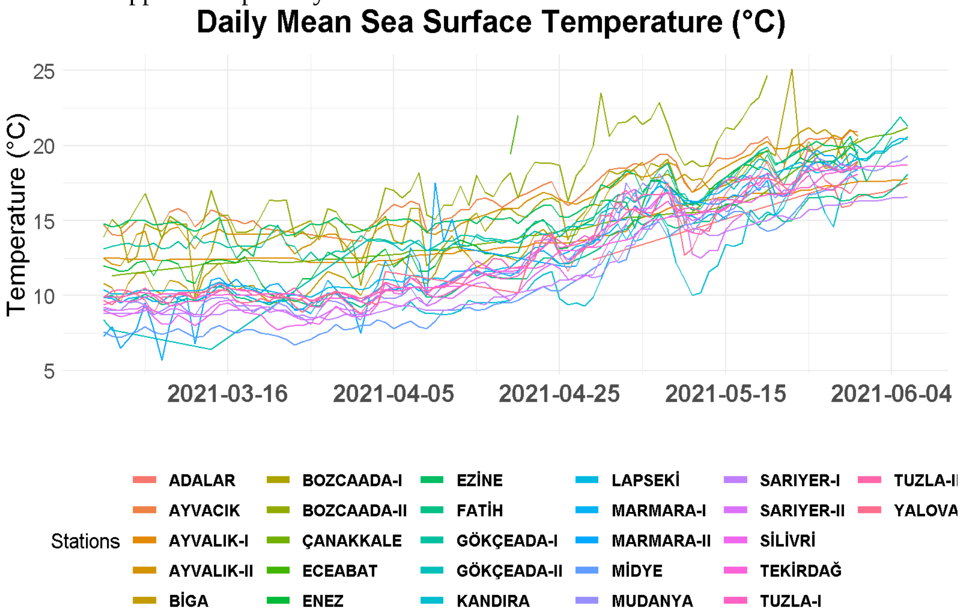


Fig. 4. Daily mean SSTs across the Marmara Sea and the Black Sea stations.

Changes in Sea Surface Temperatures at İstanbul locations

SSTs' variability is examined at four locations (Adalar, Fatih, and two Sarıyer stations) in coastal areas of İstanbul (Figure 5). It is found that in all locations mean, minimum and maximum SSTs indicate increasing trends especially during April-May 2021 period. Among these stations, Fatih, which is the most urbanized, indicates the highest increase in sea surface temperatures (Please see the Figure A3 and Figure A4 in the Appendix A section for the daily maximum and minimum SSTs at the four İstanbul locations).

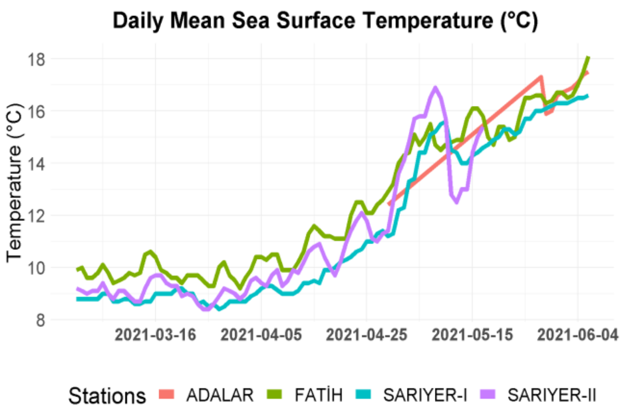


Fig. 5. Daily mean SSTs at 4 different İstanbul locations.

Wind Speed Variability in Marmara and Black Seas

Studies indicate that a decrease in the wind speed and calmer winds can have a direct or indirect effect on mucilage formation (Russo et al., 2005; Deserti et al., 2005). Sea currents become more stable during calmer winds, allowing mucilage formation as they cannot be drifted from the sea surface. It is argued that the calmer winds allowed concentration of the sledges along the shores, which would normally be drifted toward inner parts of the Marmara Sea and then to the Aegean Sea, through the Dardanelles Strait.

Observations from 8 different locations along the shores of Marmara and Black Seas indicate decreasing trends in the mean wind speed during March-June 2021 period. The decreasing trend is more apparent especially in the 2 stations located in the southern part of the Marmara Sea near the Dardanelles Strait (Figure 6). The view taken in this paper is that the reduced wind speeds slowed down the current over the surface, hence, not allowing the mucilage layers to drift from the shores toward the inner parts of the Marmara Sea and subsequently to the Aegean Sea through the Dardanelles Strait. In other words, the reduced wind speeds in and around the Marmara Sea not only triggered only mucilage formation, but also allowed increased concentration of mucilage formation along the shores of Marmara Sea.The above presented above is also supported by Ergül et al., (2021) showing how a windy environment can stimulate mucilage occurrences in the Marmara Sea. The mucilage layers were not observed on the shores of the Marmara Sea in March and April because of the gusty winds which disrupt the layered structure of the Marmara Sea. From the wind data it can be observed that the in March and early April of 2021, the winds were gusty and their speed began to decrease after the mid-April (Figure 6).

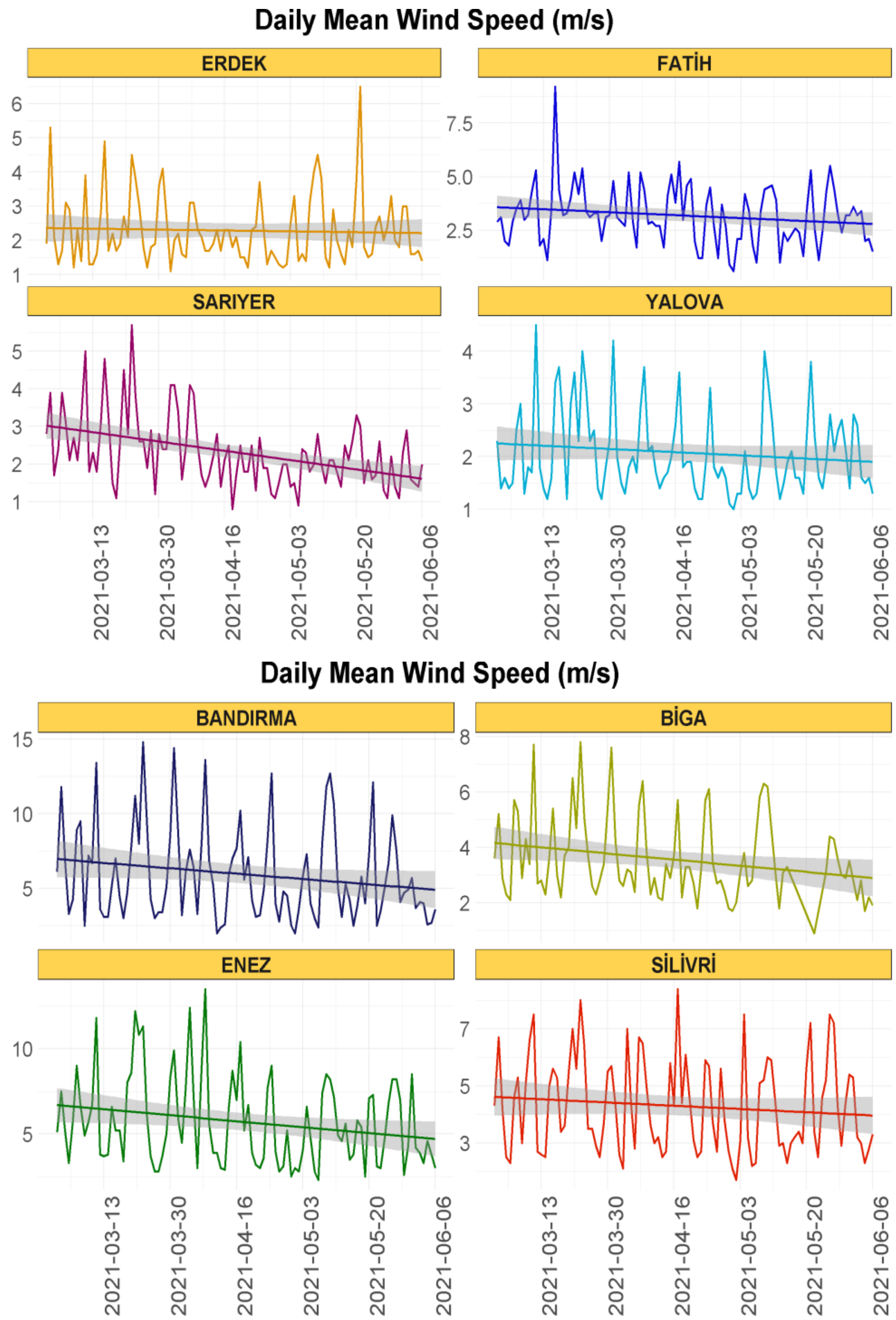


Fig. 6. Daily mean wind speed variability at different sites across the shores of Marmara Sea.

Typically from the wind rose for wind direction frequency, it is seen that the winds predominantly blow from the N-E band (Figure 7). As it gets close to the Dardanelles Strait, the frequency of the flow increases in the NE direction. The north-easterly winds support the upwelling and downwelling dynamics of the current structure in the Marmara Sea.

Monthly changes in the wind direction are analyzed at various geographic locations on the shores of the Marmara Sea. N-NE directional winds are almost prevailing during the March-June 2021 period (Figure 8). Only in Yalova station, the prevalent winds turn into a more easterly direction in May and June. As stated earlier, normally it is expected that the mucilage layers accumulated over the shores of the Marmara would be drifted by the surface current flowing from the Black Sea toward the Aegean Sea by not allowing mucilage layer concentration on the Marmara Seashores. Since no major shift in the wind direction is detected, the mucilage layer accumulation can be explained better by other meteorological factors.

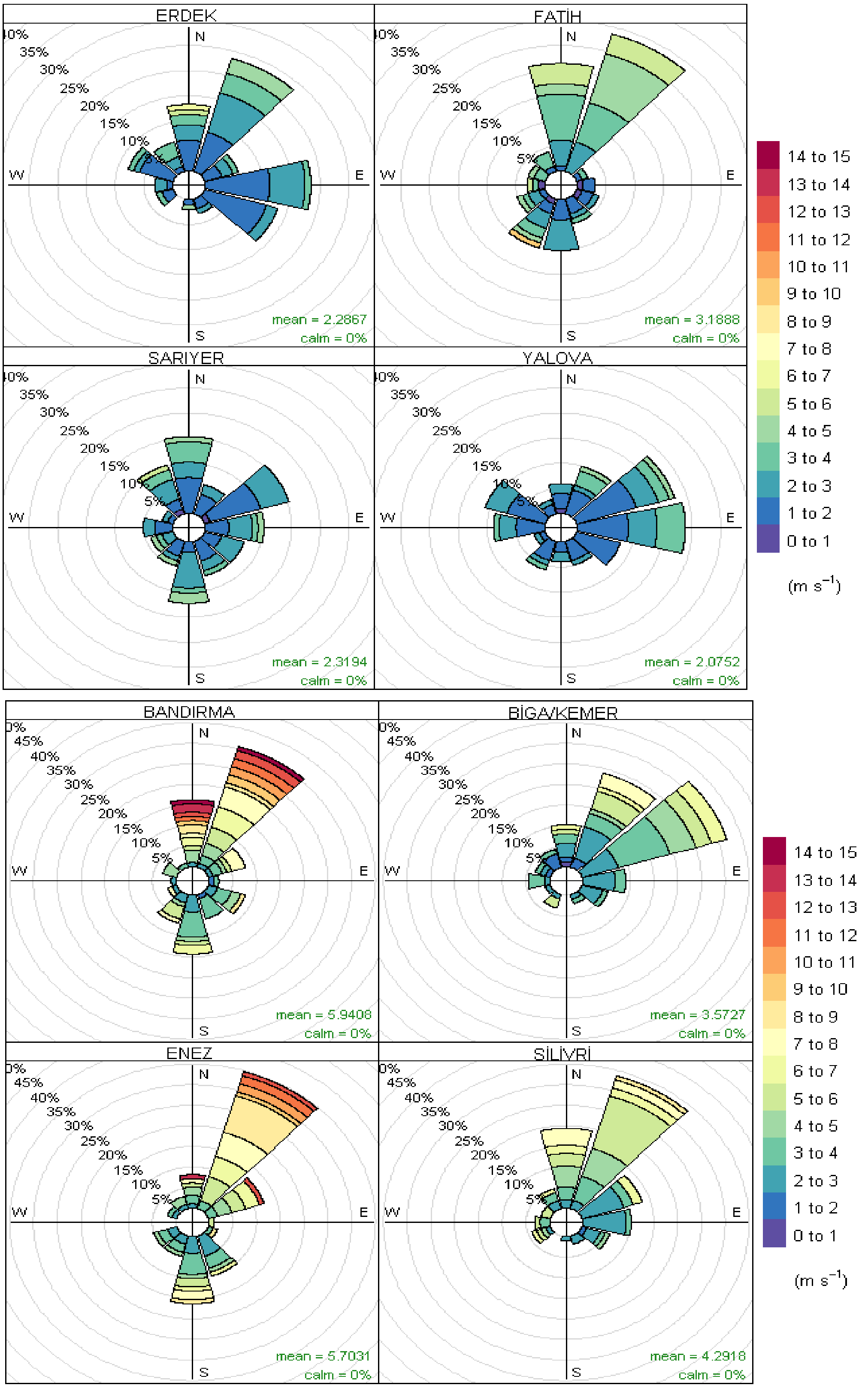
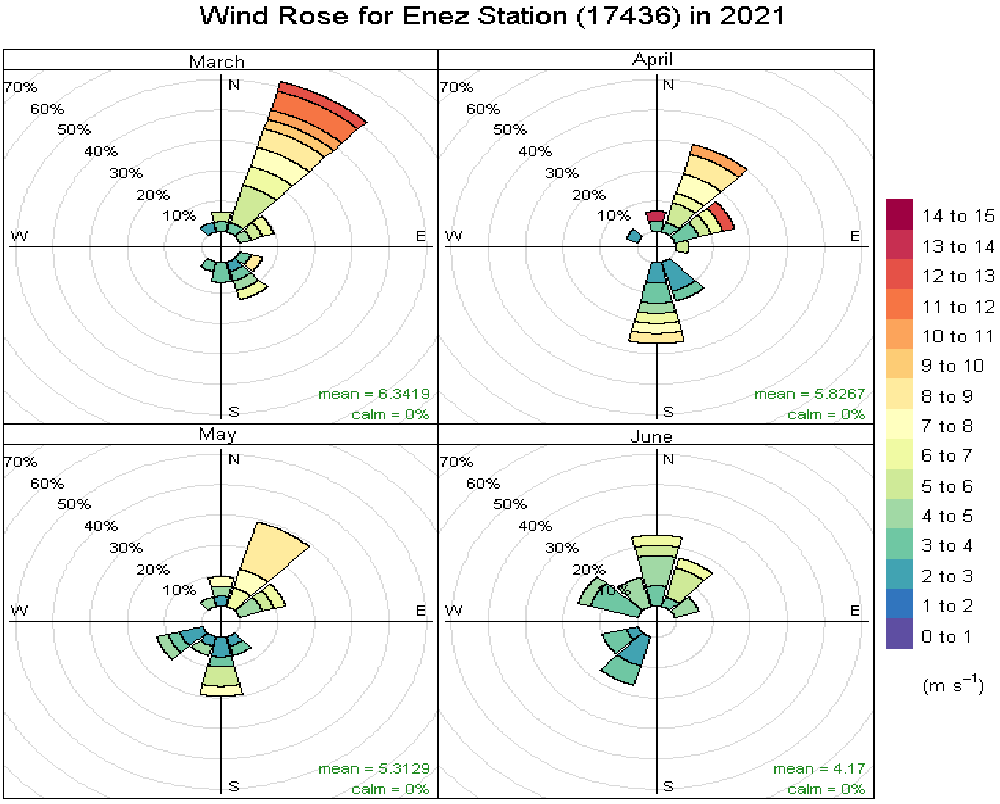
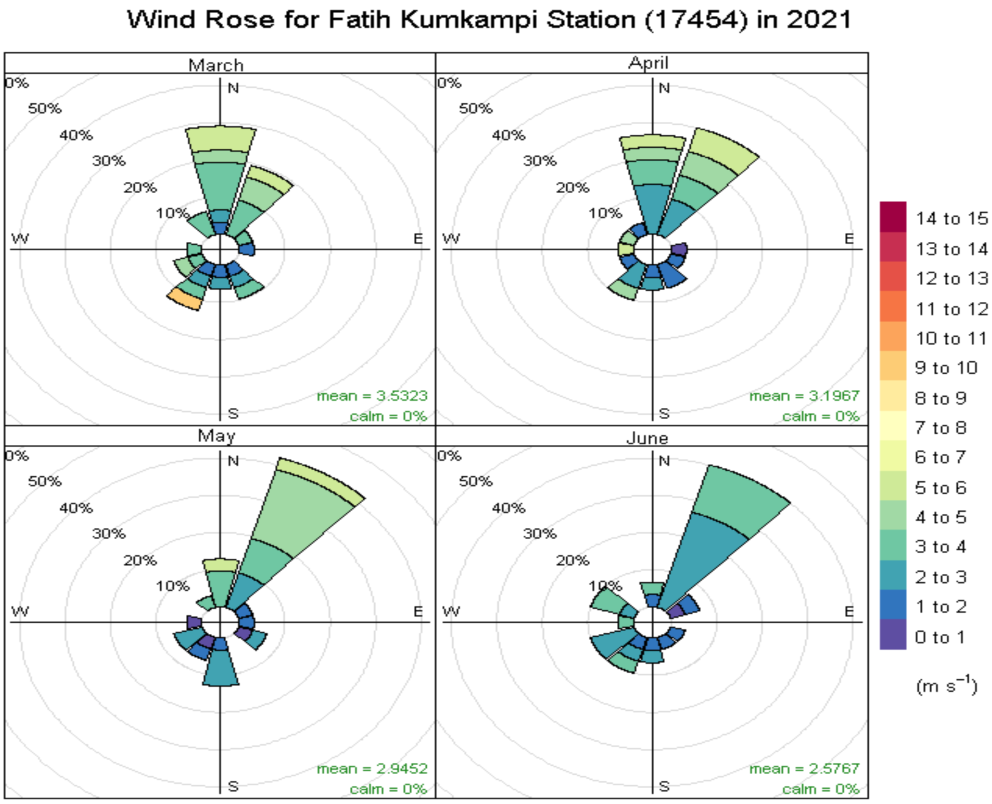


Fig. 7. Wind roses for different sites across the shores of the Marmara Sea.


Wind Rose for Enez Station (17436) in 2021
March
mean = 6.3419
calm = 0%
April
mean = 5.8267
calm = 0%
May
mean = 5.3129
calm = 0%
June
mean = 4.17
calm = 0%
14 to 15
13 to 14
12 to 13
11 to 12
10 to 11
9 to 10
8 to 9
7 to 8
6 to 7
5 to 6
4 to 5
3 to 4
2 to 3
1 to 2
0 to 1
(m s^{-1})


Wind Rose for Fatih Kumkampi Station (17454) in 2021
March
mean = 3.5323
calm = 0%
April
mean = 3.1967
calm = 0%
May
mean = 2.9452
calm = 0%
June
mean = 2.5767
calm = 0%
14 to 15
13 to 14
12 to 13
11 to 12
10 to 11
9 to 10
8 to 9
7 to 8
6 to 7
5 to 6
4 to 5
3 to 4
2 to 3
1 to 2
0 to 1
(m s^{-1})

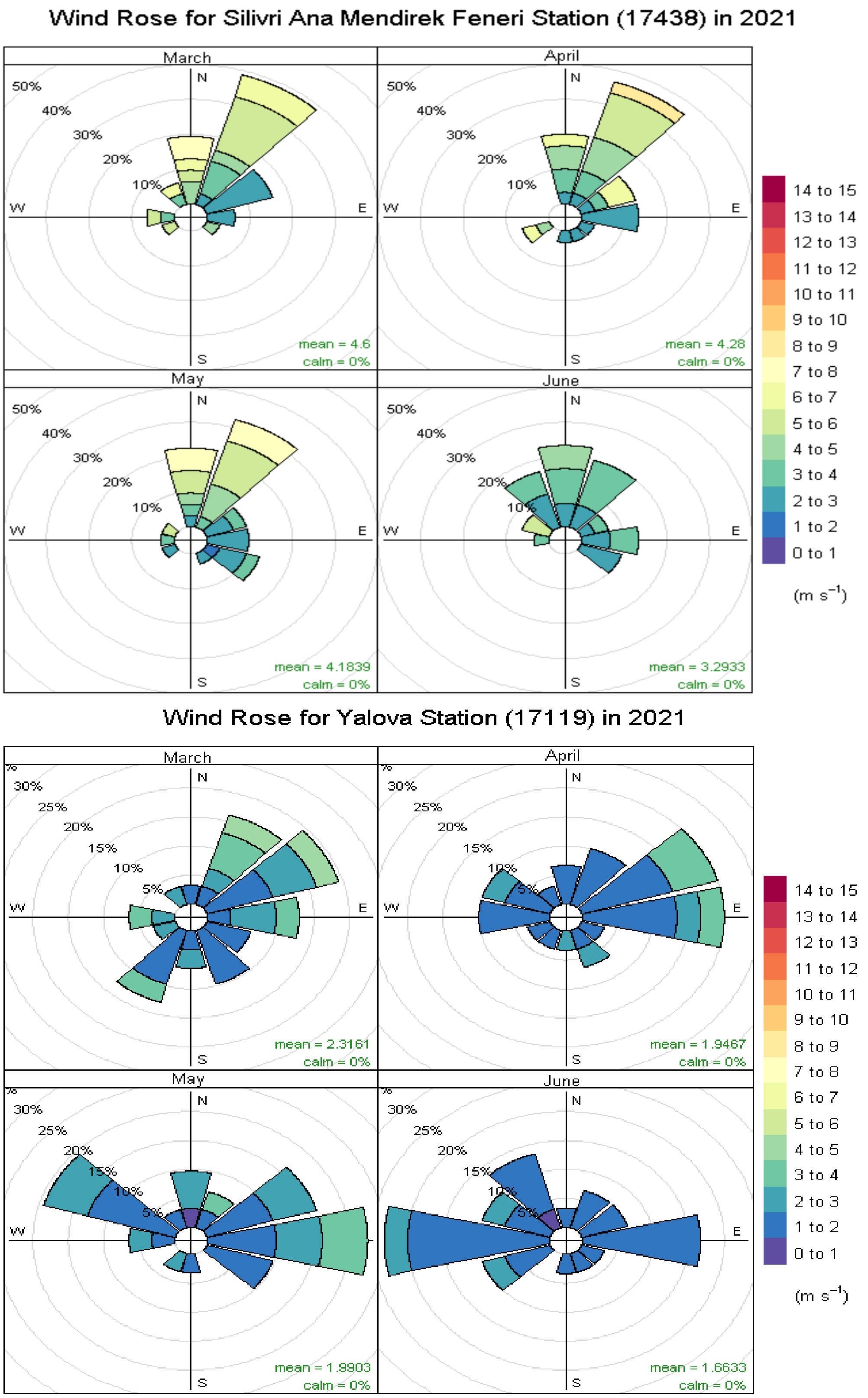


Fig. 8. Monthly changes in wind direction for different sites across the shores of the Marmara Sea.

SST Anomalies at the Marmara Sea and Black Seas

Anomalies of mean, minimum, and maximum SST at 25 locations on the shores of Marmara and Black Seas are examined to determine the cooling and warming trends for the April-June 2021 period. It is important to identify the warming and cooling trends in the SSTs at the stations to see if the trends are significantly above the normal and persistent even though they may indicate increasing trends. The analysis of the anomaly data for the mean SSTs indicates that despite increasing trends, Ayvalık (17175), Gökçeada, Tuzla, Marmara, Lapseki ve Enez stations are characterized below normal SSTs during some parts of the April-June period (Figure 9). In Ayvacık, Ayvalık (17421), Bozcaada, Gökçeada, Çanakkale, Ezine, Sarıyer, Tekirdağ stations indicate positive anomalies. In Marmara and Bozcaada stations, the positive anomalies reach nearly 6 degrees on some days, while in most of the other stations they remain within 0-3 °C. On the other hand, some stations like Kandıra, Silivri, Marmara, Midye, and Biga, indicate periodic cooling and warming trends.

Fig. 9. Daily mean SST anomalies at Marmara Sea and the Black Sea locations

When the maximum SSTs are analyzed, it is observed that while the Ayvacık, Ayvalık (17421), Bozcaada, Çanakkale, Ezine, Gökçeada, Sarıyer (17059) and Tekirdağ stations imply warmer than the normal temperatures, Ayvalık (17175), Fatih, Gökçeada, Lâpseki and Tuzla stations are characterized with cooling (Figure 10). Positive anomalies with the maximum SSTs reach 12 °C and 9 °C at Silivri and Bozcaada stations, respectively. It remained above 8°C at Marmara (17451) station. The anomaly values mostly range between 0-4 °C in other stations. It is interesting to note that maximum SST anomalies are greater than those of the mean SST anomalies. Periodic warming and cooling are observed at Ayvacık, Ayvalı ve Enez, Biga, Mudanya, Yalova, and Kandıra stations (Please see the Figure A6 and Figure A7 in the Appendix A section for the daily maximum SST anomalies for Marmara and Black Sea locations).

Finally, anomalies of minimum SSTs are analyzed and it was observed that while Ayvalık (17421), Çanakkale, Gökçeada, Sarıyer (17059), and Tekirdağ stations indicate apparent warming concerning to their normal, Ayvalık (17175), Fatih, Tuzla and Bozcaada stations are characterized with negative anomalies (Figure 11). On the other hand, Biga, Gökçeada, Kandıra, Midye and, Yalova stations indicate periodic warming and cooling without persistent trends. Minimum SST anomalies are usually within the range of 0-5 °C, and the highest values are at Ayvalık, Yalova, and Bozcaada stations (Please see the Appendix for the daily minimum SST anomalies for Marmara and Black Sea locations).

Satellite data also shows the warming over the Marmara Sea. For this purpose, NOAA NCEP Optimum Interpolation SST (OISST) data is used to identify the spatial extent of the warming and cooling over the Marmara Sea during the 2021 March-June period. The OISST data is constructed by combining observations from different platforms (satellites, ships, buoys, and Argo floats) on a regular global grid (Huang, et al., 2021). It includes data from the METOP-A and NOAA-19 to METOP-A and METOP-B satellites. It is evident that the warming is significant in March and continues until April with a slight decrease in the anomalies (Figure 10). May is also characterized by above-normal SSTs, especially in the central and eastern parts of the Marmara Sea, where the mucilage problem was worst. The satellite data clearly supported the warming at stations on the shores of the Marmara Sea during the March-May period (Figure 10).

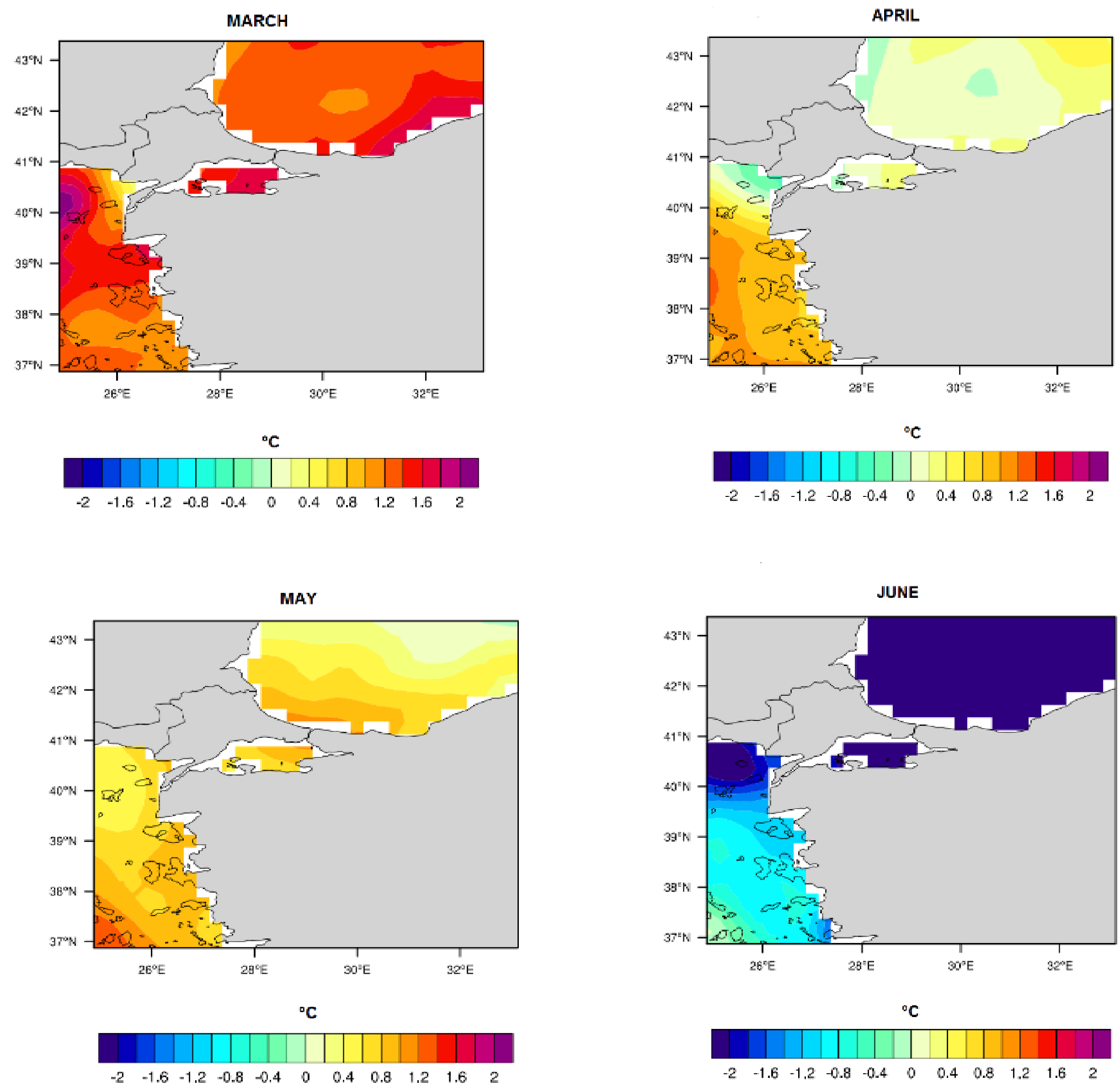


Fig. 10. Spatial distribution of the SST anomalies in the Marmara Sea during the March-June period (Data Source: NOAA NCEP Optimum Interpolation Sea Surface Temperature, OISST).

The temporal distribution of the SSTs is illustrated in Figure 11, which shows the monthly SST anomalies over the 40.7N cross-section over the Marmara Sea for the period between July 2020 and July 2021. It is evident that the SSTs are well above their normal during the September 2020-March 2021 period and remain warmer than their normal even after March 2021 with a slightly decreasing trend. It is the view in this paper that higher than the normal SSTs are conducive to triggering and enhancing the mucilage formation in the Marmara Sea during the spring of 2021.

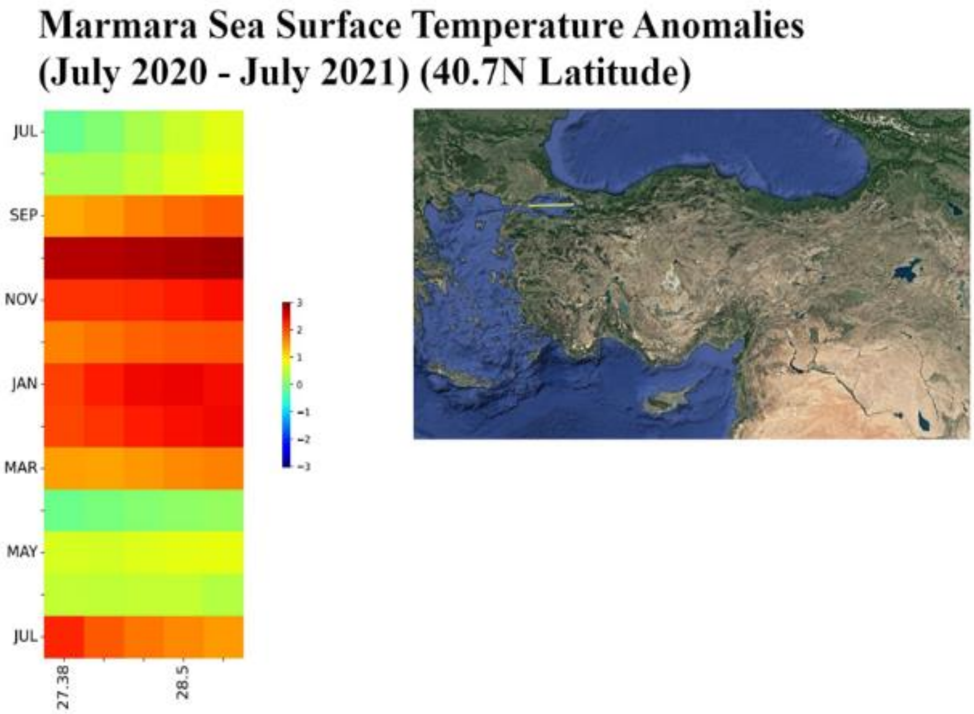


Fig.11. Monthly sea surface temperature variability between July 2020 and July 2021 at 40.7 N latitude cross-section over the Marmara Sea (Data Source: NOAA NCEP Optimum Interpolation Sea Surface Temperature, OISST)

Relationship between the SSTs and Turbidity in the Marmara Sea

As stated earlier, mucilage outbreaks are often associated with increased SSTs. In this part of the study, the relationship between the SSTs and water turbidity is examined as a factor that contributes to mucilage formation and enhancement (Xie, et al., 2018; Nazirova et al., 2021). Turbidity is caused by the presence of suspended particles and organic matter in the water column and when turbidity is low, more light can penetrate through the water column, which causes optimal conditions for algae growth. An increase of turbidity in the ocean can result from the increase of total suspended matter (TSM), the increase of algae concentration in the water, and the increase of dissolved organic matter (DOM) due to various atmosphere, ocean, and land processes (Shi and Wang, 2010). With a high rate of turbidity, more heat is trapped over the sea surface, causing the SSTs to increasing. Therefore, this study aimed to investigate if the increase in the SSTs over the Marmara Sea could result from more turbid waters or not. For that purpose, the relationship between the SSTs and sea turbidity is analyzed to determine the diffuse attenuation coefficient at the wavelength of 490 nm, Kd (490), derived from measurements of the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Aqua satellite. The diffuse attenuation coefficient at the wavelength of 490 nm, Kd (490), is an important water property that can be related to light penetration and availability in the ocean. It is a measure of how light dissipates with depth in water. The clear water is defined with Kd (490) ≤ 0.1 m^{-1}, the modestly turbid waters with Kd (490) values ranging from ~0.1 to 0.3 m^{-1}, and turbid waters are defined with Kd (490) over 0.3 m^{-1}, respectively (Shi and Wang, 2010).

The analysis is performed for the long-term (2009-2021), and especially, for the 2020-2021 period when the mucilage activity was intense in the Marmara Sea. In figure 12, the scattering plot on top illustrates the long-term (2009-2021) relationship between the diffuse attenuation coefficient variability and the SST variability, while the plot in the middle shows the relationship between the diffuse attenuation coefficient variability and the SST variability for 12 months covering the June-2020 and June-2021 period when the mucilage activity peaked in the Marmara Sea. The bottom figure represents the spatial coverage where the relationship is investigated between the two parameters. It is noticed that the correlation between the two parameters increased significantly during the latter period as compared to the long-term period. In both periods, most of the data are located in the modestly turbid category (~0.1 to 0.3 m−) but the rate of change between the two parameters increased significantly during the intense mucilage occurrence period. It is our view that with the modest turbidity, more sunlight penetrated the water, causing an increase in the SSTs in addition to the climate change-related warming.

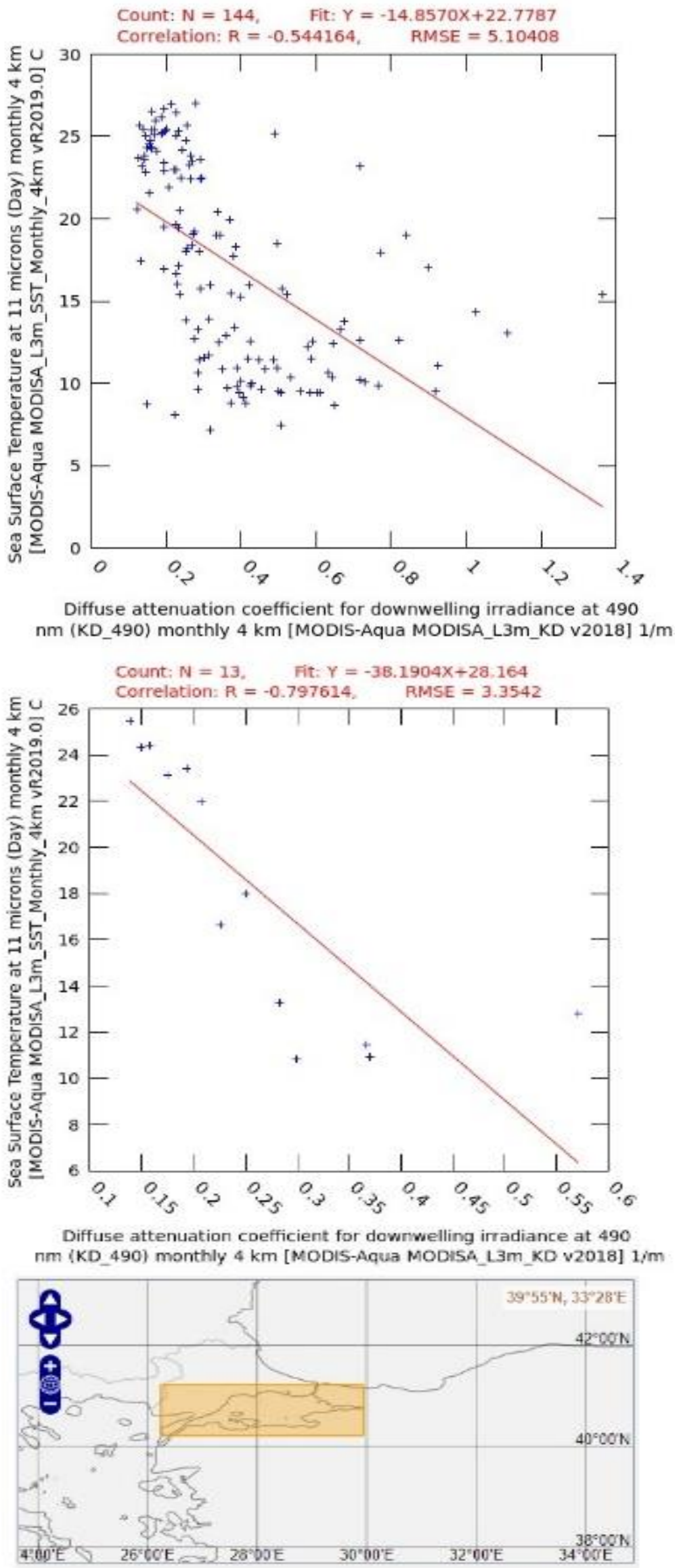


Fig. 12. Relationship between the SSTs and turbidity in the Marmara Sea based on MODIS sensor on Aqua satellite.

Results and Conclusion

Turkey's Marmara Sea experienced a severe mucilage outbreak during the March-May period of 2021, causing considerable environmental impacts, disrupting the fishing industry, and threatening marine life significantly. The impact was greater especially in the central and eastern shores of the Marmara Sea, where industrial activities and urbanization are very intensive. The Ministry of Environment, Urbanization, and Climate Change (MEUCC) began clean-up efforts in the second week of June with the coordination of local municipalities to remove the mucilage layers off the sea surface.

Industrial and urban wastes are considered as the main mucilage formation causes, but it is also believed that meteorological factors, including the increase in sea surface temperatures (SST) and reduced wind speed along with more stable current conditions, contribute to the formation and enhancement of the mucilage outbreaks. This study examined the above-mentioned meteorological conditions using surface and satellite data to establish a link between them and mucilage formation and enhancement. For this purpose, mean and maximum SSTs at 27 locations are studied in addition to wind speed variability at eight locations on the shores of the Marmara and Black Seas.

The findings indicate that the increased SST and reduced wind speed generate a favorable environment for the formation and enhancement of the mucilage outbreak during the March-June 2021 period. Most of the stations indicated warming trends and positive SST anomalies, while several other stations implied periodic warming and cooling. Few stations indicated cooling trends. It was found that the maximum SST anomalies were greater than those of the mean SST anomalies. Moreover, the NOAA NCEP Optimum Interpolation SST (OISST) data supported the warming especially in central and eastern parts of the Marmara Sea during the March-May period. The observations at 8 different locations along the shores of Marmara and Black Seas indicated decreasing trends in the mean wind speed. The reduced wind speeds led to slower current speeds, without allowing quick removal of the mucilage layers and leading concentration of the layers on the shores of the Marmara Sea. In conclusion, meteorological factors, especially the increased SSTs and the reduced wind speeds, played considerable effects in the mucilage formation and its enhancement spatially during the April-May period of 2021.

This study concludes that by monitoring SST variability either by in-situ measurements or satellite data and wind speed variability, the onset and spatial progress of mucilage outbreaks can be explored and identified better. Especially the satellite measured SST would provide more invaluable information to identify the proper meteorological environment for the occurrence of mucilage outbreaks and observe its duration and progress of the event as they provide greater spatial coverage. Eventually, monitoring of both the SSTs and wind speed parameters would allow decision makers to take precautions in advance to manage the mucilage outbreaks before they turn into a disaster and tackle the issue more timely and effectively.

After all, the view of this study is that the occurrence of mucilage outbreaks in the Marmara Sea cannot be explained by meteorological factors alone as several other (local) factors play additional roles in mucilage formation and/or increases in the magnitude of this phenomenon. However, the link between meteorological factors and the occurrence of mucilage outbreaks is evident from the analysis presented here under the light of the warming of the Marmara Sea during the March-May period of 2021. The pollution accumulation over the years also seemed to have caused serious turbidity in the Marmara Sea. When the relationship between the diffuse attenuation coefficient variability and the SST variability for 12 months from the June-2020 to June-2021 period is considered, the mucilage activity peaked in the Marmara Sea and it was noticed that the correlation between the two parameters increased significantly as compared to the long-term period. In both periods, most of the data were located in the modestly turbid category (~0.1 to 0.3 m−), but the rate of change between the two parameters increased significantly during the mucilage outbreak period. It can be argued that with the modest turbidity more sunlight was able to penetrate the water and caused to increase in the SSTs in addition to the climate change-related warming. Further research is needed to study the impact of the other factors, including the hydrodynamic regime of the Marmara Sea (i.e., current speed and water mass turnover), oxygen availability, amount of chemicals (like nitrogen and phosphorus) released through the industrial facilities. Unless some action is taken to reduce industrial and domestic pollution due to industrial and urban facilities in the vicinity of the Marmara Sea, a similar problem may emerge in the future with the warming of the Marmara Sea and stable sea conditions. It seems that the warmer SSTs in coastal areas, coupled with the nutrient-rich surface flow from containing untreated or poorly treated municipal waste will lead to increased frequency, intensity, and duration of such mucilage outbreaks in the future. It is the view of this study that when the contributing factors that led to the formation of the mucilage disappear, the problem will be resolved over time. It is another view that the only controllable factor is pollution. Measures and practices towards improving sea water quality are certainly needed and imperative to mitigate the mucilage phenomena. Advanced biological treatment facilities are urgently needed to remove pollutants such as carbon, nitrogen, and phosphorus that cause problems in wastewater. As a quick remedy for the problem, the existing wastewater treatment plants in the region should be converted into advanced biological treatment facilities. Last but not the least, the waste load from both agricultural and industrial surface areas in a close proximity to the Sea of Marmara should be reduced to minimize its impact on mucilage formation.

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APPENDIX A

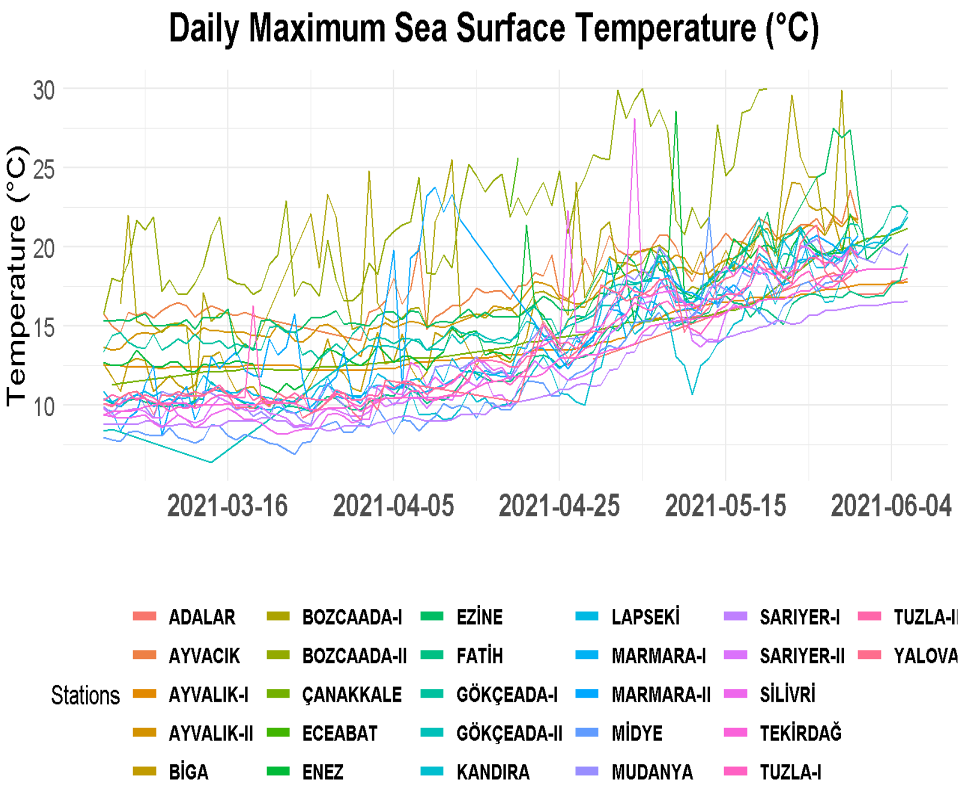

Fig A1. Daily maximum SSTs across the Marmara Sea and the Black Sea stations.

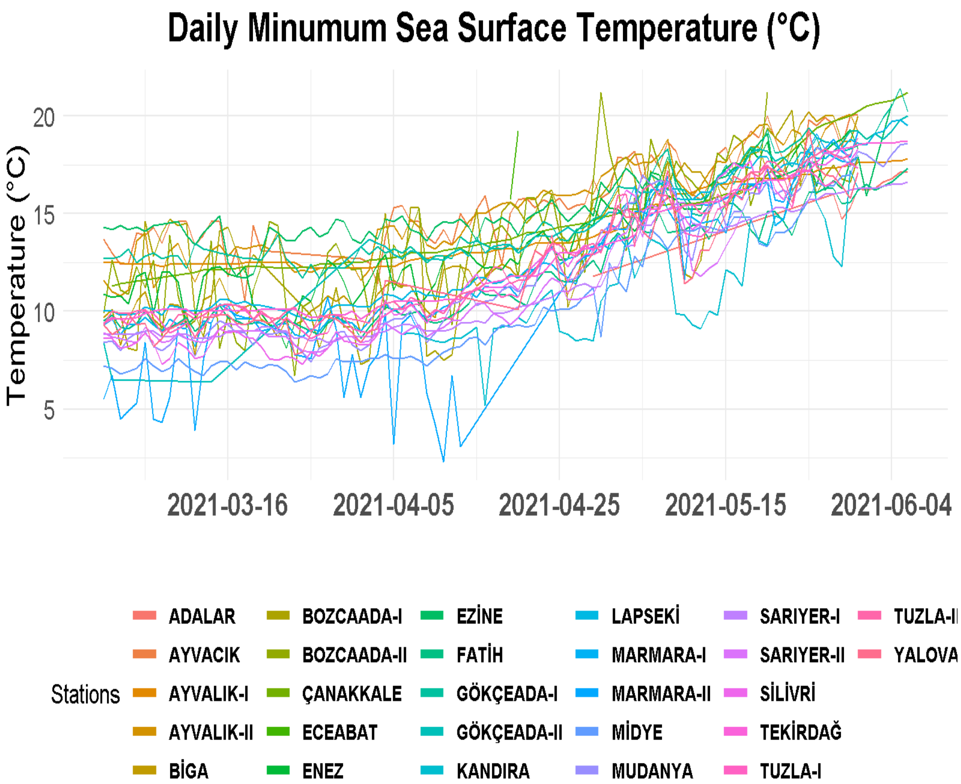

Fig. A2. Daily minimum SSTs across the Marmara Sea and the Black Sea stations.

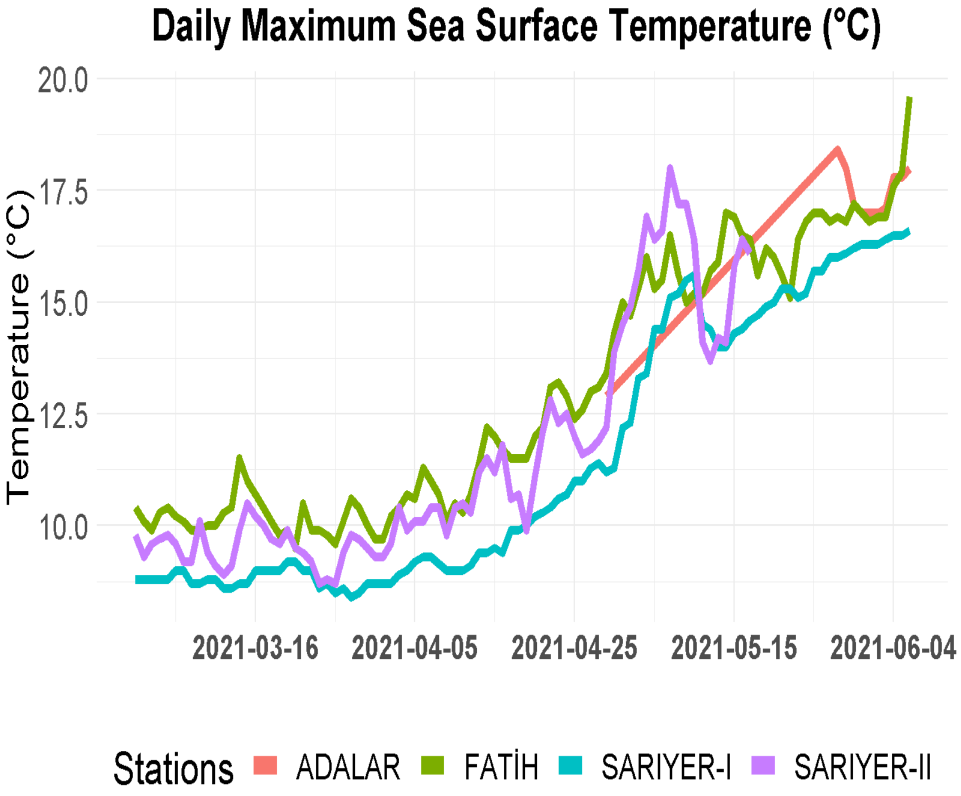

Fig. A3. Daily maximum SSTs at 4 different İstanbul locations.

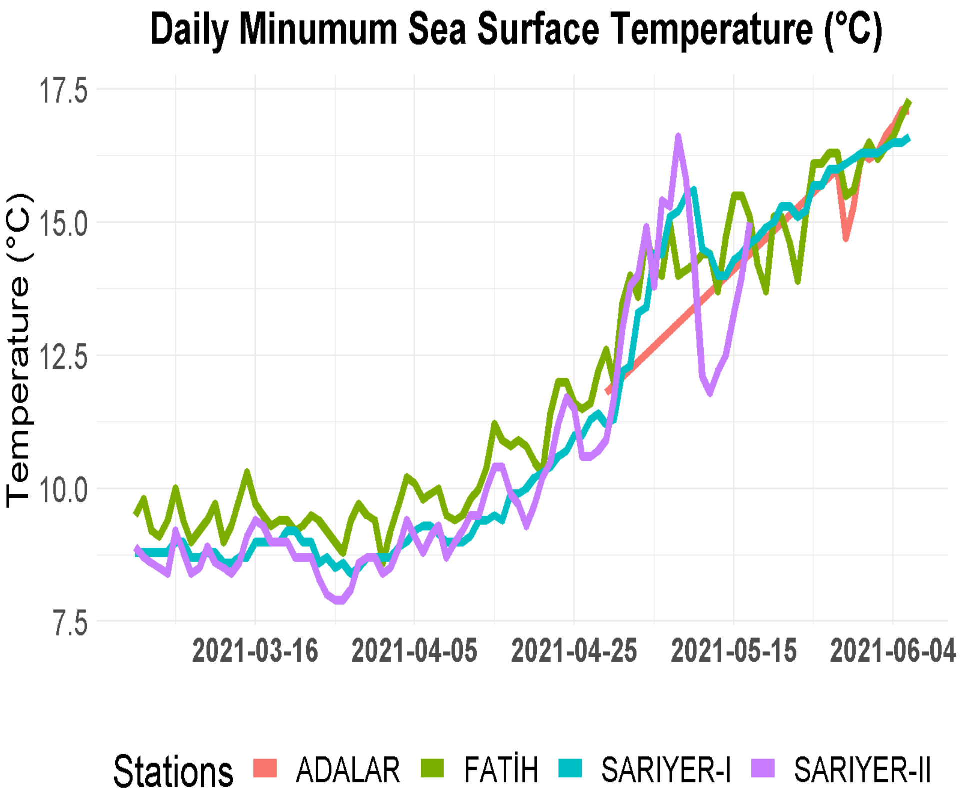

Fig. A4. Daily minimum SSTs at 4 İstanbul locations

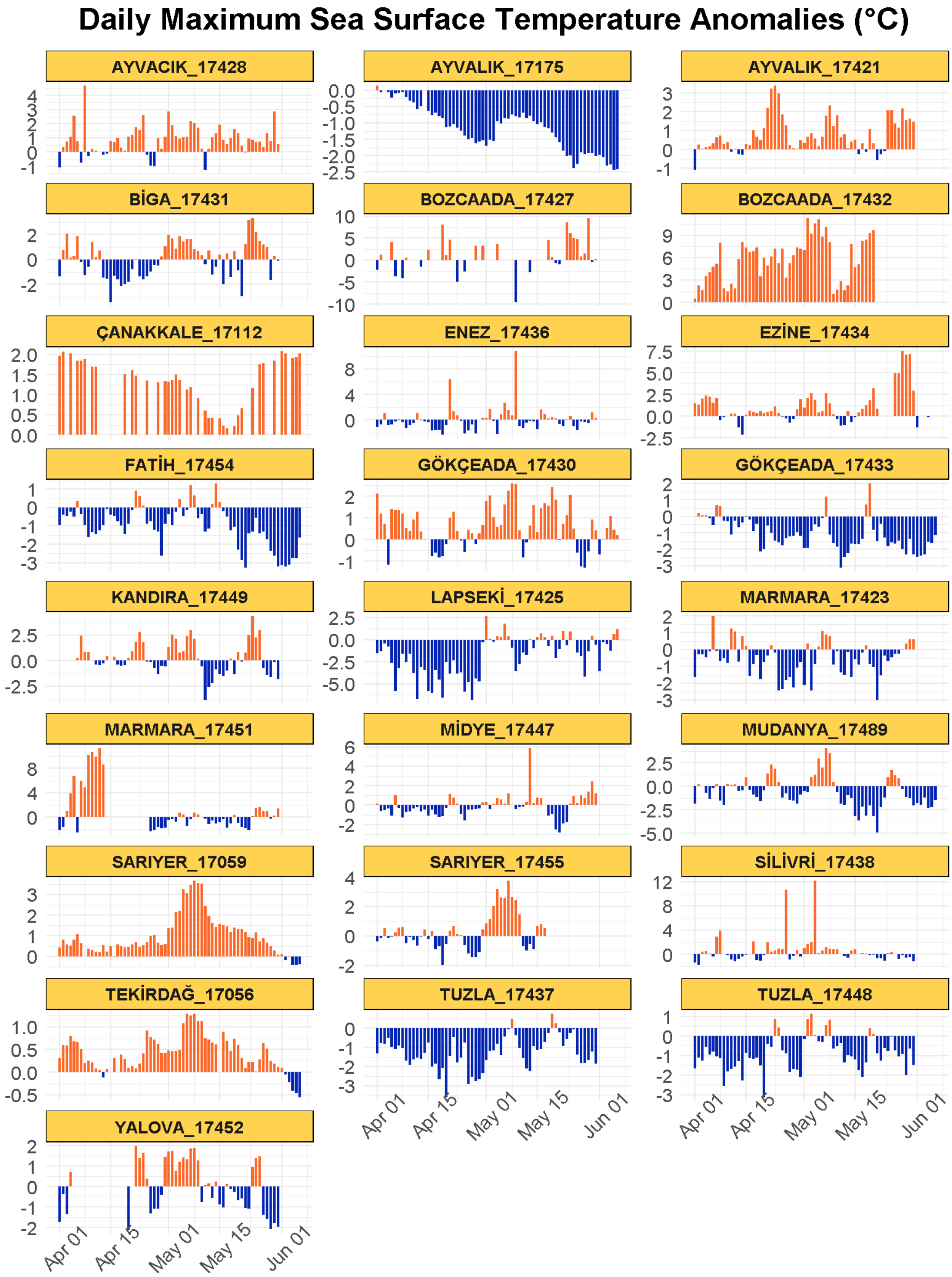

Fig. A5. Daily maximum SST anomalies at Marmara Sea and the Black Sea locations.

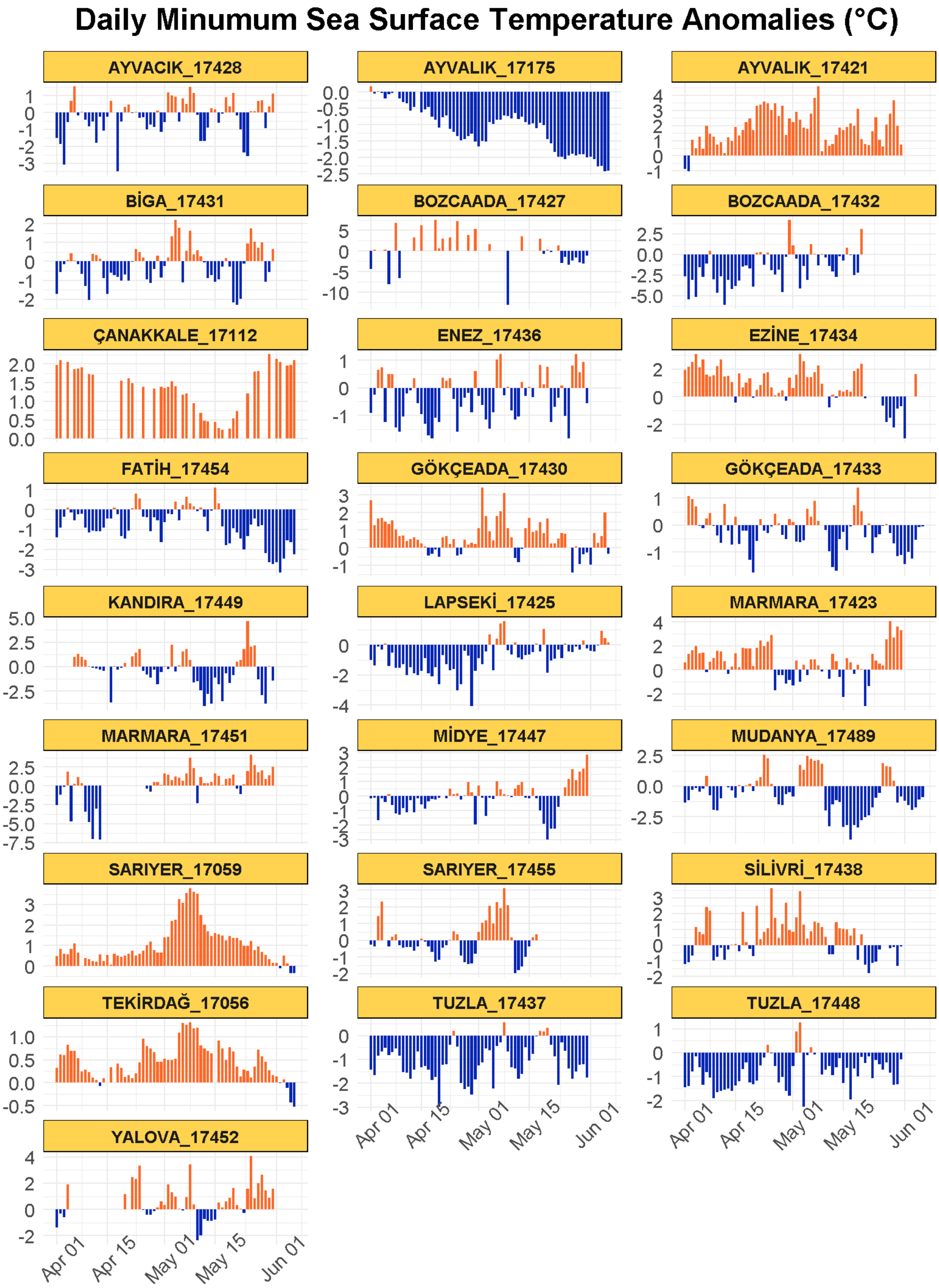

Fig. A6. Daily minimum SST anomalies at Marmara Sea and the Black Sea locations.