FLUCTUATIONS OF PELAGIC SPECIES OF THE OPEN BLACK SEA DURING 1980-1995 AND POSSIBLE TELECONNECTIONS

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Abstract

The drastic changes in the Black Sea ecosystem, i.e. the harsh decline of the Black Sea fishery in 1989 and the dramatic changes in the zooplankton were often related to the outburst of the accidentally introduced ctenophore *Mnemiopsis leidyi* and to other man made events, such as pollution, eutrophication, regulation of river outflows (irrigation, damming) and overfishing. Beginning with the question as to why such changes in the Black Sea ecosystem occurred specifically at the end of the 1980s, the fluctuation of zooplankton stocks in other regions of the world are reviewed and compared with the changes in the Black Sea ecosystem. It transpires that changes in the zooplankton community and in small pelagic fish stocks in the second half of the 1980's until the beginning of the 1990s were evident in all seas under consideration. These changes were discussed in connection with changes in the climatic regime. Striking changes were observed in the NAO (North Atlantic Oscillation), SO (Southern Oscillation), ENSO (Southern Oscillation (El Niño Index), and ALPI (Aleutian Low Pressure Index) in the second half of the 1980s resulting in changes of the hydrological and meteorological regime (river run off, salinity, sea- and air temperature, atmospheric pressure, precipitation and strength of westerly winds) in the northern hemisphere. It is concluded (hypothetically), that possibly, changes in the weather regime during the 1980s could have triggered the changes in the phyto- and mesozooplankton communities of the Black Sea, which caused the conditions for the outburst of *M. leidyi* and the decline of the anchovy stock.

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1. Introduction

The ecosystem of the Black Sea has undergone dramatic changes, starting in the 1960s. These changes became very obvious due to the spectacular mass development of the accidentally introduced ctenophore *Mnemiopsis leidyi* during 1988-1990 and the collapse of the anchovy fishery in 1989 [1, 2, 3, 4, 5, 6, 7, 8]. During the same period, at the end of the 1980s and beginning of the 1990s, severe changes in the phytoplankton and mesozooplankton composition and a sharp decrease in the total zooplankton biomass became obvious [9, 10, 11, 12]. Gradual changes in the biomass and species composition of the phyto- and zooplankton had already been observed during the 1970s. Blooms of small algal species became very frequent and the former dominant valuable fodder zooplankton species were replaced for the most part by small species, which did not provide good quality fodder for higher trophic levels [13, 14]. Since 1992 however, the Black Sea ecosystem has shown positive signs of recovery [15]. The zooplankton biomass has increased slightly whilst the number of *Mnemiopsis leidyi* has decreased to a moderate level and the total Black Sea anchovy catch in 1995 was 400,639 tonnes, nearly at the same level as it was in the good period of the mid 1980s (449581 tonnes) [16].

The decrease in biomass and changes in the species composition of the plankton and fishes, especially in coastal areas since the 1960s, were related to the increasing chemical and oil pollution, eutrophication, and other anthropogenic impacts such as dumping, dredging, and damming of the rivers [4, 14, 17, 18]. In particular the eutrophication of the northern shelf areas had far reaching effects on the benthic and pelagic communities and fish stocks [6, 14]. The northwestern shelf was the most productive area of the Black Sea and the most important feeding and nursery ground of the commercially exploited Black Sea fish stocks [19]. This means that fish larvae in their most sensitive stages, the, have to grow up in the most polluted and highly eutrophic area of the Black Sea, leading to high mortality of the young fishes. Since most of the commercially exploited Black Sea fish stocks are migrating species with feeding and spawning areas in the northern Black Sea and overwintering at the southern Turkish coasts, negative recruitment affects the entire Black Sea fishery.

The sudden and drastic changes in the mesozooplankton community and the decline of the anchovy stock during 1989/1990 were related, besides the ongoing anthropogenic impacts, to two main reasons; the impact of the mass development of *Mnemiopsis leidyi*, and the overfishing. One of the most striking causes for the drastic changes in the zooplankton composition may be the mass development of the new invader *Mnemiopsis leidyi* during 1988-90. The sharp decrease in the zooplankton biomass, and the sharp decline in anchovy eggs and larvae, reflecting the collapse in anchovy catches for the entire Black Sea in 1989, coincided with the mass development of the new invader *Mnemiopsis* which appeared in 1988. Laboratory experiments and in situ mesocosm studies on the predation and relative predation potential of *Mnemiopsis* showed that *Mnemiopsis* is an important predator of zooplankton, anchovy eggs and larvae (especially of yolk-sac larvae) [20, 21, 22, 23, 24, 25, 26]. *Mnemiopsis* could, therefore, be a threat to fishery year-class recruitment [27]. The high fecundity (an

average of 8000 eggs within 23 days) and the huge growth rates (up to daily doubling of the individual biomass) observed in this ctenophore could only be sustained by high feeding rates [28]. Since the seasonal bloom of *Mnemiopsis* starts as well in the mean spawning season of the anchovy in July/August and continues until late autumn [29], *M. leidyi* could decimate a high amount of fish larvae either by predation or due to food competition.

An argument for this theory is that the anchovy stock recovered after 1992, when the biomass of *Mnemiopsis* declined to moderate levels (Fig.1). However, in contradiction, during the mass development of *Aurelia aurita* during the 1970s (feeding on the similar prey organisms), which reached about the same biomass in terms of carbon as the *M. leidyi* bloom in 1989 [15], the impact to the anchovy stock was very little. This suggests that other factors played a role in the decline of the anchovy.

Overfishing could be seen as another reason for the decline of the Black Sea fish stock and changes in the entire ecosystem of the Black Sea [8, 30, 31, 32, 33]. Until now there has been no international management of the fish stocks of the Black Sea, of which anchovy is the most important. During winter the anchovy migrate from the northern Black Sea towards the warmer waters of the Turkish coast and form very dense schools in a narrow coastal band. Due to this schooling behavior the anchovy become extremely vulnerable to the Turkish fishing vessels, which since the mid 1980s have become very well equipped with sonar and purse seiners. Due to the intense fishing of the Turkish fishing fleet the size of the spawning stock was reduced to the extent, that not enough young fish were produced to ensure the survival of the future stock [31]. Gücü [31] concluded that the effects of over-fishing, especially that of Turkey at the end of the 1980s, should not be dismissed as a minor reason for the collapse of the anchovy fishery.

The question remains, why did the outburst of *Mnemiopsis leidyi* and the subsequent collapse of the anchovy fishery occur specifically at the end of the 1980s and not before or after? It could be assumed, that due to the man-made and natural environmental changes occurring since the end of the 1960s, the pelagic ecosystem was driven to an evermore unstable state with a changed prey-predator relationship, and that it required only a certain trigger for the outburst of *Mnemiopsis leidyi*, which was then favoured by the altered trophic structure. This trigger could be assumed to be a certain climatic signal, which occurred either during or at the end of the 1980s. In order to detect this signal we compared the long-term fluctuations of the plankton and anchovy of the Black Sea with fluctuations in different regions of the world, to discuss to which extent it is possible to link the fluctuation of species in the Black Sea and other seas to large-scale meteorological and hydrographical events.

2. Fluctuation patterns in the Black Sea and other seas

In order to detect similarities in the fluctuation patterns of different taxonomic groups in the Black Sea and in other seas, striking fluctuation patterns are listed and described. We focus mainly on events, which happened in the Black Sea at the end of the 1980s and the beginning of the 1990s. These patterns are compared with findings in other seas (Baltic Sea, North Sea, Atlantic, waters off California) and in European fresh water lakes (Lake Windermere; Great Britain, Bodensee; Germany,) and related to possible hydrographical and meteorological events.

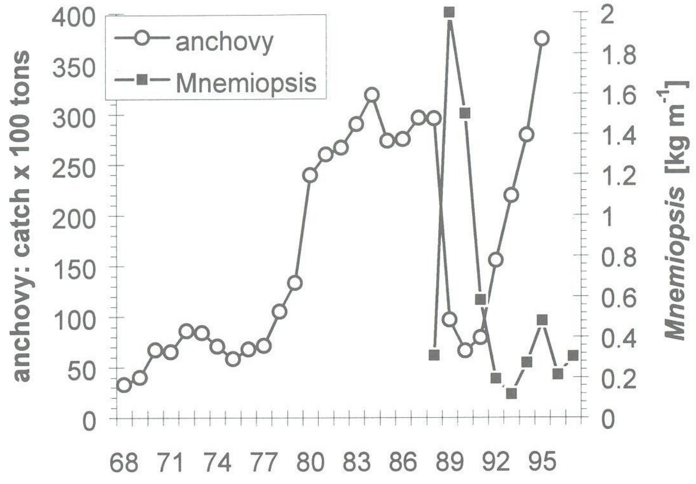

Figure 1: Black Sea 1968 - 1997: Turkish anchovy catch and *Mnemiopsis* biomass (wet weight). (Data on anchovy catch: State Statistical Institute, Turkey; data on *Mnemiopsis* (1988: Institute of Biology of the Southern Seas, IBSS, Ukraine; 1989-1990: Shirshov Institute, Russia; 1991-1997: Institute of Marine Sciences, Turkey)

2.1. OBSERVATIONS IN THE BLACK SEA

2.1.1. *Phytoplankton*

An increasing trend in the phytoplankton biomass was obvious since the beginning of the 1970s in the offshore regions of the Black Sea (see Mikaelyan, [34]). Especially after 1985, the phytoplankton biomass fluctuated, but at a steady high level. In 1989 however, the biomass was very low, but during the summer of 1990/91 very high biomasses were recorded in the open area of the Black Sea. The author analysed the fluctuation of the phytoplankton biomass in the open Black Sea in relation to the concentration of nutrients, (PO_4, NO_3, NO_2), to the fluctuation of zooplankton, to hydrodynamic features of the Black Sea and the winter air temperature. He concluded, that interannual oscillations of the average air temperature in winter are inversely related to the mean phytoplankton biomass in summer, indicating that the biomasses of the bulk of phytoplankton species are linked to the hydrodynamic processes in the Black Sea driven by climatic variations.

Changes in the species composition of the phytoplankton off the Bulgarian coast, were also obvious since 1970, when the biomass ratio of the two dominant phytoplankton groups (Bacillariophyta: Dinophyta) had undergone a dramatic change [35]. Up to 1970 the Bacillariophyta (diatoms) were dominant in terms of biomass (86 % of the total phytoplankton biomass). After 1970 the biomass of both groups displayed high oscillations indicating a period of instability. In subsequent years the biomass of the Dinophyta increased rapidly and became the dominant group in the Black Sea (1973-1974; 1978-1980; 1985-1988). Then from 1989-1993 the Bacillariophyta became dominant again (Fig. 2).

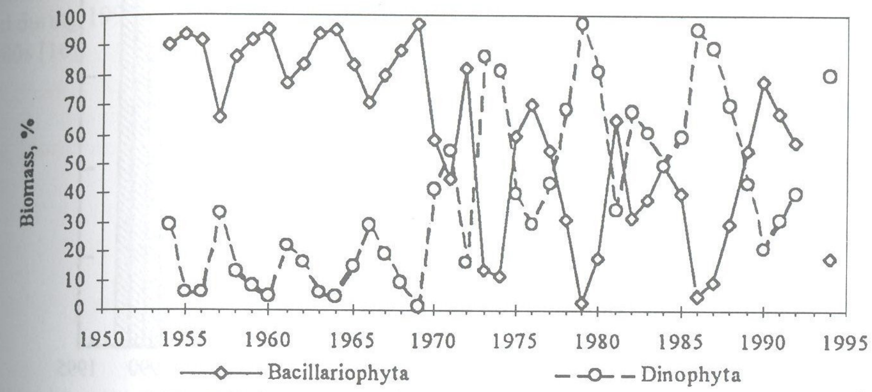

Figure 2. Black Sea 1954 - 1990. Long-term trend in Bacillariophyta : Dinophyta biomass ratio (redrawn from [32] and [36]).

An enhanced bloom of coccolithophores (mainly *Emiliana huxleyi*), with a biomass 1.5-2 orders of magnitude larger than in previous years, was observed in the Black Sea during 1989-1992 (Fig. 3; [37]. The mass occurrence of this species reduced the transparency of the sea water more than 3 fold from 21.3 to 6.2 m.

2.1.2. *Zooplankton*

The wet weight of the total zooplankton increased from the 1960s until 1990 due to mass developments of gelatinous organisms such as *Aurelia aurita* (1960s; 1970s, 1980s), *Noctiluca scintilans* (1980s, 1990s) and the new invader *Mnemiopsis leidyi* (since 1988). When the biomass of *M. leidyi* reached its climax during the end of the 1980s the biomass of *A. aurita* decreased. In the Black Sea *Mnemiopsis* showed the typical pattern of a new coloniser: After mass development in the years 1989 and 1990 with a biomass of 2 kg m^{-2} in the open sea and 4.7 kg m^{-2} at the north-western shelf [29], the numbers and biomass had dropped to a moderate level by 1991 and fluctuated till 1996 in the range of 0.2 - 0.5 kg m^{-2} [7, 10, 33]. After the decrease of *Mnemiopsis* in the summer of 1990 the biomass of *Aurelia* increased again and since the summer 1991 until 1994 the biomass of both species remained more or less at the same level [7].

Long-term series of the mesozooplankton biomass in coastal and offshore areas of the Black Sea, established by different Institutes displayed similar patterns. The composition of the zooplankton communities was different during the period before 1986 and after 1989-1992. One obvious point was the drastic decline of the mesozooplankton biomass by the end of the 1980s and beginning of the 1990s [9, 11, 12, 29, 33, 38].

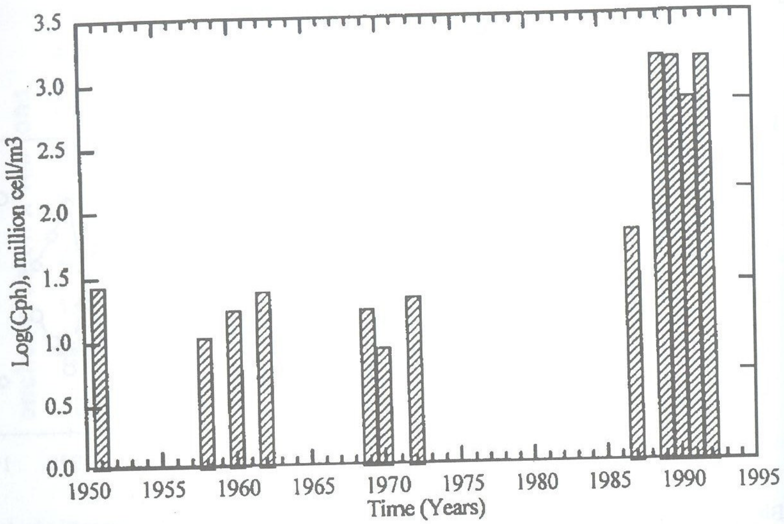

Figure 3. Phytoplankton concentration in the photic zone of the western deep part of the Black Sea during 1950 - 1992 (redrawn from [37]). The phytoplankton blooms consisted mainly of coccolithophorides (*Emiliana huxleyi*). Years without bars: no measurements.

Changes in the dominant species were already observed in Sevastopol Bay at the beginning of the 1980s. During 1960-1964 the percentage of *Acartia clausi* of the total copepod community was 17 %. This increased to over 30 % during 1981-1985, and during 1991-1994 rose to 75 %. Copepod species such as *Oithona nana*, *O. similis* and the cold water species *Pseudocalanus elongatus* and *Calanus euxinus*, which where dominant before the 1980s, decreased during the 1990s [11, 39]. The species *O. nana* was not observed from 1986-1997. In offshore areas the dominant species *Pseudocalanus elongatus, Calanus euxinus* and *Sagitta setosa* decreased about 10 fold and 100 fold respectively [15, 29]. Since 1993/1994 the biomass of the mesozooplankton has been increasing in all areas of the Black Sea [9, 11, 29, 33, 38]. And in 1995 the species *Oithona nana* appeared again in the zooplankton samples [39].

2.1.3. *Ichthyoplankton and anchovy*

In the early 1960s the number of anchovy eggs varied between 120-390 eggs m^{-2} in the Sevastopol area (From 1963 to 1986 no sampling was carried out.). In the 1980s egg and larval numbers were low compared to the 1960s. In 1989 a significant decline in the number of anchovy eggs and larvae occurred in inshore and offshore waters [6]. Since 1992 the number of eggs increased again and in July 1995 the average number of anchovy eggs in Sevastopol Bay were in the same range (180 m^{-2}) as the numbers found during the early 1960s (Fig. 4). Similarly, the highest egg and larval abundances for the anchovy of the southern Black Sea were obtained in the summer of 1996 [40]. Despite the high egg number, the number of larvae in the northern Black Sea was very poor during 1995/96 compared to the 1960s. The amount of larvae observed, compared to the egg numbers of *Engraulis encrasicolus* and *Trachurus mediterraneus* was 0.1-7% in 1995/96 whereas during the early 1960s this proportion was 30 to 50% [41].

The sharp decline in anchovy eggs and larvae at the end of the 1980s reflected the collapse in anchovy catches for the whole of the Black Sea which fell from 550,000 tonnes in 1988 to 180,000 tonnes in 1989. Since 1992 the anchovy stock has recovered and during 1995 the catch of anchovy was nearly as high as in the best period during the 1980s [16].

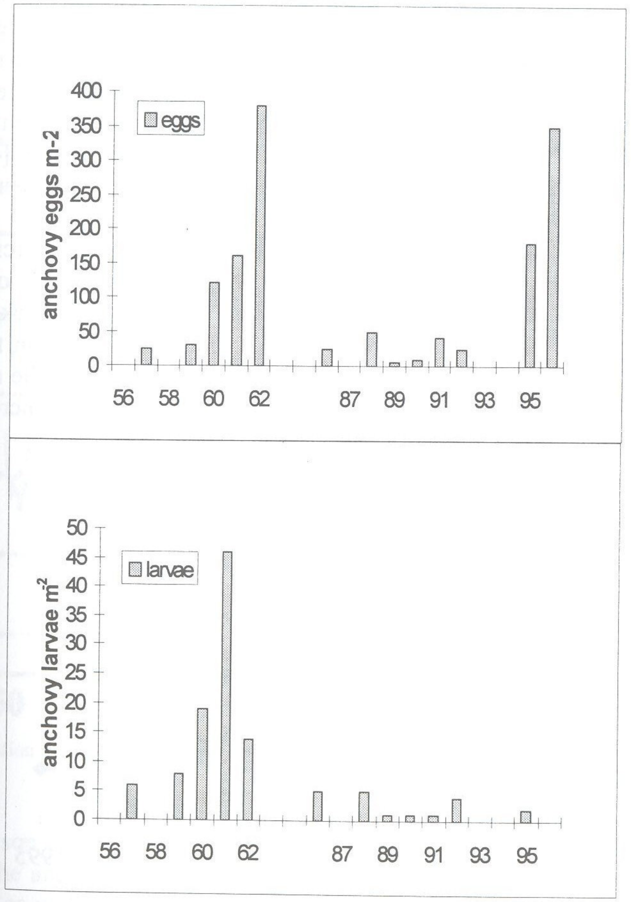

Figure 4. Black Sea: Fluctuations in the abundance of anchovy egg and larva (numbers m^{-2}) along the Crimean peninsula (1957-1996). ([6], and unpublished data of A. Gordina, IBSS, Sevastopol, Ukraine)

In summary, it is obvious that long-term data series established by different institutes in different areas of the Black Sea displayed a similar overall fluctuation pattern: high biomass in the 1970s, a decline in the biomass at the beginning of the 1980s, a rise in the biomass during the mid 1980s and a drastic decline at the end of the 1980s / beginning of the 1990s (Fig. 5). After 1993, the mesozooplankton biomass recovered and is continuing to display an increasing trend [9, 11, 12, 29, 33, 38].

2.2. FLUCTUATION PATTERNS IN OTHER SEAS

A comparison with long-term data series of other regions of the world showed similar fluctuation patterns in the zooplankton as seen in the Black Sea: high biomass in the 1970s, a decline in the biomass at the beginning of the 1980s, a rise in biomass during the mid 1980s and a drastic decline at the end of the 1980s / beginning of the 1990s and after 1993 an increasing trend. These trends in the zooplankton biomass or numbers were found as well in the open North East Atlantic (Fig. 6; [42], the waters off Iceland [43], in the North Sea (copepod numbers, [44, 45]) in the waters off California (Fig. 7; [46]), and in fresh water lakes, namely Lake Windermere; Great Britain [47] and in the Bodensee; Germany [48]. Changes in the zooplankton community as seen in the Black Sea, were also found in the North Sea and Baltic Sea [45, 49, 50, 51].

In addition to the zooplankton, the biomass of benthic and commercially exploited species also decreased at the end of the 1980s: the breeding success of eider ducks collapsed, coinciding with a dramatic decrease in the standing stocks of mussels, cockles, whelks and shrimps in the Dutch Wadden Sea and whelks in the North Sea [52]. Another interesting observation in connection with this is that the annual growth rings in the shell of *Arctia islandica* decreased in the mid 1980s and increased again at the end of the 1980s (Fig. 8; [53])

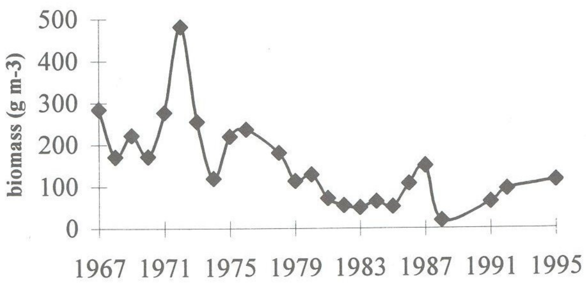

Figure 5. Zooplankton biomass off the Bulgarian Black Sea coast during summer 1967-1995. (without *Noctiluca scintilans)* [9]. This figure reflects the same trends, as were observed by Romanian, Ukrainean, Russian and Turkish Institutes [11, 12, 29, 33, 38].

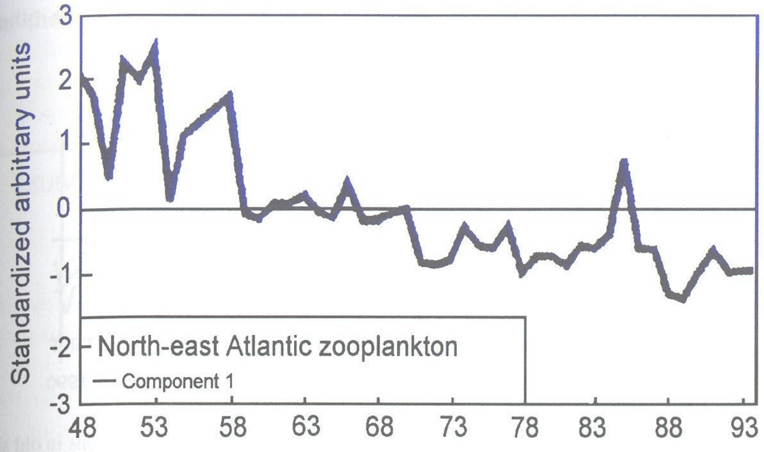

Figure 6. Trends in zooplankton of the northeastern Atlantic from 1948-1993 according to the Continuous Plankton Recorder (redrawn from [42].

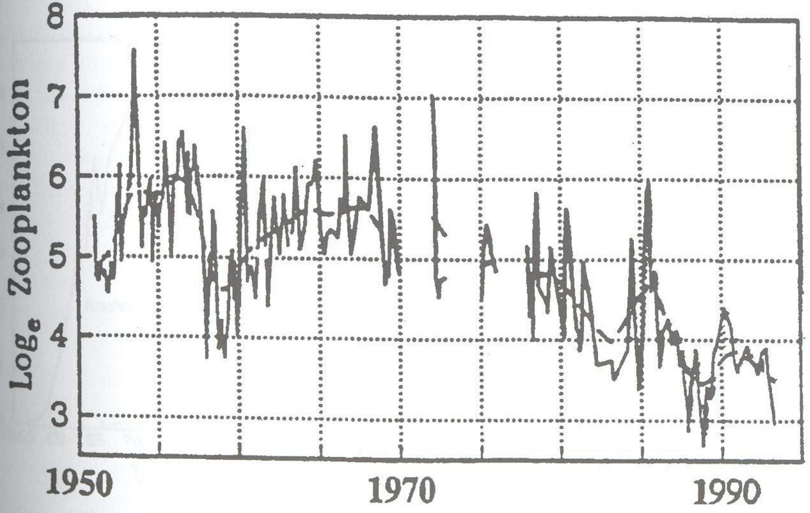

Figure 7. Fluctuation in zooplankton biomass off California from 1951-1993 (redrawn from [46]).

Comparison of the anchovy catches in different upwelling systems of the world showed that the anchovy stock of South Africa (Fig. 9) Benguela, and California (Fig. 10) collapsed as well in the same period as the anchovy stock of the Black Sea during the second half of the 1980s despite no impact of *Mnemiopsis leidyi* and in spite of different stock management regimes and fishing efforts [54, 55]. The anchovy stock in the Kuroshio-Ohashio upwelling system and the Humbolt area had already decreased during the mid seventies, but they displayed a similar increase as in the other areas during the mid 1980s.

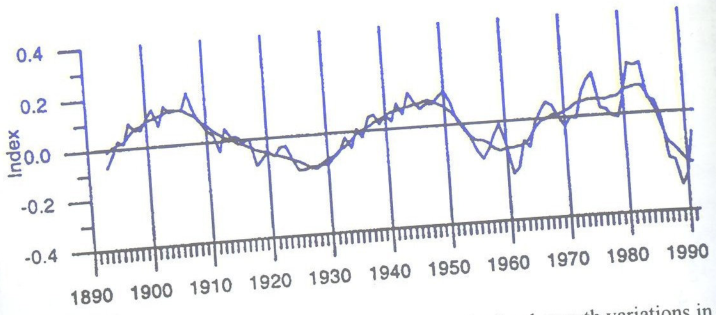

Figure 8. Growth of *Arctica islandica*: Mean chronologies of standardized growth variations in old shells from the Fladen Ground, North Sea. Shown are the unsmoothed mean chronologies with a 3-year adjacent averages. The increase at the end of the 1990s could be related to an Atlantic inflow event (redrawn from [53]).

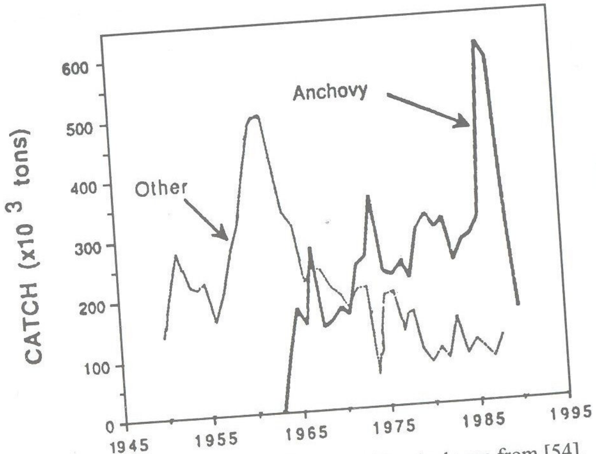

Figure 9. Anchovy catch off South Africa (redrawn from [54].

3. Meteorological and hydrological forcing and species densities

The findings of so many similarities in the fluctuation patterns of different species at the end of the 1980s leads to the question: what causes this behaviour in the different marine ecosystems mentioned above? Anthropogenic impacts, which have increased since the 1960s undoubtedly have an effect on marine ecosystems, especially in enclosed and semi-enclosed seas such as Black Sea, Baltic Sea and North Sea. Since this topic has already been discussed by many authors (reviewed by Zaitsev [14], we want to focus

solely on the influence of large scale weather patterns on the fluctuation of marine species.

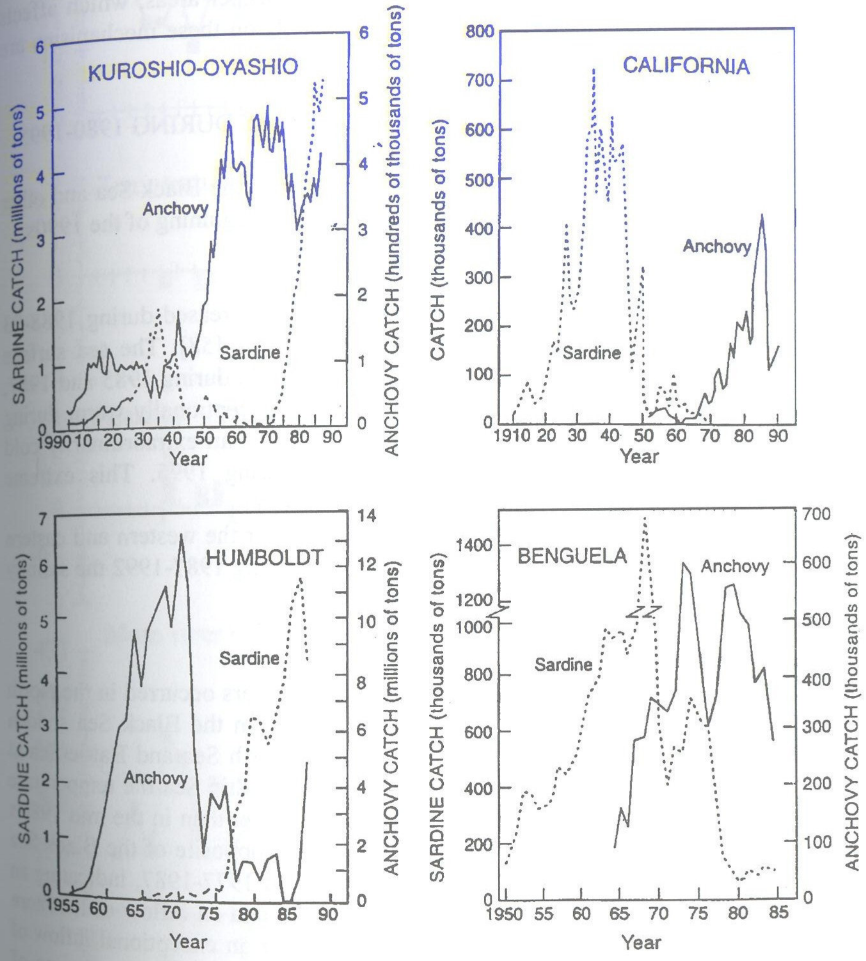

Figure 10. Annual catch of sardine and anchovy in four major current systems during the 20th century (redrawn from [55]).

Links with short-term or large-scale weather patterns have been suggested by many authors. Wind, extreme winter and summer temperatures, rainfall, high river discharges, and salinity anomalies are mentioned as possible causes in the literature [56]. Examples are: the mean phytoplankton biomass in summer is inversely related to the average air temperature in winter (Black Sea; [34]. The average zooplankton abundance in May-August is dependent on the sea temperature in March (the eastern Black Sea, in 0-100 m depth; [57]. The abundance of copepod species is dependent on the salinity: *Calanus finmarchicus* is associated with salinity in deep waters (North Sea; [44], high densities of *Pseudocalanus elongatus* correspond to years with low salinity at 5 m to 20 m depth before and during the reproduction season (Baltic Sea; [50]). Thus a shift in storm frequencies or wind directions might cause changes in the sediment water exchange in shallow areas or influence the depth of stratified waters in deeper areas, which affects the abundance of zooplankton as well [45, 56]. More details on these mechanisms are given in section 3.3.

3.1. METEOROLOGICAL AND HYDROLOGICAL REGIME DURING 1980-1995

By comparison of the atmospheric and hydrological patterns in the Black Sea and other seas we found the following similarities during the 1980's and beginning of the 1990s:

3.1.1. Black Sea

After a cold period between 1984-1987, the air temperature increased during 1988-93 [12] with exceptional warm years during1989-1991 (Fig. 11a; [58]. The sea surface temperature (SST) of the western Black Sea was extremely cold during 1985 and 1987, followed by a warm period during 1988-1991 and became exceptionally warm during 1989 (Fig. 11b). This warm period was interrupted in 1994 by an extraordinarily cold SST followed by a very strong increase of the SST during 1995. This extreme fluctuation of the SST was not obvious from the air temperature.

The sea surface temperatures anomalies were different for the western and eastern Black Sea, but during 1989-1991 the trends were similar. During 1987-1992 the salinity was well below the 40 year average (Fig. 11c; [12, 59]).

3.1.2. Atlantic, North Sea and Baltic Sea

As seen for the Black Sea, the mildest winters of the past 50 years occurred in the North Sea area between 1989 and 1994 [61], and likewise as seen in the Black Sea sudden changes in temperature and salinity were registered in the North Sea and Baltic Sea at the end of the 1980s. In the German Bight (North Sea) and Baltic Sea the temperature increased during 1988 and fluctuated after 1990 at a higher level than in the mid 1980's [51]. The salinity also increased rapidly during 1988/89 (the opposite of the Black Sea situation) and remained at a higher level as seen in the period 1977-1987, indicating an exceptional inflow of Atlantic water into the North Sea [51] and an inflow of the more saline North Sea water into the Baltic Sea [50]. Evidence for an exceptional inflow of Atlantic water into the North Sea having taken place during 1989 is the presence of Lusitanian fish species like *Trachinus vipera, Zeus faber, Mullus surmuletus* [62, 63] and other warm water species such as the siphonophore *Muggiaea atlantica* [89], the tunicate *Doliolum nationalis* [65], the cladoceran *Pelina* [64] and four phytoplankton species [66] since then. The hydrological changes during the end of the 1980s were reflected in the Baltic Sea [49] and Kiel Bight [50] as a change in the species composition and high interannual fluctuations of some species, indicating a period of instability, which often is induced by a change of environmental parameter [67].

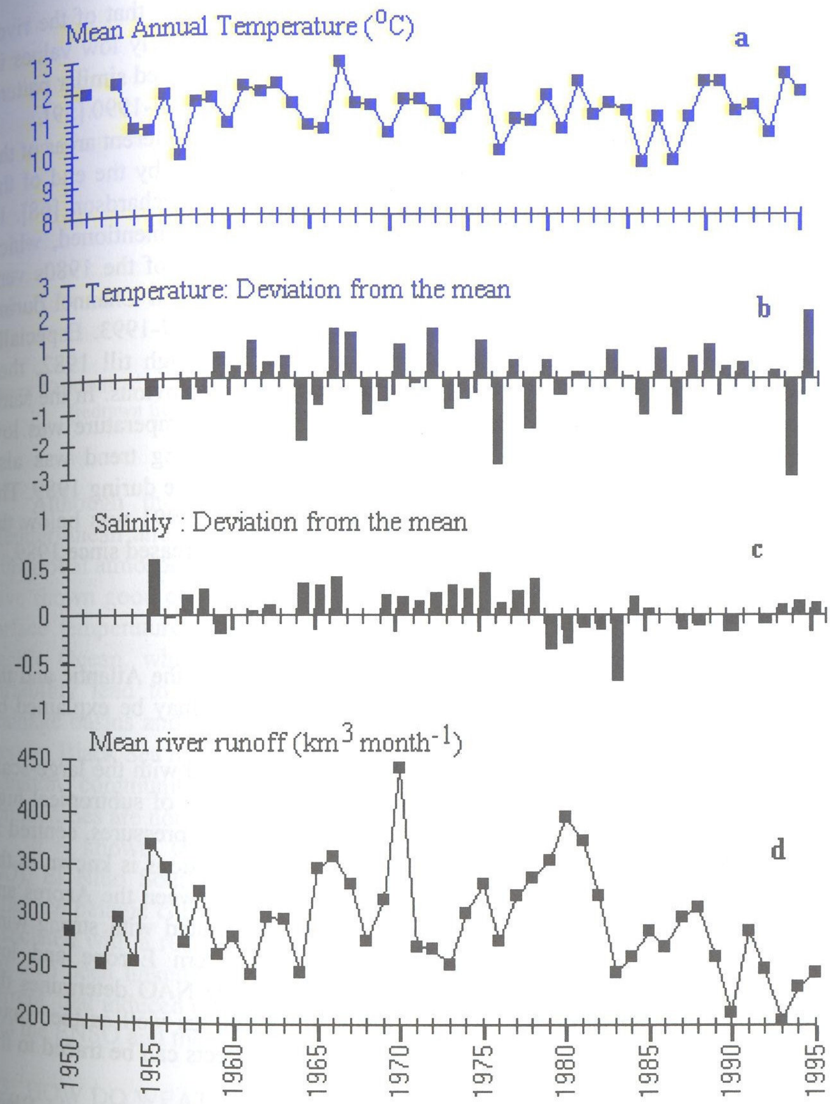

Figure 11. (a) **Air-temperature** of the western Black Sea during 1951-1995 averaged for March (measured eight times daily at the meteorological stations Odessa, Khorly, Evpatoria, Sevastopol). (b) **sea surface temperature** (SST) 1951-1994, March; (c) **surface salinity (SSS)** for March, inshore, 1951-1994. SST and SSS were registered eight times daily in the north-western area (44^0 -44^0.40`N and 31^0-33^0 E) and averaged for February. (d) **annual discharges of the Black Sea rivers** of the former Soviet Union were calculated as a sum of the monthly run-off of the Danube, Dniepr, Dniestr, Yuzniy Bug, Rioni, Ingouri, Bzyb, Mzymta, Chorokh, Kodory (redrawn from [12]).

Since the beginning of the 1980s the river discharges, especially that of the river Danube, were below the long-term average (1931-1995) with extremely low values in 1982 and 1989-1990 (Fig. 11d, [12, 58, 59, 60]). The sea level displayed similar pattern with a strong decline in the mid 1980s and a sharp increase during 1988-1990 [59].

Similar hydrological and meteorological changes, observed in different areas of the North Sea and Atlantic, resulting in changes in marine communities by the end of the 1980s and beginning of the 1990s were described by Daan and Richardson [68]. In particular, the paper of Le Fevre-Lehoerff *et al.* [69] should be mentioned, which documents the hydrological and meteorological changes at the end of the 1980s very clearly (a long-term series carried out in Gravelines; France, English Channel during 1974-1993). The sea temperature and salinity increased during 1987-1993. Especially the changes in salinity were spectacular. The salinity was very high till 1982, then decreased rapidly till 1987. From 1988 to 1993 a small increase is obvious. In the same period meteorological changes became obvious as well: The air temperature was low during 1986/87 and increased since 1988/89. The same increasing trend was also obvious for the atmospheric pressure after 1986, with a steep increase during 1989. The precipitation increased significantly during 1987-1990 and since 1991 was below the 19-year average. The number of days with strong westerly wind decreased since 1989.

3.2. LARGE-SCALE OSCILLATION SYSTEMS

These major changes in the weather - and hydrological regimes of the Atlantic and the Black Sea occurring in the same period at the end of the 1980s may be explained by large-scale oscillation systems:

The westerly winds of the European region are closely related with the large-scale alternation of atmospheric mass between the North Atlantic region of subtropical high surface pressures, centred in the Azores, and sub polar low surface pressures, centred in Iceland. This alternation of the atmospheric pressures at both locations is known as the North Atlantic Oscillation (NAO). A high pressure difference between the Azores and Iceland (corresponding to a high positive NAO index) is associated with strong wind circulation in the North Atlantic, high temperatures in western Europe and low temperatures on the east coast of Canada [45]. The state of the NAO determines the speed and direction of the westerlies across the North Atlantic, as well as the winter temperatures on both sides of the North Atlantic [70] and its effects can be traced to the Black Sea and Caspian Sea, Asia (Fig. 12; [71]).

Another oscillation system, the Southern Oscillation (SO), which affects the Black Sea region as well, exists for the Pacific. The SO is defined as an oscillation of atmospheric mass between the subtropical anticyclones over the eastern Pacific, particularly the Eastern Island anticyclone, and the Indonesian low-pressure area. The SO is associated with the El Niño phenomenon, resulting in the term: El Niño/Southern Oscillation (ENSO).

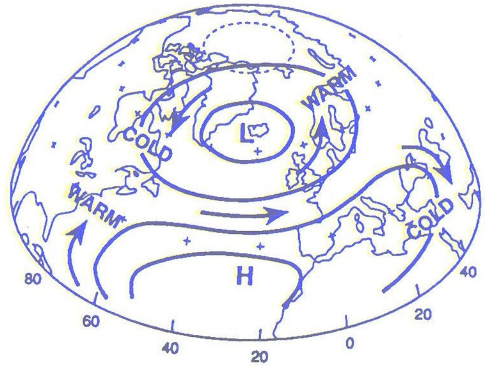

Figure 12. Idealised scheme of the NAO. If the NAO index is high, the westerly winds reach the Black Sea (redrawn from [71]).

Although the short and long term atmospheric variabilities in the eastern Mediterranean and Black Sea regions are well known, hypotheses on teleconnections with global atmospheric events have recently been put forward [58]. Polonsky *et al.* [59] have shown good correlation between the Black Sea hydrology, the North Atlantic sea surface temperature (SST) variability and the ENSO-type variability of the tropical Pacific Ocean, which indicates a global ocean-atmosphere coupling. Both types of variability lead to changes of the cyclone trajectories, precipitation over the river drainage basins and changes in the river discharges, resulting in changes in the north-western Black Sea hydrography [59], which may finally lead to changes in the Black Sea plankton community. (The effects of the recent El-Nino event on the pelagic communities are not mentioned in this paper, since the data are still being processed).

It is known, that global atmospheric changes, such as the Southern Oscillation (SO), El Niño Southern Oscillation (ENSO), and North Atlantic Oscillation (NAO) influence pelagic communities [70, 72, 73, 74, 75]. The 1982-83 ENSO event has been associated with a reduced phytoplankton biomass in the western and eastern Pacific. It has also been linked with a rise in temperature and a reduced flow of the Californian current, that induced radical changes in zooplankton biomass (Mann, 1993). It is known, that the ENSO and the Aleutian low affect the fishery in the Pacific as well [73].

3.3. HOW DO WEATHER PATTERNS AFFECT THE ZOOPLANKTON COMMUNITY?

One hypothesis as to how weather patterns may affect the zooplankton community is given by [45]. In the North Atlantic, the fluctuations of the *Calanus finmarchicus* (cold water species) and *C. helgolandicus* are closely linked with the state of the NAO. In years with high NAO a significant decline in total *Calanus* abundances is obvious [45]. Due to differences in the biology of both species (different seasonal cycles, opposite temperature affinities and different geographical locations) the species react differently. In years with high NAO the cold water species *C. finmarchicus* displays lower abundances than in high NAO years, whereas with *C. helgolandicus* the opposite is true [45].

According to Fromentin and Planque [45] the mechanism of these changes could be explained roughly by 2 factors: High NAO pattern leads to high wind stress, generating a strong mixing of the surface layer during winter and spring. Enhanced mixing delays the spring phytoplankton bloom and reduces the primary production leading to a general decrease of copepods (i.e. calanoids) due to lack of food. Additionally the westerlies are pushed farther south and the air and sea surface temperatures are higher than normal. This is unfavourable for the cold water species like *C. finmarchicus* and so more tolerant species such as *C. helgolandicus* are favoured. The situation is reversed by weak NAO patterns. Since copepod species constitute the main food resources for juvenile fish and small pelagics, like anchovy and sprat, it can be assumed, that a change in the copepod stock in terms of species composition and biomass has consequences for the pelagic fish stocks. Additionally wind-induced turbulence and temperature influence the capture efficiency, growth and development of fish larvae [76].

But not only the strength of the NAO and the westerlies influence the fluctuations of the zooplankton in the Atlantic, the position of the Gulf stream could be related with the abundance of the zooplankton in the European area as well. Larger zooplankton abundances occur around the British Isles during years with northward displacements of the northern wall than during those with southward displacements [47]. An interpretation of this association 'Gulf stream : Zooplankton biomass' is, that displacements of the northern wall may result in weak local perturbations of the atmospheric circulation, that are felt downstream on the European Continental shelf. Evidence to support this interpretation is given by the good relationship between the zooplankton fluctuation in Lake Windermere (a fresh water lake in England) located at the same latitude as the northern wall. These observations confirm, that the coupling is atmospheric. Associated air temperature and water temperature data from Lake Windermere indicate that the coupling operates through the seasonal thermal stratification [47].

3.4 CLIMATIC SITUATION AT THE END OF THE 1980S AND BEGINNING OF THE 1990s

The most important changes in the zooplankton biomass and species composition have taken place during the end of the 1980s and the beginning of the 1990s. What type of large weather patterns could trigger the hydrological and meteorological changes during this period?

According to Rodionov [71] the 1980s differed from the previous decades by the following peculiarities: The 1983-1990 period was dominated by a positive phase of the NAO (Fig. 13). The winter SST averaged over the North Atlantic was particularly low in the mid 1980s; in 1986 it reached the lowest recorded value for the entire period of observation since the late 19th century [77]. Enhanced climatic variability during the 1980s was also observed in the Atlantic European sector. The magnitude of the NAO index (computed as the difference between normalised mean winter surface air temperature (SAT) at 60°N, 10°E, Jakobshaven, Greenland and 70°N, 50°W, Oslo, Norway) increased since 1970 and its variance was about 5 fold higher during the 1970-1989 period than in the previous 2 decades (Fig. 14). Most striking was the fact that the index jumped from a record low value in 1986 to a record high value in 1989. The extremely low value in 1986 resulted in severe winters in northern Europe [77]. The high-pressure anomaly over Greenland and frequent northerly winds along its eastern flank were responsible for the negative temperature anomalies in the northeastern Atlantic. A contrasting situation occurred in winter 1989, when intensive advection of warm and moist air from the north Atlantic led to a warm winter in western and northern Europe influencing the Black Sea region as well.

The same strikingly high climatic variability as seen in the North Atlantic was also obvious in the Pacific. The decade from 1980-1990 displayed the largest global scale year to year variability of the 20th century [78]. The Southern Oscillation experienced the strongest warm (El Niño) episode of the century (1982/83) and the strongest cold (La Niña) episode in 50 years (1988). According to Trenberth and Hurrell [79], the very strong La Niña event of 1988 apparently terminated the climate regime, that was established in 1977.

Long-term data series suggest that strong climatic changes in the Black Sea surface waters was in synchronism with the adjacent seas [58]: For example, in the Black Sea an extreme event of cooling evidently took place in 1987, when similar effects were noted in the surrounding seas, *e.g.* dense water intrusion into the Marmara Sea from the Aegean [80] and deep water formation in the Rhodes Gyre region in the Mediterranean [81]. That the period at the end of the 1980s was extraordinary could be seen as well in the ice coverage in the Golf of Gdansk (Poland), which was very strong during the middle of the 1980s (1984-87) but was negligible after 1987, when the warm period started [82].

To summarise, the following hydrological and meteorological weather pattern changed over the northern hemisphere at the end of the 1980s:

- In the open Black Sea the air and the sea surface temperatures decreased after 1986, were extremely low in 1987, rose again in 1988 until 1991 and decreased again until 1994 [11, 12, 58, 83].
- Changes in hydrological and meteorological parameters as in air temperature, atmospheric pressure, precipitation and changes in the strength of westerly winds were recorded at end of the eighties (Baltic Sea; [49]; North Sea; English Channel: [51, 52, 68, 69]) and in other regions of the northern hemisphere like the Barents Sea [71].
- Distinct changes were measured in the NAO (North Atlantic Oscillation; mean sea level pressure difference between Azores and Iceland, Fig. 13), SOI (Southern Oscillation Index; mean sea level pressure difference between Darwin and Tahiti), ENSO (Southern Oscillation (El Niño) Index), and ALPI (Aleutian Low pressure Index, Fig. 15) at the end of the 1980s [46, 75]. Both the Iceland low and the Aleutian low were stronger than normal. Additionally the Iceland low shifted westward and the Aleutian low shifted south eastward from their long-term mean positions [71].

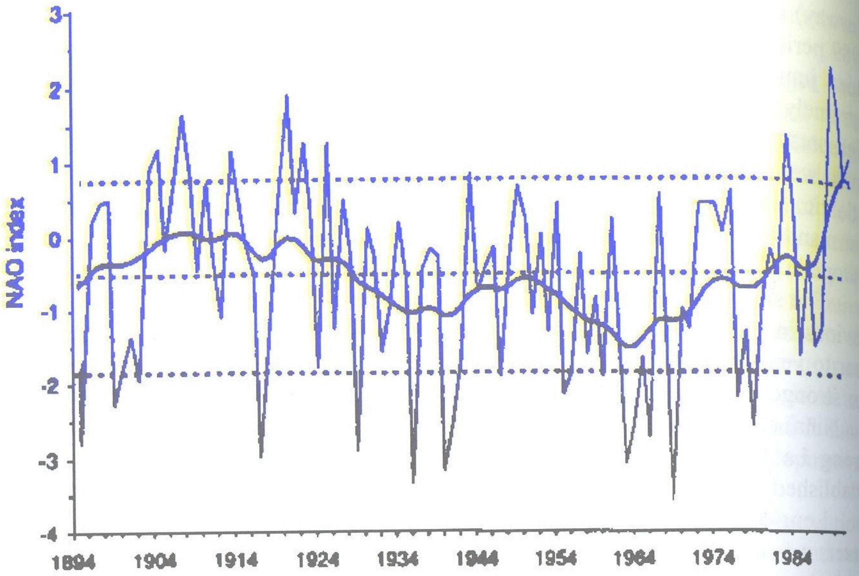

Figure 13. North Atlantic Oscillation (NAO) index based on the average pressure difference between the Azores and Iceland for the period December - April between 1985 and 1992. Dashed lines represents mean values (middle line) and standard deviations (upper and lower lines) (redrawn from [45]).

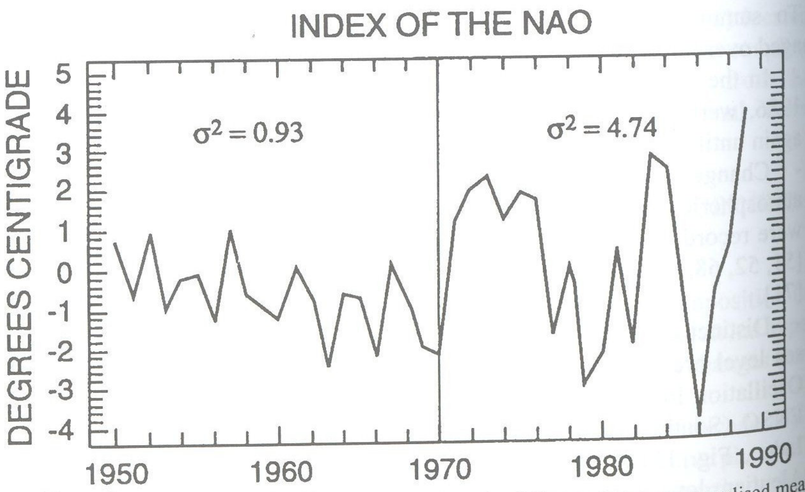

Figure 14. Index of the North Atlantic Oscillation computed as the difference between normalised mean winter surface air temperatures(SAT) at 60°N, 10°E Jakobshaven, Greenland, and 70°N, 50°W Oslo,Norway (redrawn from[71]).

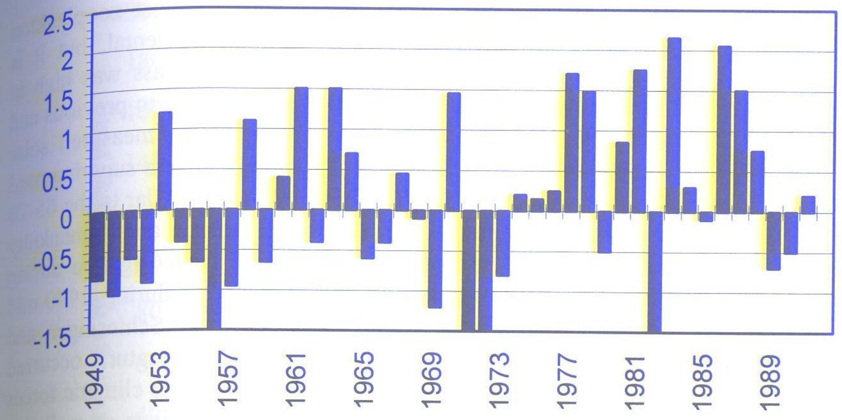

Figure 15. Fluctuation of Aleutian Low Pressure Index (ALPI) from 1949-1991 (redrawn from [46]).

- The shift of the northern wall of the Gulf Stream was far southwards during 1986-1988, compared to the previous and subsequent years [47].

In this connection it may be interesting to note, that :

- The oscillation of the global air temperature, which has a period of 65-70 years had its lowest amplitude during the mid 1980s [84].
- The sun activity, measured in terms of sun spot numbers, which has a period of 11-12 years, was very low during the mid 1980s and rose back to high values during 1988 [71].
- The moon's orbit crossed the ecliptic in 1988 (lunar tide, with a period of 18. 6 years), which causes an extreme peak in tidal forces (and has well documented effects on the sedimentation rates in the Wadden Sea) [52].

By mentioning the sun activity the question occurs, to which extent it is possible to connect the oscillation of the global coupled ocean-atmosphere system with the sun activity? Storm patterns in temperate zones may be influenced by the occurrence of sun spots [85]. Cycles of 11 to 22 years have been observed in several sedimentary records which hint at a possible influence of the 11 year sunspots cycle or the 22 year Hale cycle on marine systems [56, 86]. It was suggested that in the Black Sea, the water transparency [37] and the ratio Bacillariophyta : Dinophyta [35] could be associated with solar activity.

Comparing the fluctuation of the Black Sea communities with the sun spot cycles (Fig. 16) it becomes obvious, that the number of sun spots increased after 1987/88, when the biomass of the zooplankton decreased and were minimal during the mid eighties (minimum 1986) and during 1995, when the biomass of most zooplankton species increased again (Fig. 5; 6). This coincidence may be accidental, but it is interesting to see that during the 1970s, when the zooplankton biomass was high in many areas of the world, the frequency of sun spots was low compared to previous and subsequent years. By considering the whole available period of the measured solar activity 1745-1995 it is obvious that the 11-12 year sun spot oscillation is superimposed by another long-term fluctuation of solar activity (Fig. 17), which is similar to the 65-70 years oscillation in the global climatic system, described by Schlesinger and Ramankutty ([84]; Fig. 18): the global mean temperature anomaly changed from negative during 1900-20 to positive during 1935-1955 and back again to negative during 1970-mid 1980s and increased since the end of the 1980s. According to Schlesinger and Ramankutty [84] this oscillation pattern in the global mean temperature occurred exclusively in the northern hemisphere. This may indicate, that the same climatic forces drive the Atlantic and the Black Sea ecosystem. Indications are obvious as well that similar biological amplification may occur in terrestrial populations [87]. That climatic cycles affect vegetation and fish stocks in the same area was already shown by Ottestad in 1942 by a most interesting comparison: the yield of the cod in Lofoten fishery correlates well with periodicities in the width of annual rings in the pine trees [90].

4. Limitations

The mention of teleconnections and simultaneous meteorological events in different parts of the world, as outlined in this paper is not sufficient to explain the Black Sea events. Our ideas should be taken as stimulation for the evaluation of the existing long-term data of the Black Sea in relation to global weather patterns.

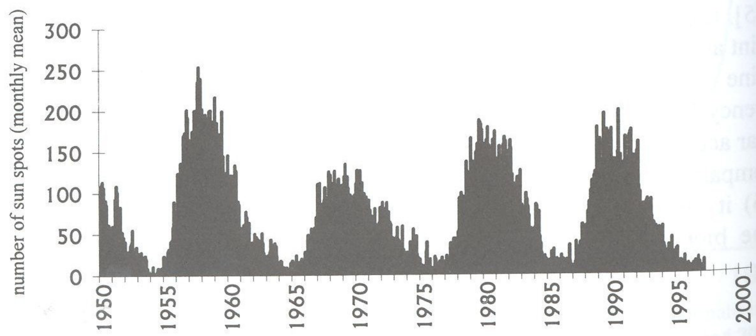

Figure 16. Monthly mean sun spot numbers from 1950-1997 (from internet http://www.ngdc.noaa.gov:8080/index.html).

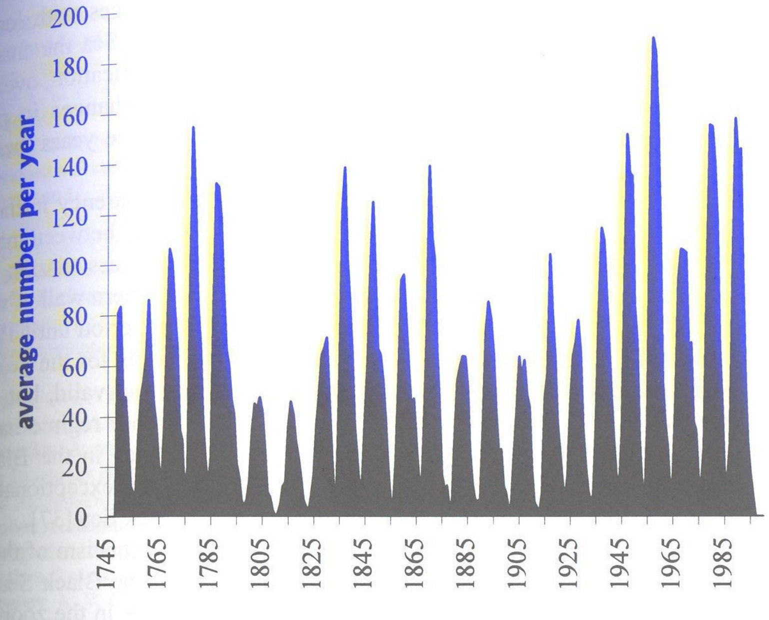

Figure 17. Average annual sun spot numbers from 1745-1997 (from internet http://www.ngdc.noaa.gov:8080/index.html)

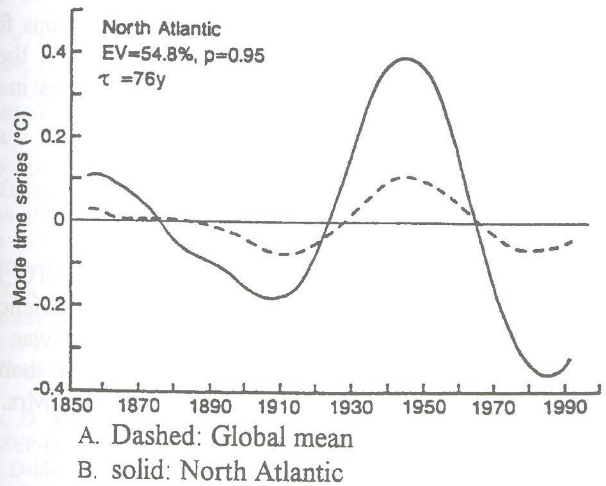

Figure 18. Global temperature anomaly periods in the North Atlantic from 1854 to 1991 (extracted from IPCC -International Panel on Climate Change, [84]). EV = eigen vector, P = correlation coefficient between regional and global means.

It would be too simple as well to relate all the natural changes with long-term climatic changes or solar activity. Especially in the enclosed Black Sea the changes in the ecosystem could be superimposed by effects of pollution, eutrophication, overfishing and other man made impacts. Commonly, correlations between changes in physical factors and changes in aquatic plankton or fish stocks hold for some years then break down [73].

It is interesting to note that the periodic oscillations of transparency in the Black Sea correlate with the 11 year cycle of solar activity, with a time lag between maximum of transparency and solar activity of 2-3 years. But since 1986 this association has not held true [37]. The same was true for the so called association "northern wall of the Gulf Stream : abundance of zooplankton" which persisted for a 22 year period until 1987 and then broke down [88]. But the relation "NAO : *Calanus*" still holds for the years after 1987 [45]. This does not mean that the first two correlations are not valid, but another stronger effect could dominate the fluctuation. It seems that another regime has taken over by the end of the 1980s. What is striking is that the diatoms in the Black Sea became dominant again by the end of the 1980s [32, 36], and the exceptionally high blooms of coccolithophores (i.e. *Emiliana huxleyi*) in the open Black Sea [37].

At the moment we are far from understanding the driving mechanism of the Black Sea ecosystem. Especially the interaction of NAO and ENSO in the Black Sea region makes the analysis more difficult. But keeping in mind, that changes in the zooplankton community and in small pelagic fish stocks in the late 1980's were evident in all seas under consideration, a climatic impact (or superimposition of different cycles or events; hydrological, meteorological and biological) could have triggered the changes in the zooplankton community in the Black Sea, which caused the conditions for the outburst of *M. leidyi* and the subsequent decline of the anchovy stock. At the present time investigations on links between climatic teleconnections and changes in the planktonic community in the Black Sea have not yet been carried out.

Acknowledgements

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