

Long-term changes in fish abundance and environmental indices in the Black Sea

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ABSTRACT: Hydroclimatic, biological and anthropogenic data-series (1915–1993) were analysed to determine and compare main trends and fish stock–environment relationships in the Black Sea. Long-term patterns were studied on different temporal scales: interdecadal, decadal and interannual variation. The results showed evidence of coherent patterns across different indices. Temperature, atmospheric pressure, wind and river run-off series were significantly correlated with most of the biological, anthropogenic and fish stock indices. Anthropogenic factors such as eutrophication and hypoxia were responsible for degradation of the coastal ecosystems, but they can also have negative impacts on open-sea populations. The correlations established allow formulation of hypotheses on the causal links between the abiotic environment, productive processes and population dynamics. The physical environment was recognised as being the main factor driving the biological productivity and essentially influencing all processes in the sea. Other factors responsible for a great part of the observed variability in marine data were biological interactions and anthropogenic impact. The rise in overall productivity after 1970 might be explained by several factors acting simultaneously: a favourable climatic regime, increased eutrophication, and the effect of trophic cascades attributable to overfishing of predators. The indices and relationships studied can be useful for integrating environmental information in fisheries and ecosystem management.

KEY WORDS: Fish-environment · Decadal change · Climate regime shift · Eutrophication · Black Sea · Trophic cascade · Recruitment

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INTRODUCTION

Human-induced factors such as eutrophication, heavy fishing and the introduction of exotic species have been evoked to explain the Black Sea ecosystem changes in recent decades (Caddy & Griffiths 1990, Zaitsev 1993, Prodanov et al. 1997). However, having recognised that natural factors are responsible for the basic physical, chemical and biological processes in the sea, several authors have recently explored possible explanations based on natural abiotic and biotic factors (Niermann et al. 1999, Ozsoy 1999, Daskalov 2002, Yunev et al. 2002).

By the early 1970s, the abundance of pelagic top-predators (dolphins, bonito, bluefish) was greatly reduced (Caddy & Griffiths 1990, Daskalov 2002). Sub-

sequently, the stocks of small pelagic fishes increased considerably and became a target for the industrial fishery. In the mid-1980s, the total catch approached 1 million tonnes, of which about 65% was anchovy and about 20% sprat and horse mackerel *Trachurus mediterraneus* (Prodanov et al. 1997). The jellyfish *Aurelia aurita* became dominant in the early 1980s, reaching more than 1 kg m⁻² of biomass (Shushkina & Musaeva 1983). By the late 1980s *A. aurita* had been replaced in terms of dominance by the exotic ctenophore *Mnemiopsis leydyi*, which reached similar quantities (~2 kg m⁻² or 700 × 10⁻⁶ t in the sea: Shushkina & Vinogradov 1991). Meanwhile, zooplankton biomass decreased almost 2-fold compared with the 1960s, and phytoplankton standing crop doubled during the 1980s. The frequent phytoplankton blooms and

the bulk of non-utilised algal biomass produced a shift in water quality to a state characterised by low transparency and high production of detritus, causing oxygen depletion and hypoxia near the bottom. Increased mortality of mussels and other benthic filter-feeders contributed to an increase in non-utilised detritus, oxygen depletion and hydrogen sulphide production on the NW Black Sea shelf (Faschuk 1995).

Previous studies have addressed diverse aspects of the physical, biological or anthropogenic effects on the Black Sea ecosystem. Low-frequency patterns in several physical variables (sea surface temperature [SST], atmospheric pressure, salinity, sea level, etc.) have been explored by Simonov & Altman (1991). Ovchinnikov & Osadchy (1991) have identified inter-annual, interdecadal and multidecadal periodicity in long-term winter air-temperature data. Polonsky et al. (1997) found significant interannual and interdecadal variability in temperature, density and run-off data in the NW Black Sea. The importance of hydroclimate for biological productivity and fish stocks in the Black Sea has been reviewed by Grese (1979), Tkacheva & Benko (1979), Vinogradov (1991), Simonov et al. (1992), Prodanov et al. (1997), and Daskalov (1999). Quantitative relationships between pollution and marine populations are more difficult to identify, but environmental degradation seems to be responsible for structural and functional deterioration in several ecosystem components (Gomoiu 1985, Bologa et al. 1995, Zaitsev & Mamaev 1997).

However, until now, neither climatic regime nor specific anthropogenic indicators have been quantitatively linked to data indexing the long-term ecosystem changes.

To elucidate the causes of the ecosystem changes, several questions must be asked, e.g.: What are the relative roles of the natural and anthropogenic factors (including fishing pressure) in the observed patterns? How do the different scales of temporal change—seasonal, annual, decadal—affect productivity? Are natural populations predominantly controlled by resource availability (bottom-up) or by predation/competition (top-down) factors? Does the recent change in the Black Sea ecosystem result from a transition from favourable to unfavourable environmental regimes?

The present paper addresses some of these questions exploring the synergistic nature of the change by analysing multiple time-series of physical, biological and anthropogenic data. It attempts to identify long-term patterns and provide possible explanations for the changes that have occurred over the past few decades. The study focuses on the long-term influences on biological productivity and fish stocks, revealing the crucial importance of the physical processes and of climate change. Evidence of decadal and

interdecadal regimes resulting in a rise in productivity in the 1980s is presented. Anthropogenic effects upon the ecosystem are linked to physical and biological factors.

MATERIALS AND METHODS

Three types of time-series data were used to explore the environmental variations—hydroclimatic, biological, and anthropogenic (Table 1). The hydroclimatic series had the best temporal resolution (monthly data). The data were derived from COADS (Comprehensive Ocean-Atmosphere Data Set: Woodruff et al. 1987) together with published marine environment monitoring data (sources given in Table 1). The biological series was generally of lower quality than the hydroclimatic series (lower resolution, missing values), but was the best series available to indicate changes in the system over time. It was difficult to describe anthropogenic influences by means of an historical time-series, because many studies give only mean values, or qualitative or semi-qualitative information (e.g. Faschuk et al. 1991, Bologa et al. 1995, Zaitsev & Mamaev 1997). As with the biological series, the best available data were included in this study.

Changes in time-series data can result from a combination of the influences of different processes. Temporal patterns could contain signatures of global and local influences, long-term trends, low-frequency cycles, and seasonality (Durand & Mendelssohn 1998). The original time-series can be decomposed empirically through a procedure of repeated fitting and the removal of components of different periodicity (Cleveland 1993). The observed series (Y_t) can be represented as a sum of non-stationary, unobserved components: seasonal (S_t), non-linear trend (T_t), $1...p$ oscillatory components ($O_{t1}...O_{tp}$), and stationary residuals (R_t):

$$Y_t = S_t + T_t + \sum_{j=1}^p O_{tj} + R_t$$

Each component can be consecutively fitted and subtracted from the series, the analysis continuing on the residuals (Cleveland 1993). First the seasonal component is filtered out, followed by the long-term trend and oscillatory components. With all regular components extracted, residuals must be stationary.

Repeated LOESS fitting was applied for visualising and exploring the time-series. Locally weighted regression or LOESS is a flexible non-parametric method for fitting curves or surfaces to data (Cleveland et al. 1992). The degree of smoothness of the LOESS fit depends on 2 parameters: the neighbourhood span, e.g. 0.5 or 0.75, of the total number of observations, and

the degree of the weighted regression, fitted locally in the neighbourhood of each data point, e.g. linear or quadratic LOESS. Smaller neighbourhoods and quadratic LOESS give more flexible regression lines, but they are sensitive to non-systematic data variation, whereas larger neighbourhoods and linear LOESS give smoother regressions, but more bias. In the present study, I used quadratic LOESS, and a span dependent on the scale of the variation of interest. For example, for fitting ~10 yr periodicity in a 30 yr time-series, a span of 0.33 was applied. Smoothed lines (extracted regular components) can be assessed visually for patterns and the relative magnitude of variations can be compared. The goodness of fit was evaluated using an approximate *F*-test (Cleveland et al. 1992). Each LOESS fit was characterised by the approximate coef-

ficient of determination (r^2) and an equivalent number of parameters that was analogous to the number of parameters in the ordinary linear regression (Cleveland et al. 1992). An STL procedure (seasonal trend decomposition based on LOESS: Cleveland et al. 1990) was applied in modelling seasonality. After removing all regular components, residuals were tested for normality and trends.

The series dominated by long-term variability may present significant autocorrelation, which could violate the significance test of the correlation coefficient (Pyper & Peterman 1998). I used the 'modified Chelton method' (Pyper & Peterman 1998) to perform a significance Student's *t*-test on the Pearson correlation coefficients from autocorrelated series (only lag-1 autocorrelation was considered).

Table 1. Time-series data used in present study. COADS: Comprehensive Ocean-Atmosphere Data Set (Woodruff et al. 1987)

| Time-series Variable | Full description | Units | Source |
|-----------------------------|---|---------------------------|--------------------------------|
| Hydroclimatic series | | | |
| SSTW | Sea surface temperature, western Black Sea | °C | COADS |
| SSTE | Sea surface temperature, eastern Black Sea | °C | COADS |
| SSTO | Sea surface temperature, near Odessa | °C | Simonov & Altman (1991) |
| SSTB | Sea surface temperature, near Batumi | °C | Simonov & Altman (1991) |
| SLPW | Sea level pressure, western Black Sea | hPa | COADS |
| SLPE | Sea level pressure, eastern Black Sea | hPa | COADS |
| WINDW | Wind speed, western Black Sea | m s ⁻¹ | COADS |
| WINDE | Wind speed, eastern Black Sea | m s ⁻¹ | COADS |
| PRECIP | Total precipitation | km ³ | Simonov & Altman (1991) |
| RIVER | Total river inflow | km ³ | Nikolenko & Reshetnikov (1991) |
| Biological series | | | |
| PHYTOPW | ln phytoplankton biomass, western Black Sea | mg m ⁻³ | Prodanov et al. (1997) |
| PHYTOPE | ln phytoplankton biomass, eastern Black Sea | mg m ⁻³ | Prodanov et al. (1997) |
| ZOOPW | ln zooplankton biomass, western Black Sea | mg m ⁻³ | Prodanov et al. (1997) |
| ZOOPE | ln zooplankton biomass, eastern Black Sea | mg m ⁻³ | Prodanov et al. (1997) |
| NOCTILW | ln <i>Noctiluca scintillans</i> biomass, western Black Sea | mg m ⁻³ | Simonov et al. (1992) |
| NOCTILE | ln <i>Noctiluca scintillans</i> biomass, eastern Black Sea | mg m ⁻³ | Simonov et al. (1992) |
| PLEUROBW | <i>Pleurobrachia pileus</i> biomass, western Black Sea | mg m ⁻³ | Simonov et al. (1992) |
| PLEUROBE | <i>Pleurobrachia pileus</i> biomass, eastern Black Sea | mg m ⁻³ | Simonov et al. (1992) |
| AURELIA | Jellyfish <i>Aurelia aurita</i> biomass | t | Prodanov et al. (1997) |
| SPRAT | ln sprat <i>Sprattus sprattus</i> recruitment | n | Daskalov (1998b) |
| HORSEMACK | ln horse mackerel <i>Trachurus mediterraneus</i> recruitment | n | Prodanov et al. (1997) |
| ANCHOV | ln anchovy <i>Engraulis encrasicolus</i> recruitment | n | Prodanov et al. (1997) |
| WHITING | ln whiting <i>Merlangius merlangus</i> recruitment | n | Daskalov (1998b) |
| TURBOT | ln turbot <i>Psetta maotica</i> recruitment | n | Prodanov et al. (1997) |
| SHAD | ln shad <i>Alosa kessleri</i> recruitment | n | Prodanov et al. (1997) |
| Anthropogenic series | | | |
| PHOSPH | Inorganic phosphorus loading, Vilkovo station, River Danube | t | Juravleva & Grubina (1993) |
| OX | Dissolved oxygen content at bottom, NW Black Sea | mg m ⁻³ | Simonov et al. (1992) |
| HYPOX | ln surface of bottom hypoxia zone, NW Black Sea | km ² | Zaitsev (1993) |
| HS150 | Mean content of hydrogen sulphide at 150 m | mg m ⁻³ | Ryabinin et al. (1991) |
| HS2000 | Mean content of hydrogen sulphide at 2000 m | mg m ⁻³ | Ryabinin et al. (1991) |
| TRANSP | Water transparency, central Black Sea | m | Vladimirov et al. (1997) |
| BLOOM | ln phytoplankton density during blooms, western Black Sea | no. cells l ⁻¹ | Moncheva & Krastev (1997) |
| PHYLOPH | Red algae <i>Phyllophora</i> sp. biomass, NW Black Sea | t | Prodanov et al. (1997) |
| MYTILUS | Black mussel <i>Mytilus galloprovincialis</i> biomass, NW Black Sea | t | Zolotarev et al. (1995) |

Principal components analysis (PCA: Lebart et al. 1995) was applied to explore long-term patterns in multiple series. PCA reveals the dominant correlation structure in data and reduces the number of variables to a few independent (orthogonal) principal components (PCs), which are linear combinations of the original variables. The newly derived PCs are non-correlated artificial variables accounting for the general long-term patterns in input variables. The initial variables are correlated to the PCs in that they share long-term patterns described by the PCs.

PCA was applied to the period 1960 to 1993, for which there was best data coverage for all series. Data were tested for normality using the Kolmogorov-Smirnov test (Scherrer 1984) and series not conforming to the normal distribution were logarithmically transformed (Table 1). Series analysed by PCA were detrended to discard external influences (e.g. effect of fishing), and standardised (zero mean, unit variance) to assure equal weight of all series; missing data were replaced by mean values for the series' (zeros in standardised series). The missing values replaced by zeros may potentially bias the PC scores by forcing the estimates closer to zero. An alternative approach for missing values could be to fit an autoregressive (AR) model and then replace the missing data with predictions from the model. Some of the series were however too short to apply the AR approach, which also can introduce spurious patterns. Replacing the missing values by the series' mean (zero) seemed to be the more cautious approach, and was thus followed here. This approach was also used by Hare & Mantua (2000) for North Pacific data. The preliminary analyses, done separately on different sets of data of similar length (Daskalov 1998a), showed temporal patterns of the PC scores similar to those obtained with the PCA performed for the whole set of variables.

RESULTS

Major patterns of variability were apparent on seasonal (for hydroclimatic series), interannual (~1 to 5 yr), decadal (~10 to 12 yr), and interdecadal (~20 to 30 yr) scales. In the present paper, only long-term patterns were analysed. Seasonal and interannual patterns, as well as detailed LOESS, spectral, and correlation analyses have been presented elsewhere (Daskalov 1998a).

Fig. 1 shows the original data series and non-linear trends fitted by LOESS. The LOESS regressions were adjusted to decadal and longer-term variability, i.e. residual, seasonal, and interannual variations were filtered out from the fitted lines. In order to make visual comparison easier, the time period in Fig. 1 was limited

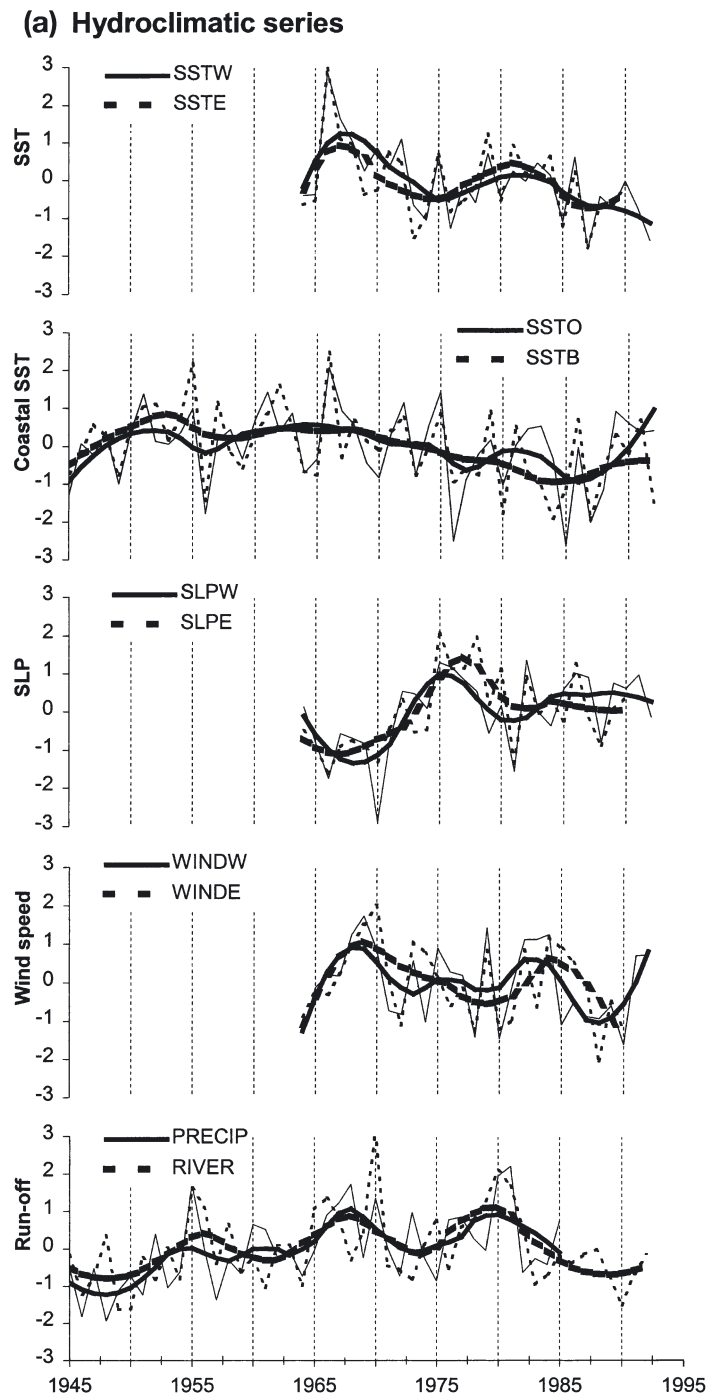


Fig. 1. Time-series—(a) Hydroclimatic, (b) biological, (c) anthropogenic—and non-linear trends fitted by LOESS. Data are standardised (zero mean, unit variance). Abbreviations as in Table 1

to 1945 to 1995. Thus, the earliest years of the longest series (SSTO, SSTB, PRECIP, RIVER) are not shown, but were included in the regression analyses (Table 2). There were significant negative linear trends for SST, wind, zooplankton, oxygen, transparency, *Phyllophora* and *Mytilus* data. The SLP, river inflow, HS2000 and

most of the biological series exhibited positive trends (Table 2).

In many series the LOESS fit explained a significant part of the variability (Table 2). Coefficients of determination were not high in hydroclimatic series, because variance was larger in monthly de-seasonalised data. A decadal signal was very clear in most of the series, especially in SST, SLP, wind and run-off (Fig. 1a), *Pleurobrachia pileus* and fish recruitment (Fig. 1b), and phosphorus, hypoxia and hydrogen sulphide (Fig. 1c). Interdecadal (~20 to 30 yr) regimes are distinguishable in coastal SST data (SSTO, SSTB), and the biological, transparency and BLOOM series.

Most of the results indicate coherent long-term patterns in the physical, biological and anthropogenic series (Table 3, Fig. 2). Temperature (SST) was positively correlated to zooplankton and *Noctilica scintillans*, and negatively correlated to phytoplankton, *Pleurobrachia pileus*, and fishes (except the shad *Alosa kessleri*). Atmospheric pressure (SLP) was positively correlated with fish recruitment. Shad are anadromous, and their reproductive success is dependent upon river run-off, which explains their positive

(b) Biological series

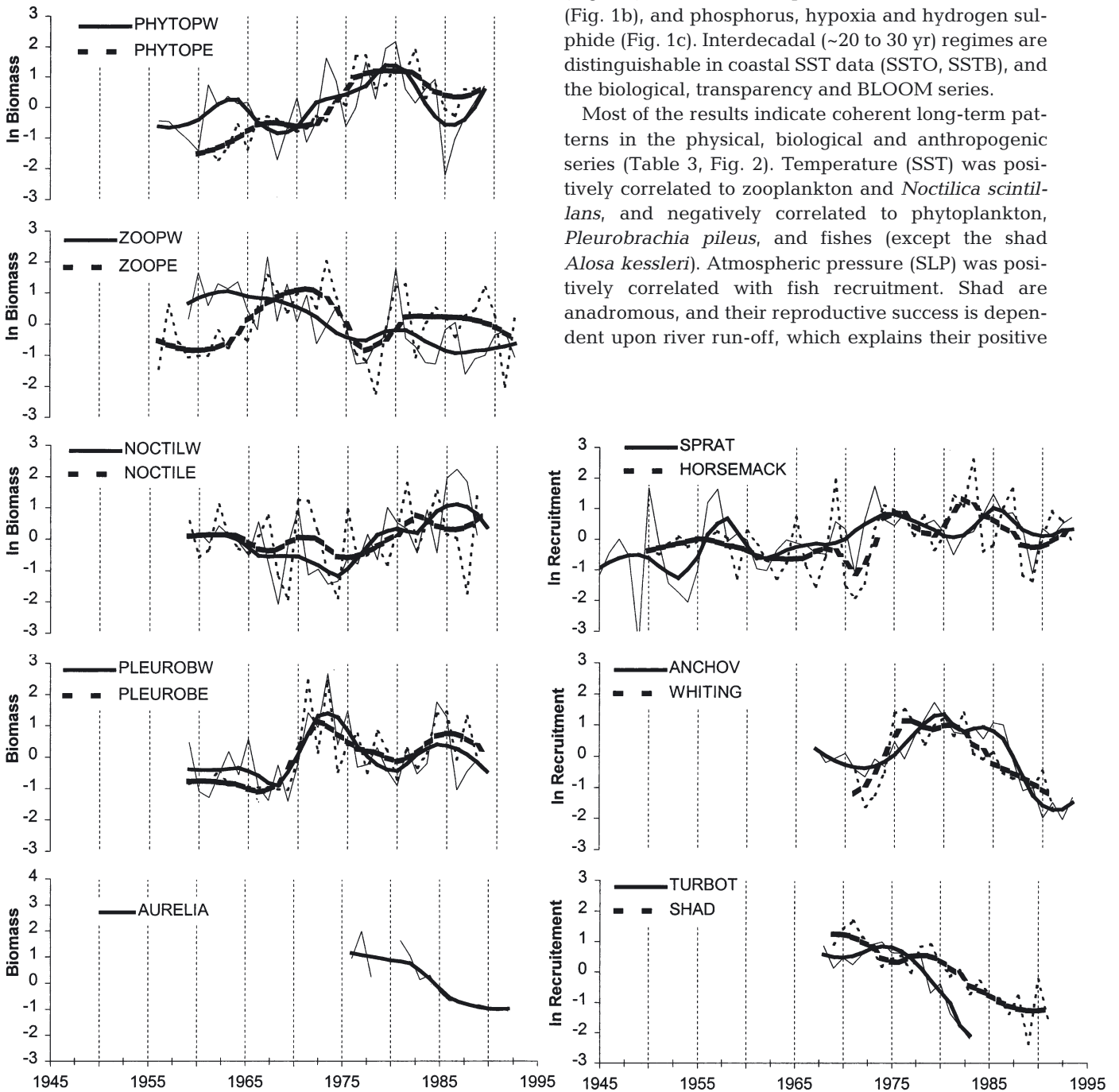


Fig. 1 (continued)

correlation with SST and RIVER. Higher run-off also appeared to favour anchovy and whiting reproductive success (positive correlation with RIVER: present Table 3a and Daskalov 1999).

There were significant cross-correlations between the hydroclimatic and anthropogenic series (Table 3b): positive = SST with oxygen, hypoxia, transparency and *Phylophora* sp.; negative = SLP with hydrogen sulphide (HS150); negative = wind with hypoxia; positive = run-off with phosphorus input, hypoxia and hydrogen sulphide (Table 3b, Fig. 2). Therefore, the effects attributed mainly to anthropogenic impact also seem to depend strongly on natural forces. Phosphorus input clearly depends on river inflow; hypoxia develops from dead organic matter in stagnant (less aerated) water and is related to run-off (nutrient and organic input) and stratification (run-off, SST, water density, turbulence, wind stress); hydrogen sulphide production in anoxic conditions is influenced by the same factors as hypoxia.

Comparison of the anthropogenic and biological series (Table 3c) helped elucidate the distinction between natural and human-induced effects on the ecosystem. Phosphorus input seemed to have a positive effect (positive correlation) on phytoplankton, *Noctiluca scintillans*, anchovy and whiting, and a negative effect on *Pleurobrachia pileus* and turbot. High phytoplankton biomass seemed to contribute to the oxygen deficit on the bottom (OX negatively, HYPOX positively correlated with phytoplankton). Hypoxia tended to negatively influence *P. pileus*, sprat and turbot (the latter was positively correlated with OX). Transparency was negatively related to BLOOM, because plankton and dead organic matter mainly contribute to water turbidity (Fig. 2). Transparency was positively and BLOOM negatively related to zooplankton, turbot and shad. *N. scintillans* abundance was positively correlated with PHOSPH and BLOOM, and negatively correlated with PHYLOPH and MYTILUS, and abundance of *N. scintillans* in itself could be indicative of ecosystem degradation (Zaitsev 1993).

The principal components analysis revealed main long-term patterns in multiple time-series data. The first 2 PCs explained ~16 and ~13% respectively of the total variance in the data, whereas all other PCs explained <9% of the total variance (Fig. 3). The first PC accounts for the decadal (~10 yr) variation, displaying 2^{1/2} decadal cycles with respective maxima around the early 1970s, 1980s and 1990s (not completed), and minima around 1965, 1975, and 1985 (Fig. 2).

(c) Anthropogenic series

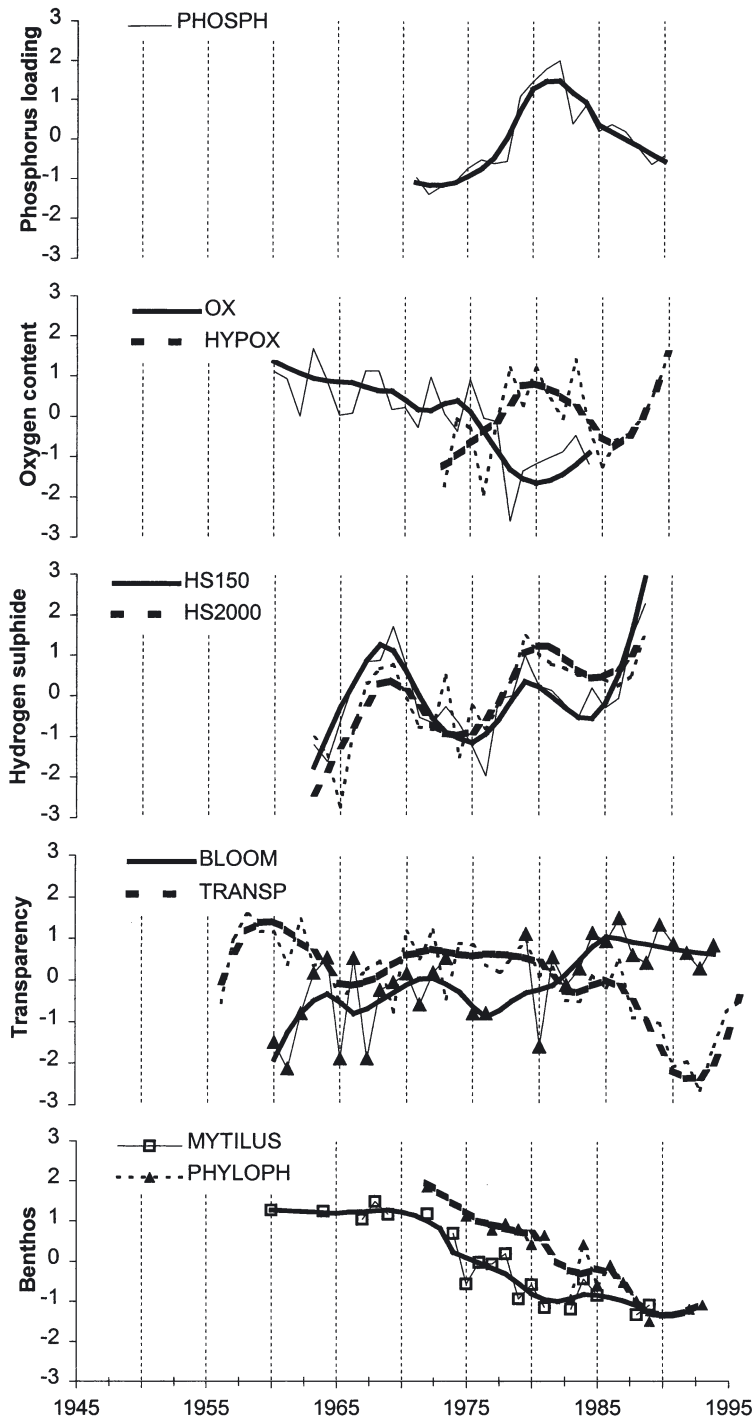


Fig 1. (continued)

Table 2. Results of the linear and non-linear (LOESS) fits of environmental variables against time. Coefficients significant at ** $p < 0.01$ and * $p < 0.05$. No.yr/no.obs.: no. of years/no. of observations; Slope: slope of linear regression; r^2 : coefficient of determination of linear regression; r^2 LOESS (P): coefficient of determination of LOESS fit (P: no. of parameters, as explained in 'Materials and methods'). Abbreviations as in Table 1

| Time-series Variable | Period | No. yr/no. obs. | Slope | r^2 | r^2 LOESS (P) |
|-----------------------------|-----------|-----------------|-----------|--------|-----------------|
| Hydroclimatic series | | | | | |
| SSTW | 1964–1992 | 29/348 | −0.031** | 0.08** | 0.14** (7) |
| SSTE | 1964–1990 | 27/324 | −0.02** | 0.03** | 0.09** (6.5) |
| SSTO | 1915–1992 | 78/936 | −0.003 | 0 | 0.05** (13) |
| SSTB | 1925–1992 | 68/816 | −0.011** | 0.03** | 0.12** (14) |
| SLPW | 1964–1992 | 29/348 | 0.056** | 0.03** | 0.08** (7) |
| SLPE | 1964–1990 | 27/324 | 0.057** | 0.03** | 0.10** (8.1) |
| WINDW | 1964–1992 | 29/348 | −0.008 | 0 | 0.09** (7) |
| WINDE | 1964–1990 | 27/324 | −0.026* | 0.02* | 0.10** (6.5) |
| PRECIP | 1923–1985 | 63/756 | 0.06** | 0.01** | 0.04** (13.6) |
| RIVER | 1923–1985 | 63/756 | 0.013 | 0 | 0.15** (14.9) |
| Biological series | | | | | |
| PHYTOPW | 1956–1989 | 34 | 0.015 | 0.07 | 0.55* (9.5) |
| PHYTOPE | 1960–1988 | 29 | 0.094** | 0.56** | 0.86** (8.5) |
| ZOOPW | 1959–1992 | 34 | −0.035** | 0.43** | 0.62** (9.5) |
| ZOOPE | 1956–1992 | 37 | 0.005 | 0.02 | 0.55* (10.3) |
| NOCTILW | 1959–1988 | 30 | 0.035* | 0.14* | 0.54* (7.9) |
| NOCTILE | 1959–1988 | 30 | 0.006 | 0.01 | 0.21 (8.1) |
| PLEUROBW | 1959–1988 | 30 | 0.923 | 0.04 | 0.51* (7.9) |
| PLEUROBE | 1959–1988 | 30 | 5.00** | 0.26** | 0.57* (7.9) |
| AURELIA | 1976–1992 | 15 | −3.16** | 0.76** | 0.79** (4.6) |
| SPRAT | 1945–1993 | 49 | 0.023** | 0.18** | 0.52* (13.4) |
| HORSEMACK | 1950–1993 | 44 | 0.02 | 0.08 | 0.42 (13) |
| ANCHOV | 1967–1993 | 27 | −0.021 | 0.13 | 0.92** (7.7) |
| WHITING | 1971–1993 | 21 | 0.013 | 0.06 | 0.78** (6.6) |
| TURBOT | 1968–1983 | 16 | −0.12 | 0.59** | 0.94** (4.8) |
| SHAD | 1969–1991 | 23 | −0.09 | 0.76** | 0.82** (6.6) |
| Anthropogenic series | | | | | |
| PHOSPH | 1971–1990 | 20 | 1.81 | 0.18 | 0.9** (5.8) |
| OX | 1956–1984 | 25 | −0.151** | 0.54** | 0.62** (6.2) |
| HYPOX | 1973–1990 | 18 | 0.048 | 0.12 | 0.57* (4.9) |
| HS150 | 1963–1988 | 26 | 0.002 | 0.09 | 0.86** (7.1) |
| HS2000 | 1963–1988 | 26 | 0.038** | 0.40** | 0.74** (6.5) |
| TRANSP | 1956–1995 | 40 | −0.206** | 0.44** | 0.80** (10.8) |
| BLOOM | 1960–1994 | 35 | 6.54** | 0.21** | 0.56* (9.7) |
| PHYLOPH | 1972–1993 | 16 | −65.9** | 0.82** | 0.93** (6.3) |
| MYTILUS | 1960–1989 | 19 | −222.08** | 0.59** | 0.95** (8.5) |

These roughly correspond to decadal cycles in SST, wind, run-off, *Noctiluca scintillans* abundance, phosphorus, hypoxia, hydrogen sulphide and BLOOM, all of which exhibited higher correlation with PC1 (Figs. 1 & 2). Decadal cycles inverse to the pattern in PC 1 (and correspondingly highest inverse correlations) were evident for SLP, *Pleurobrachia pileus*, sprat and turbot.

The second PC was positively correlated with SLP, river run-off, phytoplankton, horse mackerel, anchovy, whiting, phosphorus and hypoxia; and negatively correlated with zooplankton, *Pleurobrachia pileus*, BLOOM and *Mytilus galloprovincialis*. These were the components contributing most to the overall pattern in PC 2. The time trajectory of PC 2 accounted for the interdecadal (~20 yr) variation, displaying 1 complete cycle starting in the late 1960s to early 1970s and ending by the late 1980s to early 1990s, with a maximum

about 1980. The temporal pattern of this PC may illustrate a long-term regime shift in environment and ecosystem productivity.

Correlations and hypotheses about underlying causality must be interpreted with caution: some of the series are too short, often of different time spans, and may be strongly autocorrelated or have a trend over time caused by different processes. Final interpretation was based on evidence of multiple consistent patterns.

DISCUSSION

Coherency in the hydroclimatic series revealed the importance of global climatic factors in influencing physical characteristics and circulation in the Black Sea. As the Black Sea is a virtually closed basin, such

Table 3. Pearson cross-correlations, significant at $p < 0.05$, between hydroclimatic, biological, and anthropogenic series. (df corrected for autocorrelation used in significance tests)

| (a) Hydroclimatic vs biological series | | | | | | | | | | |
|---|------------|------------|------------|------------|------------|------------|------------|------------|-----------|------------|
| | SSTW | SSTE | SSTO | SSTB | SLPW | SLPE | WINDW | WINDE | PRECIP | RIVER |
| PHYTOPW | | | | | | | | | | |
| PHYTOPE | | | -0.40 (24) | -0.48 (27) | 0.44 (15) | 0.51 (15) | | | | |
| ZOOPW | | | | 0.29 (31) | | | | | | |
| ZOOPE | | | | | -0.46 (21) | -0.61 (20) | | | 0.37 (20) | |
| NOCTILW | | | | | | | | | | 0.35 (21) |
| NOCTILE | 0.34 (22) | 0.39 (23) | | | -0.34 (22) | | | | | |
| PLEUROBW | | | | | | | | | | |
| PLEUROBE | -0.39 (20) | | -0.39 (26) | -0.33 (27) | | | | | | |
| AURELIA | | | | | | | | | | 0.54 (10) |
| SPRAT | -0.34 (24) | -0.47 (24) | | -0.32 (31) | 0.34 (23) | | | | | |
| HORSEMACK | -0.37 (24) | | | -0.29 (31) | 0.35 (23) | | | | | |
| ANCHOV | | | | | | | | | | 0.48 (16) |
| WHITING | | | | | | 0.50 (12) | | | | 0.64 (13) |
| TURBOT | | | | | | | | | | |
| SHAD | 0.47 (17) | | | | | | | | | 0.41 (15) |
| (b) Hydroclimatic vs anthropogenic series | | | | | | | | | | |
| | SSTW | SSTE | SSTO | SSTB | SLPW | SLPE | WINDW | WINDE | PRECIP | RIVER |
| PHOSPH | | | | | | | | | | 0.46 (13) |
| OX | | | | 0.38 (23) | | | | | | |
| HYPOX | | | 0.56 (16) | | | | | -0.53 (15) | | |
| HS150 | | | | | -0.43 (16) | | | | 0.41 (16) | 0.39 (18) |
| HS2000 | | | | | | | | | | |
| TRANSP | 0.43 (22) | | | 0.36 (31) | | | | | | |
| BLOOM | | | | | | | | | | |
| PHYLOPH | 0.62 (15) | 0.57 (15) | | 0.39 (19) | | | | | | 0.46 (12) |
| MYTILUS | | | | | | | | | | |
| (c) Biological vs anthropogenic series | | | | | | | | | | |
| | PHOSPH | OX | HYPOX | HS150 | HS2000 | TRANSP | BLOOM | PHYLOPH | MYTILUS | |
| PHYTOPW | | -0.50 (17) | 0.44 (13) | | | | | | | |
| PHYTOPE | 0.60 (7) | -0.60 (12) | | | 0.47 (13) | | | | | -0.49 (13) |
| ZOOPW | | 0.43 (16) | | | | | | | | 0.49 (18) |
| ZOOPE | | | | | | 0.37 (21) | -0.59 (27) | | | |
| NOCTILW | 0.60 (9) | | | | | | 0.43 (23) | -0.65 (8) | | -0.48 (17) |
| NOCTILE | | | | | | | | | | -0.60 (27) |
| PLEUROBW | -0.53 (10) | | | | | | | | | -0.48 (24) |
| PLEUROBE | | | -0.56 (12) | | | | 0.35 (24) | | | -0.69 (24) |
| AURELIA | | | | | | 0.84 (12) | | 0.78 (6) | | |
| SPRAT | | | -0.62 (14) | | | | | | | |
| HORSEMACK | | | | | | | | | | |
| ANCHOV | 0.58 (7) | -0.68 (8) | | | | 0.68 (12) | | | | |
| WHITING | 0.56 (8) | | | | | | -0.51 (15) | | | |
| TURBOT | -0.80 (4) | 0.56 (8) | | | | | | 0.82 (4) | | |
| SHAD | | | | | | 0.63 (11) | -0.52 (17) | 0.90 (8) | | 0.49 (11) |

global influences are mainly attributable to atmospheric transfer or riverine inflow. The latter has been demonstrated as a significant factor for the overall water balance and basin-scale circulation (Simonov & Altman 1991, Oguz et al. 1995). Low-frequency signals of similar periodicity (interdecadal, decadal, interannual) have also been found in other marine areas, and their causes and propagation have been explained by

interactive ocean-atmosphere processes (Polonsky & Voskresenskaya 1996, White et al. 1997, White & Cayan 1998). The main possible sources of such variability in the Black Sea are atmospheric teleconnections with the Atlantic (Polonsky et al. 1997).

The long-term trends in the time-series of phytoplankton, *Noctiluca scintillans*, *Pleurobrachia pileus*, sprat, horse mackerel, anchovy and whiting accounted

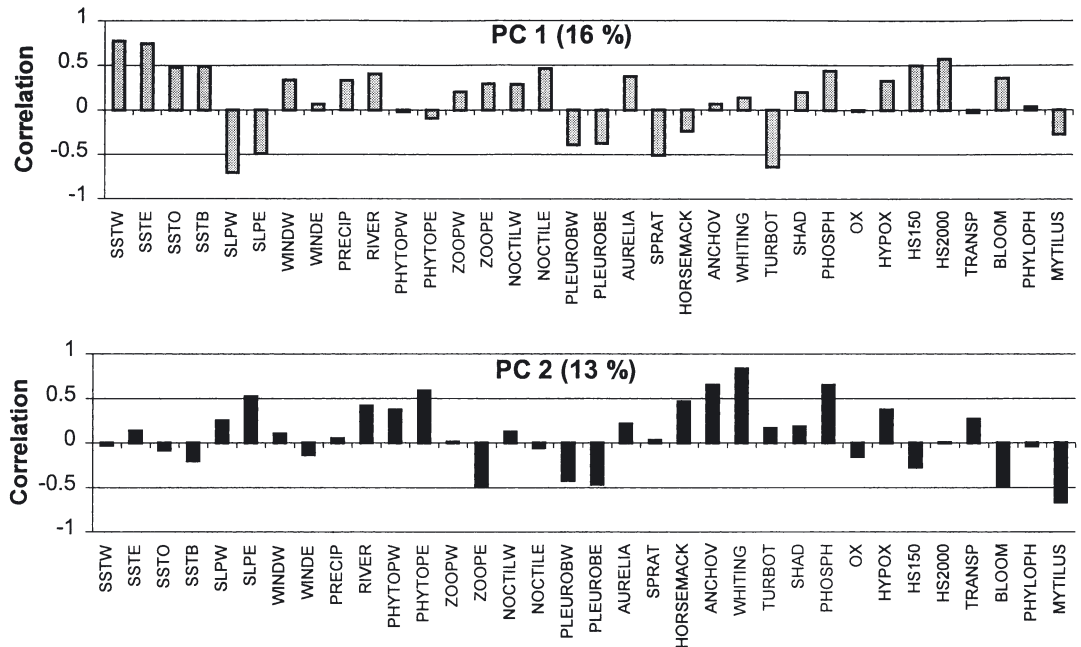
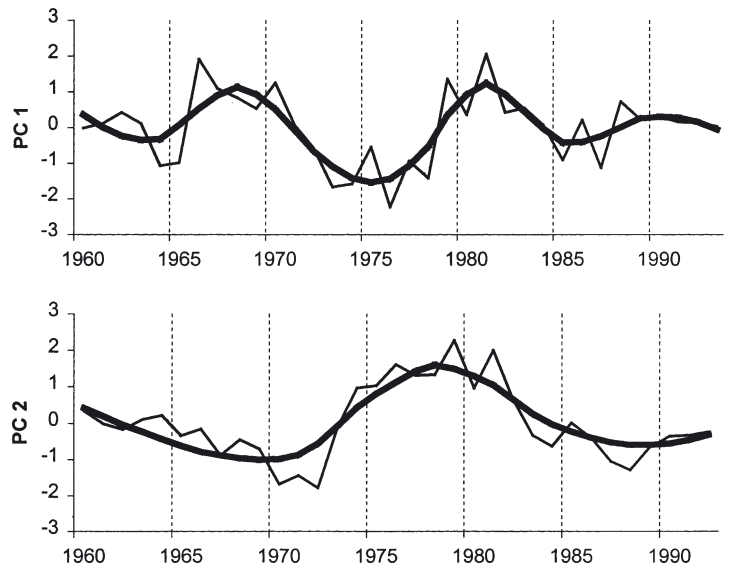


Fig. 2. Principal components analysis of hydroclimatic, biological and anthropogenic variables. Correlations (PC loadings) of the input variables with the first 2 principal components (PC1, PC2) are given in the upper panels, and PC scores against time in the lower panels

for a general increase in biological production during the 1970s and 1980s that could be related to variation in hydroclimate. A long-term decline in SST after 1965 may be responsible for increased upper-layer instability and convection (most important in winter). This process intensifies divergence (upwelling) and mixing in the central zone and over the shelf (Ovchinnikov & Popov 1987), leading to enrichment of nutrients in the photic layer. An increase in run-off, which peaked around 1980, may also have favoured increased productivity. By the end of the 1980s, the favourable conditions appear to have ended: run-off and wind forcing decreased, temperature increased. Zooplankton biomass was positively correlated with SST and exhibited an inverse trend with respect to phytoplankton and pelagic fishes. This may be related to a temperature effect on zooplankton growth or have been caused by a trophic cascade effect of increased zooplanktivory by fishes and gelatinous zooplankters (Daskalov 2002). One consequence of the trophic cascade effect may be that a bottom-up influence (trend in increased productivity) can only be expressed at the controlled-resource (uneven) levels in the food web (Fretwell 1977, Daskalov 2002). Thus, increased productivity trends are to be expected for fishes and gelatinous zooplankters (Level 3) and phytoplankton (Level 1). Mesozooplankton (Level 2), however, being controlled by zooplanktivory (top-down control), would be expected to exhibit an opposite trend in the productivity gradient. Assuming that lower temperature and higher run-off favour a rise in productivity, the results of this study (Figs. 1 & 2, Table 3) seem to agree with the predictions of the trophic cascade hypothesis. Jellyfish *Aurelia*



aurita decreased after 1985, and this has been related to mass development of the alien ctenophore *Mnemiopsis leidyi* (Grishin et al. 1994). Correlations between fish recruitment and physical variables in the Black Sea have been well documented (e.g. Simonov et al. 1992, Prodanov et al. 1997, Daskalov 1999). Daskalov (1999) demonstrated significant relationships between the recruitment of several pelagic species and SST, river run-off and wind. The decrease in commercially important turbot and shad seems to be attributable mainly to overfishing (Prodanov et al. 1997). However, both anadromous shad and demersal turbot recruitment series were correlated with river run-off,

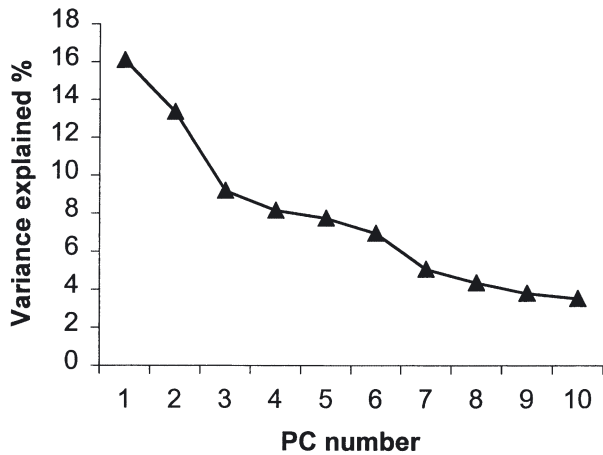


Fig. 3. Screen plot of variance (%) explained by the first 10 principal components

and were marked by a similar decadal pattern (Figs. 1 & 2). Moreover, the decrease in turbot corresponded with an increase in phosphorus and a decrease in bottom oxygen (Table 3c, Fig. 1).

It is difficult to explain the massive phytoplankton blooms and the rise in small pelagic fish abundance during the 1980s solely by the influence of natural factors. After 1970, phosphorus discharge increased, correlated with an increased hydrogen sulphide content and inversely correlated with the hypoxia extent (Figs. 1c & 2). Phosphorus, hypoxia and hydrogen sulphide indices showed ~10 yr variations similar to run-off (Fig. 1). There was a significant positive linear trend in deep-water hydrogen sulphide content (HS2000), but not in hydrogen sulphide at 150 m (HS150: Table 2). The deep-water hydrogen sulphide content (HS2000) is a more reliable index of hydrogen sulphide production, because in the deep anoxic zone the hydrogen sulphide is less exposed to oxidation. The other index (HS150) measures the hydrogen sulphide content at the break between the oxygenated and anoxic layers (the so-called oxygen-deficit zone) and could be influenced by vertical circulation and penetration of oxygenated water. The positive trend in HS2000 seems to confirm the hypothesis of an overall increase in hydrogen sulphide production in the sea (Bryantzev et al. 1988, Ilichenko & Sorokin 1991). The correlation of some anthropogenic indices (PHOSPH, BLOOM, PHYLOPH, MYTYLUS) with *Noctiluca scintillans* confirms the importance of the latter as an indicator of anthropogenic influence. *Pleurobrachia pileus*, sprat and turbot were negatively affected by anthropogenic factors (Table 3, Fig. 2). These organisms are distributed deeper and may be affected by oxygen depletion and hydrogen sulphide concentration.

Interactions between physical, biological and anthropogenic factors result in feedbacks amplifying the

original signals. Thus, in most cases overfishing can be associated with a natural decreasing trend in abundance (e.g. Fig. 3 of Pauly et al. 2002). Environmental degradation (hypoxia, hydrogen sulphide production) can worsen the conditions for recruit survival, leading to stock collapse, as in the case of Black Sea turbot. Another example of interactions between natural and anthropogenic factors creating several feedbacks is the well-documented invasion of the Black Sea by *Mnemiopsis leidyi* (Shiganova 1998) and its consequences for fish stocks. In the 1980s, the system was dominated by small pelagic fishes and the jellyfish *Aurelia aurita* (Fig. 1b). The boom of *M. leidyi* in 1989 and 1990 (Shiganova 1998) corresponded with a decrease in abundance of most fish stocks (Fig. 1b). The causes of the exact timing of the *M. leidyi* onset are not clear, but decreased planktivory caused by low abundance of overexploited fish stocks may be one of them (Grishin et al. 1994, Prodanov et al. 1997). The fast development of *M. leidyi* in subsequent years led to a great decrease in zooplankton and strong competition for food with fishes and aboriginal jellyfishes (Grishin et al. 1994, Shiganova 1998). It is possible that the fishery collapse is not the only large negative consequence of the *M. leidyi* invasion, but that massive phytoplankton blooms by the late 1980s to early 1990s (BLOOM; Yunev et al. 2002; A. Grishin, Southern Scientific Research Institute of Fisheries & Oceanography, Kerch, Ukraine, unpubl. data) can be associated with a decrease in zooplankton grazing and a trophic cascade similar to that of the 1970s to 1980s (Daskalov 2002).

Empirical analyses alone cannot reveal the causes of changes, but they do allow the formulation of hypotheses concerning the relationships between the abiotic environment, productive processes and population dynamics. The physical environment is recognised as the main factor driving biological productivity and influencing essentially all processes in the sea. Biological interactions and anthropogenic impact were responsible for another part of the observed variability in environmental series. The interaction between hydroclimatic, biological and anthropogenic factors generated synergistic responses by the marine ecosystem, resulting in the temporal patterns examined here. Climate regimes, determined by long-term changes of the physical properties and processes in the marine environment, provide the framework for a whole range of ecosystem, productivity and economical circumstances covering decades. A thorough understanding of the specific influences of diverse factors and scales is needed for reliable assessment and management of the marine environment and living resources (Rice 2001). The results given here can facilitate the integration of reliable environmental indices in the procedures of ecosystem-based fisheries modelling and forecasting.

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