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Climatic regulation of the Black Sea hydro-meteorological and ecological properties at interannual-to-decadal time scales

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Abstract

An examination of a wide spectrum of hydro-meteorological and biogeochemical records in the Black Sea from the previous century possesses a robust climatic signature at interannual to interdecadal time scales. Superimposed on the first eigenmode of the data with interdecadal changes on the order of 15 to 30-year band, the second mode reflects oscillations with the period of about 10 years. The cold and dry winters generally take place within the first half of each decade, and they switch to mild and warm winters during the second halves. All the water column physical and biogeochemical properties examined respond accordingly to such oscillations. For example, the years with the cold (mild) winters correspond to the periods of increasing (decreasing) nutrient and hydrogen sulfide concentrations, phytoplankton biomass. These variations appear to be governed by the North Atlantic Oscillation (NAO) and East Atlantic-West Russia (EAWR) teleconnection patterns comprising various combinations of the low and high surface pressure anomaly centers over the North Atlantic and Eurasia. The NAO teleconnection to the Black Sea is opposite to that taking place in the eastern North Atlantic and its marginal seas. The relatively cold and dry winters occur during the positive phase of the NAO, and visa versa for the milder and wetter winters. The Black Sea Climate Index, constructed using more than 100-year-long time series of the North Atlantic Oscillation, the sea surface temperature, air temperature, sea level anomaly, provides a composite representation of the dominant mode of regional climate variability, and explains 46% of the total variance. The results point to a very efficient coupling between the anthropogenic and climatic forcing for driving the dramatic ecosystem changes observed during the 1980s and 1990s.

Keywords: Black Sea; Ecosystem; Climate change impact; North Atlantic Oscillation; East Atlantic–West Russia climate index; Solar cycle; Decadal variability

1. Introduction

Climate–ocean interactions and their response on marine ecosystems have recently been focus of considerable attention. The climate-induced changes on stocks of plankton and fish have been reported for open oceans (e.g., Drinkwater et al., 2003 for the North Atlantic, Chavez et al., 2003 for the Pacific Ocean), and for coastal and marginal seas (e.g., Dippner and Ottersen, 2001 and Hunt et al., 2002 for the southeastern Bering Sea, Reid et al., 2001 for the North Sea, Kang et al., 2000 for the East/Japan Sea, Conversi et al., 2001 for the northeastern US continental shelf, Sirabella et al.,

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2001 for the Barents Sea, and Molinero et al., 2005 for the Western Mediterranean Sea). In identifying ecological impacts of climate variability, coastal, shelf and marginal sea ecosystems offer a particular challenge since they are most heavily affected by human interventions, and natural climatic variations are often masked by local transients.

Among marginal sea ecosystems, the Black Sea is of special interest due to combined effects of its intense eutrophication, overfishing, population explosion of gelatinous carnivores and opportunistic species (Zaitsev and Mamaev, 1997; Bilio and Niermann, 2004; Oguz, 2005a), as well as their modulation by climate-induced variations (Daskalov, 2003; Oguz, 2005b). Niermann et al. (1999) has drawn attention to a possible role of the North Atlantic Oscillation (NAO)-driven large scale atmospheric changes for the outburst of the ctenophore *Mnemiopsis leidyi* and decline of the anchovy stocks in the Black Sea during the late-1980s. Mikaelyan (1997) pointed out a close correlation among the summer phytoplankton biomass and the winter average air temperature variations, suggesting a link to climatic variations. Kovalev and Piontkovski (1998) and Kovalev et al. (1998) noted some dominant interannual fluctuations in the zooplankton data. Similarly, Prodanov et al. (1997) emphasized the role of natural climatic factors, in addition to human-induced effects, regulating pelagic fish stocks. Konovalov and Murray (2001) stated the interannual-to-interdecadal variability of nutrient, oxygen, hydrogen sulfide concentrations in the suboxic and anoxic layers. Oguz et al. (2003) documented an intimate relationship between a decade-long winter warming after the mid-1990s and subsequent unfavorable plankton growth, and reduced stocks at higher trophic levels. The footprints of the climatic fluctuations in various hydro-meteorological properties of the Black Sea have been pointed out by Polonsky et al. (1997), Reva (1997), Belokopytov (1998), Ozsoy (1999), Stanev and Peneva (2002), Tsimplis and Rixen (2003), Tsimplis et al. (2004).

The present exploratory study constitutes the first part of the series, and focuses on a comprehensive description of the interannual-to-interdecadal scale variations of the Black Sea hydro-meteorological and ecosystem structures, and their teleconnections to climate systems. A more detailed statistical-based analysis and interpretation of the data sets will be reported separately as a second part of the series. The paper is structured as follows. After a brief presentation of the data and their processing in Section 2, synchronous changes in the physical properties of the upper layer water column as well as their links to regional atmospheric variations are documented in Section 3. Possible roles of the large scale atmospheric systems as possible drivers of the regional climate-induced fluctuations are then discussed in Section 4. Section 5 relates these subtle changes in the physical climate to those of nutrients, primary and secondary productions, and ultimately pelagic fish populations. Conclusions are provided in Section 6.

2. Data description

The data are compiled from all available long-term measurements carried out in the Black Sea. The data set describing the physical properties of the sea comprises the long-term variations of (i) winter (December–March) mean sea surface temperature (Rayner et al., 2003), (ii) mean temperature of the Cold Intermediate Layer (characterized by temperatures less than 8 °C below the seasonal thermocline) for the May–November period provided originally by Belokopytov (1998) as an average of all available data from the interior basin for the period from 1950 to 2000, (iii) annual mean salinity anomaly data of the upper 200 m layer which is constructed by Tsimplis and Rixen (2003) using the original data set in the Medar/Medatlas data base, and (iv) detrended sea level anomaly data provided by Reva (1997) as an average of the measurements at 20 coastal stations around the Black Sea since 1890. The winter-mean SST data are constructed by the monthly mean data complied by Hadley Centre, UK Met Office (http://badc.nerc.ac.uk/data/hadisst) from all the available in situ measurements from 1875 to 2000 performed within the interior part of the basin with depths greater than 1500 m as well as the Advanced Very High Resolution Radiation (AVHRR) satellite observations (Rayner et al., 2003). The data coverage during the first half of the full measurement period is limited, and thus may involve some degree of inaccuracy describing the interannual-to-decadal variations. All these data have been smoothed by the three point moving average.

The atmospheric properties of the Black Sea region have been studied by long-term variations of (i) winter (December–March) mean air temperature data provided by Titov (2002) from the measurements at the meteorological station near the Kerch Strait along the north coast of the Black Sea from 1875 to 2000, (ii) winter (December–March) mean wind stress magnitude, (iii) winter (December–March) mean surface atmospheric pressure averaged over the basin, (iv) winter (December–March) mean evaporation minus precipitation averaged over the basin. The latter three data sets are formed by averaging the 1° resolution ERA

(ECMWF Re-analysis) data set over the basin for the period of 1950 to 2000. The air temperature data have been smoothed by the three point moving average.

The biogeochemical data predominantly reflect the conditions within the interior basin, which covers approximately 75% of the sea. They include the long-term variations of (i) water column integrated phytoplankton biomass provided by Mikaelyan (1997) and surface chlorophyll concentration by Yunev et al. (2002) and Vedernikov and Demidov (2002), both of which were given as averages of the May–September period, (ii) annual mean Secchi disc depth by Mankovsky et al. (1998), (iii) annual mean hydrogen sulfide concentration at 16.4 kg m^{-3} sigma-t surface by Konovalov and Murray (2001), (iv) annual-mean water column integrated mesozooplankton biomass by Kovalev et al. (1998). They are further complemented by the long-term variations of the sprat and anchovy parental and recruitment stocks estimated by Daskalov (2002), and the surface phosphate concentration in Romanian coastal waters, off Constantsa, provided by Popa (1995) and Cociasu et al. (1996). We refer to the original publications for more details on the individual data sets.

The winter (December–March) North Atlantic Oscillation index is based on the difference of monthly normalized sea level pressures between Ponta Delgada, Azores and Stykkisholmur/ Reykjavik, Iceland. It is provided at the URL site: http://www.cgd.ucar.edu/~jhurrell/nao.stat.other.html. The East Atlantic-West Russia (EAWR) index data are given at http://www.cpc.ncep.noaa.gov/data/teledoc/eawruss.html. The annual-mean sunspot number time series data are composed by the monthly data taken from http://science.msfc.nasa.gov/ssl/pad/solar/sunspots.htm. They are all filtered by the Gaussian filter using the 4-year window size.

3. Long-term changes in the Black Sea hydro-meteorological properties

3.1. Long-term changes in the physical properties

The interannual-to-interdecadal variations observed in the Black Sea physical climate are best documented through examination of temperature and salinity of the upper layer water column, and of sea level anomaly data for the winter (December–March) period. For both marine and fresh water ecosystems, water temperature is regarded as the most important physical property reflecting the climate signal on ecological changes. At multi-decadal time scales, the winter SST variations (Fig. 1a) fall into five different amplitude ranges with a warming trend of 0.25 °C during the last century. The period from 1875 to 1915 (Phase 1) is characterized by the range of SST variations between 7.6 and 8.7 °C, and comprises a sequence of three cold cycles (denoted by C1, C2, C3) and three warm cycles (W1, W2, W3); each of them lasts approximately ~5 years. Thereafter, the warm and cold cycles in Phase 2 occur at gradually higher temperature ranges of 7.9 to 9.0 °C up to 1960, and of 8.3 to 9.3 °C within the next two decades in Phase 3. The period from the early 1960s to the 1980 thus indicates the most significant warming phase of the last century dominated by persistently positive winter SST anomalies above the long-term mean. It is then followed by a pronounced cooling phase from 1980 to 1995 (Phase 4). This phase (C9, C10) is identified by a sharp temperature drop of about 1.7 °C between the years 1980 and 1985 up to the minimum temperature of 7.2 °C. The highest temperature of 8 °C within the warm cycle (W10) of this phase is approximately 0.4 °C lower than the minimum temperature of the cold cycle (C8) of the previous phase. From 1995 onwards, a new warming phase (W11) dominates the winter SST (Phase 5). These phases in fact represent the first principal mode interdecadal variability of the system, as documented in the following sections.

The winter SST data is complemented by the ~50-year-long time series of the summer–autumn (May–November) mean temperature of the Cold Intermediate Layer (CIL) since the 1950s (Belokopytov, 1998). The CIL refers to the cold core layer just below the seasonal thermocline, confined typically between 20 and 60 m depths. It is a remnant of the winter surface mixed layer water with temperatures less than 8 °C. The mean CIL temperature follows closely the winter SST variations in terms of both timing and duration of the warm cycles W7–W11, and the cold cycles C6–C10 (Fig. 1b). It therefore implies extension and persistence of the cooling/warming cyclical events below the surface mixed layer and during the rest of the year after the winter. The decadal climatic signal has also been observed with some phase shift at temperatures of deeper levels around the permanent pycnocline (Konovalov and Murray, 2001). We also note very similar temperature variations reported at 100–300 m level in the northern Aegean Sea (Velaoras and Lascaratos, 2005), whereas the cold and warm cycles are reversed in the western Mediterranean (Molinero et al., 2005) and becomes similar to those in the Eastern North Atlantic and North Sea (Reid et al., 2001).

The temporal variation of annual-mean salinity anomaly of the upper 200-m-layer taken from Tsimplis

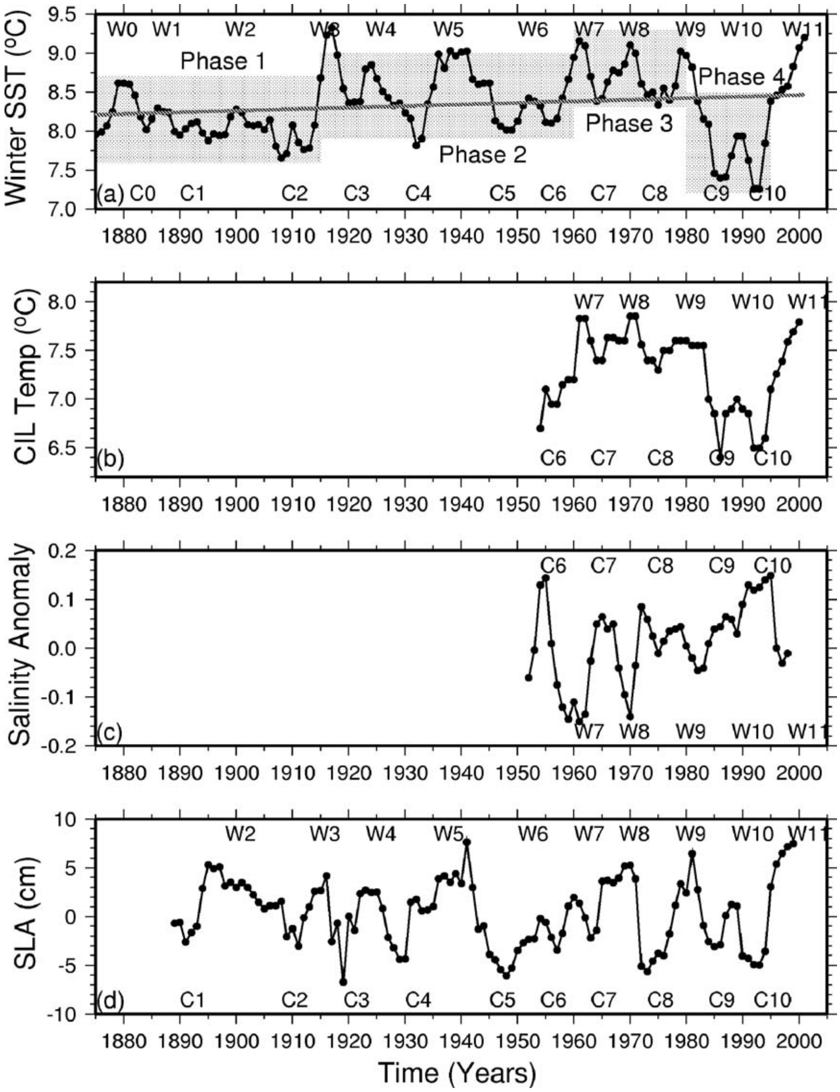

Fig. 1. Long-term variations of (a) the winter (December–March) mean sea surface temperature (°C) averaged over the interior basin with depths greater than 1500 m, (b) the mean temperature (°C) of the Cold Intermediate Layer for the May–November period, (c) the annual mean salinity anomaly of the upper 200 m layer, (d) the detrended sea level anomaly (cm). High frequency oscillations in the data have been filtered by the three point moving average.

and Rixen (2003) also reflect similar climatic signature in terms of phases and duration (Fig. 1c), and is inversely related to the temperature variations observed in Fig. 1a,b. Higher positive salinity anomalies occur at cold cycles in which combination of stronger surface cooling and intensified wind stress (see Section 3.2) give rise to stronger convective mixing and higher upwelling rate of more saline deeper waters into the upper layer. More pronounced evaporative losses to the atmosphere (see Section 3.2) also contributes to salinity increase during the cold cycles. Conversely, the negative salinity anomalies are associated with the warm cycles characterized by the opposite hydro-meteorological characteristics. The absence of a well-defined negative salinity anomaly W10 towards the end of 1980s seems to be a result of the decade-long strong cooling phase. As suggested by the SST data (see Fig. 1a), the warm cycle W10 appears to be still cold enough, implying sufficiently strong vertical mixing comparable to that in the previous cold cycle C9.

The sea level change time series provide the best response of the Black Sea physical climate to atmospheric forcing, because the link includes (i) changes in the surface atmospheric pressure through the inverse barometer effect, (ii) water density changes in response to temperature and salinity variations, (iii) changes in precipitation, evaporation and river runoff (Tsimplis et al., 2004). The detrended sea level anomaly time series (Fig. 1d) given by Reva (1997) (see also Tsimplis and Josey, 2001 and Stanev and Peneva, 2002) oscillate within the amplitude range of about 10 cm. The higher (lower) values of the sea level anomaly coincide with the warm (cold) cycles of the water temperature, indicating that a part of the observed sea level change has a thermal origin, due to the steric effect. Similarly, the linear rise of 0.18 cm year^{-1} seen in the original data (Reva, 1997) is compatible with the long-term warming trend of ~0.0022 °C year^{-1} in the SST. The fact that the sea level variations also closely follow those of the evaporation minus precipitation and of the River Danube discharge (Stanev and Peneva, 2002) suggests an important role of the hydrological control on the cyclic sea level rises and falls. In fact, all the physical properties shown in Fig. 1a–d are significantly correlated with each other (significance level $p<0.01$). The correlation coefficient of the SST with the CIL, SAL and SLA is, respectively, 0.89, −0.58 and 0.38. The other correlations between the water column physical properties are given in Table 1.

3.2. Long-term changes in the atmospheric properties

We next explore whether the observed changes in the Black Sea physical structure are compatible with those of the regional atmospheric properties; in particular air temperature, wind stress, sea level atmospheric pressure (SAP), and evaporation minus precipitation ($E-P$). The winter-mean air temperature data (Titov, 2000; 2002) from various coastal stations around the periphery of the basin exhibit very similar temporal variations during the last century, even though the mean temperatures and their range of variations may differ from the western to eastern end of the basin. Fig. 2a provides an example at a station near the Kerch Strait (connecting the Black Sea to the Sea of Azov) along the northern coast of the Black Sea. Since 1885, it reveals 11 successive warming and cooling cycles between the extreme values of 1.5 and 6.5 °C at intervals of ~5 years. The entire data set exhibits a linear warming trend with the overall temperature rise of 0.9 °C. This is consistent with the warming observed in winter temperature over Eurasia, which was explained partly by temperature advection from the North Atlantic region (i.e. connected to the NAO), and partly by the radiative forcing due to increased greenhouse gases (Hurrell, 1996). As in the case of the SST variations, the last two decades have been subject to abrupt variations of the winter air temperature over 10-year cycles. The cooling phase C9 and C10 during the 1980s was so dramatic that the winter AT decreased from the maximum value of 5.5 °C to the minimum value of 1.5 °C. The subsequent decade-long warming during the 1990s was only able to bring the winter air temperature back to its level of the previous state at the end of the 1970s. Both the timing and duration of the warm and cold cycles fit reasonably well with those shown previously in the winter-mean (December–March) SST and the summer–autumn (May–November) mean CIL temperature time-series (Fig. 1a,b). Its correlation with the SST and CIL, respectively, are −0.52 and 0.37 significant at $p<0.001$. The only major difference between the SST and AT time series is the lack of W10 peak during the second half of the 1980s. Instead, air temperature continues to decrease steadily up to the early 1990s. This peak is however captured at some other stations (e.g., see Fig. 1 in Titov, 2000).

The winter (December–March mean) surface atmospheric pressure (SAP) distribution over the Black Sea (Fig. 2b) follows closely the winter air temperature time series; their correlation coefficient is −0.49, significant at $p<0.001$. The severe winters are preferentially associated with higher surface atmospheric pressures up to 1022 hPa, whereas lower surface pressures prevail in milder winter seasons. A general tendency of severe winters during the 1980s leads to relatively higher minimum values of the surface atmospheric pressure during its occasional milder years. We recall a similar tendency in the sea surface and air temperature time series shown before in Figs. 1a and 2a.

The Black Sea has been characterized by the excess of evaporation over precipitation (i.e., $E-P>0$), but their difference oscillates depending on the intensity of winter conditions (Fig. 2c). The severe winter cycles coincide with the higher values of ($E-P$), representing more dry atmospheric conditions. Conversely, ($E-P$) signal weakens during the mild winter cycles due to more dominant contribution by precipitation. ($E-P$)

Table 1
Correlation matrix among the variations of sea surface temperature (SST), Cold Intermediate Layer temperature (CIL), salinity anomaly of the upper 200 m layer (SAL), and sea level anomaly (SLA)

Variable	SST	CIL	SAL	SLA
SST	1.00	0.89	−0.58	0.38
CIL	0.89	1.00	−0.53	0.52
SAL	−0.58	−0.53	1.00	0.38
SLA	0.38	0.52	0.37	1.00

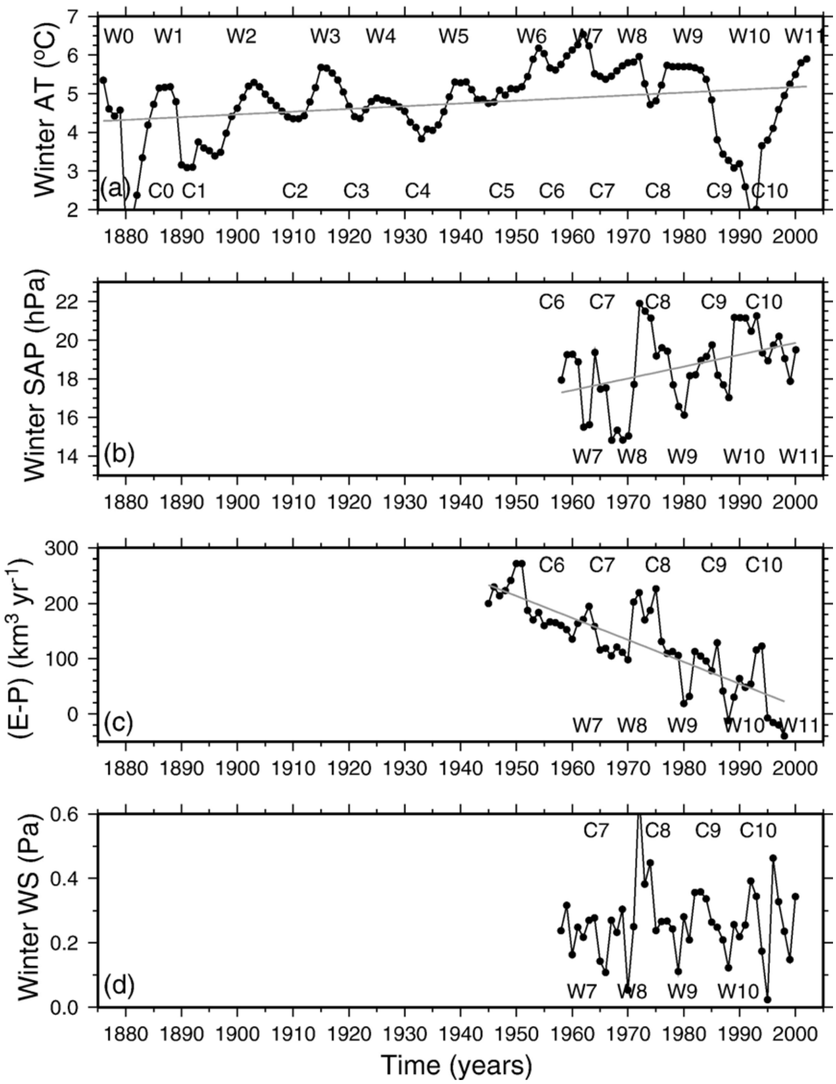

Fig. 2. Long-term variations of (a) the winter (December–March) mean air temperature (°C) measured at the meteorological station near the Kerch Strait along the north coast of the Black Sea, (b) the winter (December–March) mean surface atmospheric pressure (hPa) averaged over the basin obtained by ERA data set, (c) the winter (December–March) mean evaporation minus precipitation (km^3 yr^{-1}), (d) the winter (January–March) mean wind stress magnitude averaged over the basin obtained from the NCEP data set. High frequency oscillations in the data have been filtered by the three point moving average.

and SST are correlated with $r=0.48$ ($p<0.001$). The linearly decreasing trend of $(E-P)$ from about 250 km^3 year^{-1} to zero during the last 50 years, which was caused by gradual decrease in evaporation and increase in precipitation, accompanies the long-term warming trend of AT depicted in Fig. 2a.

The winter-mean basin-averaged wind stress time series (Fig. 2d) support other characteristics of the atmospheric circulation over the region. The periods with more intense wind stress fields correspond to the cold year cycles (C7, C8, C9, C10), as compared to weaker ones during the warm winter cycles (W7, W8, W9, W10). Their correlation is $r=0.39$ ($p<0.001$).

3.3. Black Sea composite indices for the atmospheric and water column properties

Combining all the time series data from 1960 onwards described in the previous two sections, Oguz (2005b) constructed two separate composite Black Sea climate indices called the Black Sea physical climate index (PCI) and the atmospheric index (ATI), respectively, (Fig. 3). They are formed by subtracting the

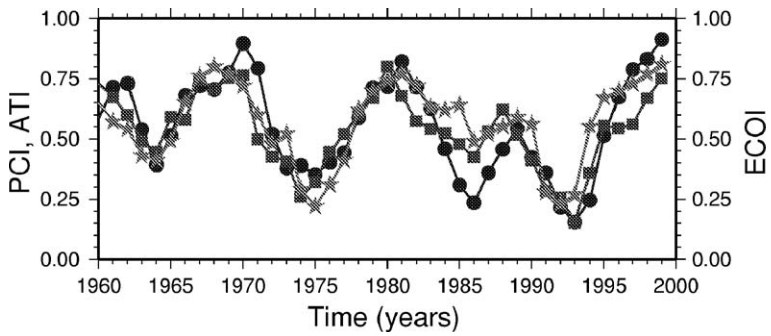

Fig. 3. Long-term variations of the atmospheric index (ATI) (squares), marine physical climate index (PCI) (dots), and ecological index (ECOI) (stars) from 1960 to 1999 formed using all the available data used in the present work (after Oguz, 2005b).

minimum value from each data set and then dividing by its range; thus they are all standardized within the interval between zero and one. For more details, we refer to Oguz (2005b). In a sense, these two highly significantly correlated ($r=0.82$, $p<0.01$) indices show a more explicit, composite representation of the synchronous decadal fluctuations observed in the hydro-meteorological properties of the Black Sea. As will be presented in Section 5, the ecological index (ECOI) time series (see Fig. 3) constructed from the ecological data sets described in Section 5 fluctuates synchronously with ~10-year period as well, and its correlation with the PCI is reasonably high, $r=0.78$ at a significant level $p<0.01$. The forms of these three indices thus imply that all components of the Black Sea respond concurrently to large scale atmospheric systems, whose characteristics are elucidated in the next section. We further note that even though the data sets used to construct these composite indices are not detrended, the composition process largely cancels out the positive and negative anthropogenically induced trends of the individual data sets, and the oscillatory climatic signal more clearly emerges in the composite indices.

4. The role of large scale atmospheric systems on the regional climatic variations

4.1. The role of North Atlantic Oscillation

The NAO is known to be the most prominent and recurrent weather system affecting the marine and terrestrial ecosystems over the North Atlantic and the Eurasia (Marshall et al., 1997). The NAO refers to a meridional shift in atmospheric mass between the subtropical 'Azore high' and subpolar 'Iceland low' pressure systems. Its influence is felt strongest over the North Atlantic Ocean and its marginal seas, and decreases further away from its center of action. Various measurements in the Mediterranean, Black and Caspian Seas (e.g., Reva, 1997; Ozsoy, 1999; Tsimplis and Josey, 2001; Stanev and Peneva, 2002) have established a regional dynamical link to the NAO. The NAO signature has been recorded in streamflow changes of the Tigris and the Euphrates Rivers (Cullen and de Menocal, 2000), as well as in the River Danube discharge (Polonsky et al., 1997; Rimbu et al., 2004). The NAO influence has been traced even in the Siberian winter temperature variations, accounting for as much as 60% of its variance in recent decades (Lu and Greatbatch, 2002). The NAO effect over the Euroasia is particularly pronounced when its dipole structure protrudes in the ridge and trough forms towards the Europe (see Fig. 9 in Hurrell et al., 2003).

The positive winter NAO index is associated with the strong pressure gradient between the Azores high pressure and the Iceland low pressure systems bringing cold and dry air masses to southern Europe and Black Sea region by strong northwesterly winds (Hurrell et al., 2003). In these periods, the Black Sea region is affected by the Azore high pressure center and thus characterized by the higher surface air pressure values. Conversely, the negative NAO index implies lower surface atmospheric pressure differences between the Azore high and the Iceland low pressure centers. This system gives rise to milder winters with warmer air temperatures and less dry/more wet atmospheric conditions transported over the Black Sea from the southwest.

The general consistency between periods with positive (negative) values of the NAO index (Fig. 4a) and those of the cold (warm) sea surface and air temperatures (Figs. 1a and 2a), higher (lower) surface air pressures and evaporation minus precipitation values (Fig. 2b,c), stronger (weaker) wind stress (Fig. 2d) supports the presence of a teleconnection between the regional atmospheric conditions and the NAO-driven

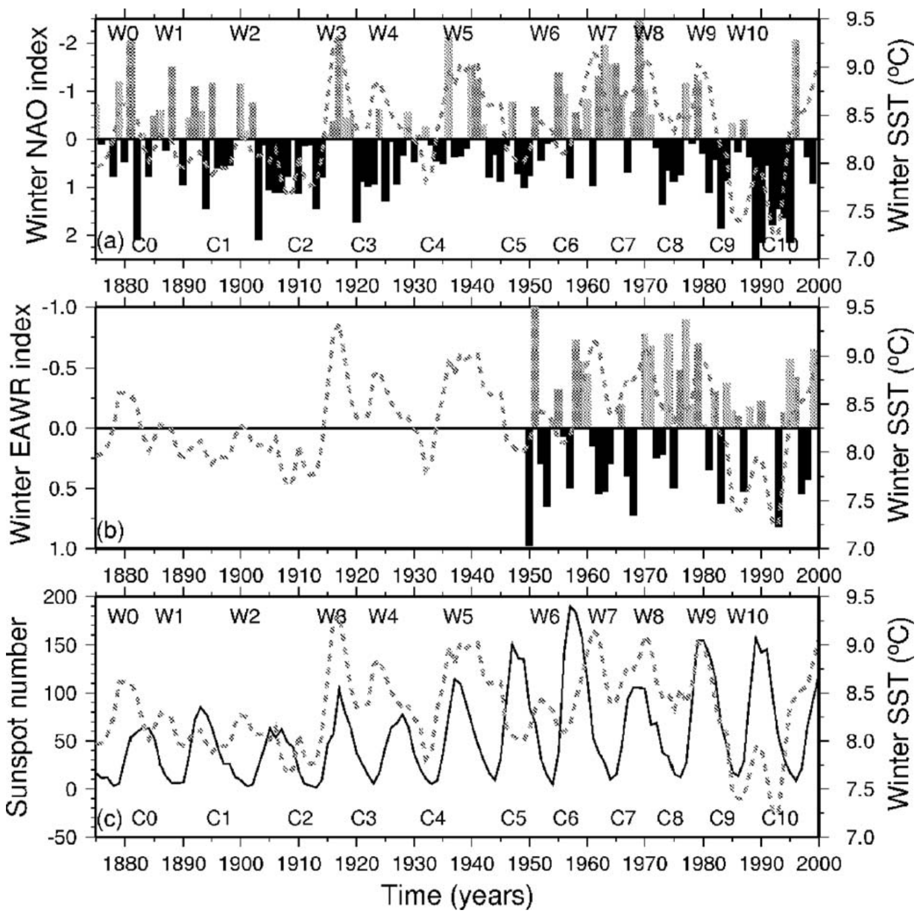

Fig. 4. Long-term variations of the winter (a) North Atlantic Oscillation index based on pressure differences between Azores and Iceland, using the normalization period 1875–2000, (b) East Atlantic–West Russia index for the period of 1958–2000, and (c) sunspot number. The sea surface temperature time series are included in all these plots in continuous line. High frequency oscillations in the data have been filtered by the three point moving average.

large scale atmospheric motion. In terms of duration and intensity of events, the sequence of mild and severe winter cycles with ~5-year duration roughly follows the temporal pattern of the negative and positive NAO cycles. This particularly applies to the 1965–1995 period. When the complete time series of each data set are considered, the level of correlations is less encouraging and varies individually between 0.1 and 0.47, with the highest correlation taking place between the NAO and the Black Sea surface atmospheric pressure (Table 2). On the other hand, the composite Black Sea atmospheric index (ATI) and the marine climate index (PCI) exhibit correlations with the NAO around 0.45 (Oguz, 2005b). Thus, the amount of variance explained by the NAO in the Black Sea is roughly half of that for the North Atlantic Ocean (Hurrell et al., 2003).

Such ~10-year fluctuations agree with an observed peak in the 8–10 year band of the power spectrum of the winter mean NAO index which was found to enhance particularly over the latter half of the 20th century (Hurrell et al., 2003; Polonsky et al., 2004). The

Table 2
Correlations of the NAO with the hydro-meteorological properties of the Black Sea including areal averages of the surface air temperature (AT), evaporation minus precipitation ($E-P$), surface atmospheric pressure (SAP), sea surface temperature (SST), Cold Intermediate Layer temperature (CIL), salinity anomaly of the upper 200 m layer (SAL), and sea level anomaly (SLA)

Pair of variables	Number of measurements	Correlation Coefficient
NAO-AT	125	−0.28
NAO-(E-P)	54	−0.10
NAO-SAP	43	0.47
NAO-SST	128	−0.27
NAO-CIL	44	−0.35
NAO-SAL	47	0.23
NAO-SLA	111	−0.20

principal component analysis (PCA) of the winter-mean NAO index (Sirabella et al., 2001) suggests that these fluctuations actually comprise the second and third modes, superimposed on approximately 18-year fluctuations of its first mode. The ~5-year cyclicity of the NAO is deformed by two specific longer-term interdecadal scale oscillations during the second half of the last century. The first comprises the 1955–1970 period dominated by the negative NAO index. This explains the cause of weak signature of the C6 and C7 cold cycles in the air and sea surface temperatures as well as in other related atmospheric and oceanographic properties (Figs 1 and 2). Similarly, the period of 1980–1995 characterizes an extended strongly positive NAO index phase. It is dominated by the cold AT and SST cycles without an appreciably strong warm cycle W10. The weak W4 and W6 warm cycles in the SST and AT time series also correspond to the weakly negative NAO cycles.

The Black Sea hydro-meteorological properties are sensitive not only to the phase of the NAO but also to the exact location of its center of action. For example, the cold period (C7) during the first half of the 1960s is negatively correlated with the NAO index, and characterized by the negative NAO phase. A closer inspection of the winter sea level pressure distributions over the North Atlantic and Eurasia for this period (e.g., see the winter 1964 case in Fig. 5) provides an explanation for this inconsistency. Because the subpolar low pressure center of action is displaced appreciably to the southwest of Iceland (centered at 40–45°W, 55–60°N), the surface pressure difference between Ponta Delgada (Azores) and Reykjavik (Iceland) does not represent adequately the strength of this dipole system, and in fact gives rise to a negative NAO index value (Fig. 4a). Even though NAO index is negative, the presence of a high pressure system over the western Europe (Fig. 5) supports cold and dry northwesterly outbreaks towards the Black Sea region (Figs. 1 and 2). On the other hand, the second half of the 1990s is predominantly characterized by the positive NAO index values, but the Black Sea hydro-meteorological conditions generally reflect a warm period. These inconsistencies point possibly to the more predominant contributions from other atmospheric systems controlling the region at certain periods, as elaborated in the subsequent section.

4.2. The role of East Atlantic–West Russia atmospheric system

The winter (December–January–February) mean East Atlantic–West Russia (EAWR) system representing the quasi-persistent high and low surface pressure anomaly centers over the Western Europe and the Caspian region characterizes the second strongest mode of the North Atlantic climate (Molinero et al., 2005), and modulates the NAO over the Eurasia continent. Its positive phase results from the joint effect of the increased anticyclonic anomaly center over the North Sea, and the increased cyclonic anomaly center over the Caspian Sea. The Black Sea region is then exposed to cold and dry air masses from the northeast-to-northwest sector. Alternatively, in its negative phase associated with the cyclonic anomaly center over the North Sea and the anticyclonic activity over the Caspian Sea, the Black Sea region is affected by warmer and wetter winter conditions under the influence of increased southwesterlies-to-southeasterlies. These alternative phases

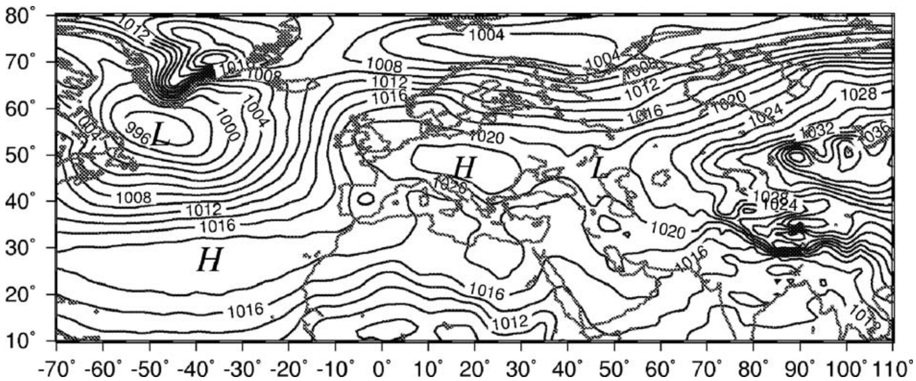

Fig. 5. The mean sea surface pressure distribution pattern for winter (December–January–February) period of 1963–1964. The NAO dipole system is characterized by the Iceland low (L) and Azore high (H) pressure centers over the North Atlantic. The EAWR dipole system is characterized by the high pressure cell (H) over the northwestern Europe and a low pressure cell (L) over the Caspian region. The region in red colour near the eastern boundary of the plot represent Siberian high pressure system.

are identified by the positive and negative values of the EAWR climate index (Fig. 4b). Its characteristics generally resemble the North Sea–Caspian Pattern (NCP) index introduced using 500 hPa geopotential anomaly patterns by Kutiel and Benaroch (2002).

For explaining interannual variability of precipitation over the eastern Mediterranean, Krichak et al. (2002) have incorporated the additional contribution of the EAWR system into the classical NAO-based analysis of the 41-year (1958–1998) monthly mean winter (December–January–February) sea level pressure anomaly patterns. Krichak et al. (2002) have essentially identified four possible combinations of a quadrapole system formed by the high and low surface pressure anomaly centers over the North Atlantic and the Eurasia as representative of different states of the eastern Mediterranean–Black Sea atmosphere. They were identified by different combinations of the positive and negative winter NAO and EAWR index values. When both NAO > 0 and EAWR > 0, the system is governed by the low pressure anomaly centers over Iceland and Caspian Sea and a high pressure anomaly centers over Azore and the North Sea. The Black Sea region is then characterized by cold air mass outbreaks from the northwest and the northeast. This case leads to strongest cold winters in the Black Sea as in the case of early 1990s. When NAO > 0 and EAWR < 0, the Caspian low is replaced by an anticyclonic anomaly center, and the Black Sea region is then controlled by either cold air outbreaks from the northwest or warm air outbreaks from the southeast depending on the relative strengths and spatial coverages of the Icelandic low and Caspian high pressure systems. The reverse case of NAO < 0 and EAWR > 0 gives rise to the cold winters with cold air outbreaks from the northern sector, as in the case of early 1960s (see Fig. 5). Alternatively, the warm and mild winters may also prevail in the region when the Azore high pressure system is sufficiently strong and protrudes towards the east. As suggested by the Black Sea hydro-meteorological time series data, the latter case generally occurs during the second halves of the 1980s and 1990s. When both NAO < 0 and EAWR < 0, the system is affected by the warm air mass intrusions from both the southwest and southeast, giving rise to mild winters in the Black Sea. Its typical example was observed during the second half of the 1970s.

The EAWR index time series (Fig. 4b) was generally found to differ from that of the NAO index (Fig. 4a) during three particular periods. One of the differences occurs during the first half of the 1960s (C7), which corresponds to the case of NAO < 0 and EAWR > 0. The others occur during the second halves of the 1980s (W10) and of the 1990s (W11) characterized predominantly by NAO > 0 and EAWR < 0 case. For these particular periods, the EAWR index better represent the Black Sea hydro-meteorological conditions implying that the regional atmospheric conditions are predominantly controlled by zonal variability of the atmospheric systems over the Eurasia. The combination of the NAO and EAWR indices thus explain, to a first order, most of the Black Sea climate-induced variability.

4.3. Solar influence

Solar influence on the Earth's climatic parameters, especially at interannual and longer time scales, has long been the issue for discussions. On the time-scale of the 11- and 22-year solar cycles, a growing evidence of possible link was suggested between solar variability and climate (Haigh, 2001; Rind, 2002), although this link remains somewhat unclear and was rejected on several occasions (Lindstrom et al., 1996). Statistically significant correlations were found between the solar activity parameters and surface air temperature, surface air pressure, precipitation, electrical properties of the atmosphere, stratospheric ozone, lake and sea level variations, river flow, as well as the parameters like occurrence of the thunderstorms, migration in the centers of Icelandic Low and Azores High, cyclone tracks (Herman and Goldberg, 1978; Hoyt and Schatten, 1997). For example, the ~11-year oscillations observed in the sea level data of the Caspian and Aral Seas have been shown to follow the sunspot cycles (Shermetov et al., 2004). Similarly, annual sardine landings from 1906 to 2002 off the northwest coast of the Iberian Peninsula of the North Atlantic Ocean have been found to vary in consistent with the sunspot cycles (Guisande et al., 2004). A possible impact of sunspots in the Black Sea ecosystem was postulated by Niermann et al. (1999) as a mechanism explaining observed variations of the long term Secchi disk and Bacillariophyta–Dinophyto biomass ratio data. The role of solar activity has also been pointed out for terrestrial ecosystems, such as fluctuation of Canadian porcupine abundance with 11- and 22-year periodicities since 1868 (Klvana et al., 2004).

Plausible explanation for a direct link of the solar signal to climate and local properties poses a great difficulty because of rather small variations in the solar irradiance reaching the Earth. Their direct effect must be amplified somehow in the climate systems through the coupling of processes between the middle and lower atmospheres and between the atmosphere and oceans. Potential mechanisms by which the solar signal may be amplified require consideration of the natural modes of variability in the climate systems such as the El Nino-Southern Oscillation and NAO. Number of papers has in fact recently drawn attention to the relation between the NAO and the solar-induced variations via a teleconnection between the tropospheric and stratospheric circulation. Kodera and Kuroda (2002, 2005) showed that the zonal wind anomalies in the stratopause are altered according to the variation in solar activity. In the periods of high solar activity, the leading zonal wind mode has a meridional dipole-type structure that extends downward from the stratosphere to the troposphere through interaction with the planetary waves, and produces a hemispherical scale seesaw pattern in the surface pressure between the polar region and surrounding regions. The NAO during such high solar activity periods thus constitutes a more dominant hemispherical pattern. During the periods of low solar activity, the downward extension of zonal wind anomalies is weak, so the regional-scale variations become less dominant in the troposphere. The NAO is then more localized, and confined to the Atlantic sector. Similarly, the NAO and the wintertime northern hemispheric temperature are found to be more positively correlated during solar maximum phases (Gimeno et al., 2003). During these periods, the region of positive temperature anomalies extends to the Eurasian continent and eastern North America when compared to the region of the negative temperature anomalies. For the solar minimum phases, correlations are not significant or even negative, and the region of positive temperature anomalies is only limited to the northern Europe, as in agreement with the results of Kodera and Kuroda (2005). High and significant correlations between different geomagnetic indices of the solar activity and the NAO index have been further suggested by Kirov and Georgieva (2002), Thejll et al. (2002) and Lukianova and Aleksev (2005). The correlations were dominated by decadal oscillations and were particularly pronounced for the 1973–2000 periods as compared to the previous period of 1949–1972.

The decadal variations observed in the Black Sea hydro-meteorological properties described in the preceding sections appear to be consistent with the 10–12-year solar (sun spot) variations particularly after the early 1960s (Fig. 4c). The periods of solar minima coincide with those of reduced air temperature (Fig. 2a), and sea surface temperature (Figs. 1a or 4c), which generally correspond to the periods of positive NAO index values (see Fig. 4a). In contrast, the periods of solar maxima coincide with the periods of higher air and sea surface temperatures characterized by negative values in the NAO index. Table 3 consistently shows positive correlation between the PCI and the sunspot number for each 5-year bins of the consecutive cold and warm cycles of the 1960–2000 phase. On the contrary, the correlation between the PCI and the NAO is significantly negative during the 1960–1965 and 1995–2000 periods and neither significantly positive nor negative at 1985–1990. We recall that these three periods also correspond to a lack of correlations between the NAO and EAWR indices. The in-phase variations between the sun spot number and the regional hydro-meteorological characteristics may thus suggest possible impact of the solar activity through modulating large scale motions in the lower atmosphere and subsequently air and sea surface temperatures of the Black Sea.

4.4. EOF analysis

The apparent contributions of the NAO and EAWR systems on the Black Sea climate is further demonstrated here by decomposing the data into a finite series of empirical orthogonal functions (EOFs). The first and second EOFs of the winter (December–January–February) mean sea level pressure (SLP) anomaly patterns computed for the region extending from 70°W to 30°E and from 30°N to 70°N using 5°×5° gridded data of the 1900–1996 period (Trenberth and Paolino, 1980) explain 41% and 18% of the total variance, respectively. As shown in Fig. 6 of Dippner and Voss (2004), the first eigenmode pattern formed by the Azore high and the Islandic low pressure anomaly system controls the zonal westerly wind component. Its influence decreases with increasing eastern longitude and higher modes therefore need to be considered further east, as demonstrated in the Gulf of Riga of the Baltic Sea by Dippnerr and Ikauniece (2001). The second eigenmode pattern, which is orthogonal to the

Table 3
The sign of correlations between the PCI, sunspot number (SUN) and NAO variations for 5-year periods of the 1960–2000 phase

	1960–65	1965–70	1970–75	1975–80	1980–85	1985–90	1990–95	1995–2000
NAO-PCI	−	+	+	+	+	?	+	−
SUN-PCI	+	+	+	+	+	+	+	+
NAO-SUN	−	+	+	+	+	?	+	−

The + and − signs, respectively, indicate the positive and negative correlations.

first one, shows a dominant high pressure system to the west of Ireland in the region roughly between 40–60°N and 50°W–10°E and controls the meridional wind component. As depicted in Fig. 6a,b, the NAO and EAWR indices respectively correlate well with the first and second modes of these SLP patterns, whose smoothed versions using a low pass (1,3,5,6,5,3,1) filter with a cut-off length of 4 years are further displayed in Fig. 7a,b.

The first mode smoothed SLP time series (Fig. 7a) matches well with the first mode of the NAO index (see Fig. 4b in Sirabella et al., 2001), and represent the interdecadal variability of the system in the 15–30-year band. Even though the second mode (Fig. 7b) having a periodicity in the order of 10 years is correlated primarily with the EAWR index, as shown in Fig. 4c in Sirabella et al. (2001), the 8–9-year fluctuations of the second and third modes of the NAO index also contribute to the North Atlantic climate. We further note that the interdecadal variations shown in Fig. 7a explain well the phases 1, 3, and 4 in the SST time series (Fig. 1a). For the phase 2, the correlation however exists for only from 1935 to 1950, whereas the former part (1920–1935) of the first SLP mode (Fig. 7a) indicates an opposite (cooling) cycle instead of the warming cycle in the SST. Moreover, the negative and positive cycles of the second mode (Fig. 7b) agree with the corresponding successive ~5-year-long warm periods (W2–W10) and cold periods (C2–C10) of the SST data, respectively. All these findings inevitably suggest that the observed interannual to interdecadal variability in the Black Sea is not only controlled by the zonally varying first mode, but also influenced from the meridionally varying second mode.

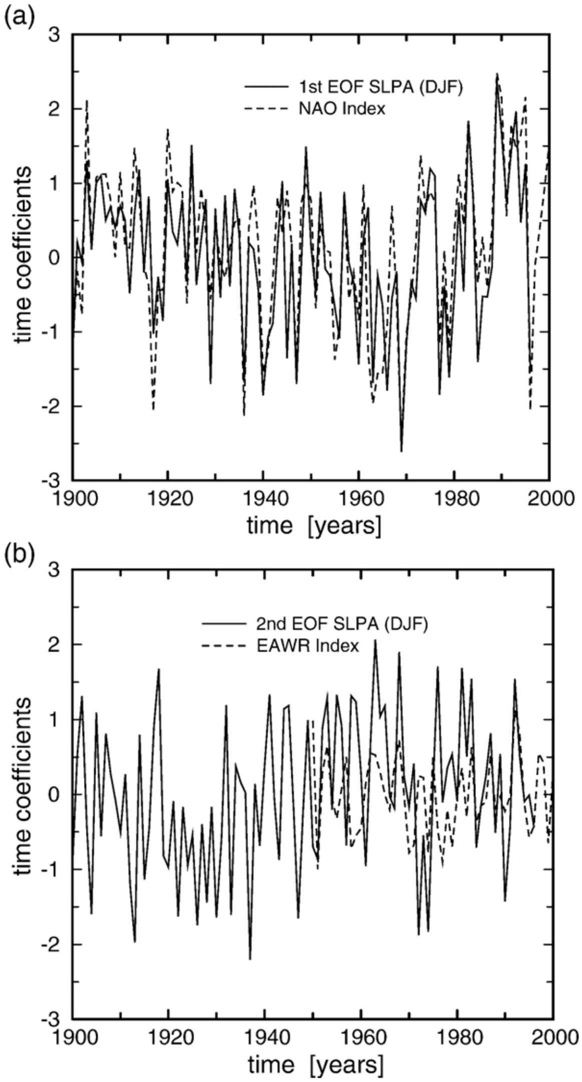

Fig. 6. Long-term variations of (a) the first, and (b) the second eigenmodes of the empirical orthogonal functions of the sea level pressure time series data (continuous lines). Superimposed on these plots, temporal variations of the NAO and EAWR indices are included, respectively, by broken lines.

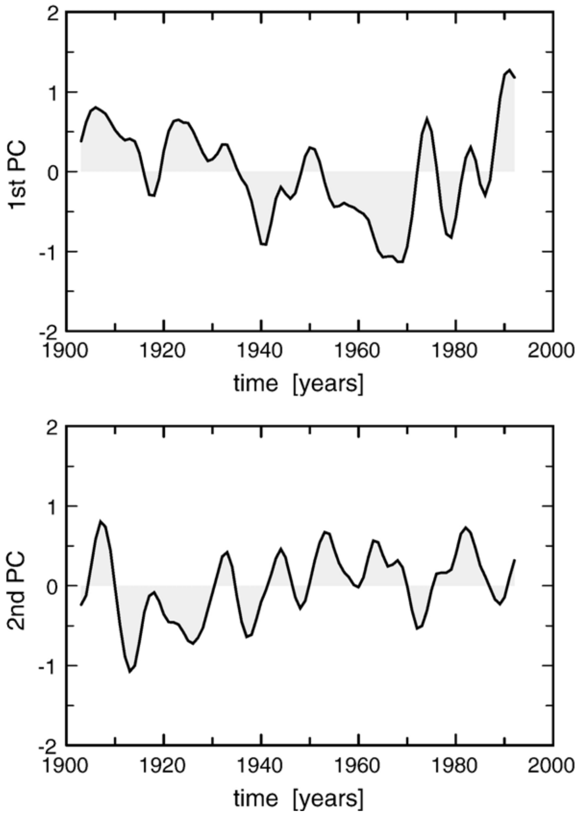

Fig. 7. Long-term variations of the smoothed (a) first, and (b) second eigenmodes of the empirical orthogonal functions of the sea level pressure time series data using the low pass (1,3,5,6,5,3,1) filter.

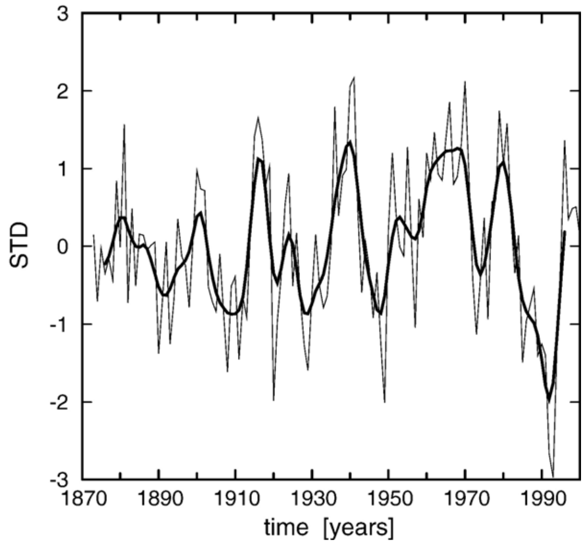

Fig. 8. Long-term variations of the first dominant eigenmode of the Black Sea climate index (thin line) constructed using more than 100-year-long time series of the NAO, winter-mean SST, winter AT and the mean sea level anomaly. The one standard deviation (STD) on the *y*-axis corresponds to 1.05 hPa in the NAO, 0.54 °C in the winter SST, 0.96 °C in the winter AT, and 4.75 cm in the mean sea level anomaly. The thick line represents its smoothed version with the low pass (1,3,5,6,5,3,1) filter.

Finally, putting all these pieces together, the Black Sea climate index is constructed by using more than 100-year-long time series of the NAO, winter-mean SST, winter AT and the mean sea level anomaly after their standardization in the form of zero mean and unit standard deviation (STD). Its first dominant eigenmode, which explains 46% of total variance, is displayed in Fig. 8 where the one STD corresponds to 1.05 hPa in the NAO, 0.54 °C in the winter SST, 0.96 °C in the winter AT, and 4.75 cm in the mean sea level anomaly. The thick line in Fig. 8 represents the smoothed data using the (1,3,5,6,3,1) low pass filter.

5. Long-term changes in the ecological properties

We now identify the role of climate on the long-term changes of the Black Sea ecological properties. For example, phosphate concentration time series of the northwestern coastal waters (Fig. 9a) show a remarkable consistency between its low and high values and the Black Sea physical properties described in the previous sections. This consistency is particularly striking and suggests the presence of the climatic signal in the data even under the conditions of intense eutrophication. These periodic changes are superimposed on an order of magnitude increase of concentrations from 1 μM during the 1960s up to ~10 μM during the 1970–1980s as a result of the heavy anthropogenic load, followed by an opposite trend in the 1990s due to the decrease in the anthropogenic load in response to implementation of

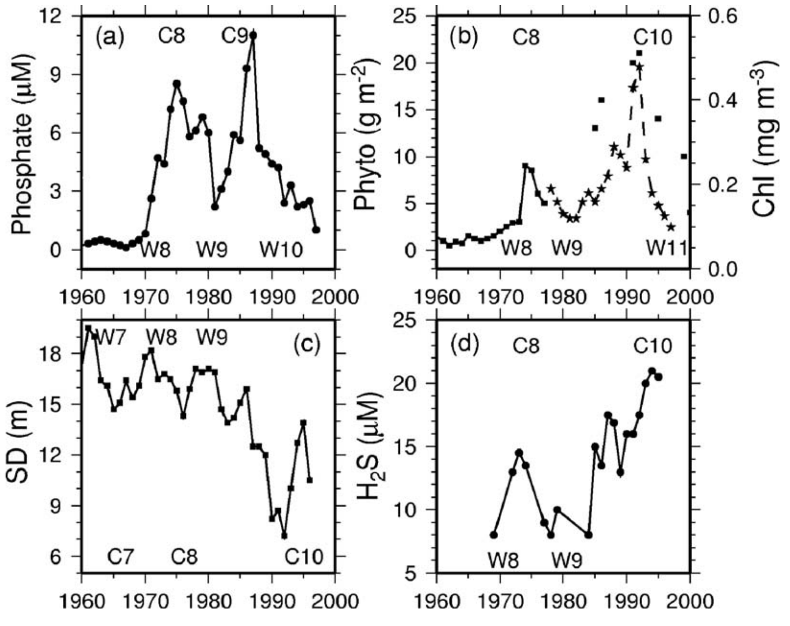

Fig. 9. Long-term variations of (a) the surface phosphate concentration in Romanian coastal waters, off Constantsa, (b) the phytoplankton biomass (squares) surface chlorophyll (stars) distributions for the May–September period within the interior part of the sea, (c) the annual mean Secchi disc depth for the interior basin, (d) the annual mean hydrogen sulfide concentration (μM) at 16.4 kg m^{-3} sigma-t surface.

some control measures. The years with mild winters encountered during the second halves of the 1960s, 1970s, 1980s, and 1990s (W8–W11) correspond to the periods with lower (decreasing) phosphate concentrations. Conversely, the periods with increased phosphate concentrations observed during the first halves of the 1970s and 1980s (C8, C9) match well with the severe winter years. The C10 peak during the 1992–1993 cold winter period is not well-pronounced as the others because of low phosphate concentrations associated with decreasing anthropogenic supply. The higher phosphate concentrations during cold winters arise due to stronger vertical mixing rate in the water column. The intense vertical mixing gives rise to considerable entrainment of subsurface phosphate, which has been accumulated near the bottom and the sediment following their supply from the River Danube. The correlation between the phosphate and winter PCI data is relatively weak; $r=-0.35$ ($p<0.001$), which increases to -0.46 when the low phosphate concentration data before 1970 and after 1990 are excluded from the analysis.

The summer surface phytoplankton biomass data from the interior of the basin (Fig. 9b) also exhibit similar cyclic variations superimposed on the linear trend of biomass increase from ~2 g m^{-2} during the late 1960s to ~20 g m^{-2} during the 1980s as a consequence of the intense eutrophication in the Black Sea (Mikaelyan, 1997). The low level biomass in the pre-eutrophication period (i.e., 1960s) hinders a clear sign of cyclic variations. Three consecutive ~5-year cycles of the increasing–decreasing–increasing biomass variations are then clearly traced in the data from the beginning of the 1970s to the mid-1980s (C8, W9, C9). The subsequent reduction in the biomass during the second half of the 1980s (W10) was not captured due to the lack of data. But, high biomass during the subsequent cold period of the early 1990s (C10), as well as the reduction during the following warm cycle (W11) are evident. These variations are further supported in Fig. 9b by similar variations of surface chlorophyll concentration (Yunev et al., 2002; Vedernikov and Demidov, 2002).

The out-of-phase cyclic variations of phytoplankton biomass and chlorophyll concentrations with the winter-average PCI attain the correlation coefficient of -0.79 ($p<0.01$). High rate of nutrients, which are imported into the euphotic zone from the chemocline zone below due to stronger vertical mixing during cold and severe winters, gives rise to relatively stronger early-spring and summer phytoplankton blooms (Oguz et al., 2001; Tian et al., 2003). This relation is supported by the presence of highest peak at the time of the exceptionally cold cycle during the early 1990s. Some delay in the early-spring primary production due to cold water temperatures and more gradual shallowing of the mixed layer can also promote more active regenerated production and higher phytoplankton biomass in summer months.

The climate-induced variations can even be traced in the Secchi disc data set (Fig. 9c), which typically involves much less precision with respect to other hydro-meteorological and biochemical measurements. Higher phytoplankton biomass implies higher organic matter content and consequently more turbid conditions in the water column, as suggested by decreasing Secchi disc depth values during the first halves of the 1960s (C7), 1970s (C8), 1980s (C9), and 1990s (C10). Being consistent with the eutrophication-induced continuous rising of the phytoplankton biomass during the 1980s, the Secchi disc depth undergoes to a continuous decreasing trend. Conversely, increasing Secchi disc depths correspond to less productive and thus less turbid, milder climatic cycles (W7, W8, W9) during the second halves of the 1960s, 1970s, and 1990s. The Secchi disc and PCI correlation is $r=0.65$ ($p<0.001$).

Hydrogen sulfide concentration variations along the density surface of $\sigma_t=16.4$ kg m^{-3} (Fig. 9d) also signify contributions of the climate-induced variations to the Black Sea biogeochemistry. This density surface lies along the base of the permanent pycnocline, and therefore its sulfide concentrations signify how far the surface signature can propagate within the water column. Starting from the relatively low concentrations at the early 1970s (W8), the data show first an increasing and then decreasing concentrations in the first and second halves of the 1970s (C8 and W9), respectively. It is then followed by a decadal trend of strong increase from ~7 to ~20 μM in the cold period of the early 1990s (i.e. C10). This trend also encompasses some fluctuations, which follow those of the hydro-meteorological properties (C9 and W10). A slight reduction of sulfide concentrations superimposed on this trend towards the end of 1980s corresponds to the warm climatological cycle (W10). During the mild winter years, a more limited upward supply of sulfide occurs from deep, and relatively weaker local sulfide production takes place due to more limited organic matter supply. The correlation with PCI is again reasonably high, $r=-0.76$ at a significant level $p<0.01$.

The three-fold increase in the hydrogen sulfide concentration within a decade is a consequence of the intense eutrophication as already indicated by the similar sharp changes in the phosphate, phytoplankton, and Secchi disk data. It is caused by much higher rate of

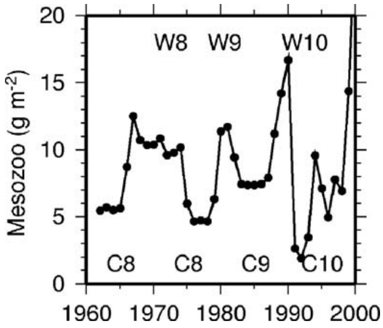

Fig. 10. Long-term variations of the annual-mean mesozooplankton biomass (g m^{-2}) within the interior basin.

organic matter decomposition within the anoxic layer of the water column in the eutrophic environment (Konovalov and Murray, 2001). While the anthropogenic forcing was responsible from the linear trend of increase of the H_2S concentration, the fluctuations superimposed on this trend was driven largely by varying rate of supply from the deep anoxic pool during cold and warm phases of the Black Sea. Undoubtly, climate-induced variability associated with organic matter production and decomposition processes also contributes to the decadal changes in the H_2S concentration.

In practice, long-term variations of mesozooplankton biomass are regulated by the temperature dependence of their growth, in addition to the combination of complicated bottom–up and top–down interactions among different trophic levels of the food web. A regular cyclic pattern of their biomass should thus be hardly expected. On the other hand, beyond all expectations, the annual-mean mesozooplankton biomass time series (Fig. 10) possess higher (lower) biomass during the years with warm (cold) winter cycles. Its correlation with the PCI is 0.39 (at $p<0.01$). The mesozooplankton growth thus seems to be regulated to some extent by physical climate in the water column (Kovalev et al., 1998); warmer waters promote metabolic processes and favor more efficient growth, whereas colder waters limit mesozooplankton production albeit producing stronger phytoplankton blooms. The preferential increase of mesozooplankton biomass during the warm years suggests a limited role of the bottom up control on mesozooplankton production. The observational evidence for temperature dependence of copepod production has been given by Huntley and Lopez (1992). The primary role of water temperature has also been pointed out by Planque and Taylor (1998) for regulation of *C. finmarchicus* stocks in the North Sea and the northeast Atlantic, and by Hunt et al. (2002) for the southeastern Bering Sea. The temperature effect on the mesozooplankton biomass is most clearly suggested by a substantial reduction in the biomass during the exceptionally cold 1991–1993 period of the Black Sea, which also coincided with the substantial decrease in the *M. leidyi* biomass and pelagic fish stocks, even though the phytoplankton biomass attained its highest level (see Figs. 5 and 6 in Oguz, 2005a). As their predator control was at the minimum level and the bottom-up control was very efficient, there was no biotical reason for the decline of mesozooplankton biomass, except its abiotic control.

The climate impact on the rise and fall of pelagic stocks also emerges very clearly in the temporal distributions of sprat and anchovy biomass (Figs. 11 and 12). They are two most dominant small pelagic fish species in the Black Sea, and they have acted as the top predators in the ecosystem following the depletion of higher predators due to overfishing during the 1960s and the early 1970s. Sprat is a cold water species spawning in autumn and winter months. Sprat stocks are therefore expected to be higher during the cold years as shown by a substantial increase in the parental sprat biomass from 100 to 600 ktons during the first half of the 1970s (C8) (Fig. 11a). It was followed by a decrease to 200 ktons during the subsequent warm cycle (W9) in the second half of the 1970s, up to the early-1980s. The biomass then increased first to 450 ktons during the mid-1980s

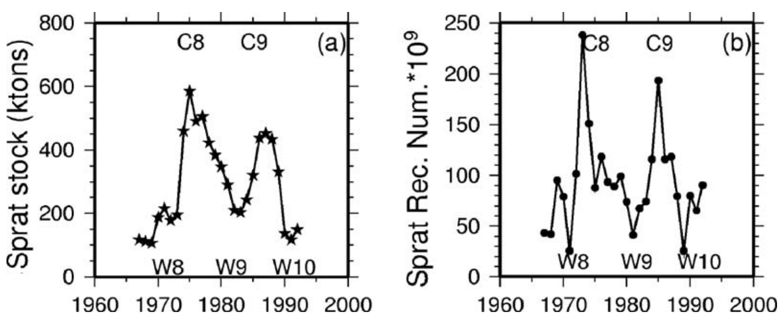

Fig. 11. Long-term variations of (a) the sprat parental biomass (ktons), and (b) sprat recruitment (number*10^9) stock.

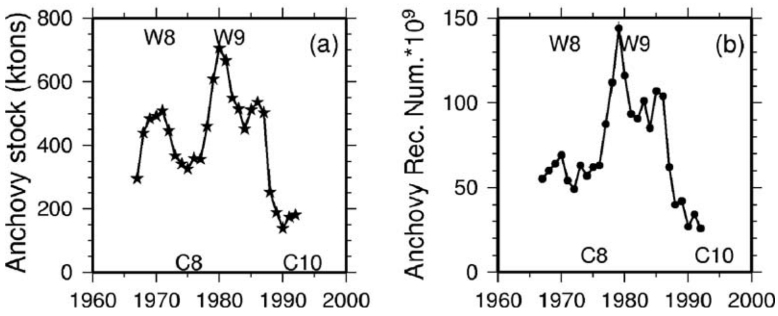

Fig. 12. Long-term variations of (a) the anchovy parental biomass (ktons), and (b) anchovy recruitment (number*10^9) stock.

(C9), and finally dropped to its lowest level of ~100 ktons at the end of the 1980s (W10). Sprat recruitments followed a similar pattern of oscillations roughly between 20 to 240 billions of juveniles during the 1970s and 1980s and, once again, dropped to its minimum level at the end of the 1980s (Fig. 11b). Low level adult and juvenile sprat stocks observed during the early 1990s are not consistent with the cold cycle of climatic variations and therefore require an alternative explanation. As suggested by Gucu (2002), the overall small pelagic stock exceeded a sustainable level in 1987, and collapsed during 1990. In addition to the overfishing, excessive feeding pressure introduced by *M. leidyi* population during 1989–1990 should also contribute to depletion of the sprat stocks (e.g. Shulman et al., 1998; Shiganova, 1998; Vinogradov et al., 1999; Kideys et al., 2000; Kideys, 2002). As a result, sprat was not able to sustain high stock in the cold 1991–1993 period as expected. The correlation of the sprat time series with PCI is −0.44 ($p<0.01$).

Anchovy is a warm water species, and spawns preferentially during summer and autumn months. Thus, cold years are expected to be unfavorable for anchovy stocks. This assertion is supported by the temporal variation of parental anchovy stocks (Fig. 12a), which was as low as 300 ktons during the mid-1960s (C7) and mid-1970s (C8), and 450 ktons during the mid-1980s (C9). Much higher stocks, on the other hand, were accomplished during the warm years; stocks raised up to 500 ktons at the end of the 1960s (W8), and to 700 ktons at the end of the 1970s (W9). Similarly, anchovy recruitment around 50 billions in the cold period of the early 1970s increased up to 150 billion at the end of the subsequent warm cycle, decreased thereafter up to about 25 billion in the early 1990s. On the other hand, instead of an increasing trend of the parental anchovy stock within the subsequent warming cycle (W10) towards the end of 1980s, the stock started declining by 1988 up to about 150 ktons in 1990. The reduction during 1988–1990 must therefore be related to non-climatic factors such as overfishing and outburst of *Mnemopsis* population leading, respectively, to more limited spawning and high rate of consumption of their eggs and larvae by *M. leidyi* in the surface mixed layer (Prodanov et al., 1997). The correlation of the parental anchovy stock time series with PCI is 0.53 ($p<0.01$).

The composite Black Sea ecological index (ECOI) constructed by standardizing the time series data presented in Figs. 9 and 10 (Oguz, 2005b) exhibits more clearly the fluctuations with ~10-year periodicity (see Fig. 3). It has a reasonably high correlation coefficient of $r=0.78$ significant at $p<0.01$ with the PCI.

6. Conclusions

This exploratory descriptive study merely elucidates a specific link between changes in the Black Sea properties and large scale climatic variability associated with the atmospheric systems over the North Atlantic and the Eurasia. Superimposed on the interdecadal scale changes in the 15–30-year band, the prominent oscillations are shown to take place around 10 years. Generally speaking, 11 simultaneous cold and warm cycles, each with an approximate duration of 5 years, are noted in the long term hydro-meteorological data sets. The 10-year fluctuations observed in the NAO index can explain partially the Black Sea climate signal. But, when its seesaw structure is extended to include the high and low pressure anomaly centers over the Caspian and North Seas, the quadrapole atmospheric system provides more coherent synchronous fluctuations with the Black Sea hydro-meteorological properties. This point has been elaborated in terms of four possible combinations of the NAO and EAWR climate indices representing two independent teleconnection patterns in the sea level pressure. These combinations readily account for blocking anticyclones or cyclones developed occasionally over the eastern Atlantic and western Europe, modifying the NAO-driven westerly zonal flow by strong meridional components.

The way in which these teleconnections are further modulated by local transient weather systems and controversial role of the solar activity are topics of further research. Moreover, the nature of correlations between the hydro-meteorological and ecological properties and the climatic teleconnection systems need to be further elaborated by future statistical and modeling studies as well. While statistical approach will clarify more explicitly the possible correlation channels linking the large scale climate variability to the regional conditions, the deterministic models will be particularly useful for mechanistic understanding of the response of the system as a whole to different forcing agents, testing various hypotheses put forward for explaining observed features, and forecasting the future state of the ecosystem. Further research is also required to find out possible teleconnection mechanisms with other large scale climatic oscillations, and the ways in which they affect the ecosystem structure and functioning. For example, Ozsoy (1999) and Ginzburg et al. (2004) pointed out teleconnection between some cold years (e.g., 1982–1983, 1986–1987, the early 1990s) and negative values of the El Nino-Southern Oscillation index.

The climate-driven ecosystem changes provide insights for sustainable use of marine living resources in the Black Sea, and effective management policies. Our analysis show that the decadal oscillations in the ecological properties are superimposed on the abrupt rise and fall type anthropogenically induced trends. The data after the 1970s suggest a clear evidence of anthropogenic-based alterations, characterized by drastic increases in nutrient concentrations, plankton biomass and pelagic fish stocks. The nutrients supplied by the River Danube and others into the northwestern shelf region were distributed within the entire basin by the circulation system and deposited eventually within the chemocline zone confined between the euphotic layer above and the suboxic layer below (see Fig. 2 in Oguz et al., 2000). In the absence of any physical mechanisms to efficiently supply these inorganic nutrients into the euphotic zone, the eutrophication would not play efficient role in biological production within the sea, except in coastal regions. The dynamical processes necessary to supply these nutrients into the surface layer were most effective during the 1980s corresponding to the strongest NAO cycle of the 20th century. The large scale atmospheric motion provided sufficiently strong wind stress forcing and intense cooling in the region, which subsequently set necessary mechanisms to supply nutrients into the euphotic zone from its subsurface pool. Therefore, the climatic forcing intensified the anthropogenically driven biogeochemical processes during the 1980s. Conversely, without appreciable subsurface nutrient accumulation in the absence of the eutrophication, strong vertical advective and convective processes in the water column would not be so effective for generating strong biological production in the basin. The strong NAO-induced regional atmospheric motion alone would thus be unable to promote an order of magnitude changes in the ecosystem properties. Thus, the changing ecosystem conditions observed during the 1980s were not solely depended up on the anthropogenic effects, but they were the result of very efficient coupling between the anthropogenic and climatic forcing.

The eutrophication–climate interaction also holds for the second half of the 1990s. While the milder climate conditions resulted in biologically less favorable period, introduction of more effective control measures for preventing eutrophication reduced the anthropogenic nutrient supply and led to gradual decrease in the nutrient concentrations of the chemocline layer. This is reflected as a gradual reduction in the biological production even in the case of equally strong vertical mixing as took place in the previous decade.

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