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An Evaluation of the Main Physical Features and Circulation Patterns in the Black Sea Basin

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ABSTRACT

Having as target the semi-enclosed basin of the Black Sea, the primary purpose of the existing paper is to present an overview of its extensive physical features and circulation patterns. To achieve this goal, more than five decades of data analysis - from 1960 to 2015 - were taken into consideration and the results were validated against acknowledged data, both from satellite data over the last two decades and in-situ measurements from first decades. The circulation of the Black Sea basin has been studied for almost 400 years since the Italian Count Luigi Marsigli first described the “two-layer” circulation through the Bosphorus Strait in the year 1681. Since climate change projections for the Black Sea region foresee a significant impact on the environment in the coming decades, a set of adaptation and mitigation measures is required. Therefore more research is needed. Nowadays, the warming trend adds a sense of immediate urgency because according to the National Oceanic and Atmospheric Administration’s National Centre for Environmental Information, July 2020 was the second-hottest month ever recorded for the planet. Its averaged land and ocean surface temperature tied with July 2016 as the second-highest for the month in the 141-year NOAA’s global temperature dataset history, which dates back to 1880. It was 0.92°C above the 20th-century average of 15.8°C, with only 0.01°C less than the record extreme value measured in July of 2019.

1. Introduction

The Black Sea is clearly one of the most conspicuous inland seas throughout the entire world. Squeezed between Central Asia and Western Europe, the wider Black Sea area borders Turkey to the South and Russia to the north. Following the Persian Gulf, this region is the second-largest reservoir of oil and natural gas and has considerable deposits of coal and, of course, a traditional adherence to fossil fuels^[1]. At the same time, it is renowned for the

potential of its substantial renewable in hydropower, solar, and wind energy, and altogether^[1-7], these factors raise awareness whenever climate change generate concern. The Black Sea is cut off from the world’s ocean through its unique particularities. The dominant forces acting upon the Sea are represented by gravity, buoyancy - the floatation force of a material of lower density than the liquid that is immersed in - and wind, generating its dynamics of currents, tides, and mixing waters. Taking into consideration that the Black Sea’s surface is relatively small

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- roughly 423 000 square kilometres - the surface tides produced by the gravitational attraction of the moon are almost insignificant. However, on the other hand, buoyancy maintains less dense layers of water floating on top of thicker ones, remaining unmixed, unless the buoyancy of either layer changes considerably through cooling of the lighter layers or warming of the denser ones. Another likelihood of mixing the layers would be the increasing or decreasing of the salt amount ^[8].

The Black Sea is permanently stratified, given the fact that it has developed two primary water layers which are separated by a strong density gradient, or pycnocline ^[8]. Its unique body of water is represented by the cold intermediate layer, below 70-150 metres, colder and saltier than the upper layer. It must be outlined that the Black Sea has a positive freshwater balance, which implies that it receives more freshwater from rivers (Europe's second, third, and fourth largest rivers - Danube, Dnipro, Don - flow into the Sea) and rainfall than it loses from evaporation ^[8]. Every year, the Black Sea receives roughly 350 square kilometres of river water and about 250 square kilometres of precipitation, while evaporation releases only 350 square kilometres of water ^[9]. Given the positive freshwater balance, the level of the Black Sea is higher than that of the Marmara Sea by an average of 0.43 metres ^[9]. Therefore, the excess of water flows through the Bosphorus Strait into the Marmara Sea, resulting in the development of two flows throughout the strait. The upper one leaves the Black Sea and transports surface water out of it.

Meanwhile, the bottom flow carries salty water, with salinity between 35 and 36‰ from the Mediterranean to the Black Sea ^[9]. The much saltier water mixes with the waters of the basin, ending in a relatively low salinity at the surface, with an average of 18.2‰, though it could be much lower near river outflows. The lower layer of the Bosphorus Strait has an average salinity of 21.8‰. One could say that a difference of 3.6‰ is insignificant, but is enough to prevent the bottom, hydrogen sulfide water from reaching the sea surface ^[4,8], posing a significant threat to human life and the surrounding environment ^[8].

According to statistics and researchers ^[8-10], an average of 300 cubic kilometres of bottom water mixes into the surface layer yearly, which is equivalent to a layer of almost 2 millimetres thick of bottom water per day. Therefore, it would take somewhere near 2000 years for all that bottom water to be circulated through the pycnocline ^[8]. According to ^[8], the layer nearest the surface with constant density is mixed by the wind and waves, and it is known as the "upper mixed layer". Secondly, the deepwater area has minimal variation regarding the density, and the

temperature is warming the water near the surface - the measurements took place during middle spring - but it is getting colder with depth until a cold intermediate layer of around 7.5-8°C is reached. The more bottomless Sea is warmer, mainly from the Mediterranean water, but also from geothermal processes underneath the seabed ^[8].

Gradually, but at a plodding pace, the bottom water layer does mix, to form the upper layer. The rate of overall mixing can be determined from the water balance through the Bosphorus Strait, as it is the only gateway of seawater to the Black Sea. Logically, in the long run, the amount of salt entering must be equal to the one leaving; otherwise, the seawater would become fresher or saltier ^[8].

2. Circulation Patterns in the Black Sea Basin

On a global scale, thermohaline circulation is part of the ocean circulation driven by density gradients created by surface heat and fluxes of freshwater, and it is a significant regulator of the Earth's climate. The thermohaline circulation process of the Black Sea is similar but on a smaller, regional scale. One of the distinctive characteristics of the Black Sea is the cold intermediate layer (also known as CIL), a relic of the cold winter water masses, which in summer are covered by warmer surface water, being a subject of constant debate among researchers. Different hypotheses on the establishment of the cold intermediate layer were put forward throughout the years. Some say that it was formed as a result of advective and convective contributions taking place along anticyclonic regions of the Sea, largely dawning from the shelf and the continental slope area throughout the winter and expanding during spring and summer ^[11]. It was Luigi Marsigli who first recognized that the Bosphorus currents were purely a simple outcome of the difference among the water densities in the Black and Mediterranean Seas. He succeeded in demonstrating this density difference by developing a physical model that captured the striking features of the phenomenon that has intrigued oceanographers since 1681 - considered by scientists the year of the foundation of modern oceanography ^[12]. Water from the cold intermediate layer is essential for the biology of the Black Sea since it is richer in plant nutrients than offshore surface water and fertilizes the Sea when it is mixed back to the surface ^[8].

The Black Sea's general circulation features consist mainly of the cyclonic Rim current, drifting along the continental slope, and various cyclonic and anticyclonic mesoscale eddies located inside the primary current or between it and the shore ^[4,13]. Nevertheless, the mesoscale eddies emerge along the borderline of the basin, as part of the Rim structure. It is mesoscale circulation that ef-

fectively links coastal hydrodynamic and geochemical processes to those in the deep Sea, hence providing a mechanism for two - way transport between nearshore and offshore areas^[13].

Horizontal circulation of the Black Sea is characterized by gyres, which are wind-driven cyclonic and anticyclonic currents with similar dimensions to that of ocean basins. Black Sea's circulation is nearly driven by the winds and the buoyancy differences between inflowing freshwater and the saltier Mediterranean inflow^[8]. Consequently, throughout the year there is a cyclonic circulation at variable speed. Figure 1 depicts a changeless feature of the upper layer circulation - the Rim Current surrounding the whole Black Sea. From place to place, it has a width of some tens of kilometres and sometimes may achieve a maximum speed of 0.8-1 knot, which is between 40 and

50 cm/sec, at times increasing up to 1.6 knots, or 80-100 cm/sec^[8]. Direct observations have determined these results and in situ measurements, as well as available satellite data of the current velocity from surface buoys^[8,11,14]. Figure 1 reveals the circulation of the Black Sea on 23rd of October 2020 using a snapshot from^[14], and the navigation traffic at that specific moment.

Figure 2 indicates the characteristics of the circulation in gyres, with the permanent Rim current following the continental shelf, as a general rule. Nevertheless, the coast's shape sends it on seawards short cuts in some places, outwitting another gyre, much smaller, between the coast and the Rim - Bosphorus gyre, in the south-western part, and the Batumi gyre, in the south-eastern coast, both of them represented as continuing features. Inside the Rim current, there are two (more or less) permanent gyres,

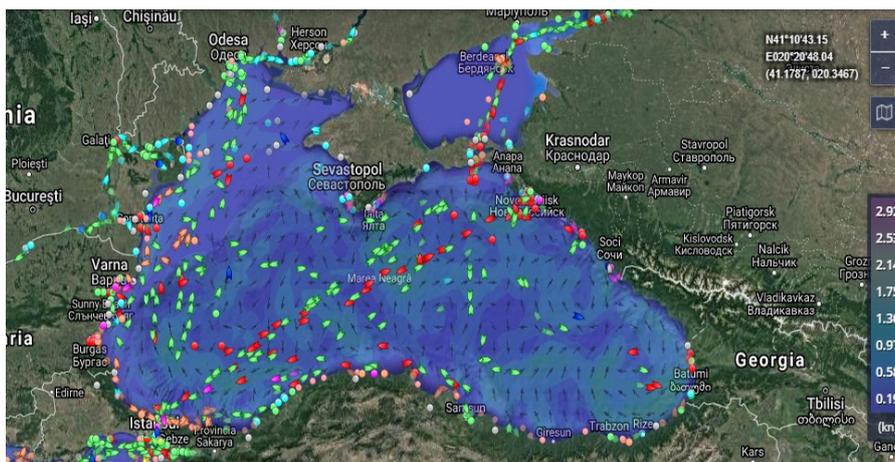


Figure 1. Circulation patterns in the Black Sea (23rd of October 2020) and the most circulated navigation routes. Snapshot from^[14]

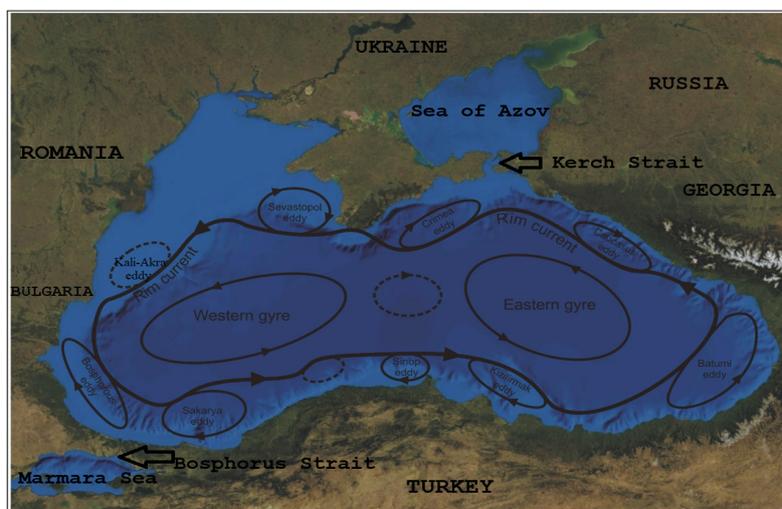


Figure 2. Schematic diagram of the general circulation in the Black Sea basin - the solid lines indicate the habitual features of the general circulation. (Modified satellite map provided by NASA - a screenshot from NASA's globe software World Wind)

marked and known as the “Western” and “Eastern” gyres. They are of great significance as they mark the pathway of planktonic larvae - that cannot swim against the currents and their whole lifecycle has been adjusted to the circulation. Within the Rim Current and the shore, there is also a range of seasonal gyres, with as much significance as the ones as mentioned earlier, as they play a significant role in the redistribution of Danube and Dnipro’s water and mixing it with the Black Sea surface water^[8].

It has been confirmed that the interannual wind variability has a meaningful effect on the mesoscale activity and consequently on the Black Sea’s circulation. The mesoscale activity is shallow when the wind force has long-lasting, vital cyclonic events which strengthen the large scale circulation. However, the large scale circulation is less intense, and the mesoscale activity expands when the wind is anticyclonic. Consequently, it is of utmost importance to take into consideration wind variability in numerical modelling to avoid undervaluing the contribution of critical physical processes that dominate the ocean’s response to the climatic forcing, as presented in ^[11,15,16].

Knipovich first described in 1932 that the general cyclonic circulation is attributed to the cyclonic nature of the wind field. Nevertheless, various classifications and further investigation of the circulation have been carried out since then, suggesting that the circulation patterns are dominated by fundamental factors such as the sequence of the seasonal thermohaline circulation induced by non-uniform surface fluxes, the wind, and the topography of the basin. Another major determinant that contributes to the Black Sea’s general circulation is the freshwater inflow from the rivers along with the dense Mediterranean inflow in the Bosphorus proximity, generating lateral buoyancy fluxes. The spatiotemporal inconstant sub-basin scale features are typically cyclonic gyres in the deep Black Sea and some anticyclones positioned at the shelf split between the coast and the Rim Current.

The semi-permanent characteristics are schematized in figure 2. Beginning from the north-eastern part, in a clockwise way, the Caucasus eddy in the north-eastern coast, the Batumi eddy in the south-eastern corner of the basin, a range of anticyclones along the Anatolian coast (including the Sakarya, Sinop and Kizilirmak eddies), the Bosphorus and Kali-Akra eddies in the western part, the Sevastopol eddy at the west of the Crimean peninsula, and the Crimea eddy at the east of the peninsula.

Generally, seas have a significant component of mesoscale circulation^[11], and eddying movements are nearly everywhere. Eddies stir the flow, transport heat and trace chemicals across it. Globally, the humblest circulations are

merely a few millimetres in size, yet the greatest is more than ten thousand kilometres in diameter. Circumstances such as latitude, nearby bottom topography, energy level, as well as the nature of their generation, contribute to the variation of the horizontal scales of mesoscale eddies^[11]. This fabulous range of variety comes from the tendency for the high-latitude ocean to have lighter density stratification and larger Coriolis rate. Mesoscale eddies are often created by the uncertain meandering of a strong current where the waving deflection of the current is itself a form of the underlying eddy, which might finally turn into a circular one. However, wind or a colder sea surface water, as well as a flow over a former island or rocky seafloor can contribute to the creation of a mesoscale eddy, which is a fundamental mechanism of transport of impulse, heat, and trace water properties (for example oxygen, chemicals, biological communities, and nutrients).

As regards the Black Sea, oceanographic surveys and the availability of satellite data added considerable detail to the description of its circulation. Thus, a novel feature discovered is that the regular circulation is not as steady as beforehand thought, and there is unusual mesoscale activity in the region. While mesoscale eddies in the Black Sea usually have 80 to 100 kilometres in diameter and they seep deeply into the pycnocline (dropping to almost 400 m in some areas), with a velocity near the sea surface between 15 and 50 cm/s.

3. Statistical Analysis of the Circulation Patterns in the Black Sea Basin Using Satellite Data, Recent Measurements, and Simulations with Numerical Models

It has been stated that the general circulation of the Black Sea is wind-driven and also driven by extensive freshwater input from the “three-D” rivers - Danube, Dnipro, and Don. In the year 1994, the Danube river was declared one of the ten Pan-European transport passages - the seventh one. The Danube outflow produces a current system that seldom generates strong interactions with waves - especially at the Saint George’s arm in the southern part^[2]. Its alluvium has led to the creation of the Sacalin Islands in 1897, which measure 19 kilometres in length - and still growing.

Generally speaking, validated models that have been used to reproduce the Black Sea hydrodynamics fall into two major categories, such as data assimilation models and those with weak/strong relaxation. An approach of the interannual variability of the Black Sea’s hydrodynamics is reported in^[17], providing a model without relaxation; however, neither sea surface salinity nor water column

salinity is displayed. The models presented in [18,19,20,21] are based on data assimilation and available satellite data for altimetry and sea surface temperature to force model works. Given the lack of consistent data for sea surface salinity, typically climatological datasets are utilized instead. However, they failed to replicate the vertical Black Sea thermohaline structure, such as the cold intermediate layer's properties, realistically, but are suitable for operational forecasting (CMEMS, [4]). The second category includes stand - alone ocean models with distinct relaxation plots to climatological or observational sea surface temperature and sea surface salinity time series.

Because of the complexity and hardness of reproducing the surface salinity and its extensive vertical gradients, newer versions of statistical modelling of currents are bound to continue to use sea surface salinity relaxation. Besides, the Black Sea's surface salinity observational data is still rare and meagre. Notwithstanding its shortcomings, the present data can be used to some extent for relaxation in hindcast simulations, as presented in [19,20,21]. Nevertheless, a model capable of performing scenarios for the future is highly needed, not only for the phytoplankton blossom but also to foresee potential ecological changes.

Consequently, these factors motivated researchers to generate a model capable of simulating the mesoscale and thermohaline circulation in the Black Sea for a perpetual multidecadal period without any relaxation via external

fields. The 3D hydrodynamic model presented in [13] covers the 3D General Estuarine Transport Model (known as GETM - which implements primitive equations with hydrostatic approximations to calculate the 3D flow field and the free surface [22]) and the General Ocean Turbulence Model (known as GOTM). The goal of the scientists was The study presented in [23] emphasizes the realistic representation of the Black Sea circulation and mean thermohaline structure, with a particular focus on the mean sea surface salinity variation. Since salinity, temperature and density are approximately uniform in the deep water, the main focus is on the dynamics of the upper surface down to 250 metres depth. Besides, long - term trends of temperature over salinity fluctuations are discussed.

Having as target the Black Sea basin, the increased resolution obtained from oceanographic surveys and the availability of satellite data (AVISO - Archiving, Validation, and Interpretation of Satellite Oceanographic data and ECMWF - European Centre for Medium-Range Weather Forecasts) added considerable detail to the description of its circulation. Thus 18 years of satellite data were analyzed from 1993 until 2010 [5] to achieve a greater level of understanding of the circulation in the Black Sea basin. The satellite data was obtained from AVISO and contained daily measurements of the "U-V" parameters of the currents with a spatial resolution of roughly 10 kilometres horizontally and 13 kilometres vertically. The monthly averaged values of the current velocity are pre-

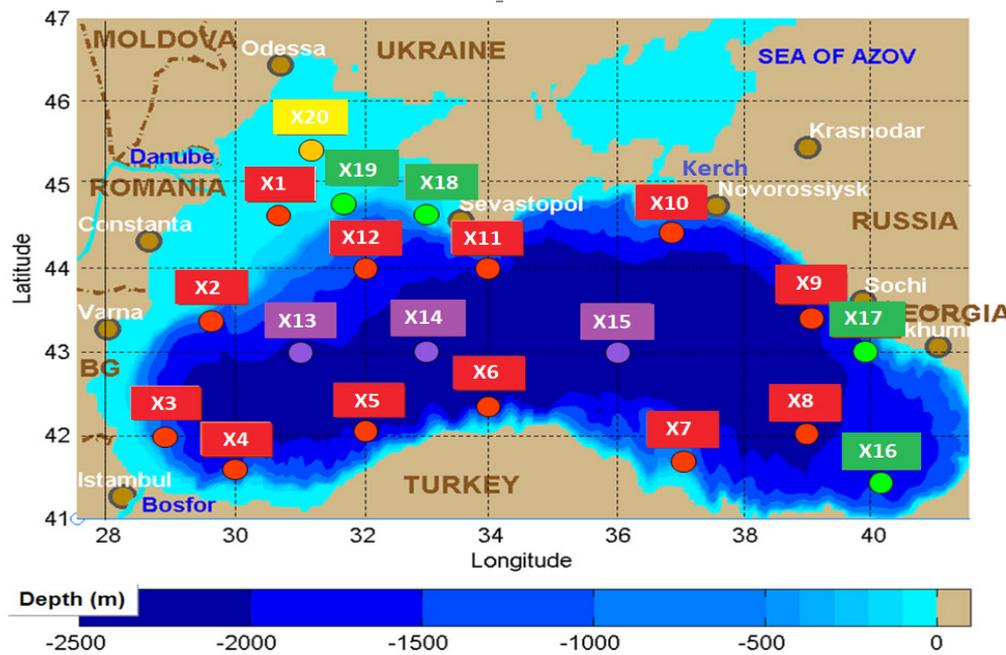


Figure 3. The bathymetry of the Black Sea (from GEBCO - The General Bathymetric Chart of the Oceans) with 20 points of reference

Table 1. Monthly averaged values of the current velocity (measured in ms^{-1}) for the reference points taken into consideration [X1 - X20] for 18 years, from 1993 until 2010

Points (with coordinates)	Months											
	January	February	March	April	May	June	July	August	Sep.	Oct.	Nov.	Dec.
X1(44.4N/30.43E)	0.08	0.07	0.07	0.08	0.08	0.07	0.07	0.06	0.06	0.06	0.06	0.07
X2 (43.18N/29.43E)	0.11	0.12	0.13	0.12	0.11	0.11	0.09	0.11	0.11	0.10	0.10	0.11
X3 (41.58N/29E)	0.13	0.12	0.13	0.11	0.10	0.09	0.11	0.12	0.11	0.10	0.11	0.10
X4 (41.36N/29.58E)	0.08	0.08	0.08	0.09	0.07	0.07	0.07	0.08	0.09	0.08	0.08	0.09
X5 (42.7N/31.59E)	0.06	0.06	0.06	0.07	0.07	0.06	0.06	0.05	0.06	0.08	0.08	0.07
X6 (42.21N/34.2E)	0.08	0.08	0.08	0.07	0.08	0.07	0.07	0.08	0.07	0.07	0.07	0.07
X7 (41.32N/36.59E)	0.07	0.09	0.08	0.08	0.06	0.06	0.07	0.07	0.08	0.08	0.08	0.08
X8 (42.1N/39.3E)	0.14	0.10	0.10	0.10	0.09	0.11	0.12	0.13	0.13	0.11	0.12	0.13
X9 (43.32N/39.14E)	0.13	0.11	0.11	0.11	0.11	0.10	0.10	0.13	0.12	0.11	0.13	0.12
X10(44.38N/36.49E)	0.15	0.14	0.14	0.13	0.10	0.11	0.13	0.13	0.15	0.15	0.13	0.14
X11 (43.59/33.59E)	0.08	0.07	0.07	0.07	0.07	0.07	0.06	0.06	0.08	0.08	0.08	0.07
X12 (44N/32E)	0.15	0.14	0.16	0.18	0.17	0.16	0.15	0.13	0.13	0.14	0.12	0.14
X13 (43N/30.6E)	0.07	0.09	0.08	0.08	0.08	0.08	0.07	0.07	0.08	0.09	0.10	0.08
X14 (43.1N/32.58E)	0.07	0.06	0.07	0.07	0.06	0.07	0.06	0.07	0.06	0.07	0.07	0.07
X15 (42.59N/36E)	0.08	0.08	0.08	0.08	0.07	0.08	0.09	0.09	0.09	0.10	0.09	0.08
X16 (41.23N/40.4E)	0.11	0.10	0.11	0.10	0.11	0.12	0.11	0.10	0.11	0.11	0.10	0.11
X17(43.32N/9.57E)	0.12	0.08	0.09	0.09	0.10	0.09	0.09	0.09	0.11	0.14	0.14	0.13
X18 (44.37N/33E)	0.11	0.12	0.12	0.10	0.10	0.10	0.10	0.09	0.12	0.12	0.10	0.12
X19 (44.4N/31.46E)	0.18	0.18	0.18	0.17	0.16	0.18	0.17	0.14	0.14	0.13	0.14	0.16
X20 (45.21N/31E)	0.07	0.07	0.07	0.06	0.06	0.06	0.06	0.07	0.07	0.08	0.08	0.07

sented below in table 1, with results provided by AVISO. The 20 points of reference taken into consideration are outlined in figure 3, having the bathymetric map of the Black Sea in the background.

At first glance, the values outlined in table 1 confirms that the average current velocity values in the Black Sea basin are normally low, compared to the Global Ocean. Most of the points selected on the Rim cyclonic current and at the edge of the anticyclonic eddies have higher velocities than the ones located in the north-western shelf and central gyres. Another characteristic of the Black Sea's current velocities is the variation between summer and winter periods, as the table reveals that the lowest

values are measured during June, July, and August. The points in the interval [X1-X12] have higher current velocities, being positioned near the Rim current. The points with almost insignificant velocity variation are those in the interim determined by [X1 - X6], points positioned in the south-western part of the Black Sea. In addition, the points situated on the Rim or the two anticyclonic eddies have greater velocity values than, for example, X13, X14 and X15, points located inside the Rim current. As regards point X20, which is situated in the north-western shelf, it can be observed that it has the smallest value and no other significant circulation feature can be recognized.

4. Discussion

According to the National Oceanic and Atmospheric Administration's National Centre for Environmental Information, July 2020 was the second-hottest month ever recorded worldwide. Its averaged land and ocean surface temperature tied with July 2016 as the second-highest for the month in the 141-year NOAA's global temperature dataset record, which dates back to 1880^[24]. It was 0.92°C above the 20th-century average of 15.8°C, with only 0.01°C less than the record extreme value measured in July of 2019. From a regional point of view, warmer winters are beginning to remould the structure of the Black Sea, which could foreshadow how ocean configurations might vary from future climate change, according to brand-new observations and research^[25].

Studies imply that what is causing the CIL to warm is climate change, as gigantic water masses determine the planet's climate and transfer nutrients throughout the world. Therefore, changes in oceanic masses' composition might remodel global currents, with adverse effects on the global ecosystems. Since it is quite challenging to study massive masses of water as a whole, researchers and oceanographers use regional water masses to discover how oceanic masses could be affected^[25]. A novel study published last year in American Geophysical Union's Journal of Geophysical Research-Oceans and analyses salinity, density, and seasonal temperatures in the Black Sea during the last 14 years reveals a warming trend in the middle layer of the Black Sea (CIL). As has been outlined in other publications^[13,16,23,26-29], this unique layer had its fluctuations in the past, but since 2005 its core temperature has warmed up to 0.7 °C, according to^[25]. The blending of the other layers of water with the CIL will, consequently, allow the masses of water from the deeper layers of the Sea to infiltrate into the surface one. Thus hazardous impacts on the marine environment might befall, and it could even lead to the displacement of hundreds of millions of inhabitants from the coastal area.

Due to its specific and unique thermohaline structure, the Black Sea is of keen interest. A warming trend in the surface water is not precisely defined for the last century, while a positive trend for the last three decades has been demonstrated in^[23,26]. Consequently, changes in the regional climate appear to have their impact firstly on other thermohaline features, such as the temperature of intermediate layers, succeeded by an increase in the temperature of the sea surface water. The CIL, whose formation and evolution are not yet entirely explained, it is certain to

have the lowest Black Sea temperature - less than eight °C - and most of its pycnocline^[27-29]. Since in the Black Sea basin has been meaningful ecological degradation since the 1970s, mainly due to overfishing, pollution and natural climatic changes. To understand at least up to a certain extent how the Black Sea's circulation and physical features may evolve in the near future, simulations of future scenarios and mapping courses in its ecosystem are a matter of immediate urgency.

There have been numerous studies and significant research related to the Black Sea's cold intermediate layer and its general circulation patterns^[31-37], but little information has been presented on its changes over time. In this up-to-date study^[25], researchers mapped the evolution of the Black Sea's CIL in the period from 2005 until 2019, comparing its development with the region's climate courses. Utilizing battery-powered buoys to measure salinity, density, and temperature from the sea surface down to one thousand metres, at various points throughout the year. Thenceforth, after comparing the measurements with the surface air temperature in order to find a correlation between the weather and the CIL's salinity and temperature, the result was that weather fluctuations during wintertime changed the temperature and salinity of the CIL while keeping the density values almost the same.

The trials performed in^[23] comprising more than 50 years of data analysis revealed no major long-term trend in the Sea's average surface water temperature. This absence of a trend is a fundamental discovery based on a long-term trial that had not previously been fortunately conducted. This period from 1960 to 2015 was taken into consideration, and the results provided were compared with acknowledged data from available satellite data over the last two decades and less complete, but reliable data, from first decades. Before the accomplishment of this study^[23], experts had relied on scarce surface temperature values from ship cruises to understand the Black Sea's particular features better.

The final results of the simulation presented in figure 4 came as a great astonishment to researchers. They expected the study to reveal some warming trend, while it revealed a decreasing course in salinity at the surface of the Black Sea of 0.02% per year. There was no particular correspondence between wind speed or direction and salinity, which implies that combinations of weather contingencies are accountable for this trend.

Furthermore, three distinct periods outlined an important shift in the saltwater and temperature properties of the Sea, and these are between 1960 and 1970, 1970 and

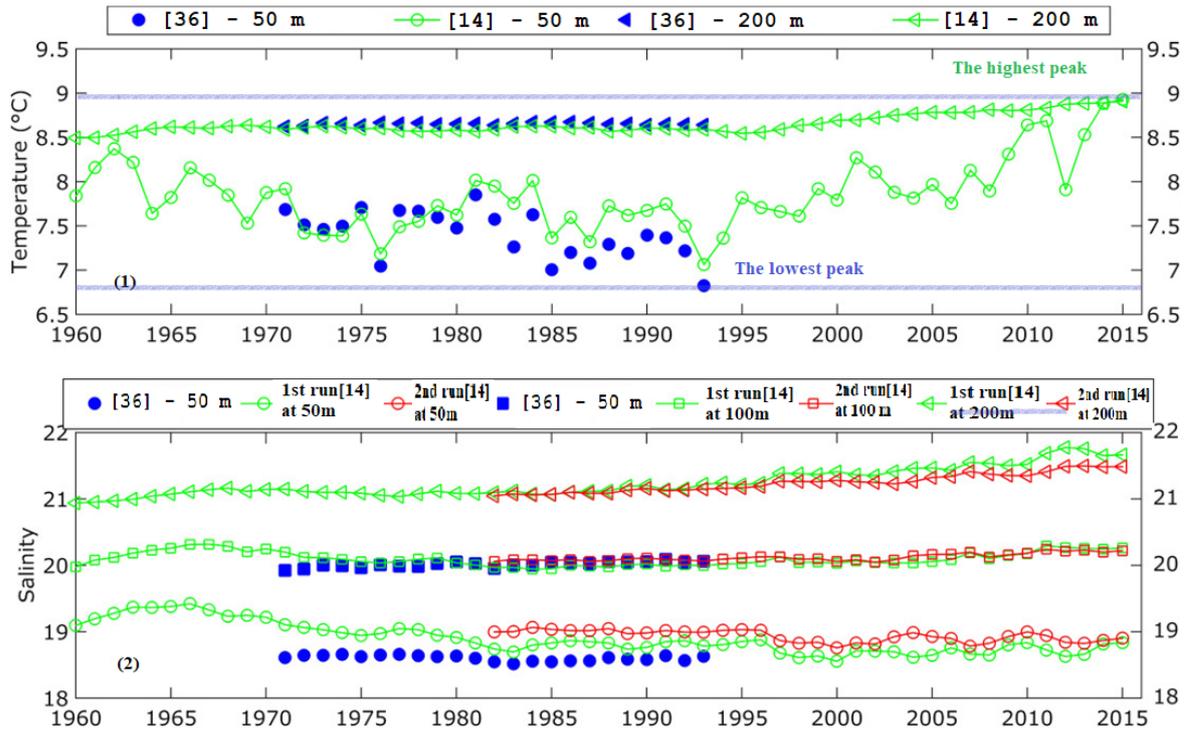


Figure 4. Time series from observations and simulations: (1) averaged temperature over the interior basin at levels of 50 metres, and 200 metres depth; (2) salinity averaged over the Black Sea basin at levels of 50, 100, and 200 metres depth from the ^{first} and second run—reanalysis data processed from ^[23] and ^[36]

1995, and 1995 to 2015. This observation may be related to the changes of currents that took place in the Sea's general circulation, as these periods were characterized by major changes from a small and disorganized current circulation during 1960 until 1970, to a strong central Rim circulation starting from 1970 until 2015, as outlined in ^[23].

Even though there has been no long-term positive trend in the temperatures measured at the surface waters of the Black Sea, this does not mean that it is “untouched” by the global warming trend. One explanation might be that air temperature in the region is still increasing, thus hiding or moderating these effects. The study ^[23] even took into account the average temperature trends at particular depths (50, respectively 200 metres), resulting in a positive course at 50 metres below the surface, which implies a warming pattern of the deeper waters, instead of the surface layer.

Moreover, the study confirmed that the surface waters are colder in the central-deep interior parts of the Black Sea basin during winter, as well as the moving of cold water masses formed in winter on the north-western slope by the principal cyclonic current and by mesoscale eddies

on the shelf break ^[38,39]. The innovative part of the study is the quantification of the significance of these newest findings during an extended period. Particularly, the fact that surface waters are colder than usual play a crucial role in the cold intermediate layer's formation in the interior basin, while the transport of cold water masses regulates the renewal of the cold intermediate layer along with the principal cyclonic currents and the exterior basin, also in the south-eastern part of the basin ^[23].

To completely isolate the effects of basin circulation and the contribution of the north-western shelf cold water masses, the Joint Research Centre studied the frequency of a latent tracer originating in this area. The result shows that a substantial fraction of the cold north-western shelf water mass is transported through the principal cyclonic current to the eastern confluence and anticyclonic regions. In contrast, only a tinier fraction of the cold water mass is transported to the central part of the basin. The temporal cooling capacity of the cold intermediate layer is extremely variable and has decreased dramatically during the past decade, being comparable to nothing, which insinuates that the CIL has disappeared, as figure 5 outlines.

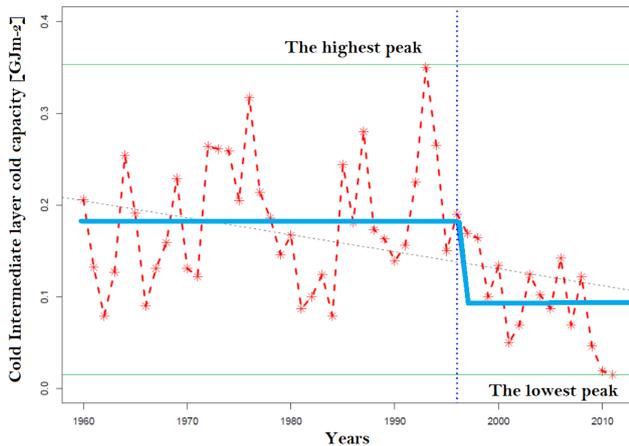


Figure 5. The CIL cold capacity trend is showing a dramatic drop at the beginning of the 21st century

Therefore, the additional heat from regional warming is transported downward to greater depths, thus warming the CIL, instead of contributing to the warming of the upper layer. This could potentially explain the missing increasing temperature trend in the Black Sea surface waters reported in 2019 by the European Commission of Science^[30].

5. Conclusion

A first conclusion that can be drawn is that in most of the cases a good correlation between the satellite data, historical data, and simulation results can be observed, revealing a warming trend during the last decades. Should this warmer trend happen to continue, there might be potential changes in the stratification of the unique Black Sea, that could carry sulfide, noxious and corrosive chemicals from the bottom of the Black Sea, up to the upper surface layer, endangering aquatic wildlife and tourism as well. Even though past research has proved that the Black Sea's water layers had their cycles through warm and cold times since the 1950s, the CIL has never touched this extraordinary temperature. Nevertheless, more intensive analysis on the progression of the Black Sea's circulation must be conducted, along with studies on the cold intermediate layer and its fluctuations, to determine whether global warming is responsible for the cold intermediate layer's gradual disappearance or not.

Physical oceanography is a fascinating and complex study, and as it has been proved in this paper, the chemistry and the biology of the Sea are in direct correlation with the physical processes within it. The state-of-the-art satellite measurements are improving our understanding of physical processes. Knowledge of the main physical features and circulation patterns in the Black Sea is of paramount importance, as their trends and variability might

pose a significant threat to an extensive range of marine pursuits. Such activities might include a safe and economical design and development of offshore oil and gas amenities, naval architecture design, decisive planning for extended marine towing operations. Additionally, a better understanding of the wind, wave and the current climate is indispensable for coastal foundation, including lessening shoreline erosion and more extensive protection, sediment transport and wave search for seafloor pipeline, as well as a better design of harbours.

Overwhelming is the fact that scientists warn that if the global average temperature rises by another three °C, sea and ocean levels will rise by approximately 6.5 meters. Such apocalyptic scenarios will lead to the displacement of hundreds of millions of people from the coastal region, including the Black Sea coast. Moreover, the average temperature of the Earth's surface has already risen by one degree since the end of the 19th century, enough to lead to extreme weather events. However, an increase from 2 to 6°C can lead to a real catastrophe. Climate change would destroy civilization and redraw the map of the world. From 6°C upwards, sea and ocean levels would rise by 10 meters for each degree, which would raise the oceans to levels not seen for millions of years.

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