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RESEARCH ARTICLE

Spatial and Temporal Variability of the Surface Temperature in the Black Sea Between 2000-2022

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Abstract: This study presents a comprehensive assessment of the spatio-temporal variability of Sea Surface Temperature (SST) in the Black Sea at monthly to interannual scales, with a focus on understanding its connection to major large-scale atmospheric forcing during the period 2000-2022. Monthly variations of SST in the Black Sea reveal distinct seasonal patterns. The study evaluates the potential impacts of large-scale atmospheric patterns on interannual SST variations using climate indices such as the North Atlantic Oscillation (NAO), East Atlantic/West Russia (EA-WR) and El Niño-Southern Oscillation (ENSO) during the winter months. The results indicated that these large-scale atmospheric oscillations played a substantial role in influencing SST anomalies, with the NAO and EA-WR indices particularly affecting the Black Sea's SST anomalies. The NAO index exhibited negative values during warm winters and positive values during cold winters, with extreme cold and warm winters corresponding to specific years, as observed in 2003, 2006, 2012, 2017 (cold) and 2018, 2020, 2021 (warm). Notably, the relationship between NAO and SST anomalies was not as dominant during 2000-2022. This difference might be explained by the combined influence of NAO and ENSO, which is beyond the scope of this study. The EA-WR pattern was identified as another significant large-scale atmospheric dynamic affecting the Black Sea's SST. Although it explains the cold SST anomalies in certain years, it cannot account for extreme warm SST years. While the influence of ENSO remains somewhat inconclusive for the extreme warm period, the SST pattern between 2016-2022 aligns closely with El Niño events, particularly in 2018 and 2021 when positive SOI index values coincide with warm SST years in the Black Sea.

Anahtar kelimeler:

Karadeniz
Deniz yüzey sıcaklığı (DYS) değişkenliği
DYS anomalisi
İklim
Isınma eğilimi
İklim endeksi

Karadeniz'de 2000-2022 Yılları Arasında Yüzey Sıcaklığının Mekansal ve Zamansal Değişimi

Öz: Bu çalışma, 2000-2022 yılları arasında Karadeniz'deki Deniz Yüzeyi Sıcaklığının (DYS) uzamsal-zamansal değişkenliğinin aylık ve yıllar arası ölçeklerde kapsamlı bir değerlendirmesini sunmakta olup, uzun dönemli DYS değişimlerinin büyük ölçekli atmosferik sistemlerin bağlantısının anlaşılmasına amacındadır. Karadeniz'deki DYS'nin aylık değişimleri farklı mevsimsel dağılım biçimleri göstermektedir. Çalışma, kış aylarında Kuzey Atlantik Salınımı (NAO), Doğu Atlantik/Batı Rusya (EA-WR) ve El Niño-Güney Salınımı (ENSO) gibi iklim endekslerini kullanarak büyük ölçekli atmosferik modellerin yıllar arası DYS değişimleri üzerindeki potansiyel etkilerini değerlendiriyor. Sonuçlar, incelenen büyük ölçekli atmosferik salınımların SST anomalilerini etkilemede önemli bir rol oynadığını, özellikle NAO ve EA-WR endekslerinin Karadeniz'in SST anormalliklerini etkilediğini göstermektedir. NAO endeksi, 2003, 2006, 2012, 2017 (soğuk) ve 2018, 2020, 2021 (sıcak) yıllarında gözlemlendiği, sıcak kışlarda negatif değerler ve soğuk kışlarda pozitif değerler sergilemiştir. NAO ve DYS anomalileri arasındaki ilişki 2000-2022 döneminde o kadar baskın değildir; bu farklılık, muhtemelen bu çalışmanın kapsamı dışında tutulan NAO ve ENSO'nun birleşik etkisinden kaynaklanmıştır. EA-WR paterni, Karadeniz'in DYS'nı etkileyen bir diğer önemli büyük ölçekli atmosferik dinamik olarak tanımlanmıştır. Belirli yıllardaki soğuk DYS anomalilerini açıklasa da aşırı sıcak DYS yıllarını açıklayamaz. ENSO'nun etkisi DYS ekstrem ısınma dönemlerini açıklamak için bir şekilde sonuçsuz kalsa da 2016-2022 arasındaki DYS değişimleri, özellikle pozitif SOI endeks değerlerinin Karadeniz'deki sıcak SST yıllarıyla çakıştığı 2018 ve 2021'deki El Niño olaylarıyla yakından uyumludur.

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Introduction

The river runoff predominately from the northwestern Black Sea and the Mediterranean inflow through the Bosporus Strait are the major fluxes to the Black Sea conserving extremely stable two-layer stratification in the Black Sea (Oğuz et al., 1993a; Özsoy & Ünlüata, 1997; Sur et al., 1994). The upper layer is confined to approximately 150m which leads the Black Sea surface layer sensitive to atmospheric conditions. The physical characteristics change further by the circulation dynamics which are mainly the Rim Current following the continental slope surrounding the cyclonic gyres inside and anticyclones on the peripheries (Korotaev, 2003a; Oğuz et al., 1993a). One of the most important features in the Black Sea is the accumulation of cold waters at an intermediate depth above the main halocline, the so-called Cold Intermediate Layer (CIL), maintaining the sinking of surface waters, making colder and denser by loss of heat towards the atmosphere in the winter (Akpınar et al., 2017; Akpınar et al., 2022; Belokopytov, 2011; Capet et al., 2012, 2020; Gregg, 2005; Miladinova et al., 2018; Oğuz & Beşiktepe, 1999; Stanev & Chtirkova, 2021).

Sea Surface Temperature (SST) is one of the essential parameters for oceanography to evaluate physical dynamics and biogeochemical processes and ecological conditions in the upper ocean as well as reflecting the climate signal on marine ecology (Capet et al., 2012; Ginzburg et al., 2004, 2007, 2021; Oğuz et al., 2003, 2006; Stanev et al., 2019). The winter SST variations give insight about the trend of the Cold Intermediate Layer (CIL) formed in the winter as observations of the mean CIL temperature follows the same trend with the winter SST (Akpınar et al., 2017; Oğuz et al., 2006). Therefore, SST is an indicator of the intensity of convective mixing and hence the CIL formation. Black Sea SST has significant variability at seasonal to inter-annual time scales as being subject to varying atmospheric conditions together with the combined effect of meso-scale to large-scale dynamics (Artamonov et al., 2020; Capet et al., 2012; Efimov & Komarovskaya, 2018; Ginzburg et al., 2004, 2007; Kazmin & Zatsepin, 2007; Shapiro, Aleynik, et al., 2010). In the long term time scales, many studies have shown a warming trend of SST began in 1900's in the Black Sea and leading changes in its physical and biochemical properties (Capet et al., 2012, 2016, 2020; Çokacar et al., 2004; Ginzburg et al., 2004; Kazmin & Zatsepin, 2007; Kubryakova et al., 2018; Mikaelyan et al., 2011; Oğuz et al., 2003; Shapiro, Aleynik, et al., 2010; von Schuckmann et al., 2016). Black Sea is considered one of the hotspots globally (Bulgin et al., 2020). The intermediate layers warming trend is found to be even stronger than the surface layers (Miladinova et al., 2017). As Stanev et al., (2019) pointed out this tendency could result in disappearance of a distinctive layer in the Black Sea.

Large-scale atmospheric systems determine the variations in the ocean-atmosphere climatic system and have an important role on regional climatic changes. The North Atlantic Oscillation (NAO), the East Atlantic-West Russia (EA-WR) atmospheric system and El Niño-Southern Oscillation (ENSO) are the systems that are mostly studied for the Black Sea. The positive phase of the NAO shows colder winters, and the negative case corresponds to the milder and more wet winters in the Black Sea. It was shown that during 1980-1995, SST under cold winter conditions was in accord with the positive face of NAO index, whereas 1960-1980 period corresponded to negative phase of NAO index with warm SST. While the north Atlantic Oscillation (NAO) significantly influences the Mediterranean weather and the Black Sea hydrodynamics (Hurrell & Deser, 2009), the east Atlantic-west Russia (EA-WR) pattern, has been found to be more closely associated with the Black Sea SST (Oğuz et al., 2006). It is also shown that the combination of the NAO and EA-WR teleconnection patterns is effective in explaining variability link to climate change in the Black Sea region (Oğuz et al., 2006). In addition, Ginzburg et al., (2004) observed that the El Niño Southern Oscillation (ENSO) contributes to the occurrence of extreme (i.e., minima and maxima) sea surface temperature (SST) values in the Black Sea.

The decade between 2000 - 2009 is called the "global warming hiatus" during which the global mean SSTA changed less than those in the previous or subsequent decades (Fyfe et al., 2016; Trenberth & Fasullo, 2013). Therefore, our study focused on the period between 2000 - 2022. This study aims to improve our limited knowledge on the spatial and temporal variability of SST and the general pattern of the long-term SST variability in the Black Sea during 2000–2022, associated with the major large-scale atmospheric forcing. Including the analysis of trends in SST with the latest data, this study complements earlier studies based on the analyses of spatial and temporal changes of SST and their links to large scale atmospheric systems.

Material and Methods

Data

The Copernicus Marine Environment Monitoring Service (CMEMS) SST analyses regional SST product is used in this study. Reprocessed Black Sea SST dataset (REP BS SST, https:// resources. marine. copernicus.eu / product- detail / SST_ BS _ S ST_ L4_REP_ OBSERVATIONS _ 010_ 022 / INFORMATION, is accessed on 2 June 2023. The collated Level- 3C (merged single-sensor, L3C) climate data record provided by the ESA Climate Change Initiative (CCI) and the Copernicus Climate Change Service (C3S) initiatives, but also include in input an adjusted version of the AVHRR Pathfinder dataset is built from reprocessed BS SST products (Merchant et al., 2019; Pisano et al., 2016). Basic statistics were computed with the daily SST data, including monthly temporal means. Monthly means were estimated from daily data spanning January 2000 and December 2022. The spatial distribution of SST analyses to evaluate seasonal changes built on 12 months of a year and winter months associated with the standard deviations were constructed from data in between the years 2000 and 2022.

The most relevant measure of large-scale air pressure oscillations to Black Sea are North Atlantic Oscillation (NAO), the East Atlantic – Western Russia (EA-WR) and El Niño–Southern Oscillation (ENSO). The index data sets were obtained from https://psl.noaa.gov/. The NAO index is based on the surface sea-level pressure difference between the Subtropical (Azores) High and the Subpolar Low. The EA-WR index associated with four positive phase is associated with four centers: Europe-northern China, and central North Atlantic-north of the Caspian Sea. Southern Oscillation (SOI) index is based on differences in sea level pressure (SLP) between Tahiti and Darwin, Australia. i.e. between western and eastern tropical Pacific, oscillating with El Niño and El Nina events. The winter means are calculated by averaging December, January, February and March following the approach in earlier studies (Ginzburg et al., 2007; Oğuz et al., 2006).

Results

Monthly variabilities of SST

The monthly means computed using 23 years SST data (2000-2022) shows a clear seasonal cycle with the highest temperatures in July and August (Figure 1). In general, temperature spatial contrasts are larger in the coldest months with 6-7 °C differences between the northwestern and southeastern areas. The spatial temperature differences in the summer are reduced to 3-4 °C when the SST can exceed 25 °C. The winter conditions typically persist for January, February and March, after which the circulation structure evolves to its subsequent spring phase during April, May and June. The period between December to March is characterized by west to east SST gradient with lower temperatures in the western basin and warmer in the eastern (Figure 1). This meridional gradient in the SST is related to the Rim Current. The coldest waters in the northwestern shelf spread along the western and southern coasts to the eastern part along the Rim Current periphery while the relatively warm water from the east follows the periphery area to the west in accordance with cyclonic circulation (Korotaev, 2003b; Korotaev et al., 2006; Oğuz et al., 1993b; Özsoy & Ünlüata, 1997). The zonal gradient in the central cyclonic area can be explained by the exchanges between the Northwestern Shelf and the cyclonic interior part mainly mediated by the Sevastopol eddy (Capet et al., 2012; Oğuz & Beşiktepe, 1999; Shapiro, Stanichny, et al., 2010). With the onset of spring, the thermocline starts in the upper water column. The southwestern and northeastern parts of the basin SST are colder than the rest of the basin (Figure 1). The eastern part becomes the warmest area in the basin. In fact, it is related with the formation of the Batumi anticyclone in this area. Batumi eddy, which was absent in the winter months, begins to appear in the southeastern corner of the basin and persists during the spring period. The Batumi anticyclone is the greatest and most persistent coastal eddy which forms in early March and lives until the end of October. In summer, the lowest SST distribution is again observed in the northwestern part of the sea. These cold-water observations are related with the wind driven coastal upwelling frequently observed in the area in summer (Ginzburg et al., 2002; Tolmazin, 1985). Then the anticyclonic eddies propagate this cold water along the continental slope (Ginzburg et al., 2002; Oğuz & Beşiktepe, 1999). May, June July can be considered as a transitional period because of the shift of SST gradients from zonal to meridional. Finally in August, basin SST gradients shift to meridional gradient in which the colder temperatures are observed in the north and warmer in the south. The temperature in the inner cyclonic part and the NWS are the lowest SST areas compared to the rest of the area.

In the autumn, the temperature minimum off the southeast of Crimea stands out (Figure 1). These relatively cold waters can be related to the divergency. On the other hand, warmer waters in the northern border of this cold formation are related with the Rim Current and the coastal anticyclones propagating with the Rim Current (Ginzburg et al., 2004).

The 23-years temporal mean of winter SST shows a significant meridional temperature difference (Figure 2 top). While the NWS has the lowest temperatures, the highest temperatures are observed in the southeast of the basin. In the entire basin, the mean winter temperature ranges between 4 °C and 11 °C. The variation of SST are highest on the northwestern shelf (Figure 2, bottom) which is related to changes in river fluxes; wind forcing and propagation of anticyclonic eddies within the area (Ginzburg et al., 2002; Shapiro, Stanichny, et al., 2010). In the southern Rim Current periphery and southeast of the Black Sea, the standard deviations of SST are also high (Figure 2 bottom) due to the local dynamical features branches of the Rim Current and anticyclones (Akpınar et al., 2022; Ginzburg et al., 2007; Korotaev, 2003a; Oğuz et al., 1993a).

Interannual variabilities of SST link to large scale atmospheric variabilities

The seasonal cycle spatial means of monthly SST is given in Figure 3a. Overall, 2010 was the hottest summer with 27.93 °C and 2006 winter is the coolest winter with 6.23 °C basin wide mean SST's. The winter SSTA indicated that 2003, 2006, 2012 and 2017 were colder in the winter about ~-1°C STA (Figure 3b). In addition, 2021 winter was the warmest (0.9°C) and warm sea surface temperature anomalies were observed in 2018 and 2020. The 2020 winter SSTA was slightly lower than that in 2021. The entire mean winter SSTA data exhibited a linear warming trend with 0.68 °C per decade. The rise in SST is higher (0.78 °C per decade) if all seasons are considered for the calculations. This is consistent with the global warming trend observations (Bulgin et al., 2020; Merchant et al., 2019). There is considerable decadal variation in sea surface temperatures. SSTA variations of the last decade showed mainly positive variations during 2010-2021 while in the preceding decade it was mainly negative. This 10-

year cycles of cold and warm periods are explained by large scale atmospheric dynamics influencing the Black Sea in the study (Oğuz et al., 2006). In order to show the response of the Black Sea SST to NAO, EA-WR, ENSO, we first evaluated similarities between the extreme winter SST values. We used means of the winter months as the indices to compare with winter SSTA. The sign of NAO index was negative for the warm winters and positive in the cold winters. Only 3 winters (2010, 2012, 2021) out of 7 years matched with the extreme cold (2003, 2006, 2012, 2017) and hot (2018, 2020, 2021) winter years. The correlation between the negative phase of NAO and SSTA was determined to be -0.5. The EA-WR pattern was concerned as the next important large scale atmospheric dynamics affecting the Black Sea (Capet et al., 2012; Oğuz et al., 2006). Positive winter EA-WR index corresponds to cold and dry air masses from the north to Black Sea, at its negative values, warm and moist air masses arrive to basin from the south. The combinations of winter EA-WR indices with the winter NAO was found in the studies of Capet et al., (2012) and Oğuz et al., (2006). The study identified that different combinations of the positive and negative winter NAO and EA-WR index values defined either cold or warm winter in the Black Sea. For example, at EA-WR > 0 and NAO < 0, the anomalously cold winters were observed. EA-WR < 0 and NAO < 0 corresponded to warm winters (Capet et al., 2012). Since the evaluation of the combined effect requires the assessment of the change of positions of high and low atmospheric pressure centers, it is not considered in this study. The cold SSTA years 2003, 2006, and 2017 match with positive EA-WR (Figure 3d). On the other hand, extreme warm SSTA years cannot be explained by EA-WR index. Nonetheless, the negative phase of EA-WR demonstrates the highest correlation (-0.63) with SSTA among the indices.

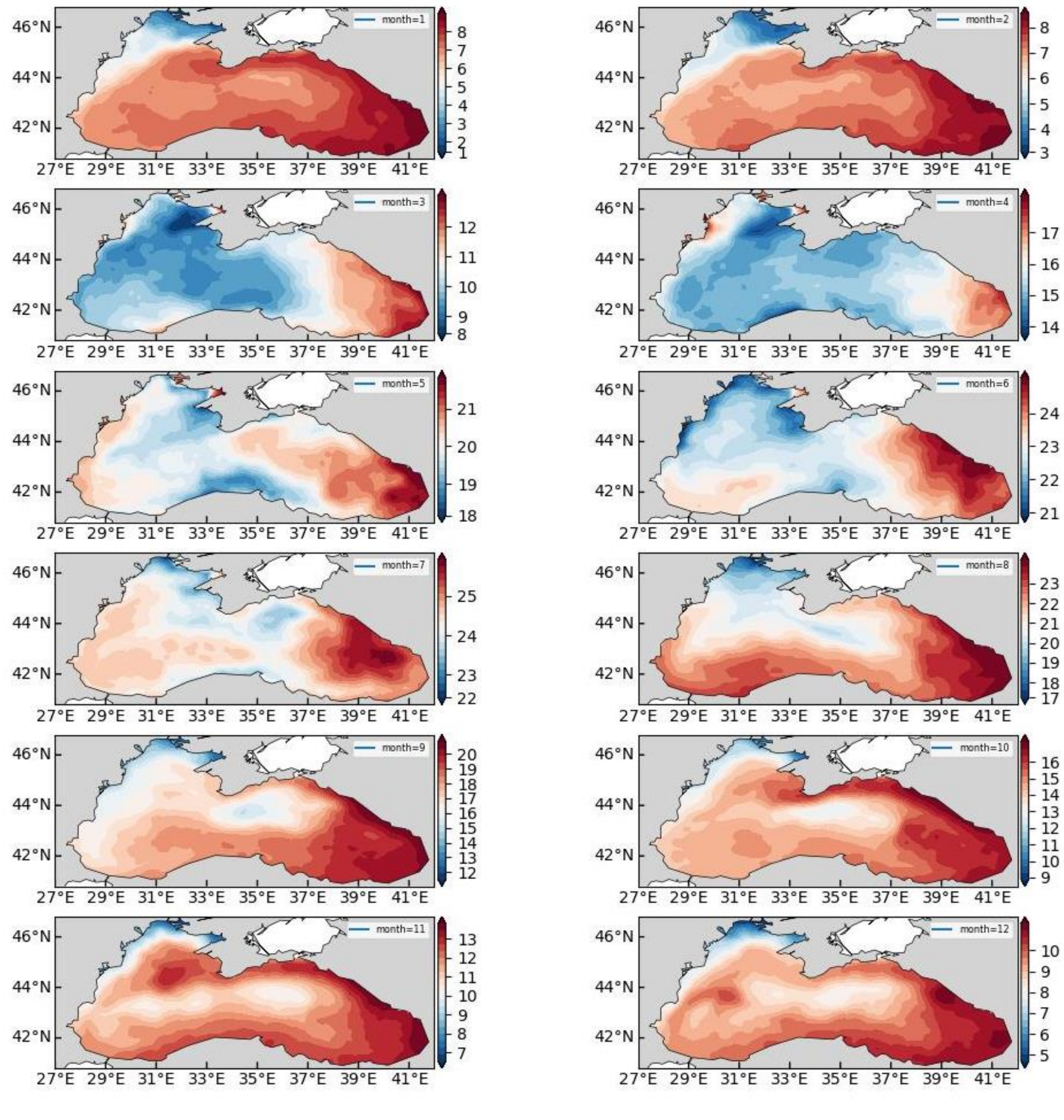

Figure 1. Monthly mean SST calculated from Copernicus CMEMS gridded BS-SST product data during 2000-2022

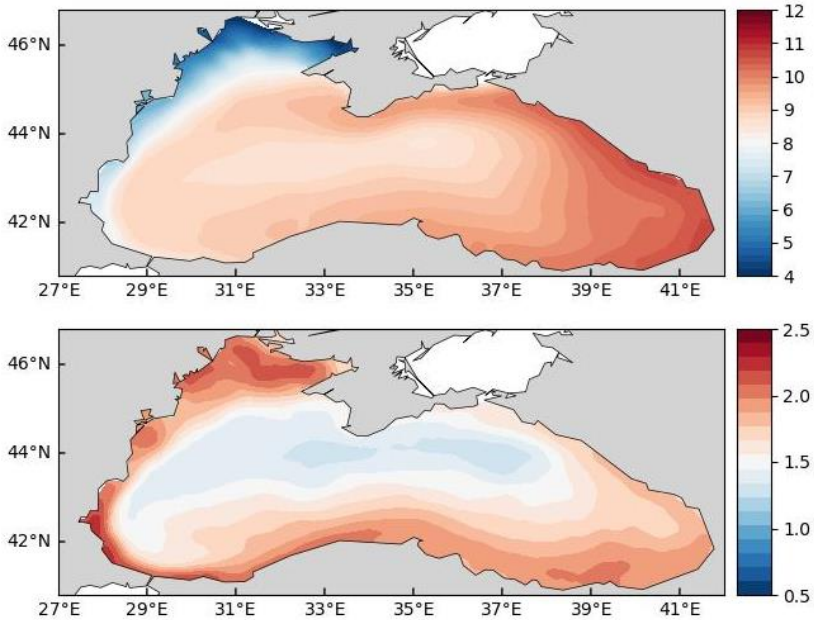

Figure 2. (a)Winter mean and (b) standard deviation of SST calculated from Copernicus CMEMS gridded BS-SST product data during 2000-2022.

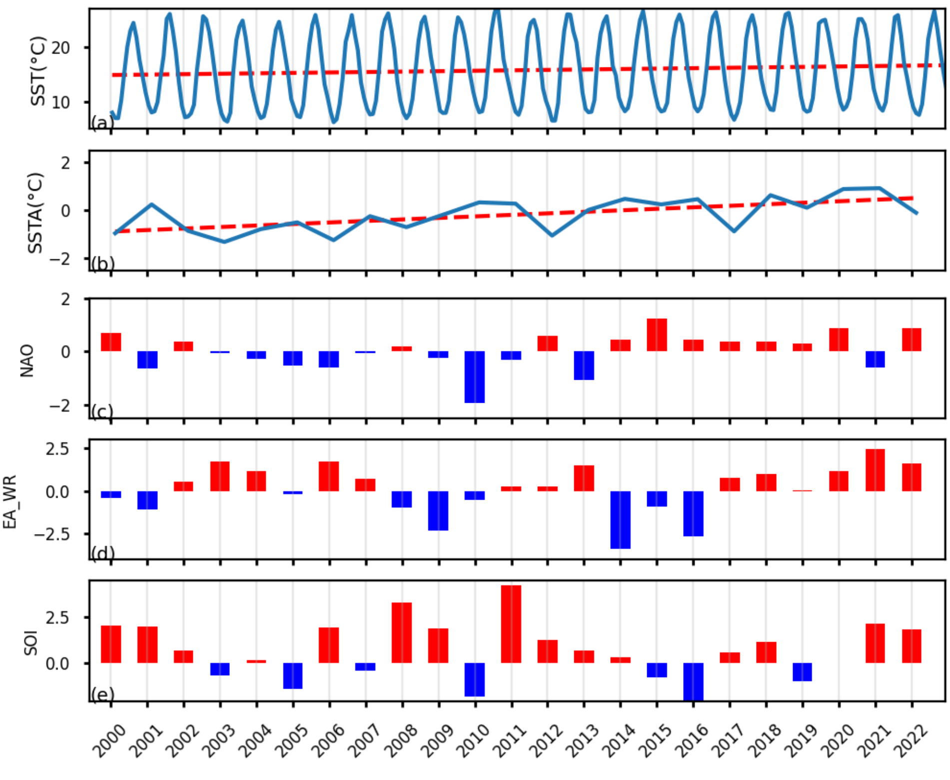

Figure 3. Inter-annual variations of a) the winter (January-March) mean sea surface temperature b) winter mean SSTA calculated from Copernicus CMEMS gridded BS-SST data. Red dash line represents the trend line c) NAO d) EA-WR e) SOI indices.

ENSO is low-frequency oscillation in comparison with the NAO. In the literature, although a consistency was found between the extreme anomalies of SST and the El Niño phases (Ginzburg et al., 2004), no clear relationship was found in the study of Oğuz et al. (2006). The character of the changes in the SSTA during 2016-2022 is very close to the El Niño events. As follows from Figure 3e in the period 2000–2022, El Niño events (positive SOI index) in 2018 and 2021 agreed with the warm SST years in the Black Sea.

Discussion

This study assesses the spatial and temporal variability of SST in monthly to interannual scales and analyses the connection between the general pattern of the long-term SST variability in the Black Sea and the major large-scale atmospheric forcing during 2000–2022, including the analysis of trends of SST in this period.

In the winter, meridional gradient in the SST field was observed with the warming gradient from western to east of the basin. In the spring, by the onset of seasonal warming, the Batumi anticyclone is generated in southeast of the basin. Moreover, SST is colder in the southwestern and northern part of the basin compared to the rest of the basin. The Batumi anticyclone persists in the area between early March and end of October. In the summer, the lowest SST distribution is again observed in the northwestern part of the sea. May, June July can be considered as a transitional period that SST gradients shift from zonal to meridional. Meridional gradients form in SST where the colder temperatures in the north and warmer in the south are observed in the summer. The temperature in the inner cyclonic part and the NWS are the lowest SST areas compared to the rest of the area. In the autumn, the temperature minimum off the southeast of Crimea stands out. Winter SST distributions 23 years seasonal mean of winter SST shows a significant variation in the southern Rim Current periphery and southeast of the Black Sea due to the local dynamical features of the Rim Current and accompanied by small to mesoscale scale anticyclonic formations.

The potential impacts of large-scale atmospheric patterns on the interannual variations on the SST are assessed by the climate indices NAO, EA-WR and ENSO obtained for the winter months. Different time scales of influence from large-scale teleconnection patterns on air temperature (AT) are distinguished: the East Atlantic/West Russia (EA-WR) pattern influences short-term (1-5 years) variations in the sea surface temperature (SST), whereas the long-term trends of the North Atlantic Oscillation (NAO) drive prolonged (8-10 years) SST trends (Capet et al., 2012). The SST anomaly follows both the long-term influence of the NAO index and the rapid oscillation governed by the EA-WR index. Simultaneous cold and warm cycles, each with an approximate duration of 5 to 10 years, are noted in SSTA time series. The sign of NAO index is negative for the warm winters and positive in the cold winters. The SSTA analysis depicts extreme cold winters for the years 2003, 2006, 2012, and 2017 and hot winters for 2018, 2020, and 2021. The correlation between NAO and SSTA found to be exist for negative phase of the NAO. In contrast, the general consistency found between the interannual SST variations and the NAO in the Black Sea (Capet et al., 2012; Oğuz et al., 2006). This relation is not so dominant during 2000-2022. This difference may be explained by analyzing the combined NAO and ENSO during the years 2000-2022. However, it requires the analysis of the change in positions of high and low atmospheric pressure centers, which is out of the scope of this study. The EA-WR pattern is concerned as the next important large scale atmospheric dynamics affecting the Black Sea (Capet et al., 2012; Oğuz et al., 2006). The cold SSTA years 2003, 2006, and 2017 match with positive EA-WR however, extreme warm SSTA years cannot be explained by EA_WR index. Among the indices, the negative phase of EA-WR demonstrates the highest correlation with SSTA. Even though the influence of the ENSO index could not be deduced clearly from the analysis in this study, the changes the SSTA pattern during 2016-2022 is very close to the El Niño events. El Niño events (positive SOI index) occurred in 2018 and 2021 agreed with the warm SST years in the Black Sea. The dataset, spanning 23 years, is relatively short for accurately estimating SST trends. However, the analyses of the influence of NAO, EA_WR and ENSO on SSTA shows statistically significant correlations for negative phases of the EA-WR pattern and NAO index between the years 2000-2022. This study complements earlier studies based on the analyses of spatial and temporal changes of SST and their interaction to large scale atmospheric systems. This study improves our limited knowledge during the period of 2000-2022 and compares the recent results with the literature.

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Conflict of Interest

The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethics Approval

Ethics committee approval is not required for this study.

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