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RESEARCH PAPER

Alterations of the Physical and Biochemical Structure in the İzmit Bay Following the Blockage Events at the İstanbul Strait

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Abstract

In December 2021 and March 2022, synoptic-scale weather systems triggered blockages in the İstanbul Strait, resulting in a notable alteration of the water dynamics of the upper layer of the northeastern Marmara Sea. The blockages resulted in the disruption of water mass exchanges between İzmit Bay and the eastern Marmara basin, driven by intensified hydrodynamic forces and severe wind conditions. The blockage of the two-layer flow in the strait led to an intensification of upper layer dynamics, resulting in an elevation of nutrient levels through mixing with nutrient-rich lower waters and/or the redistribution of nutrient fluxes via an enhanced jet current.
This study demonstrates the occurrence of rapid changes in the biochemical structure of İzmit Bay, as evidenced by Acostic Poppler Current Profiler (ADCP) measurements and near-weekly temperature and salinity profiles. The analyses demonstrate significant shifts in flow dynamics, with salinity serving as an indicator of enhanced mixing. This mixing enabled the transport of nutrient-rich deep waters to the upper productive layer, thereby stimulating increased biological activity. The findings highlight that the altered dynamics resulted in a notable surge in nutrient concentrations and biochemical activity, potentially fostering the expansion of mucilage-forming species in İzmit Bay.

Introduction

Oceanographic properties of two-layer system of the İzmit Bay, follow to a large extent changes in the Marmara Sea (Ünlüata et al., 1990). The unique oceanographic characteristics of the İstanbul Strait plays a central role in the Marmara Sea's overall dynamics. The İstanbul Strait exhibits a hydraulically controlled two-layer maximum exchange regime, influenced by its unique geometry, particularly at the constricted areas near the northern and southern exits (Farmer and Armi, 1986; Ünlüata et al., 1990; Özsoy et al., 1998; Gregg and Özsoy, 2002). The water level differences between the Black Sea and Marmara Sea, along with wind and atmospheric pressure, significantly affect the variability of the upper and lower layer flows in the strait (Oğuz et al., 1990; Ünlüata et al., 1990; Özsoy et al., 1998). Annual water exchanges within the Turkish Straits System (TSS) has been studied extensively (Beşiktepe et al., 1994; Özsoy et al., 1996; Jarosz et al., 2011a, b; Altıok et al., 2014). Jarosz et al. (2011b) calculated the upper- and lower-layer flows at the southern exit of İstanbul Strait at 444 and 333 km³/year, and at the northern exit at 375 and 253 km³/year, based moored ADCP measurements in the strait.

Extreme meteorological events, such as storms due to atmospheric system transitions leading to disruptions in the two-layer flow system which changes the layer dynamics and may lead flow blockages and the reversals in the İstanbul Strait. Earlier studies highlight the significant flow rates, particularly in the upper layer, which is strongly influenced by atmospheric forcing (Jarosz et al., 2011a; Altıok and Kayışoğlu, 2015). During periods of high-water levels in the Black Sea, northerly winds can block the lower layer flow, while southerly winds during low water levels can block the upper layer flow (Özsoy et al., 1986; Latif et al., 1991; Doğan et al., 1998; Alpar et al., 1998, Altıok et al., 2014). The upper and lower layer flows in the İstanbul Strait show strong seasonal variability, with higher flow rates Black Sea surface waters in winter (Özsoy et al., 1995). Temel Oğuz (2017) emphasized the critical role of the Bosporus jet flow in shaping the dynamics and biochemistry of the Marmara Sea.

The variations in the Marmara Sea oceanographic properties largely influence the oceanographic characteristics of the two-layer system in İzmit Bay (Ünlüata et al., 1990; Sur, 1988). During spring and summer, upper-layer water flows into the bay, driven by sea level differences between the Marmara Sea and the bay's interior. Conversely, in autumn and winter, when these sea level differences diminish, the upper layer flows outwards toward the Marmara Sea (Sur, 1988). However, strong winds can disrupt this pattern, inducing vertical mixing between the upper and lower layers at shallow depths (Baştürk et al., 1985; Sur, 1988; Algan et al., 1999; Altıok et al., 1996). There are limited studies focusing on reactions of İzmit Bay's hydrodynamics to severe wind conditions. Altıok et al. (2020) studied the diurnal variation of stratification in İzmit Bay under changing meteorological conditions demonstrated the effective mixing caused by strong winds lasting more than three days. In another recent study, Mutlu et al. (2024) investigated the sensitivity of İzmit Bay water circulation to wind based on process-oriented modeling where they neglected all forcing factors except wind stress. The interactions of Marmara Sea and İzmit Bay need to be researched further to improve our limited understanding of İzmit Bay dynamics. The nutrient loads entering to the Marmara Sea from the Black Sea shows seasonal variation. It is 2-3 times higher than in autumn during the winter (Polat and Tuğrul, 1995; Tuğrul et al., 2002). The nutrient load increases by both enhanced winter mixing and flux of Black Sea (Özsoy et al., 1995; Çokacar and Özsoy, 1998). The Marmara Sea lower layer nutrient concentrations are high with the values 8-10 μM NOx and 0.7-1.2 μM PO_4 (Polat et al., 1998). The concentrations of nutrients and DO within İzmit Bay are primarily influenced by the physical exchanges of water with the adjacent Marmara Sea waste load inputs and primary production (Morkoç et al., 1997). The sinking of organic matter leads imbalance between the DO consumption and its replenishment, making these exchanges crucial for the bay's ecological balance. Surface nitrate and phosphorus concentration levels in the İzmit Bay are generally low throughout the year (Bayram Partal, 2022). The increased nutrient concentrations observed during the winter months, due to the rise in terrestrial inputs from precipitation, decrease in the spring months with the increase in phytoplankton growth, and remain low during the summer due to the continued but relatively reduced growth and decreased inputs (Bayram Partal, 2022). The highest chlorophyll-a concentrations have been recorded in the southern Marmara coastal waters and the İzmit Bay (Tutak et al., 2012; Dursun et al., 2020). In general phytoplankton biomass and species composition are rich in the coastal regions of the Sea of Marmara and in the İzmit Bay. The renewal capacity is determined in order of 1-2 month in the Bay (Tuğrul and Morkoç 1990). The water quality deteriotions affect phytoplankton abundance and diversity significantly (Okuş and Yüksek, 1996; Okuş and Taş, 2001; Ediger et al., 2013). It is known that the abundance of diatom and dinoflagellate species in the bay shows seasonal variation. Since 2008, dinoflagellate dominance has been reported in the İzmit Bay during the spring and summer periods. In a seasonal study conducted between 2015 and 2018 in the northeastern region of the Marmara Sea, including İzmit Bay, it was determined that diatom and dinoflagellate species were dominant (Ergül et al., 2018; Deniz and Taş, 2020; Bayram Partal, 2022,). Approximately 15% of the species identified during the study were toxic or potentially harmful species (Bayram Partal, 2022).

This study contributes valuable insights into the abrupt oceanographic characteristics changes of inflowing eastern Marmara upper water column under the influence of system passages with accompanying severe wind conditions. Its implications to İzmit Bay marine ecosystems are analyzed based on monitoring oceanographical parameters following the system passage. The reactions of İzmit Bay's ecosystem to the abrupt changes in layer dynamics are evaluated. Further emphasis is given for mucilage forming phytoplankton species since it has been a recurring issue in the Marmara Sea since 2007 (Tüfekçi et al.2010, Aktan et al., 2008; Balkıs et al., 2011; Taş et al., 2020) The formation of mucilage is shown to be related to abrupt changes of hydrometeorological and biogeochemical conditions on short temporal scales (Cozzia et al., 2004; De Lazzari et al., 2008; Martin et al., 2010). The complex mechanisms behind mucilage formation involve both climatic changes and anthropogenic pressures, particularly the increase and imbalance of nutrient inputs (Purcell et al., 2007; Yüksek and Sur, 2010; Yüksek, 2021). This research contributes to improving our understanding of the potential impact of biochemical changes on mucilage formation in the Marmara Sea

Material and Method

Oceanographic and meteorologic data stations used for this study are shown in Figure 1 The Acoustic Doppler Current Profiler (ADCP) transects were carried out along the track line perpendicular to the strait axis at the northern and southern exits of the İstanbul Strait and at the entrance of İzmit Bay, as shown in red lines in Figure 1. Atmospheric forcing was received from the European Centre for Middle-Range Weather Forecasts (ECMWF) ERA5 reanalysis (https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-

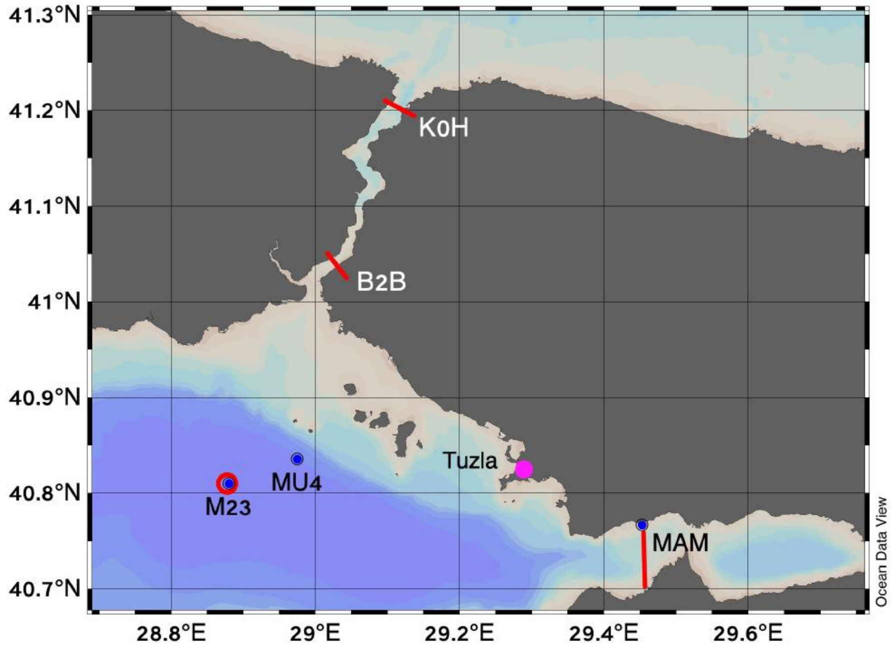

Figure 1. Sampling stations: Station M23 shown by red circle; MU4 and MAM stations are shown by blue dot. Tuzla meteorology station is shown by magenta dot. ADCP transects are indicated by red lines. K0H and B2B are stations are the deep stations placed near to the transects in the İstanbul Straits.

levels?tab=overview). Moreover, the local meteorological data (wind and air pressure) representing İzmit Bay is obtained from the Tuzla Meteorological Station of the Turkish State Meteorological Service (TSMS).

The MU4 is the station resembling the eastern Marmara open waters close to the İzmit Bay. The MU4 station and the nearest station in climatologically available data (M23 station İstanbul Water Sewerage Administration (IWSA) monthly monitoring program during 1996-2009) are compared (Figure 1). The salinity profiles of climatological data are analyzed to identify the mean and variation range of the layer structure. The measurements at MU4 station following the blockage is evaluated against the climatological data. MAM station at the entrance of the İzmit Bay is evaluated against MU4 station. Following the upper layer Black Sea blockage observation on December 2, 2021, six measurements were performed at the MAM station over the course of the month. After the lower layer blockage observation on March 14-15, 2022, nine sampling were performed at the MAM station across almost two months. Table 1 displays the measurement types and the dates.

The sampling at the MAM station was determined/targeted by considering that phytoplankton overgrowth lasted several weeks and the life span of each individual was several d ays (Lindsey and Scott, 2010). In order to determine phytoplankton change, abundance chlorophyll-a and marker pigment measurements were carried out. The CTD (conductivity, temperature, depth) equipped with Niskin type water sampler was used. Dissolved oxygen was performed with the oxygen sensor (SBE43 and Exo). NOx, PO_4 and Si analyses were carried out with an autoanalyzer, while chlorophyll-a concentrations were measured using the acetone extraction method in a spectrophotometer. Samples were prepared according to Özel, 1998; and examined under a NIKON TE 2000 model microscope using a Sedgwick-Rafter counting chamber. Marker pigment analyses were analyzed with HPLC (Agilent 1200 Series – High Performance Liquid Chromatography Device–Thermo Scientific MOS-2 HYPERSIL Dim. (mm) 150x4.6 SN: 0307687K Lot:9082 Particle Sz (micron) 3 - Column) (Barlow et al., 1993).

Results and Discussions

December 2021 Upper Layer Blockage

The storm, generated by a cyclone passage on November 28–30, affected wide areas, covering the entire Sea of Marmara. The sea level pressure dropped to 1000 hPa, and the south westerly winds exceeded 10 m/s (Figure 2). Indeed, atmospheric system transitions accompanied by storms are frequent in the region during this period (Deniz et al., 2013).

Under these atmospheric conditions, oceanographic measurements on 2 December indicated that the Black Sea current was completely blocked in the south exit of the strait, and in great extent at its northern exit (Figure 3). A thin layer with a salinity of approximately 18.6 psu (Figure 3a) and weak southward currents was observed at the northern exit at the K0H station. The northern part maintained the two-layer structure, keeping the restricted flow of Black Sea water

Table 1. Summary of observational data collected at stations MU4 and MAM in İzmit Bay between December 2021 and May 2022.

	İstanbul Strait	Marmara Sea Stations	MAM Station							İstanbul Strait	Marmara Sea Stations	MAM Station								
	2 Dec 2021		3 Dec 2021	6 Dec 2021	10 Dec 2021	20 Dec 2021	23 Dec2021	4 Jan 2022	9 Jan 2022	14-15 Mar 2022		15 Mar 2022	17 Mar 2022	22 Mar 2022	29 Mar 2022	10 Apr 2022	12 Apr 2022	15 Apr 2022	21 Apr 2022	11 May 2022
Current (ADCP)	■		■	■						■			■			■				
CTD	■	■	■	■	■	■	■	■		■	■	■	■	■	■	■	■			
NOx, NH_4,PO_4			■	■	■	■	■	■				■	■	■	■	■	■			
DO			■	■	■							■	■	■	■	■	■			
Abundance			■	■	■	■	■	■	■			■	■	■	■	■	■	■	■	■
Chl-a, M. pigments			■	■	■	■	■	■	■			■	■	■	■	■	■	■	■	■

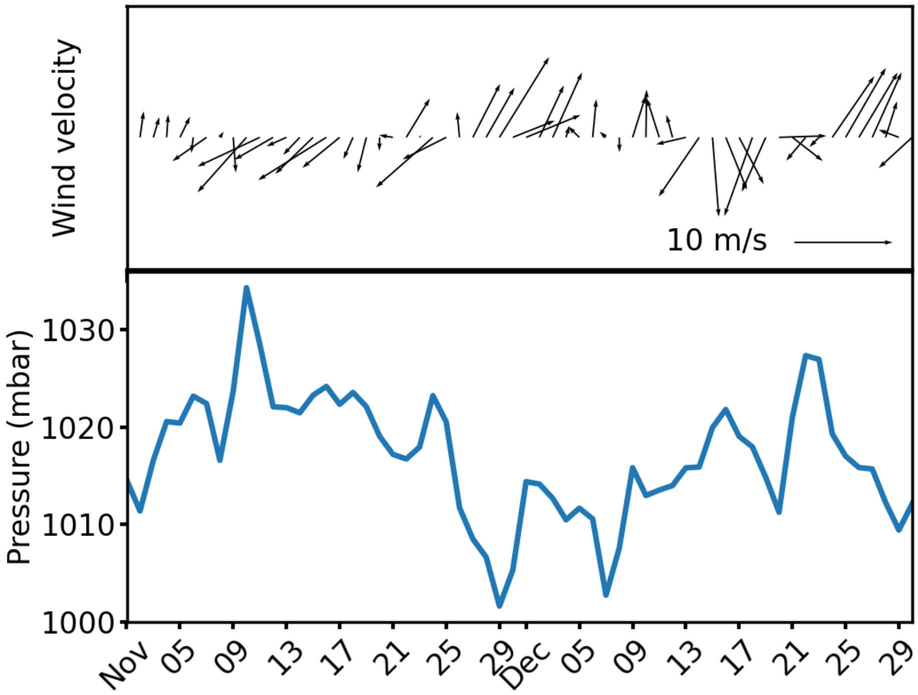

Figure 2. Mean wind velocity vectors (top panel) and atmospheric pressure (bottom panel) during November and December 2021. The daily means are calculated for the eastern Marmara Sea (area depicted in Figure 1).

to the strait. ADCP transects at the northern end of the İstanbul Strait revealed a stagnant surface layer approximately 10 m thick, with velocities around 0.2 m/s (Figure 3b). At the southern exit, the two-layer structure was no longer observed, transitioning to a homogeneous salinity distribution extending down to a depth of 70 meters, with values around 26.6 psu at the B2B station (Figure 3a). This was accompanied by a current profile reaching velocities of up to 1 m/s, with currents directed northward (Figure 3c).

Oğuz (2017) demonstrates that the buoyant jet originating from the İstanbul Strait is the primary driver of the Marmara Sea's complex, buoyancy-induced basin-scale circulation. The study also highlights that when the upper layer flow in the strait is blocked, the buoyant jet disappears at the junction of the İstanbul Strait and the Marmara Sea for several days. The analysis in the present study indicates no flow from the İstanbul Strait to the Marmara Sea on 2 December, which implies the absence of jet flow in the Marmara Sea. The lack of jet flow would expected to have significant basin-scale consequences.

In order to identify the consequences of the blockage and accompanying strong wind speeds to the eastern Marmara Sea, the climatologically available data is evaluated. The MU4 station, located away from the coast and close to İzmit Bay, was selected for the analysis. The goal was to examine the difference in the water column's vertical structure at the MU4 station on 2 December compared to the mean climatological observations. The 1996-2009 IWSA monitoring M23 station (very close to MU4) data which held on-+ 10 days of December 2, are used for comparison. Figure 4 presents the MU4 salinity profile alongside the climatological data from M23. When comparing the halocline depths, the MU4 halocline, with a depth range of 22-25 m, is observed to shift deeper than the climatological mean depth range of 18-22 m during the same period of the year (Figure 4). This shift is attributed to effective mixing at the boundary of the two-layer system, which leads to halocline erosion, deepening the halocline and resulting in the salinification of the upper surface layer.

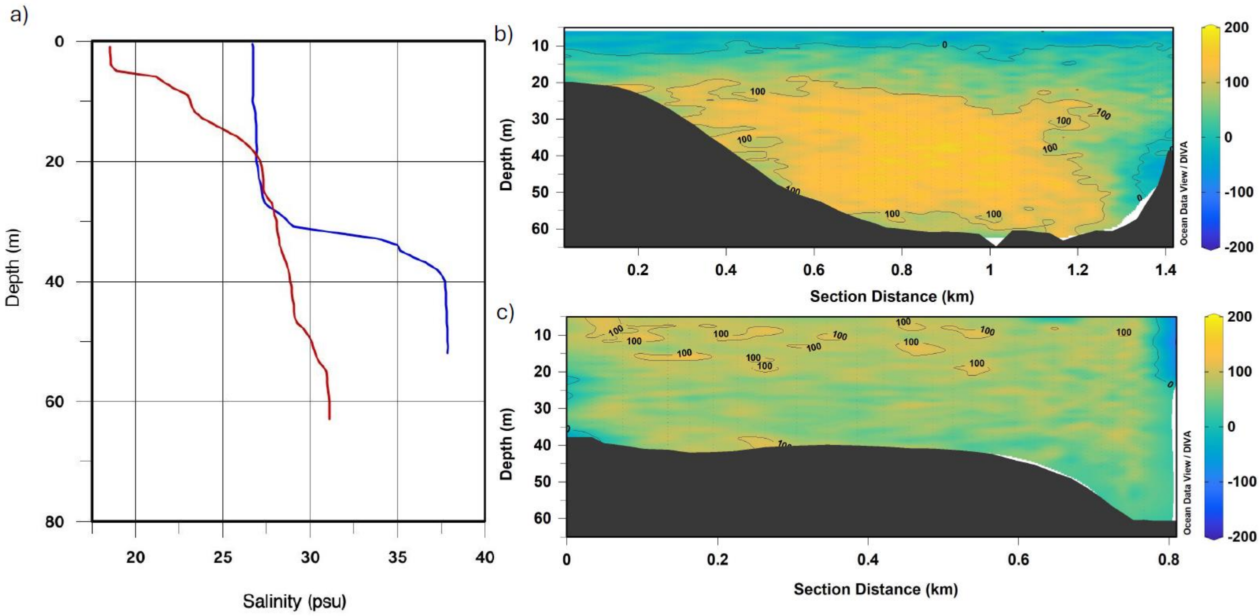

Figure 3. December 2, 2021, cruise: (a) salinity profiles at the K0H (red line) and B2B (blue line) stations; and current measurements aligned with the İstanbul Strait thalweg at (b) the northern and (c) the southern transects.

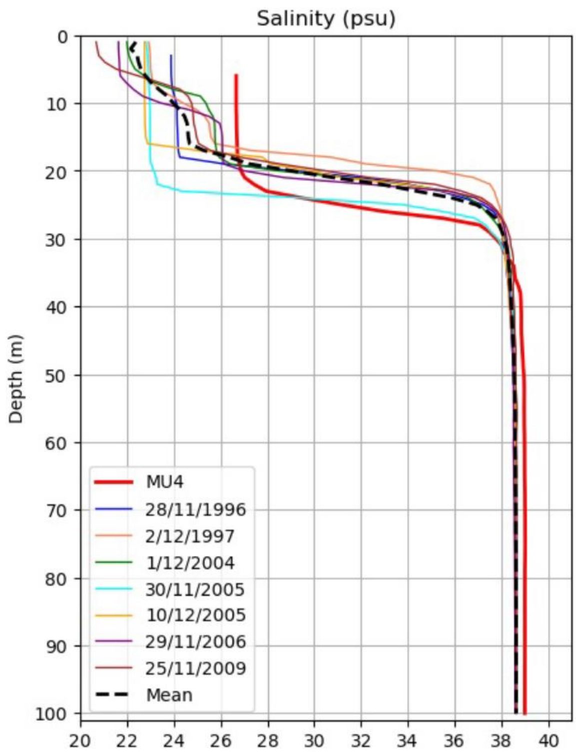

Figure 4. The salinity profiles are presented with the red line representing the MU4 station measurement on December 2, 2021, and the dashed line indicating the mean salinity profiles from M23 station during the 1996–2009 İSKİ cruises conducted within ±10 days of 2 December, as shown in the legend.

Up to this point, the abrupt transition from a two-layer dynamic to a single homogeneous layer in the İstanbul Strait, along with the intense mixing between the two-layer interfaces in the open waters of the eastern part of the Marmara Sea, has been clearly demonstrated. As a result of this intense vertical mixing, nutrient-rich lower-layer Mediterranean waters reach the productive upper layer. Hence the abrupt shifts in physical characteristics would drive changes in the chemical and biochemical properties in the eastern Marmara Sea.

İzmit Bay's oceanographic characteristics following the upper layer blockage detection on the İstanbul Strait are analysed in this study. The abrupt shifts in physical characteristics on its boundary in the eastern Marmara and its own dynamics under the severe wind conditions are evaluated. The physical, chemical and biological parameters at the MAM station were analyzed.

On December 3, ADCP measurements indicated an inward surface flow to the İzmit Bay contrary to the winter months characteristics (Figure 5). The current speed along the transect was very low and almost uniformly distributed through the water column, around 10 cm/sec on December 3 (Figure 5). The low current speeds strongly suggest that the flow was just the reverse direction before December 3. Following ADCP measurement on December 6, ADCP showed reversed flow directions (outward surface and inward bottom) back to the seasonal characteristics. It increased to up to 30 cm/s in the upper surface layer on 6 December. Tuzla Meteorology station shows southerly wind speeds reaching to 15m/s along 28-30 November (Figure 6) aligning with the prevailing severe wind conditions in the Marmara Sea (Figure 2). Wind records from the meteorological station indicate a wind speed of 8 m/s during the ADCP recording period on December 3 (Figure 5). The rapid return of the two-layer flow system's direction to the winter norm within a few days suggests that the flow dynamics in İzmit Bay are primarily influenced by the passage of a synoptic atmospheric system between November 28 and 30.

Comparison of the thermohaline structures at MU4 on December 2, 2021, and the MAM station on December 3, 2021, reveals alignment in the deep mixed layer depth, which is approximately 22 meters, while the salinity of upper layer at MU4 slightly higher than at MAM station (Figure 7). These findings indicate that the characteristics of the İzmit Bay upper layer were largely governed by the eastern Marmara upper layer flow following the upper layer blockage in the İstanbul Strait. The halocline depth at the MAM station gradually rose as the upper layer flow reverted to its outward direction on December 6, 2021. Next four samplings until 23 December 2021 on the MAM station shows gradual rise of the halocline and accompanying rise in upper layer salinity and decrease in temperatures (Figure 7). While bottom layer salinity increase was about 1 psu, temperatures changes were restricted to 0.5 °C. On January 4, 2022 a decrease in the salinity of both the surface and bottom layers can be explained southerly strong winds persisted in the region between 24-28 December 2021 (Figure 6).

During the study period from December 3, 2021 to January 4, 2022, surface layer PO_4 concentrations at the MAM station ranged from 0.02 µM to 0.45 µM while DIN (NO_3+NO_2 and NH_4) concentrations ranged from 0.09 µM to 2.5 µM (Figure 8). The mixed layer depth extending down to 22 m (Figure 8) suggests that high nutrient concentrations from the lower layer were mixed with the upper layer. The lower nutrient

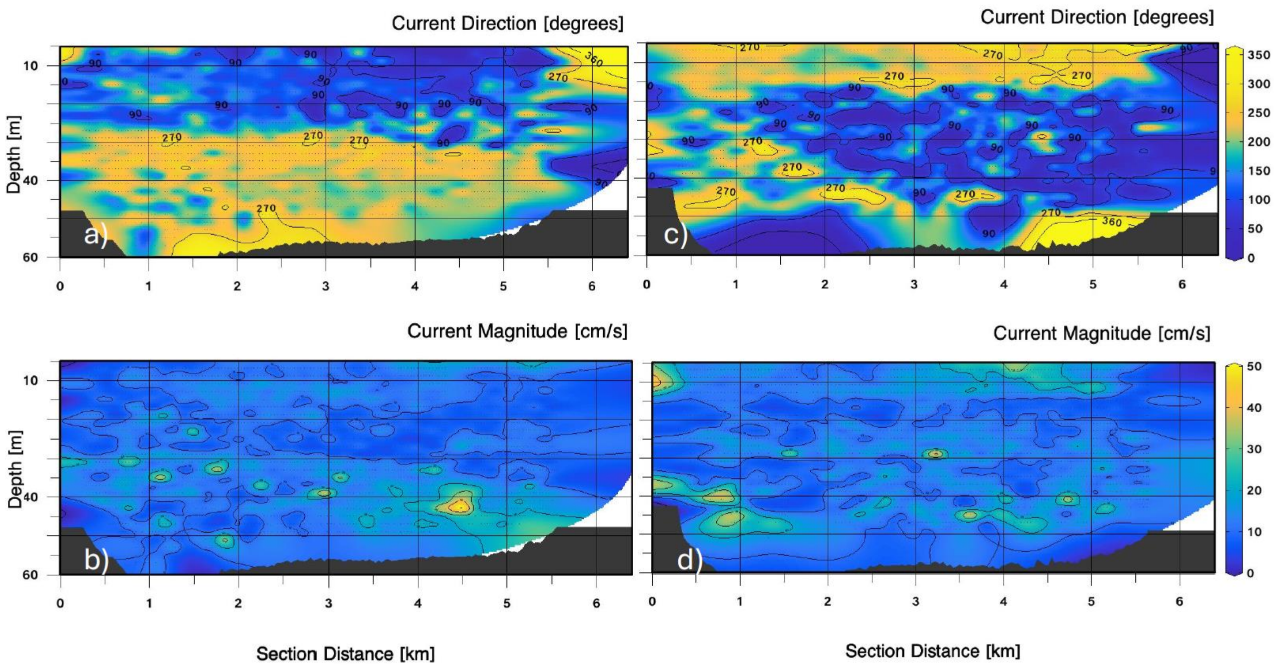

Figure 5. ADCP transect crossections illustrating a) the current direction and b) magnitude on December 3, 2021, and c) the current direction and d) magnitude on December 6, 2021, along the transect at the entrance of İzmit Bay.

concentrations at 20 m depth on December 2, 2021, compared to subsequent measurements, support this proposition. Notably, lower layer concentrations increased in the following days, coinciding with the shoaling of the mixed layer depth. DO concentrations generally low in 20m depths due to its utilization on remineralization also rose with the deepening of the mixed layer (Figure 8). In the upper layer persistence of low NOx concentrations depicts the utilization in the upper layer.

Each phytoplankton group has one or two specific marker pigments. Fucoxanthin (FUC) is the marker pigment of the diatom group, Peridinin (PER) is the trace pigment of the dinoflagellate group, Alloxanthin (ALLO) is the marker for the silicoflagellate group, and 19'-hexanoyloxyfucoxanthin (HEX) is specific to the Prymnesiophyceae group. The changes in marker pigment concentrations showed similarities to the distribution of chlorophyll-a, with high concentrations observed in the December 23, 2021 sampling (Figure 9).

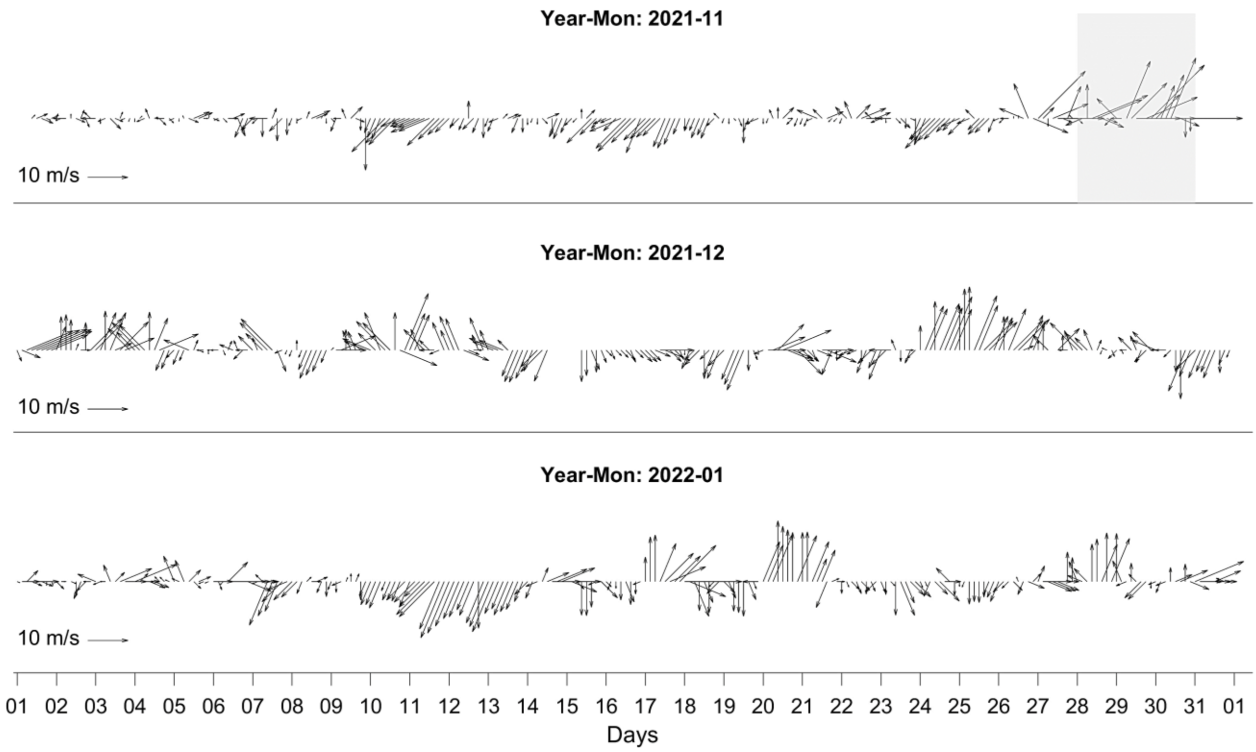

Figure 6. Hourly wind velocities, measured at Tuzla Meteorology Station during November 2021-January 2022.

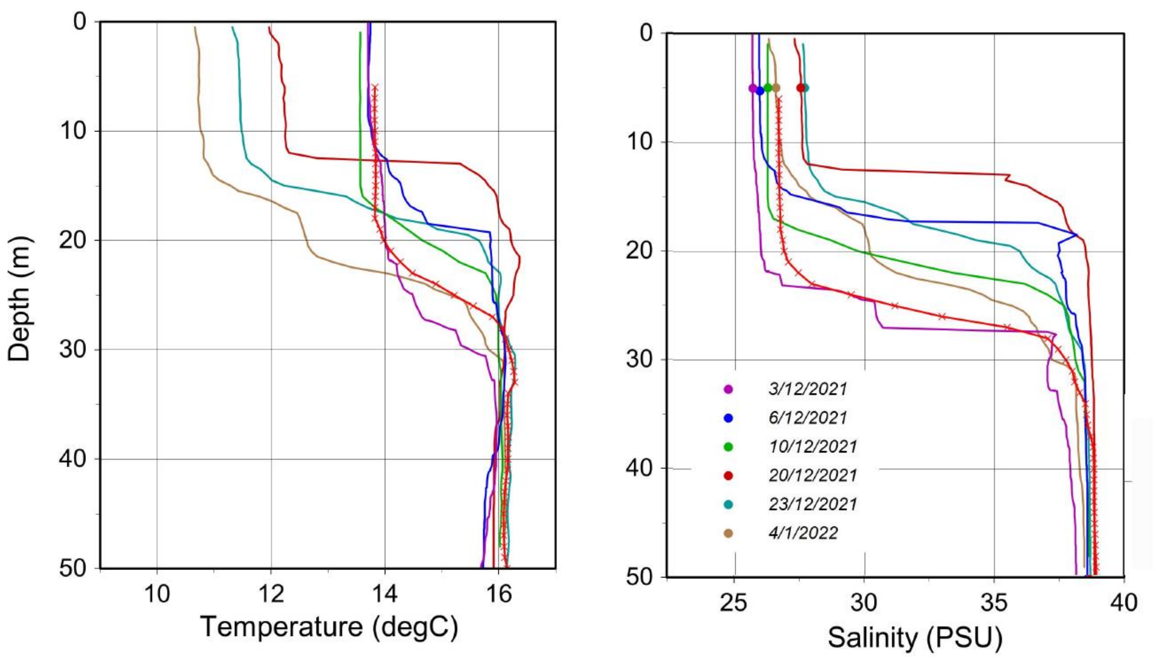

Figure 7. MAM station profiles a) temperature and b) salinity recorded between 3 December 2021 and 4 January 2022. The MU4 station profile recorded on December 2 2021 is overlaid with a cross-lined red line.

The increase in marker pigment concentrations follows the mixing of high nutrient concentrations from the nutrient rich lower layer, transported diapycnal to the upper productive layer, caused an increase in biological activity. This is by the deepening of mixed layer induced by severe southern wind induced mixing and the blocking of Black Sea flow to the Marmara Sea. The deepening of mixed layer and hence the nutrient entrance from the lower nutrient rich layer, followed another rise in chlorophyll-a on 9 January 2022.

Following the upper layer blockage, the potential for mucilage formation species abundances is derived (Table 2). Among the species identified in the sampling study, *Prorocentrum micans* is a dinoflagellate species known to contribute to mucilage formation. The diatom species *Cylindrotheca closterium* and *Skeletonema costatum,* also present in the environment, are listed in the literature as species that can cause mucilage. In this study, *Prorocentrum micans* (dinoflagellate) and *Cylindrotheca closterium* (diatom) were among the species observed, which were also reported during the mucilage formation in September-October 2008 (Polat Beken et al., 2011). The numbers of these species (individuals/L) are compared with those observed during previous mucilage events in Table 2. During the mucilage events observed between 2007 and 2010, the

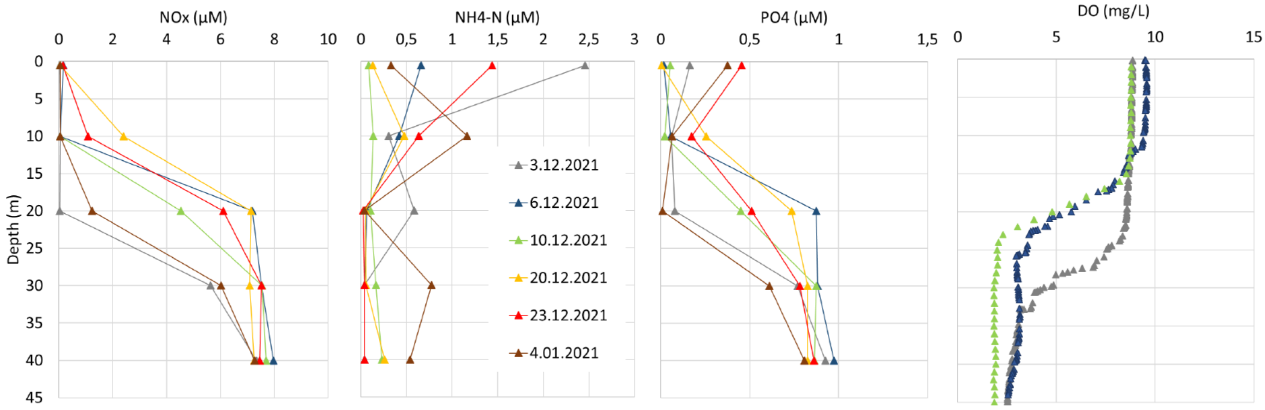

Figure 8. MAM station NOx, NH_4-N, PO_4 and DO profiles during 3 December 2021-4 January 2022.

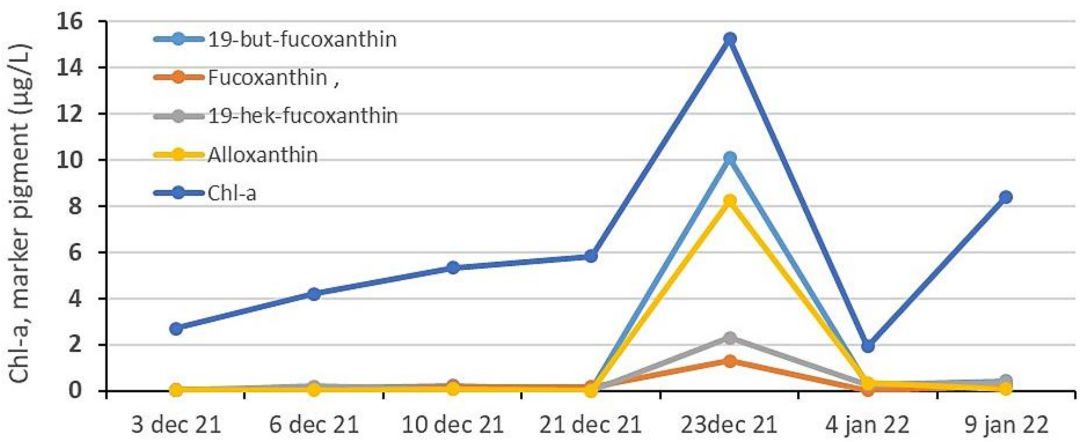

Figure 9. Chlorophyll_a and marker pigment concentrations during 3 December 2021-9 January 2022.

Table 2. Species abundance measured at MAM station during 15 March -11 May2022 and corresponding abundance in 2008 and 2010 during the mucilage formations in İzmit Bay.

	P. micans	*C. closterium*	*S.costatum*
03.12.2021	122400	400	0
06.12.2021	147600	400	0
10.12.2021	124800	0	0
20.12.2021	135600	1000	0
23.12.2021	144000	1000	3600
September 2008	537420	174000	0
October 2008	732000	61500	28000
January 2010	18000	40000	1710000

presence of the dinoflagellate species *Gonyaulax fragilis* was detected. However, this species was not observed in this study. Instead, the number of *Prorocentrum micans*, another mucilage-causing species from the same group, reached a maximum of 147,600 individuals/L during the dates when the upper water blockage occurred, compared to 732,000 individuals/L in October 2008. Another peak concentration with 140,000 individuals/L follows the strong southerly winds in the region.

March 2022 Lower Layer Blockage

On 9-11 March 2022 a Siberian High affected the Black Sea and the Marmara Sea extensively. The atmospheric pressure rose to 1034 mbar and the mean wind speed exceeded 11m/s for three consecutive days (Çokacar, 2024). The cruise in the following days on 14 March 2022, complete blockage of the lower layer flow was observed in the northern part of the strait. ADCP transects at the northern end of the İstanbul Strait revealed a single layer flow of the Black Sea waters (Figure 10a,b). Temperature and salinity profiles at the K0H station were homogeneous, with temperatures ranging from 6.3 to 6.6°C and salinities between 17.6 and 17.9 psu, indicating the presence of a single layer of Black Sea water. Current profiles showed a southward flow in the central part of the strait at speeds of 0.5–1 m/s. The two-layer structure, however, persisted, with weak Mediterranean inflow confined to the bottom 20 m (Figure 10a,c). Upper-layer current speeds reached 1–2 cm/s, flowing southward.

On March 14, 2022, a jet current with speeds reaching 2 m/s bent westward into the Marmara Sea, while another branch, though not exceptionally strong was directed on eastward with the speeds ~0.5m/s (Figure 11). Along the southern offshore track from Büyükada towards İzmit Bay, ADCP measurements showed a gradual decrease in current speeds near to İzmit Bay. Oğuz T. (2017) highlighted that the buoyant jet flow can sustain enhanced production even without the addition of new nutrients from upstream or surrounding sources. In regions with supercritical flow downstream of the strait, strong upward currents, driven by hydraulically controlled outflow dynamics, transport subsurface nutrients into the upper layer (Oğuz T., 2017).

The 1996-2009 IWSA monitoring station M23 (located near MU4) provided data within - ±10 days of 14 March, which were compared with MU4 measurements. In Figure, the red line represents MU4 station measurements from14 March, while the dashed line indicates the mean of the M23 station salinities. The comparison reveals that the lower layer blockage raised the halocline depth to 18–36 m, compared to its climatological mean range of 20–38 m (Figure). The excessive volume of Black Sea inflow 1024 km³/year (exceeding Jaroz et al., 2011b flux measurements) eroded the upper boundary of the halocline, facilitating mixing between lower-layer saline waters and the surface layer. This halocline displacement may also reflect storm-driven lateral advection associated with flow from the İstanbul Strait. These findings align with those of Chiggiato et al. (2011), documented a significant rise in the pycnocline in the eastern Sea of Marmara under strong northeasterly winds. Their study suggests that this response results from a combination of wind setup and outflow from the İstanbul Strait. These mechanisms likely enhance mixing and the entrainment of water and nutrients from the lower layers, contributing to the observed pycnocline displacement.

The ADCP measurements carried on 17 March cross the İzmit Bay mount reflecting outward flow pattern in the İzmit Bay. Two-layer flow structure disappeared on the northern sector of the ADCP cross

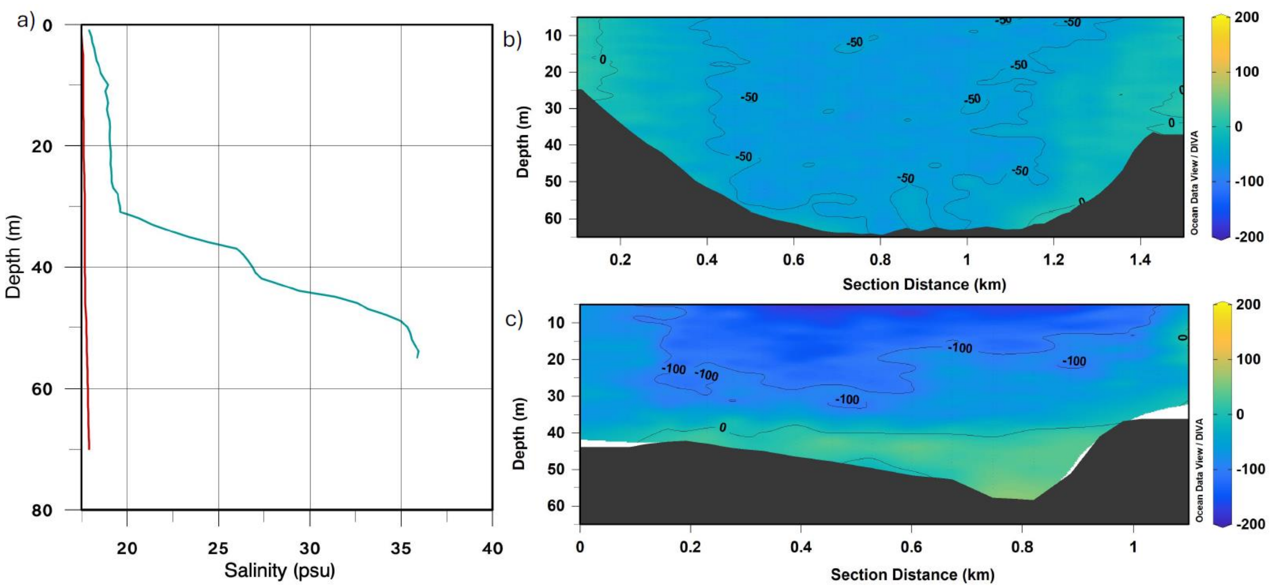

Figure 10. March 14, 2022, cruise: (a) salinity profiles at the K0H (red line) and B2B (blue line) stations, with currents aligned with the İstanbul Strait thalweg; and current measurements at (b) the northern and (c) the southern transects of the İstanbul Strait.

section in outward direction (Figure 13a) with the magnitudes increasing at the deeper depths (~30 cm/sec). The wind speeds at Tuzla meteorology station were ~10 m/s and consecutive synoptic system on 17-20 March (Çokacar, 2024) brought the strong winds once again to the region (Figure 14)

The surface layer (~20m) thermohaline structure of MU4 on March 14, 2022, and MAM station on March 15, 2022, is shown in Figure 15. Surface temperatures of approximately 8°C were observed at both stations. The halocline at MAM station stretches between 10m and 37m, with the highest salinities observed on March 15 and 22, following the consecutive cold episode periods, as analyzed in Çokacar (2024). Following this period, stratification reestablished at MAM station, with the upper layer extending to approximately 20m, characterized by higher temperatures and lower salinities. Figure 14 shows the local wind velocities at meteorology station recorded such intense north westerlies during April and May 2022. However, could

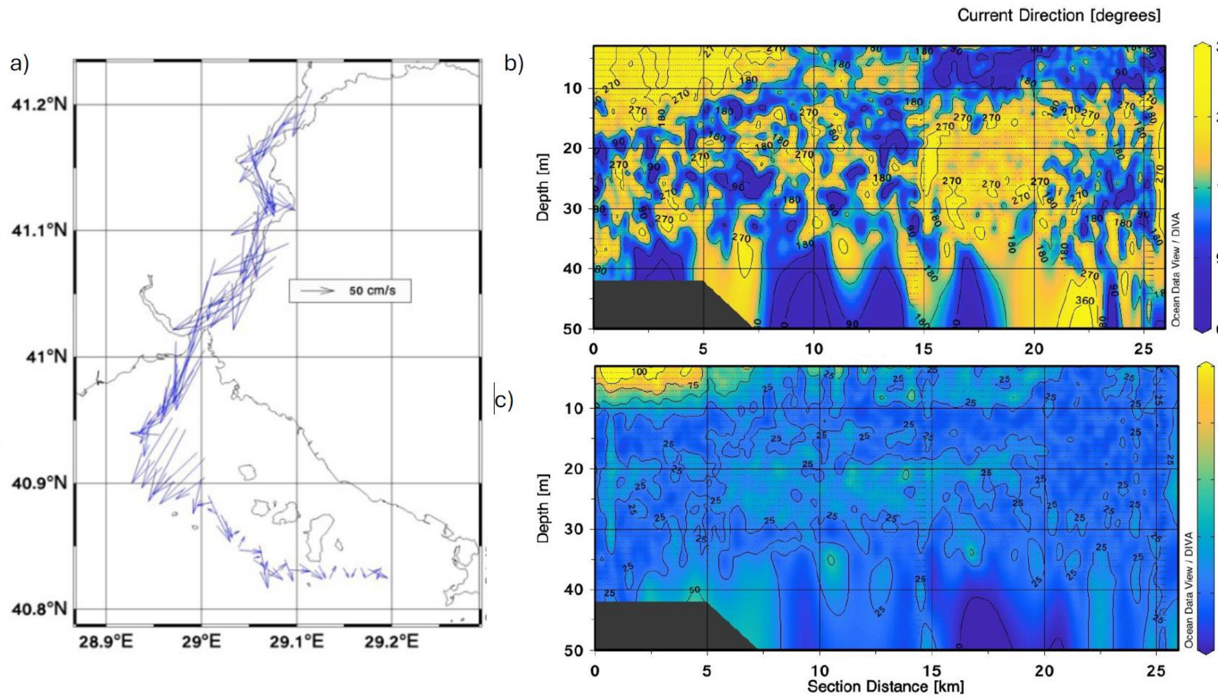

Figure 11. ADCP measurement on 14 March 2022 a) surface current velocities along the research vessel track line ; vertical cross section of b) direction and c) magnitude of the current along the segment of the track south of 40.95° N.

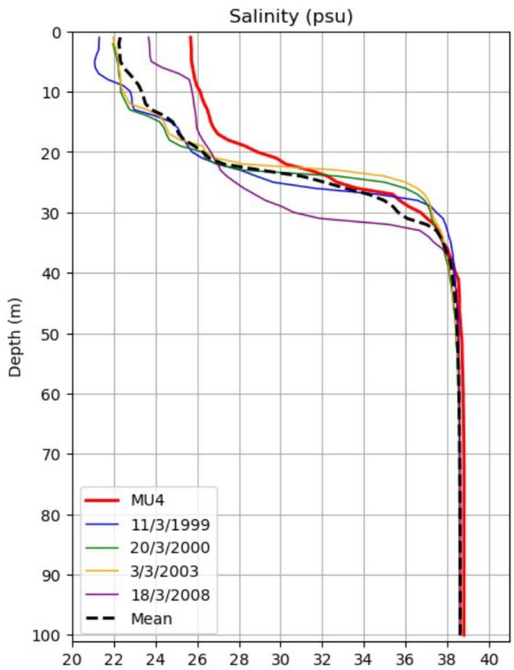

Figure 12. The salinity profiles are presented with the red line representing the MU4 station measurement on March 14, 2022, and the dashed line indicating the mean salinity profiles from M23 station during the 1996–2009 İSKİ cruises conducted within ±10 days of March 14, as shown in the legend.

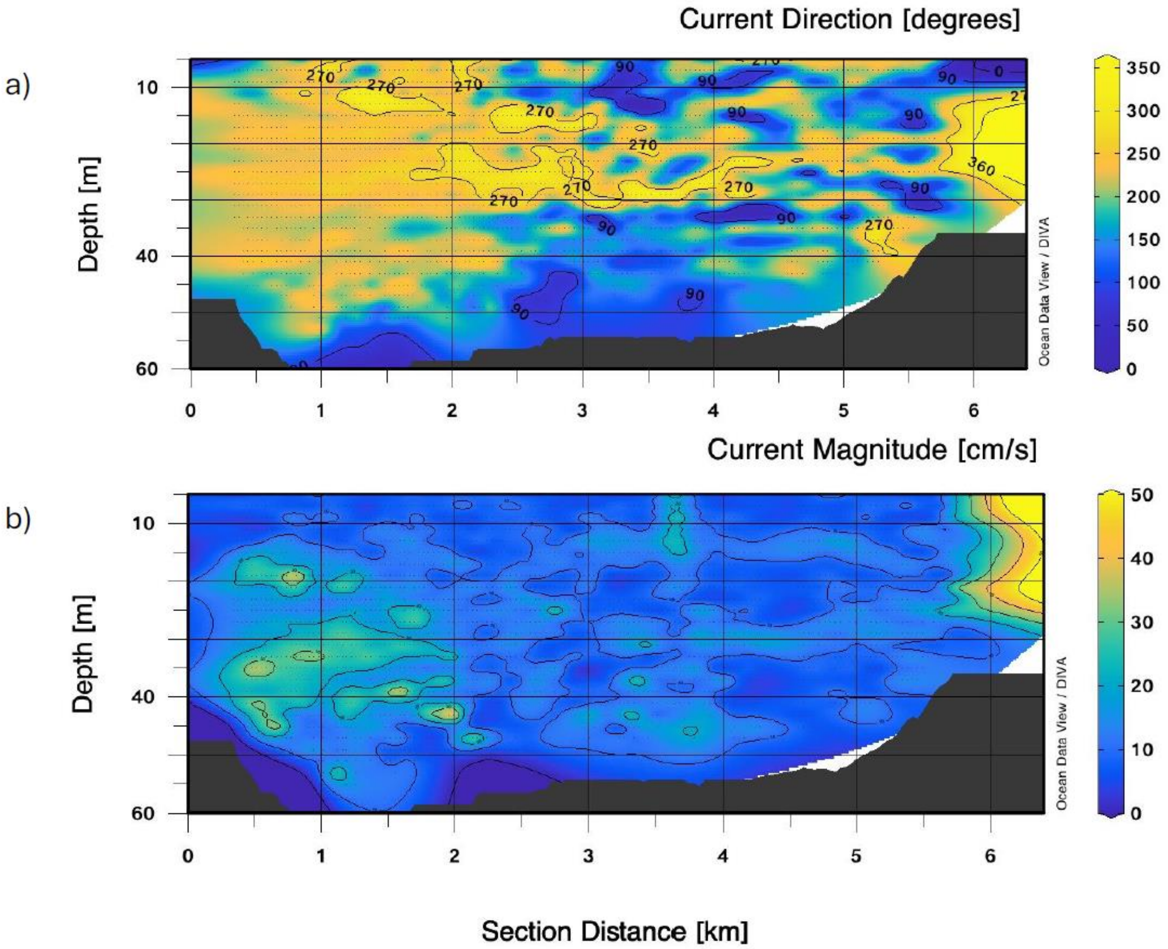

Figure 13. ADCP transect on March 17, 2022, illustrate the vertical cross section of a) direction and b) magnitude of current along the transect at the entrance of İzmit Bay.

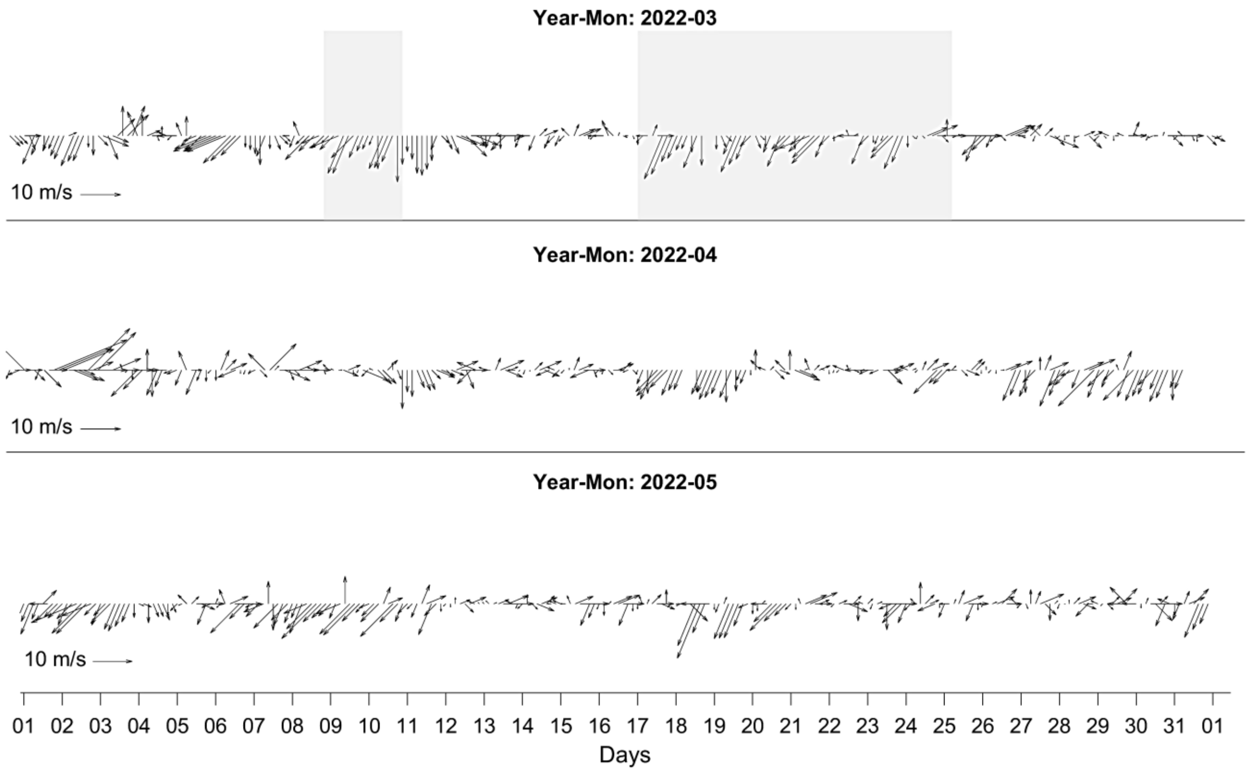

Figure 14. Hourly wind velocities, measured at Tuzla Meteorology Station during March-May 2022.

not break the re-established strafication as observed at the MAM station (Figure 15).

Obviously, the local dynamics of İzmit and the adjacent Marmara Sea waters to İzmit Bay as well as intensification of jet flow through the İstanbul Strait greatly influence the İzmit Bay dynamics. It is beyond of this study to quantify the effect of these dynamics on İzmit Bay.

The highest levels of DIN was observed on March 17, 2022 at MAM station (Figure 16). March 17 ADCP measurements show, Marmara Sea enriched by the nutrient following the blockage entered the surface layers of İzmit Bay from approximately 1 km wide window.

The concentrations ammonia increases in the upper layer induces by the intense dynamics following the cold episodes and accompanying severe wind conditions. Low NOx and PO_4 concentrations can be explained by their use in photosynthetic activity in top layer (Figure 16). The high levels of NO_x and PO_4 concentrations in the lower layers at MAM station on April 10-12, 2022, can be explained by the establishment of the thermocline due to the onset of seasonal warming (Figure 16).

Maximum DO concentrations were observed on 22 April can be explained by the primary production in this period as seen on Figure 17 peak concentrations of Chlorophyll-a.

The potential for mucilage formation species abundances is compared with the abundances during the mucilage formation in September-October 2008 (Polat Beken et al., 2011). The numbers of these species (individuals/L) are compared with those observed during previous mucilage events in the table below (Table 3). The diatom species *Cylindrotheca closterium* was recorded at 174,000 individuals/L in September

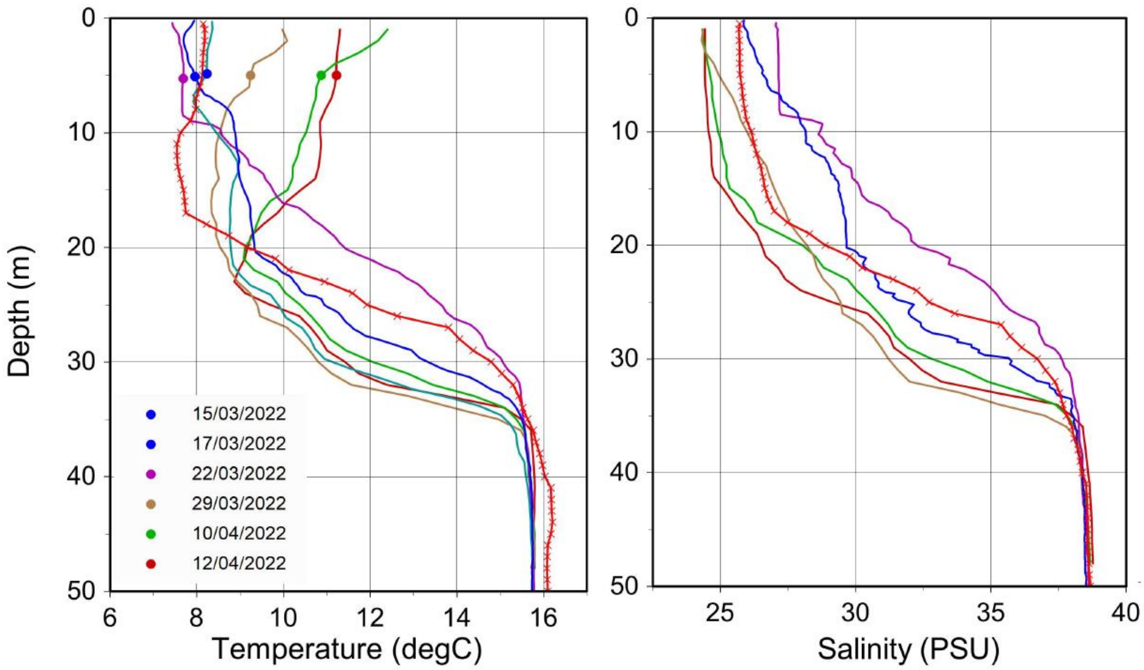

Figure 15. MAM station profiles of a) temperature and b) salinity recorded between 15 March and 12 April 2022. The MU4 station profile recorded on March 15 is overlaid with a cross-lined red line.

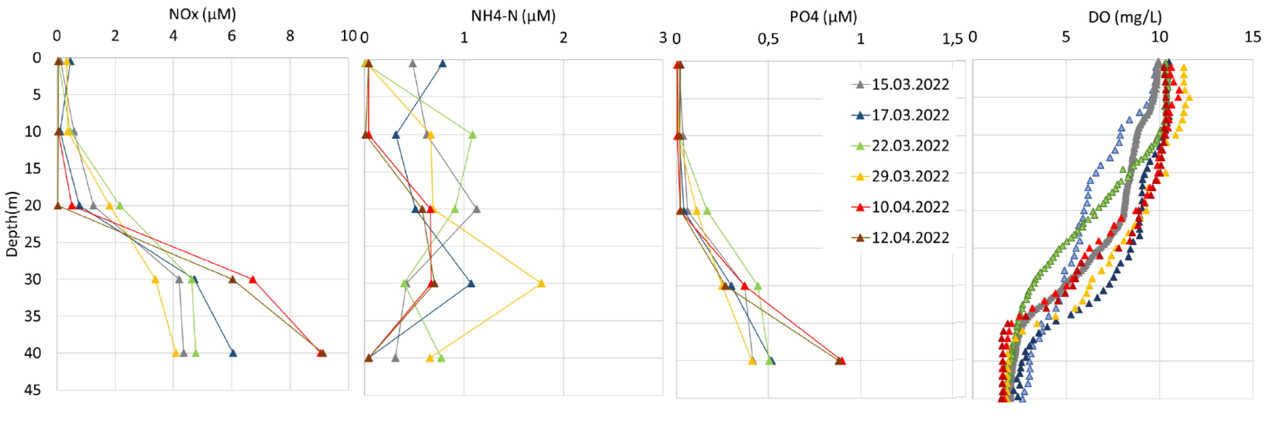

Figure 16. MAM station NOx, NH_4-N, PO_4 and DO profiles during 15 March – 12 April.

2008, while in this study, it was observed at a maximum of 64,800 individuals/L during the period of bottom water blockage. Similarly, *Skeletonema costatum*, which had a count of 1,710,000 individuals/L during the January 2010 mucilage event, was recorded at a maximum of 217,200 individuals/L during the bottom water blockage in this study.

Conclusion

This study provides an in-depth analysis of the oceanographic characteristics and water dynamics affecting İzmit Bay, focusing on the oceanographic properties in the Eastern Marmara following the synoptic-scale weather systems that prevailed in the region on November 28-30, 2021, and March 9-10, 2022.

Comparison of upper layer records from December 2, 2021, during the upper layer blockage at the İstanbul Strait, with climatological data near İzmit Bay reveals halocline deepening and increased upper layer salinity. On March 14, 2022, during the lower layer blockage, the halocline raised due to increased Black Sea inflow. Both blockages caused deviations in upper layer salinities from climatological means through halocline erosion and mixing of saline deep waters with the surface.

The reversal of flow dynamics in İzmit Bay highlights the significant influence of changing oceanographic layer properties in the eastern Marmara, following the upper layer blockage in the İstanbul Strait. This findings infer that the water mass characteristics of İzmit Bay were significantly influenced by the eastern Marmara.

During the March 2022 lower layer blockage, a comparison of the two stations revealed that while the upper layer characteristics of İzmit Bay were consistent with those of eastern Marmara, the lower layer exhibited distinct variations. This period was characterized by an intensified Bosphorus jet current and increased nutrient flux. The thermohaline structure of the surface layer at both the eastern Marmara and MAM stations displayed similar conditions following the upper layer blockage. After consecutive cold episodes, stratification was re-established at MAM station, and despite intense northwesterly winds in April and May 2022, stratification was maintained. The dynamics of

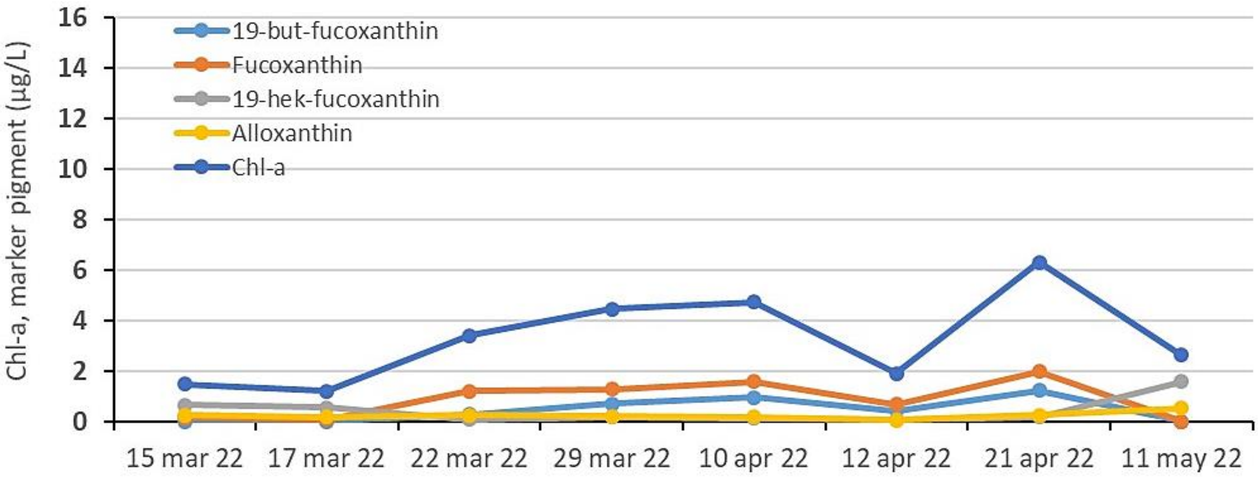

Figure 17. MAM station profiles of a) temperature and b) salinity recorded between 15 March and 12 April 2022. The MU4 station profile recorded on March 15 is overlaid with a cross-lined red line.

Table 3. Species abundance measured at MAM station during 15 March -11 May2022 and corresponding abundance in 2008 and 2010 during the mucilage formations in İzmit Bay.

	P. micans	*C. closterium*	*S.costatum*
15.03.2022	1200	37200	81600
17.03.2022	1800	15400	67200
22.03.2022	3000	34400	217200
29.03.2022	400	64800	79200
10.04.2022	1800	1600	15200
12.04.2022	3200	10400	12000
15.04.2022	9600	3600	7800
21.04.2022	16400	4000	0
11.05.2022	19400	30000	0
September 2008	537420	174000	0
October 2008	732000	61500	28000
January 2010	18000	40000	1710000

İzmit Bay and the adjacent Marmara Sea, along with the intensified jet flow through the İstanbul Strait, significantly influence İzmit Bay's dynamics, although quantifying their effect is beyond the scope of this study.

The study highlights that following the blockage events in the İstanbul Strait, combined with severe wind conditions, nutrient concentrations and subsequent biochemical activity surged abruptly in İzmit Bay.

The study identified several species, including *Prorocentrum micans*, *Cylindrotheca Closterium,* and *Skeletonema costatum*, which were also present during mucilage formation in İzmit Bay. Although not reach high abundance levels, the observed increase in the abundance of mucilage-forming species due to the disruption of the delicate balance presents a potential threat to İzmit Bay. Moreover, the study suggests that future episodes of this nature could heighten the risk of mucilage formation, especially when compounded by other stressors such as increased nutrient loading from anthropogenic sources.

Ethical Statement

The study does not involve human subjects, animals, or any data that requires ethical review.

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Author Contribution

Tülay Çokacar: Conceptualization, Writing, review; Hüsne Altıok; writing and review, Sabri Mutlu; visualization, review; Ahsen Yüksek; visualization, review, Dilek Ediger; visualization, review, Fatma Bayram Partal; data process.

Conflict of Interest

The authors declare that they have no known competing financial or non-financial, professional, or personal conflicts that could have appeared to influence the work reported in this paper.

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