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Research Article

Coastal Upwellings In The Sea of Marmara

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Abstract

Based on in situ measurements between 2017 and 2022 in the Sea of Marmara, three "warm and saline" upwelling events were observed during autumn and winter scientific expeditions. These observations were crucial and worth mentioning since the surface salinity value increased and even reached the lower layer value, which is ~38 psu, during the process. Other characteristics of the lower layer were also detected, either as they are or in between upper- and lower-layer values due to mixing. After analyzing the effects of coastal upwellings on the upper layer, it was concluded that coastal upwelling, which has been underestimated for a long time, has to be well studied because it could be another reason or way of nutrient enrichment in the upper layer and salinity increase in winters. This phenomenon also has huge potential to change the characteristics of the upper layer with a rise in frequency. Therefore, it is advised that coastal upwelling should always be considered with other well-known features during marine studies and for future engineering solutions in the basin.

Keywords: Marmara Sea, coastal upwelling, pycnocline, salinity

Introduction

Upwelling, a well-known oceanographic event, is defined as an upward movement of water parcels in the ocean. There are several types of upwelling, e.g., large-scale wind-driven upwelling in the ocean interior, upwelling associated with eddies, topographically associated upwelling, broad-diffusive upwelling in the ocean interior, and coastal upwelling. The most common and best-known type of upwelling is coastal upwelling, since it supports some of the most productive fisheries in the world. Ekman (1905) described the mechanism of the coastal upwelling as owing to the Coriolis effect of the Earth's rotation and frictional forces, a system of "three currents" (pure wind-current, "midwater" gradient current, and bottom current) is generated, where the flow is deflected off the coast, which is balanced by upward flow from deep layers (Suursaar, 2021). Coastal upwelling exists year-round in some regions, known as major coastal upwelling systems (e.g., the Canary Current, Benguela Current, California Current, and Humboldt Current), and only in certain months of the year in other regions, known as seasonal coastal upwelling systems (e.g., Australia's southern shelf, around New Zealand, in the Gulf of Mexico and the southern Caribbean Sea, on the Brazilian shelf, and in the Eurafrican Mediterranean Sea). Many of these upwelling systems are associated with relatively high carbon productivity and hence are classified as Large Marine Ecosystems (Kampf and Chapman, 2016).

On the Turkish coastal waters, intense summer upwelling on the southern Black Sea and the eastern Aegean Sea results from steady winds (also known as the Etesian wind regime) aligned with the coast (Göktürk et al., 2015). Tyrlis and Lelieveld (2013) compiled a climatology of Etesian outbreaks over the Aegean Sea during summers. Turunçoğlu et al. (2018) simulated the coastal upwelling of the Aegean Sea, driven by Etesian winds. Tükenmez and Altiok (2022) investigated the effectiveness of different upwelling index calculations in the Aegean Sea. In short, coastal upwelling studies in the Turkish coastal waters are focused either on the Black Sea or on the Aegean Sea.

Even though the Marmara Sea is a relatively small landlocked sea (~11.111 km^2: Gazioğlu et al., 2002), it has many distinctive physical properties, as well as those described by Ünlüata et al. (1990), Beşiktepe et al. (1994), Beşiktepe (2003), Müftüoğlu (2008), Dorofeyev et al., (2012) and Özsoy and Altıok (2016). In brief, there are mainly two distinct water masses in a layered structure. A less saline but highly productive Black Sea origin water (~18 psu) is entering the Marmara Sea via the İstanbul Strait and floating with increased salinity (seasonally around ~23 psu in summer and ~28 psu in winter) over a high saline (~38.5 psu) Mediterranean Sea origin water. Between these layers, a salinity-driven sharp pycnocline is located at ~25 m depth, with limited mixing. This pycnocline is generally accepted as permanent since even the abrupt cooling of surface waters in winter is not able to break this structure (Özsoy and Altıok, 2016). On the other hand, severe wind events are able to erode the pycnocline down to deeper levels, up to about 40 m (Beşiktepe et al., 1994). Beside these field observation-based studies, there were also many modelling efforts in order to simulate the layered structure and basin-wide circulations (Gonenc and Wolflin, 2004; Chiggiato et al., 2012; Sannino et al., 2017; Aydoğdu et al., 2018; Ilicak et al., 2021). In these efforts, high-resolution models with fewer forcing factors were built at the beginning, and then they were improved towards operational ones, including realistic atmospheric forcing with open boundaries.

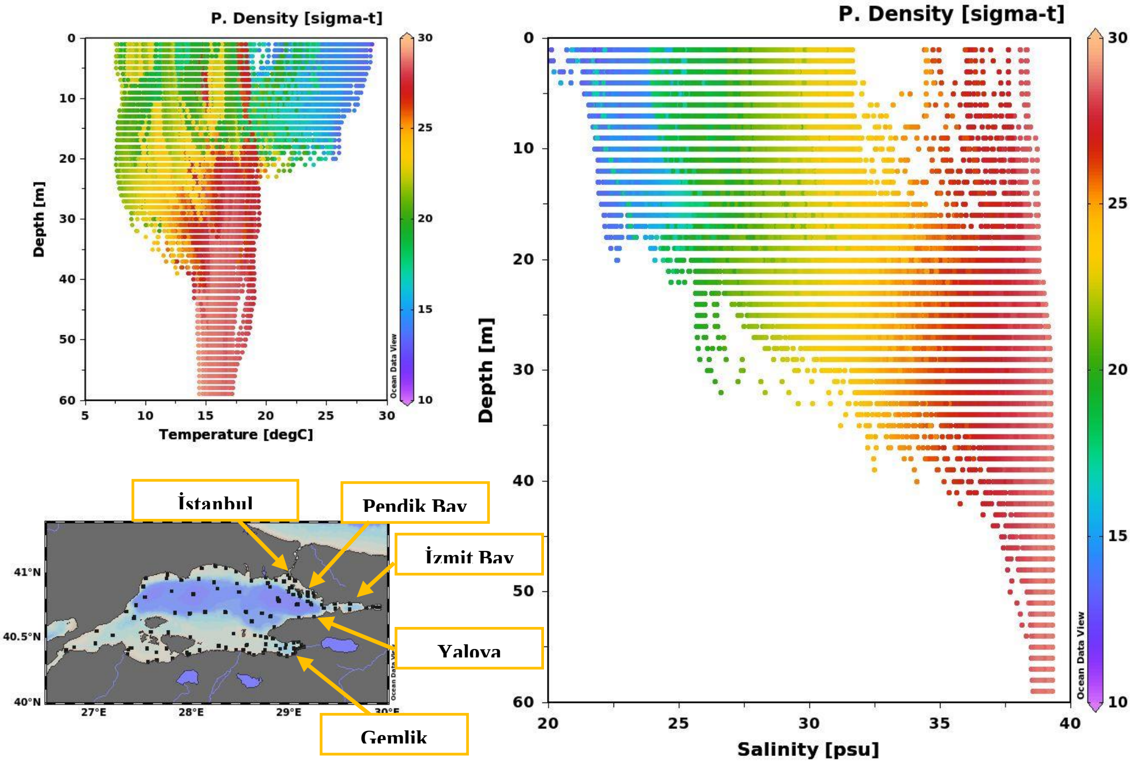

Fig. 1 The locations of the stations in the Sea of Marmara (left-bottom). Temperature (left-top) and salinity (right) scatter plots up to 60 meters deep were obtained between 2017 and 2022. Colors represent the potential density.

Though the Marmara Sea has been observed and simulated thoroughly since Marsili's scientific work on the Istanbul Strait in 1680 (Pinardi et al., 2010), there have been few mentions of coastal upwelling events in the Sea of Marmara. Tuğrul et al. (1986) observed some short-term increase (~5 ppt) in the surface salinity due to strong wind episodes (e.g., 10 m/sec north-easterly wind) in the winter months in the Izmit Bay. This could be considered a weak upwelling event with the rise of the sub-halocline waters (also known as the "lower layer") in the vertical without reaching the surface. Large displacements of the pycnocline depth were also observed during the sea trials in the study of Chiggiato et al. (2012). They interpreted these displacements as storm-driven upwelling/downwelling dynamics associated with north-easterly winds. They also noticed an upwelling event of warm, salty waters in the model, marked by the sea-surface temperature front on the south-eastern side of the sea. However, neither the sea trials nor the model results demonstrated a strong upwelling event in which the lower layer reaches the surface without losing its own properties.

In this study, we present three strong coastal upwelling events observed in the Sea of Marmara. During these events, the sub-halocline waters reached the surface while preserving their own properties.

Materials and Methods

All coastal upwelling events described in this study were observed during the scientific expeditions of the "Integrated Marine Pollution Monitoring Program (2017-2022)" by the Turkish Ministry of Environment, Urbanization, and Climate Change and the "Gemlik Bay Water Quality Monitoring, Evaluation, and Imaging of Deep-Sea Discharge Pipes Project (2020–2024)" by the Bursa Metropolitan Municipality. Both projects have been conducted by the Marine Research and Technologies Group under the Vice Presidency of Climate Change and Sustainability at the TÜBİTAK Marmara Research Centre. These expeditions were conducted three times (winter, spring, and summer) in a year for the whole basin and four times in a year (i.e., seasonally) for Gemlik Bay. The in situ data were obtained by SeaBird SBE25Plus CTD+DO (SBE4 conductivity, SBE3 temperature, and depth; plus, SBE43 dissolved oxygen), which was installed on the RV TUBITAK MARMARA research vessel (Figure 1).

During scientific expeditions, the CTD instrument at a measuring speed of 16 Hz was lowered from the sea surface to the seabed at the pre-determined 100 points to represent the Sea of Marmara completely. The dense data were averaged to a 1-meter bin size after quality control and post-processing.

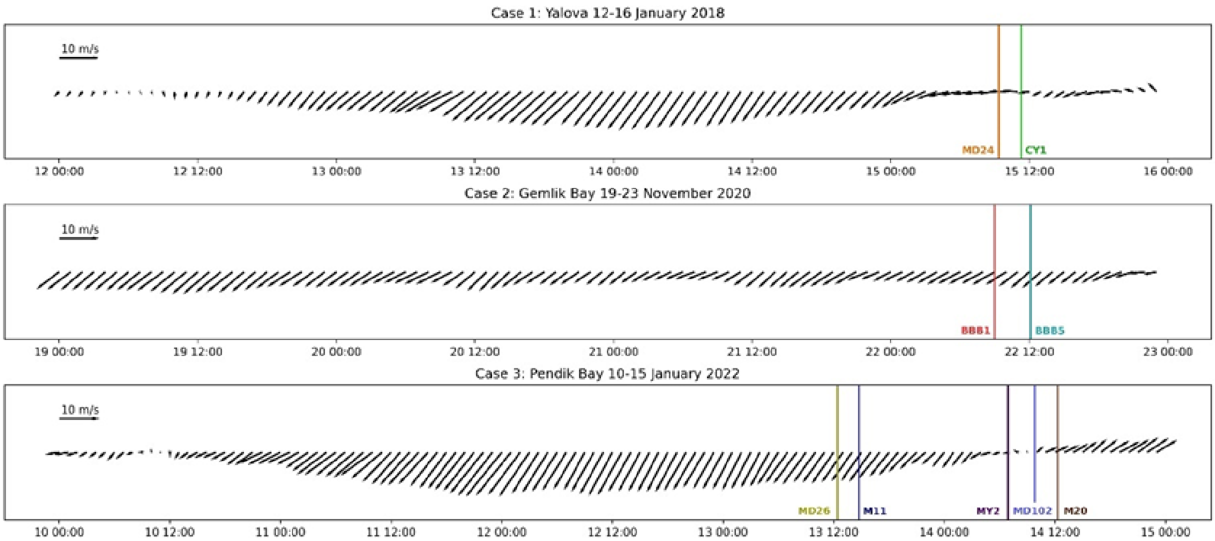

Fig. 2 Hourly wind velocities, where the north is up and the time zone is GMT+0, for the last 5 days of each case. Data was obtained from the "ERA5 hourly data on single levels from 1940 to present" data set..

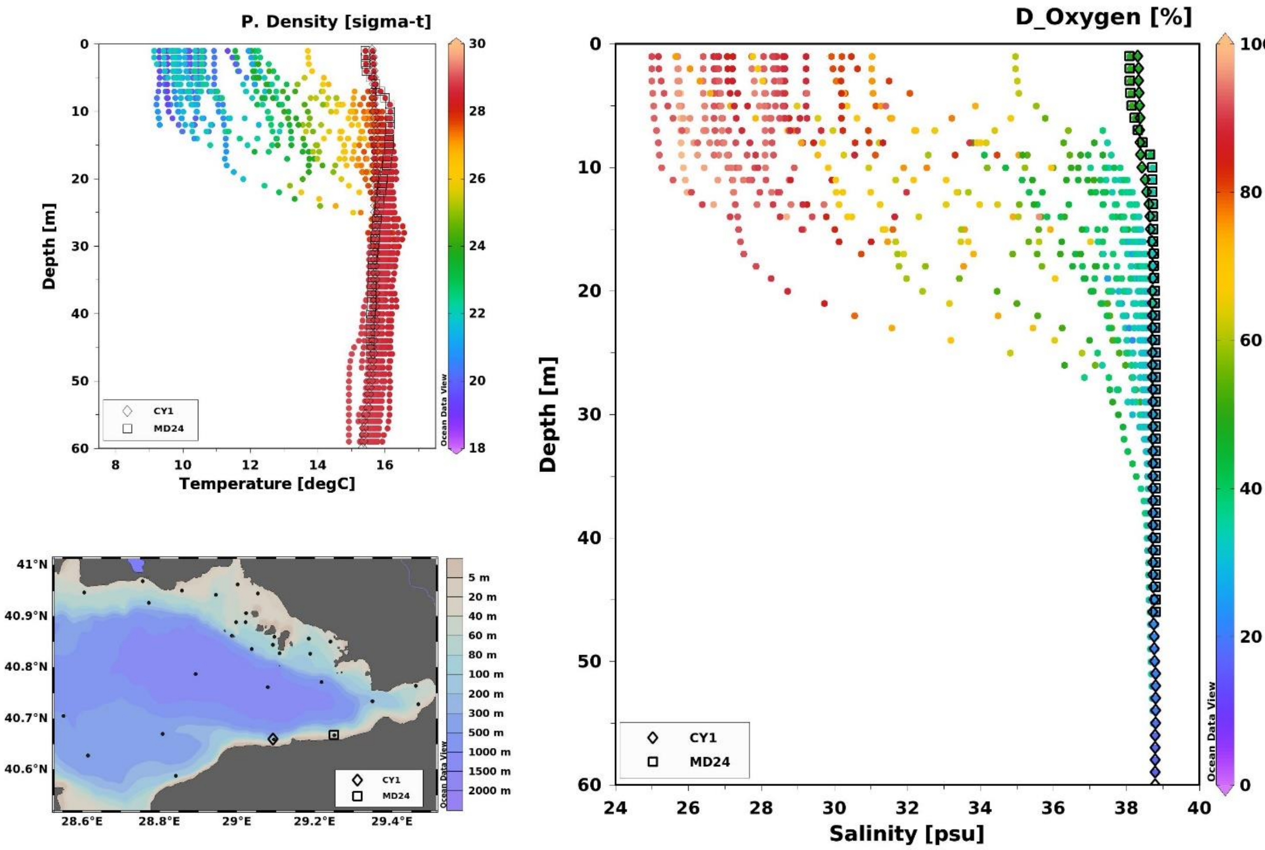

Fig. 3 The upwelling (CY1 and MD24) and neighbour stations located in the eastern part of the Sea of Marmara (left-bottom). Potential density at the surface increased even though the temperature increased at the same time (left-top). The dissolved oxygen percent decreased while the surface salinity increased because of the lower-layer rise (right).

For the wind direction and speed in meters per second at a height of 10 meters above the surface of the Earth before and during the upwellings, the data set named "ERA5 hourly data on single levels from 1940 to present" was preferred (Hersbach et al., 2023). ERA5 combines model data with observations from across the world into a globally complete and consistent dataset using the laws of physics. The horizontal resolution of the reanalysis wind data set is 0.25° x 0.25° on regular latitude-longitude grids with an hourly temporal resolution.

Results

The surface salinity increases were noticed by the authors at the first visual inspection of Figure 1. The increases were abrupt and reached up to 38 psu, which is the salinity value of sub-halocline waters as defined by Beşiktepe et al. (1994). This means that in the Marmara Sea, the permanent pycnocline due to the layered structure can be broken down during upwelling events (rising of the lower layer waters to the surface) or after strong vertical mixing between the layers. In this paper, the abrupt increases in surface salinity were examined in three cases since they were observed independently at different temporal and spatial scales.

Case 1: Yalova: The first observation was done on January 15, 2018, during the winter cruise of the "Integrated Marine Pollution Monitoring Program (2017–2022)". The closest stations to the epicentre of the lower layer rise were CY1 and MD24, which were along the coastline between Çınarcık district and the Yalova city centre. During the measurement at these stations, the soak time of the instrument was longer than usual to be sure that the real-time data was correct and to eliminate any possible suspicious data since the temperature and salinity values were not in the seasonal range (Figure 3). The surface temperature and salinity values (15.5 °C and 38 psu) were unexpectedly greater than the winter ranges (9–12 °C and 25–31 psu, respectively), and these high values were also observed along the water column. Unlike other stations, dissolved oxygen percent and fluorescence at the surface dropped to 50% and 0 mg/m^3, respectively. The observed parameters were so close to the lower layer values that the usual suspect for such a drastic change in water conditions could be a coastal upwelling.

To interpret the observations above because of an upwelling, the wind speed and direction of the region were examined for the existence of a favourable weather condition. The 5-day wind data before the upwelling at the closest ERA5 grid point for each case was selected and presented in Figure 2. During the sampling, there weren't any favourable winds for the upwelling; on the other hand, at 00:00 GMT+0 on the 14th of January, the wind speed reached its highest speed (12.3 m/s) coming from the north-east direction. This windy condition started at 12:00 GMT+0 on the 12th and lasted until the sampling time. The wind veered on the sampling day, decreasing its speed. In short, there wasn't any upwelling favourable wind condition during the sampling time, but there had been one previously.

Case 2: Gemlik Bay: The second upwelling event was observed on November 22, 2022, during the autumn cruise of Gemlik Bay. This time, the greatest surface salinity value was detected at the most inner part of the bay, where the station BBB1 is located (Figure 3). On the same day, the nearby stations were studied by the science team on board, and the upwelling effect on the surface was observed until the BBB5 station to the west. However, at the station BBB5, the temperature and salinity values (16.8 °C and 34.5 psu) at the surface are between those at BBB1 (18.3 °C and 37.6 psu) and the others' average (15.7 °C and 29.8 psu). Thus, the starting point of the Ekman transport was the east coast of the bay, and the direction of the transport was towards the exit of the bay with strong lateral mixing since the distance between two stations was not so far (about 9 km).
Both the previous and next day, there wasn't any abrupt change at the surface. The duration of the event was less than one day, which could be considered an acute event. The major difference between Case 1:Yalova and this one was that the decrease in dissolved oxygen percent was minor instead of a sudden drop. This was due to the bathymetry of the inner part. The bottom depth of the BBB1 station was about 25 metres, which was 10 metres above the oxycline starting depth at the deeper stations.

The ERA5 reanalysis data (Figure 2) show that the wind was exclusively blowing from the north-east, and its mean speed was 6.1 m/s, with a range of 3.5 to 8.5 m/s. Although the wind condition in this case was not as powerful as that in Case 1: Yalova, it lasted for a longer time.

Case 3: Pendik Bay: The third one lasted two days (January 13–14, 2022) during the winter cruise of the Marmara Sea. On the first day of this case, the highest salinity increase at the surface was detected at the station called "M11" in Pendik Bay. Temperature, salinity, and potential density values were increased to 15.9 °C, 38.3 psu, and 28.3 σ-t. However, the maximum values of these parameters at the surface of nearby stations were 11.2 °C, 27.9 psu, and 21.8 σ-t, respectively. The surface dissolved oxygen level of upwelling stations dropped to 46.8% as a result of the uprising of sub-halocline waters with less oxygen. On the same day, the station called MD26 was also measured, and it was observed that this station was under the horizontal advection of upwelling waters since the surface values were between the upper- and lower-layer values. On the second day, the other stations left from the previous day were studied. The nearest station to the centre of the upwelling was MY2, even though the surface values were not as high as M11. But this station's surface values were well close to lower layer values, proving that the upwelling event continues in the same bay. Other stations were also affected by the same phenomenon. In Figure 4, M20 and MD102 stations were emphasised to show that a larger area was dominated in comparison with the other cases mentioned above. The distance between M11 and MD102 was about 16.5 km. The last remark in this case was about the fluorescence values in the water column of M11 and MY2 stations. At these two stations, fluorescence had the lowest values, which was against the characteristics of the upper layer since it is well known as productive.

The wind conditions in this case were similar to those in Case 1:Yalova. On January 10, 2022, at 12:00 GMT+0, windy conditions began, lasting for 3.5 days. The strongest wind was blowing from the north-east with a speed of 14.2 m/s on January 12, 2022, at 0:00 GMT+0. Two stations (MD26 and M11) were sampled under

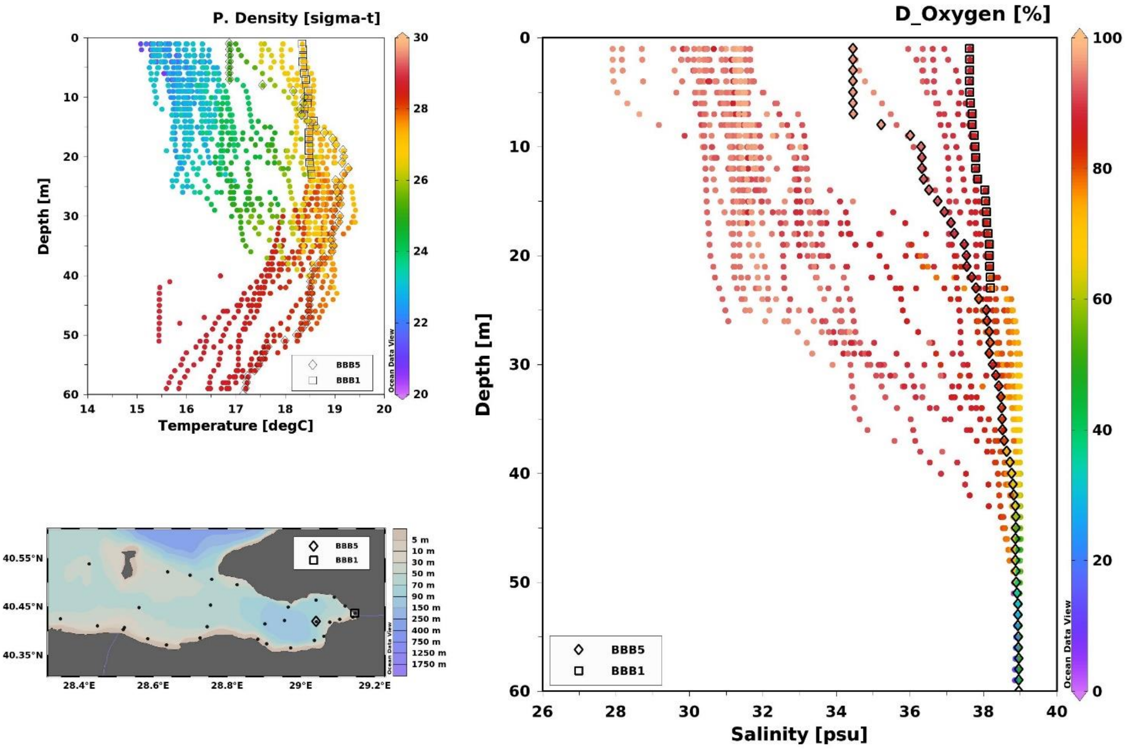

Fig. 4 The monitoring stations in Gemlik Bay (left-bottom). Potential density and temperature increased in the water column (left-top). The salinity increased while the dissolved oxygen decreased slightly (right).

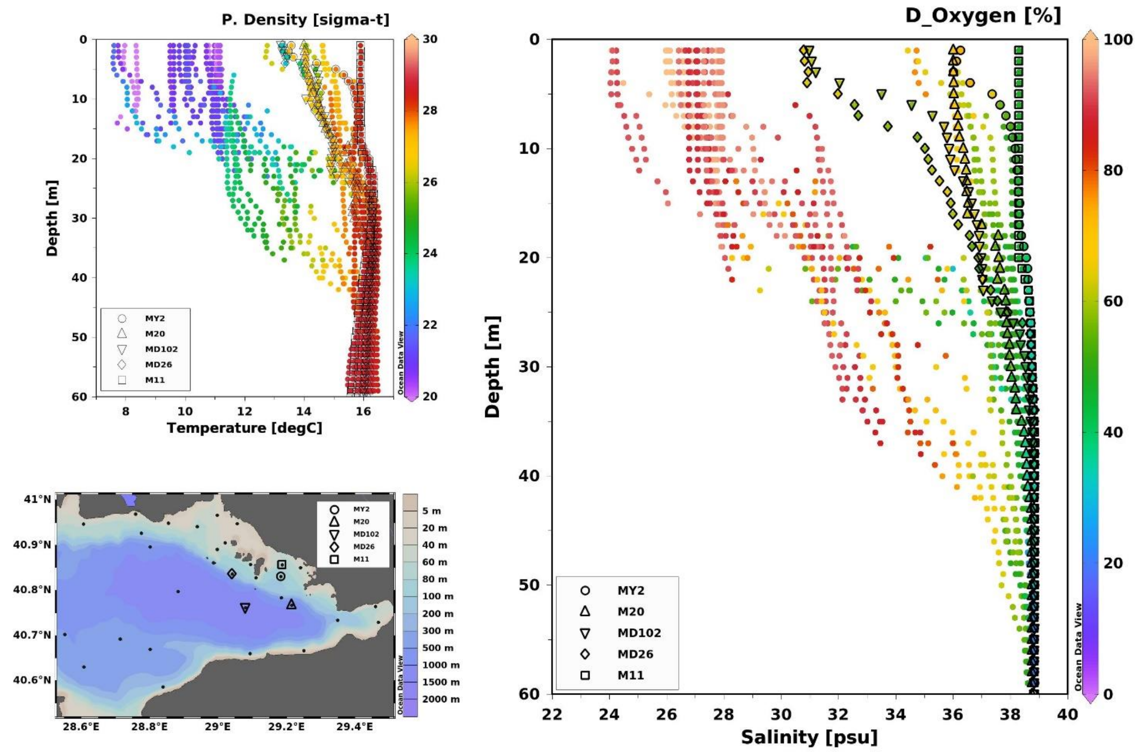

Fig. 6 The same region as Case 1, but upwelling events had happened in different stations. M11 station was in the centre (left-bottom). Others were affected by advection. The temperature and pot. density increased again (left-top). The dissolved oxygen level was lowered by the upwelling event, in which the salinity increased up to sub-halocline values (right).

severe conditions where the wind speed was 9 m/s, while the other three (MY2, MD102, and M20) were sampled when the wind was calmer and its direction changed to the opposite.

Discussion and Conclusion

In the literature, the summer upwellings of the Black and Aegean Seas are well-known and have been studied before by many researchers (Göktürk et al., 2015; Turunçoğlu et al., 2018; Tükenmez and Altiok, 2022). The coastal upwelling described in these studies depends on the Etesian winds dominating the climate along its pathway. The primary effect of this steady wind aligned with the coast is the intense upwelling in the southern Black Sea and the eastern Aegean Sea. Because of these seasonal upwellings, the eastern Aegean Sea has a lower sea surface temperature than the western part at the same latitude during the summer (Sayın et al., 2011). On the Black Sea surface, sharp dropouts of temperature last from a few days to a few weeks in the summer as well (Göktürk et al., 2015). Therefore, the upwellings in the Marmara Sea differ from the ones driven by the Etesian winds in the summer. The first difference is that the Marmara Sea upwelling events were not observed in summer, and the key drivers of them were not steady winds but low-pressure systems passing by the basin and causing severe north-east winds. The second difference is that the Marmara Sea's upwelling events last shorter than the summer ones. Since the Marmara Sea is spatially much smaller than the adjacent seas, this small basin allows for temporally shorter ocean processes. The third difference is about the effect on the sea surface. The coastal upwellings driven by the Etesian winds in summer result in cooler sea surface, while the coastal upwellings in the Marmara Sea in winter cause warmer surface with higher salinities. This kind of effect (warmer and saltier sea surface) is similar to the ones observed in the Gulf of Finland (Suursaar, 2021). Both winter upwellings cause a rise in temperature and salinity values at the surface. Additionally, the main body of upwelled water in the Gulf of Finland stays ca. 1–10 km off the coast relatively unchanged, which is also quite similar to the ones observed in the Marmara Sea.

Upwelling as a phenomenon in the Marmara Sea has long been either ignored or underestimated. Tuğrul et al. (1986) mentioned short-term peaks in the surface salinity due to strong wind episodes in the winter months in Izmit Bay, the most eastern part of the Marmara Sea. An example was given to show the increase up to 5 ppt as an effect of a 10 m/sec north-easterly wind in February. It was not considered an upwelling since the surface salinity increased from 24 ppt to 29 ppt and the lower-layer waters rose along the water column without reaching the surface. This could be circumstantial evidence of an upwelling event occurring in the bay, but it was not considered an upwelling since the surface salinity rise reaching 30 ppt in March in the same study was due to the inflow of high-saline bottom waters with vertical mixing.

Ünlüata et al. (1990) mentioned three mechanisms regarding the upward mixing within the Sea of Marmara. Two of them were located in the straits, and the last one was under the influence of winds down to the shallow halocline. Beşiktepe et al. (1994) stated that wind mixing and a reduction in the influx from the Black Sea caused the upper layer salinity to increase in winter. A salinity value of 30 ppt during February 1987 was given as an example of how the mixing of the upper layer waters depends on long-term variations in weather.

For the first time, the "upwelling" term for the Marmara Sea was used in the Chiggiato et al. (2012) study. Large displacements of the pycnocline depth were observed during the sea trials between September 2008 and February 2009. They interpreted these displacements as storm-driven upwelling and downwelling dynamics associated with north-easterly winds. They also explained that the Marmara Sea exceeds the upwelling inhabitation threshold, 2R (Cushman-Roisin et al., 1994), where R stands for the internal radius of deformation and is 17 km for the Marmara Sea. This explanation was significant for understanding the surface salinity rise up to 30 ppt in winters, but it was focused on the large displacement of the pycnocline, which had not been clearly documented before. Another study mentioning the upwelling term for the Marmara Sea is the Ph.D. thesis of Aydoğdu (2016). In the thesis, the mean true wind stress on the sea surface was computed in the Turkish Straits System for the 2009–2013 period. According to this computation, the true stress was maximum on the northern coasts of the Aegean and Marmara Seas and exceeded 0.05 N/m^2, which is favourable for upwelling and downwelling on the northern and southern coasts.

Another study on upwelling in the Marmara Sea was done by Oğuz (2017). However, it was studied the outflow plume zone of the Istanbul Strait and the topographically induced upwelling regions with their effects on plankton production. The concluding remark of the study was that the hydraulically controlled buoyant jet within the junction region of the Istanbul Strait and the topographically induced localized upwelling events persistently enrich the upper 30 m layer with nutrients and make the Marmara Sea a highly productive system. A third one, in addition to the events emphasised by Oğuz (2017), could be the wind-driven coastal upwelling event since it is another way for the lower layer to rise to the surface. Therefore, wind-driven coastal upwellings should be well studied not only for the hydrography of the basin but also for the primary production.

Another successful modelling study was done by Sannino et al. (2017), in which the basic hydrodynamics of the Turkish Straits System were modelled in high resolution. The mixed baroclinic-barotropic response of the system and the surface currents in the Marmara Sea were well examined, except for coastal upwellings, since the intense surface jet issuing from the Istanbul Strait was found to drive the basin-wide circulation of the Marmara Sea. A similar simulation of the Turkish Straits System using a high-resolution, three-dimensional, unstructured mesh ocean circulation model with realistic atmospheric forcing was presented by Aydoğdu et al. (2018). The solutions captured important responses to high-frequency atmospheric events such as the reversal of the upper layer flow in the Bosphorus due to southerly severe storms, i.e., blocking events, except coastal upwellings since other major processes were focused on in the study.

The last modelling study to be discussed was that of Ilıcak et al. (2021). They developed a high-resolution, unstructured finite element grid model to simulate the Turkish Strait System using realistic atmospheric forcing and lateral open boundary conditions. This model could be the best candidate for future operational runs; however, like previous modelling studies, this one also focused on major oceanographic processes in the Marmara Sea. There were few mentions of coastal upwellings to explain why some regions were saltier than expected in the results.

As seen above, the wind-driven coastal upwelling in the Marmara Sea has been missed or undervalued by many researchers except Chiggiato et al. (2012), since this mesoscale spatially and temporarily variable process occurs in small regions and does not last long, or it was believed that it was not as significant as other major features of the sea. On the other hand, we showed that coastal upwellings are as significant as wind stirring, turbulent entrainment, and topographically induced upwelling in the Marmara Sea. Coastal upwellings should also be considered with others to explain why the surface salinity reaches its maximum in the winter. It was observed that the upwelled water masses had high salinity values (~38 psu). Therefore, the frequency of the coastal upwellings and the pycnocline depth of the sea must be well monitored for their changes in time. The increase in upwelling frequency with a shallower pycnocline will definitely result in higher surface salinities in future winters. The other importance of this process is that it is an alternative way for the nutrient-rich waters to reach the surface and make the Marmara Sea highly productive. During the upwelling events, primary production could be temporarily halted in the region, but they would lead to favourable conditions for blooms later.

All coastal upwellings described above were observed under severe northeasterlies (the most frequent winds), which were in good agreement with the sea trials of Chiggiato et al. (2012) and the findings of Aydoğdu et al. (2018). However, there weren't any simultaneous measurements done on the opposite coast to detect downwelling events. Another missing observation is the measurement done under severe southwesterlies, which are the secondarily prevailing winds in the region. The pycnocline response to south-westerly winds is also significant in figuring out the role of the wind direction in coastal upwelling processes in the Marmara Sea. The second issue with the observations in the study is the lack of observation of coastal upwelling processes from the beginning. As a result, the minimum wind speed and duration required for an upwelling are unknown. For this reason, we suggest a sensitivity study to analyse the sole impact of the wind on the circulation of the basin. In the sensitivity study, a basin-wide model can be forced by ordinal and cardinal winds at different speeds, representing the regional climatology.

The last concluding remark is that it was understood once again that the Marmara Sea is highly dynamic and is hosting many mesoscale and smaller ocean processes to be discovered.

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References

Aydoğdu, A. (2016). *Advanced Modeling and Data Assimilation Methodsfor the Design of Sustained Marine MonitoringNetworks. PhD*, Universita Ca'Foscari Venezia, Venice, Italy.

Aydoğdu, A., Pinardi, N., Özsoy, E., Danabasoglu, G., Gürses, Ö., Karspeck, A. (2018). Circulation of the Turkish Straits System under interannual atmospheric forcing. *Ocean Science*, 14(5), 999-1019.

Beşiktepe, Ş.T., Sur, H.İ., Özsoy, E., Latif, M.A., Oğuz, T., Ünlüata, Ü. (1994). The circulation and hydrography of the Marmara Sea. *Progress in Oceanography*, 34(4), 285–334. https://doi.org/10.1016/0079-6611(94)90018-3

Beşiktepe, Ş.T. (2003). Density currents in the two-layer flow: an example of Dardanelles outflow. *Oceanologica Acta*, 26(3), 243-253.

Chiggiato, J., Jarosz, E., Book, J.W., Dykes, J., Torrisi, L., Poulain, P.M., Gerin, R., Horstmann, J., Beşiktepe, Ş.T. (2012). Dynamics of the circulation in the Sea of Marmara: numerical modeling experiments and observations from the Turkish straits system experiment. *Ocean Dynamics* 62, 139–159. https://doi.org/10.1007/s10236-011-0485-5

Cushman-Roisin, B., Asplin, L., Svendsen, H. (1994). Upwelling in broad fjords. *Continental Shelf Research*, 14(15), 1701-1721.

Dorofeyev VL, Oguz T, Sukhikh LI, Knysh VV, Kubryakov AI, Korotaev GK. 2012. Modeling long-term changes of the Black Sea ecosystem characteristics. *Ocean Science Discussions.* 9:2039–2080. doi:10.5194/osd-9-2039-2012.

Ekman, V.W. (1905). On the influence of the Earth's rotation on ocean-currents. *Ark.Mat.Astr.Fys.*2(11).

Gazioğlu, C., Gökaşan, E., Algan, O. Yücel, Z. Y., Tok, B., Doğan, E., (2002). Morphologic features of the

Marmara Sea from multi-beam data, *Mar. Geol.*, 190(1– 2): 397–420.

Gönenç, I.E., Wolflin, J.P. (2004). Coastal Lagoons: Ecosystem Processes and Modeling for Sustainable Use and Development, CRC Press,

Göktürk, O.M., Çevik, S., Toque, N., Hordoir, R., Nagy, H., Özsoy, E. (2014). Effects of the Etesian wind regime on coastal upwelling, floods and forest fires in the seas of the old world. *Black Sea/Mediterranean Environment*, 117.

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., Thépaut, J-N. (2023): *ERA5 hourly data on single levels from 1940 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS),* https://doi.org/10.24381/cds.adbb2d47

Ilicak, M., Federico, I., Barletta, I., Mutlu, S., Karan, H., Ciliberti, S.A., Clementi, E., Coppini, G., Pinardi, N. (2021). Modeling of the Turkish Strait System using a high resolution unstructured grid ocean circulation model. *Journal of Marine Science and Engineering,* 9(7), 769.

Kämpf, J., Chapman, P. (2016). *Upwelling systems of the world* (pp. 31-42). Springer International Publishing Switzerland.

Müftüoğlu, A.E. (2008). *Marmara Denizi Haliç ve Körfezlerinin hidrodinamik yapısı.* PhD, İstanbul University, İstanbul, Türkiye.

Oğuz, T. (2017). Impacts of a buoyant strait outflow on the plankton production characteristics of an adjacent semi-enclosed basin: A case study of the Marmara Sea. *Journal of Marine Systems,* 173, 90-100.

Özsoy, E., Altıok, H. (2016). A review of hydrography of the Turkish Straits System. The Sea of Marmara–Marine Biodiversity, Fisheries, Conservation and Governance, *Turkish Marine Research Foundation (TÜDAV) Publication*, 42, 13-42.

Pinardi, N., Moroni, F., Özsoy, E. (2010). Marsili's first scientific oceanographic cruise (1679-1680) and exposition of Bosphorus density currents. *Proceedings of The Symposium "The Marmara Sea".* 1-5. TÜDAV.

Sannino, G., Sözer, A., Özsoy, E. (2017). A high-resolution modelling study of the Turkish Straits System. *Ocean Dynamics,* 67, 397-432.

Sayın, E., Eronat, C., Uçkaç, Ş., Beşiktepe, Ş.T. (2011). Hydrography of the eastern part of the Aegean Sea during the Eastern Mediterranean Transient (EMT). *Journal of Marine Systems,* 88(4), 502-515.

Suursaar, Ü. (2021). Winter upwelling in the Gulf of Finland, Baltic Sea. *Oceanologia,* 63(3), 356-369.

Tuğrul, S., Sunay, M., Baştürk, Ö., Balkaş, T.I. (1986). *The Izmit Bay Case Study. The role of the oceans as a waste disposal option,* 243-274.

Turunçoğlu, U.U., Önol, B., Özcan, C. (2018). Analysis of Aegean Sea coastal upwelling system using in-situ visualization integrated Regional Earth System Model (RegESM). *In EGU General Assembly Conference Abstracts* (p. 9835).

Tükenmez, E., Altıok, H. (2022). Upwelling Index Calculations in the Aegean Sea. *Turkish Journal of Fisheries and Aquatic Sciences,* 22(12).

Tyrlis, E., Lelieveld, J. (2013). Climatology and dynamics of the summer Etesian winds over the eastern Mediterranean. *Journal of the Atmospheric Sciences,* 70(11), 3374-3396.

Ünlülata, U., Oğuz, T., Latif, M.A., Özsoy, E. (1990). *On the physical oceanography of the Turkish straits. The Physical Oceanography of Sea Straits,* 25–60. https://doi.org/10.1007/978-94-009-0677-8_2