I - Executive Summary of CIESM Workshop 39

"Climate forcing and its impacts on the Black Sea marine biota"

by

Turan C., Boero F., Boltachev A., Duzgunes E., Ilyin Y.P., Kideys A., Micu D., Milliman J.D., Minicheva G., Moschella P., Oguz T., Öztürk B., Pörtner H.O., Shiganova T., Shivarov A., Yakushev E. and F. Briand

This synthesis was written by all participants of the workshop, under the coordination of Cemal Turan and with the support of Paula Moschella. Frédéric Briand, the Monograph Series Editor, reviewed and edited this chapter along with the entire volume, whose physical production was carried out by Valérie Gollino.

1. INTRODUCTION

In welcoming the participants Dr Frédéric Briand, Director General of CIESM, remarked that Trabzon – the famed, mythical Trebizond – marked the first, long-delayed encounter of a CIESM Workshop with the Black Sea shore and that there would be many further returns to a Sea that was an essential part of the Commission scientific and geographic scope. This specific meeting would extend to the Pontic region a brainstorming exercise engaged one year earlier, with CIESM Workshop 35, for the Mediterranean ecosystem, and would be carried out in the same integrative spirit as reflected by the presence around the table of marine biologists and physicists. After presenting the two co-Chairs of the CIESM Committee on Living Resources and Marine Ecosystems, Drs Cemal Turan and Ferdinando Boero happily reunited on this occasion, he expressed his gratitude to Dr Bayram Öztürk, Turkish Representative on CIESM Board for his very efficient assistance in helping prepare the ground logistics.

1.1. Black Sea climate change and hemispherical teleconnection

The global warming observed since the end of the 19th century has been caused not only by natural climate changes on the decades-centuries scale but also by the impact of human activities on the Earth's climate system, expressed in greenhouse effect. According to IPCC (2007), mean global surface air temperature rise for the last century (1907-2006) was on average about 0.7 °C, and the trend of temperature for the last 50 years was almost twice as much (+ 0.13 °C/10 years). One of the most significant processes in the ocean-atmosphere system that influence climate fluctuations in Eurasia is the Atlantic Multi-decadal Oscillation (AMO) of sea surface temperature, with periods of 50-100 years (more often reported as 60-80 years), represented also by the low-frequency mode of North-Atlantic Oscillation (NAO) of surface pressure field (Polonsky, 2008) (Figure 1).



Figure 1. Atlantic Multidecadal Oscillation (AMO) and North Atlantic Oscillation (NAO), 5-yr running means, 1880-2005.

In general, positive NAO indexes correspond to more northern tracks of cyclones, bringing more heat/ cold in winter/ summer and more precipitations to northern Europe, whereas southern regions experience opposite conditions. Negative NAO phases mean more southern cyclone trajectories, toward the southern Europe areas, including the Mediterranean and Black seas. Estimation of climatic variations of these oscillations on a timescale over 30-years, and of related anthropogenic impacts such as the greenhouse effect and river hydraulic controls, contribute to determine long-term variability (trends and fluctuations) of the Black Sea ecosystem.

Regional atmospheric processes are under the influence of external climatic changes and they, in turn, affect processes on sea surface and in water column. The observed changes in the physical compartments determine in many respects the present and future changes of marine ecosystem state and productivity.

2. CLIMATE VARIABILITY (HYDROMETEOROLOGICAL PARAMETERS) AND ITS EFFECT IN THE BLACK SEA REGION

Based on secular observations from marine hydro-meteorological stations along the northern and eastern Black Sea shores, linear trends and long-term oscillations reveal annual, seasonal and monthly air temperature (AT) trends. Significant long-term secular linear trends of annual mean AT in most studied Black Sea regions are positive, with slopes (0.4-0.8 °C/100 years) that correspond to the secular rise of mean global surface air temperature (Ilyin and Repetin, 2006a). However, on the decadal scale, the long-term trend is interrupted by severe departures on the order of 1-3 °C (Figure 2), which corresponds to variations also seen in the sea-surface temperature (SST) as well as sub-surface (Figure 3). These decadal fluctuations agree with AMO and NAO signals (Figure 1).



Figure 2. Long-term variability of AT anomalies (°C) in Yalta (Ukraine) approximated by superposition of harmonic functions having periods 31, 41 and 62 yr.



Figure 3. Annual trends in air temperature (AT), sea-surface temperature (SST) and the winter NAO index, 1870-2006.

The uniform response of the Black Sea drainage basin to AMO/NAO can also be seen in the closeness of temporal variations in river discharge throughout the area, ranging from the Sakarya in the south, to Don in the north-east, to Danube and Dnieper in the west (Figure 4). Changes in freshwater input also have been observed (Figure 5) together with a weakening in wind activity, which is manifested as a general deceleration of horizontal circulation and vertical mixing of surface waters in the Black Sea (Ilyin, 2008b). This in turn leads to changes in the transport of heat and chemical constituents, including nutrients and pollutants, as well as a change in self-cleaning processes, such as surface water renewal by wind-driven coastal upwelling.



Figure 4. Annual discharge (5-yr running means) from the Danube (Da), Sakarya (SA), Dniepr (Dn) and Don rivers to the Black Sea.



Figure 5. Interannual variability and trends of the Black Sea fresh water budget (FWB) and its components (km³).

In addition to lowering the salinity of surface waters, increased rainfall can lower SST, especially on the eastern coasts of the Black Sea. Moreover, pollutants and nutrients brought about via increased precipitation are comparable with those derived by riverine input; in fact, the atmospheric input of nutrients is estimated in ten-thousands (nitrites, phosphates) and hundred-thousands (nitrates, sulfates, chlorides) tons per year (Chaykina *et al.*, 2008; Voitsekhovich *et al.*, 2004).

River-derived nutrient discharge of nitrogen and phosphorus to the Black Sea rose sharply in the 1950s-1960s, in response to increased agricultural activity in the Danube, Dnieper and Don watersheds. Nitrogen and phosphorus fluxes, however, declined abruptly in the late 1980s, following the economic recession which affected the former eastern block countries in that period (Figure 6). Silica discharge declined in the 1970s in part due to river damming (e.g., Iron Gates Dam; Humborg *et al.*, 1997), and shifts from siliceous (mainly diatoms) to non-siliceous phytoplankton (Petrova-Karadjova, 1984; Humborg *et al.*, 1997; Bodeanu *et al.*, 2002). Data from the NE Black Sea reveal similar trends to those observed in the NW Black Sea, but with only a slight shift in the phosphate content (Figure 7).



Figure 6. Five-year means fluvial flux of nitrogen (N), phosphorus (P) and Silica (SiO₂) to the Black Sea (data from Ludwig *et al.*, 2009).



Figure 7. Interannual changes of upper layer concentrations of inorganic species of N, P, Si in the North-Eastern Black Sea averaged for the 5-years intervals.

In the open waters, the low NO₃/ PO₄ ratio in the nutricline below the euphotic zone resulted in nitrogen limited phototrophic production in the surface layers. This can be explained by intensive loss of inorganic nitrogen under suboxic conditions. According to Cociasu *et al.* (1996) and Yilmaz *et al.* (2006), the NO₃/ PO₄ ratio in the euphotic zone and the upper nutricline is very low (2 - 6.5) in the open sea. The same tendency can be observed in the NE Black Sea, where the N:P ratio decreased during the last 10-15 years from 30 to 5.

One of the indicators of the Black Sea biogeochemical system recovery should be the reappearance of the nitrogen fixation. The process of production of gaseous nitrogen through denitrification and anammox is a well known feature in oxygen-deficient basins. In terms of budgeting, this loss of bound nitrogen should be compensated by nitrogen fixation (Yakushev *et al.*, 2007). Denitrification and anammox were measured in the Black Sea during the last decades (Murray *et al.*, 2003; Kuypers *et al.*, 2003), whereas N-fixation was not observed in the 1980s-1990s. In contrast, in 1950s, before the initiation of intensive eutrophication, N-fixation in the Black Sea was well-developed (Pshenin, 1963). As shown above, the low N/P ratios in the different parts of the Black Sea testify to nitrogen-limited primary production, which favors N-fixation as part of the normal functioning of the ecosystem. Recently, N-fixation was again measured in the Central Black Sea in 2003 (McCarthy *et al.*, 2007). We thus can conclude that there are present positive signs of recovery of the Black Sea ecosystem after several decades of decline in anthropogenic impact (Black Sea Commission Report, 2008).

3. COASTAL OXYGEN DEPLETION AND HYPOXIA, OXIC ZONE VOLUME

Seasonal development of low oxygen zones (oxygen concentrations below 2 mg/l, oxygen concentrations <30% saturation value) in bottom waters of the Black Sea (e.g., northwestern shelf, Anapa shelf, Sea of Azov) depends on the intensity of eutrophication as well as circulation, stratification and meteorological conditions (wind, heat flux, etc.). In the Black Sea, the development of hypoxia typically begins in June-July and attains maximum coverage in August. There is a relationship between the rate and timing of river discharge and the scale of hypoxic conditions (Berlinskii, 2003). In years with high river discharge, hence high nutrient input and organic matter production, oxygen concentrations in bottom layers are ~20% lower than in years of low river discharge.

Hypoxia is also subject to longer-term variations, and a simple correlation to environmental factors may not always hold. For instance, a two-fold increase in hypoxia occurred in the northwest shelf in the 1980s, but has since decreased in its Ukrainian sector. In contrast, no hypoxia was reported in Bulgarian waters or off other Black Sea states, other than an intensive summer anoxia in the Sea of Azov in 2001 (Yakushev et al., 2003). A long-term detailed study of the anoxic zone in the northeastern Black Sea near Gelendzhik (Podymov, 2008; Yakushev et al., 2008) (Figure 8) show that the depth of disappearance of hydrogen sulphide was characterized by values $\sigma_{\Theta}\sigma_{\Theta}=16.15$ -16.25 kg m⁻³ in 1991-1998. In 1999-2000 the shoaling of this boundary appeared. The value of this shoaling of ~5-15 m was about σ_{θ} =0.05-0.15 kg m⁻³. After the year 2000 the position of hydrogen sulphide stabilized, as also seen in ammonia, total manganese and methane (Yakushev et al., 2006). These oscillations can be connected with the corresponding winter weather conditions. For example, the two warm winters in 1998-1999 may have affected the winter formation of the oxygen-rich cold intermediate layer (CIL). These years were remarkable for the increase in SST (Figure 8), increase in temperature in the core of CIL (Oguz et al., 2006; Krivosheya et al., 2002), and shoaling of CIL in the density field (Murray et al., 2003). The decrease of intensity of CIL formation should lead to an increase in temperature and a decrease in oxygen content in its core. To check these assumptions we calculated the average concentrations of dissolved oxygen in CIL (defined as the layer from σ_{θ} =14.45 kg m⁻³ to $-\sigma_{\theta}$ =14.60 kg m⁻³) (Figure 8). In 1999-2000, when the shoaling of reluctant occurred, the oxygen content declined. The minimal concentrations were registered in 2001-2002. In 2003-2004 the oxygen content in this layer returned to values typical of the early 1990s.



Figure 8. Onsets in the density field of hydrogen sulphide (A), averaged concentration of oxygen in the CIL (in the layer σ_{θ} =14.45-14.60 kg m⁻³) (B), temperature in CIL core in the Northeastern Black Sea (data of V.G. Krivosheya); averaged temperature in the CIL core (data of the MHI oceanographic database and ARGO floats) (C) and interannual variability of the winter NAO index (crosses averaged for February-April, lines –averaged for three successive years (D). The variability in the Black Sea hydrophysical-biogeochemical system can be connected with the weather conditions change as it follows from the NAO index behaviour (Figure 8). The results obtained illustrate the mechanism of reaction of the natural system of the Black Sea on the Global Climate changes. The correlated changes in the decadal NAO index behaviour under winter weather conditions result in larger or smaller cooling of the upper layer waters. As it follows from the analyzed estimates, the changes in sea surface temperature lead to changes in winter CIL formation intensity and to oxygen renovation there. The oxygen inventory in the CIL acts as a specific accumulator that supports the consumption of oxygen for the organic matter decay and downward diffusive flux during the whole year. The interannual variations of this oxygen renovation in CIL lead to changes in the suboxic layer hydrochemical structure and, in particular in the position of the anoxic boundary in the density field. Therefore, the distribution of the chemical parameters in the density field in the Black Sea might be a good indicator of the Global Climate variations. Another factor that might affect the interannual dynamics of the hydrogen sulphide position is eutrophication. It should be emphasized that one result of 5-10 m oscillations in the anoxic boundary is a 5-10% change in the volume of the oxic waters. Such oscillations are considered vitally significant and should be studied further.

4. THE HISTORY OF BLACK SEA BIODIVERSITY

4.1 Mediterranization of the Black Sea biota

Low species diversity (i.e. low competition) combined with high habitat diversity (i.e. availability of potential niches) in the Black Sea provides favorable conditions for the introduction of alien species. Some of these species become invasive, altering the stability and functioning of the ecosystem and threatening the indigenous species. There have been increasing numbers of Mediterranean species in the Black Sea since the first records in 1920s. This is particularly true for the fish fauna. The diversity of the Black sea ichthyofaunahas increased due to the intrusion of fish from the Mediterranean Sea, a process that has been defined as "mediterranization" (Pusanov, 1967; Boltachev and Yurakhno, 2002). In addition, fish species of Indo-Pacific origin naturally migrated to the Mediterranean Sea via the Suez Canal (Lessepsian migrants) along with those introduced accidentally (via ballast waters) and intentionally (e.g. for farming purposes) further modify the Black Sea fish diversity. The water mass exchange between the two seas also facilitates the introduction of species which may become later established in the Black Sea.

Any comparison between Black Sea and Mediterranean biota is however impaired by the fact that the Mediterranean fauna is itself still incompletely known. Caspers (1957) estimated the Black Sea metazoans at ca 21% of the Mediterranean fauna. Later research in both seas showed that the Black Sea fauna is only about three and a half times poorer (see Bianchi and Morri, 2000). Comparing the Mediterranean and the Black Sea - the decrease in total number of species is paralleled by disappearance and a decline in many oceanic groups, such as Sponges, Salps, Doliolids, Pteropods, Siphonophores, Euphausiids, Nemertini, etc. These changes are undoubtedly salinity-driven. Salinity ranges from 33 to 39‰ in the Mediterranean Sea, from 17 to 22 ‰ in the Black Sea. However, the degree of faunal impoverishment is not directly proportional to salinity. Between the Mediterranean and the Black Sea, salinity drops by more than a factor two, while the number of animal species decreases by a factor 3-3.5.

Indeed, 80% of the Azov-Black Sea fauna is of Atlantic-Mediterranean origin, and its share continues to increase; only 10.4% and 9.6% of species are of freshwater and Ponto-Caspian origin, respectively. The species of Atlantic-Mediterranean origin mainly come from the Mediterranean Basin, the Lusitanian province, and the boreal zone of the Atlantic Ocean. The biota of the Black Sea shares more similarities with the biota typical of higher latitudes, that is few species with high biomass, whereas the Mediterranean Sea is characterized by many species with low biomass (Table 1).

Таха	World	Medit.	M/W(%)	BS	BS/M(%)
Phytoplankton	~4375	673	15.4	746	110.8
Red algae	5250	867	16.5	143	16.5
Brown algae	1500	265	17.7	75	28.3
Green algae	1200	214	17.8	83	38.7
Sea grasses	50	5	10	6	120.0
Total Macrophytes	12375	2024	16.4	1053	52.0
Sponges	5500	600	10.9	25	4.2
Cnidarians	11 000	450	4.1	44	9.8
Bryozoans	5000	500	10	12	2.4
Annelids	8000	777	9.7	153	19.7
Molluscs	32 000	1376	4.3	125	9.1
Arthropods	33 600	1935	5.8	288	14.9
Echinoderms	6500	43	2.2	5	11.6
Tunicates	1350	244	18.1	16	6.6
Other invert.	~13 550	~550	4.1	278	50.5
Total invert.	~116 500	~6475	5.6	946	14.6
Cartilage Fishes	1170	84	7.2	12	14.3
Bony Fishes	13 151	532	4.1	180	33.8
Reptiles	~6700	355	5.3	175	49.3
Mammals	114	21	18.4	4	19.1
Total vertebrates	21 135	992	4.7	371	37.4
Grand Total	~137 635	~7467	5.4	1317	17.6

Table 1. Numbers of marine species in the World Ocean, the Mediterranean and the Black Sea.

4.2. The diversity of Black Sea fish fauna

The current Black Sea ichthyofauna is the result of a long process started after the last junction of the Black Sea to the world ocean and continued for about eight thousand years. At present, the Black Sea only connection with the Mediterranean Sea is the Turkish Strait system, comprising the Istanbul Strait, the Sea of Marmara, and the Dardanelles. Therefore the Black Sea can be considered as the 'arm' of the Mediterranean and many of its species are common to both seas.

The Black Sea fish fauna accounts for about 200 species and subspecies, including occasional freshwater and marine fish, recorded as single individuals in the Black Sea (Svetovidov, 1964; Oven, 1993; Boltachev, 2003). However, a considerable decrease in the numbers of many native Black Sea fish is observed; some of them have not been recorded since several decades largely due to the effects of anthropogenic pressures, namely: chronic pollution, in particular eutrophication, which increases fish mortality, overfishing and poaching, the physical destruction of spawning grounds, of nursery and feeding areas, and the invasion of new hydrobionts.

According to their phylogenetics gene, ecological traits, and life cycles, in the Black Sea Basin four main fish groups can be singled out.

The fully marine fish – about 140 species and subspecies – make the core of the Black Sea ichthyofauna. The most representative species of this group, are of Atlantic – Mediterranean, tropic and sub-tropic origin. They are euryhaline and inhabit mainly the upper warmer layer in the water column. Among them, 60 naturalized completely, and formed endemic subspecies, all stages of their life cycle being spent in the Black Sea. The other species migrate regularly at the warm time of the year from different areas of the Mediterranean Basin (Vodyanitsky, 1930). Boreal–Atlantic fish are represented by 12 species, inhabiting mainly the cool subsurface layer in the warm season and penetrating the surface layer during the winter period (Svetovidov, 1964; Oven, 1993).

Brackish water fish count 22 species including species endemic of the Black Sea or species and subspecies shared with the Caspian Sea, which are autochthonous relicts of the ancient brackish-water Ponticus lake – sea (Rass, 1949). Many of these species are distributed in the brackish-coastal waters and river estuaries, mostly in the north-western part of the Sea or near the Kerch Strait.

The diadromous and semi-diadromous group includes 25 species, which are of quite ancient origin – about 1.5-2 million years. This is related with fast migrations of these fish (with the exception of the eel fish, *Anguilla anguilla*) from the northern rivers into the Pontic lake basin and then returning back to the rivers for spawning (Oven, 1993). This group is affected by the mostly negative influence of human economic activities, which result in the destruction of reproduction sites, blockage of the migration pathways in rivers and over-catches, as many species are of high commercial value, such as sturgeons, salmons and herrings.

Typical freshwater taxa count only 15 species, occasionally reaching the Black Sea Basin coastal area usually during high water in the rivers (Oven, 1993).

<u>New records in the last 20 years:</u> up till now one observes a trend of increasing arrival of exotic species into the Black Sea; often resulting in the establishment of the new species (see Tables 2 and 3). The native Black Sea ichthyofauna also registers an increase of certain commercial and/or rare species (Boltachev, 2003; Boltachev, 2009). For example, there is an increase in frequency of round sardinella (*Sardinella aurita*), bogue (*Boops boops*) and salema (*Sarpa salpa*) in Turkish costal waters, and, in the coastal zone of the south-western Crimea, of "previously endangered" species such as Black Sea salmon (*Salmo trutta labrax*), common bass (*Dicentrarchus labrax*), dotted dragonet (*Callionymus risso*), bearded umbrine (*Umbrina cirrhosa*), yellow gurnard (*Chelidonichthys lucernus*), puntazzo (*Diplodus puntazzo*) and green wrass (*Labrus viridis*) (Table 4). The sea horse (*Hippocampus hippocampus*), which practically disappeared in the middle of the 1990s, suddenly increased in abundance in 2002 and 2008 along the coasts of Crimea, the north-western part of the Black Sea and the Northern Caucasus.

Species	Origin	Presence in the 60s	Reappearance in BS	Location first record	Established in Black Sea	Abundance	Habitat	Geographic distribution	Vector	References
Sardinella aurita	Med Mar	yes	1997	Sile	yes	abundant	pelagic, Turkish coast	Atlantic- Mediterranean	natural migration	B. Öztürk
Boops boops	Med Mar	yes	1989	Sile	yes	abundant	pelagic, Turkish coast	Atlantic- Mediterranean		B. Öztürk
Thalassoma pavo	Med Mar	yes	2006	Igneada	partially	abundant	pelagic, Turkish coast	Mediterranean		B. Öztürk
Sarpa sarpa	Med Mar	yes	2001	Igneada	yes	abundant	pelagic, Turkish coast	Mediterranean		B. Öztürk
Sphyreana pinguis	Med	Vec	2004	Sile	a few	a few ind.	pelagic,	Indo-pacific	Loceone	B. Öztürk
Sphyreana sphraena	wica	yes	2005	Sile	migrant	a few ind.	Turkish coast	mgran	Lesseps	
Centracanthus cirrus	Med	no	1988	off Odessa, littoral zone of Romania, common in Turkish area	a few individuals, eggs in 1988 2 adults off Romania in 2004	a few ind.	pelagic	Mediterranean		Tsokur, 1988: Radu, 2006 (pers. com.)
Micromesistius poutassou	Med	no	1999	coastal area of Crimia, common for Turkish area	a few ind.	a few ind.	pelagic	Mediterranean, Marmara	Med Mar	Boltachev, 2006
Gobius auratus	Med	no		common for Crimea			pelagic	Atlantic- Mediterranean	Med	
Gobius cruentatus	Med	no	2007	for Crimea, Turkish area	a few ind.		pelagic	Atlantic- Mediterranean	Med Mar	Boltachev, 2006 Engin et al., 2007
Gobius xanthocephalus	Med	no	2004	for Crimea, Turkish area	a few ind.	a few ind.	pelagic		Med Mar	Boltachev, 2006 Vasilyeva and Bogorodski, 2004
Parablennius incognitus	Med	no	2005	Common for Crimea, Abhazya, Turkish area	a few ind.	a few ind.	pelagic, Turkish coast	Atlantic- Mediterranean	Med Mar	Boltachev, 2006 Bogorodskii, 2006
Zebrus zebrus	Med	no	2008	Turkish area	a few ind.	a few ind.	pelagic, Turkish coast	Atlantic- Mediterranean	Med Mar	Kovacic and Engin, 2008
Sphyraena chrysotaenia	Med	no	1999	Turkish area	a few ind.		pelagic, Turkish coast	Indo-pacific pelagic, migrant	Lesseps	Boltachev, 2006

Table 2. Exotic fish species recorded in the Black Sea.

Taxa	<1960s	1960-1970	1971-1980	1981-1990	1991-2000	2001-2009
Phytoplankton		37				
Copepoda		15	19	12	7	51
Gelatinous plankton						1
Macrophytes					26	
Benthos	1	45	30	56		5
Total	1	97	49	68	33	57

Table 3. Total number of Mediterranean plankton, algae and invertebrate species recorded in the southern Black Sea (mainly off Bosphorus).

Table 4. Historical trends of Mediterranean fish species in the Black Sea.

Species names	1920s	1930s	1940s	1950s	1960s	1970s	1980s	1990s	2000s	2010s
Sardinella aurita	+	+	+	+	+	not present	+	+	+	+
Boops boops	+	+	+	+	+	+	+	+	+	+
Thalassoma pavo	+	+	+	+	+	+	+	+	+	+
Sarpa salpa	+	+	+	+	+	+	+	+	+	+
Sphyreana sphraena	+	+	+	+	+	+	+	+	+	+
Centracanthus cirrus	-	-	-	-	-	-	-	-	+	
Micromesistius poutassou	-	-	-	-	-	-	-	-	+	+
Gobius auratus	-	-	-	-	-	-	-	-	+	-
Gobius cruentatus	-	-	-	-	-	-	-	-	+	+
Gobius xanthocephalus	-	-	-	-	-	-	-	-	+	-
Parablennius incognitus	-	-	-	-	-	+	+	+	+	+
Zebrus zebrus	-	-	-	-	-	-	-	-	-	+
Sphyraena chrysotaenia (obtusata)	-	-	-	-	-	-	-	-	+	-

The barfish (*Chromis chromis*), the lettered perch (*Serranus scriba*), the blotched picarel (*Spicara maena*) and the bogue, (*Boops boops*), are recorded again in the Black Sea. The European pilchard (*Sardina pilchardus*), though in small number, is frequently found in fixed nets and trawl catches along the whole Black Sea shelf of the Crimea. Catches of two Mediterranean migrant fishes, such as the thin-lipped grey mullet (*Liza ramada*) in 2006 and the European barracuda (*Sphyraena sphyraena*) in 2007 near Sevastopol are unique, because these species had not been encountered there since 1930 and 1950 respectively.

In the last decade, 15 fish species, new to the Black Sea ichthyofauna, or whose presence was previously doubted, were recorded in the coastal zone of the southwestern and southern Crimea. Among them, seven Atlantic-Mediterranean species: the thick-lipped mullet (*Chelon labrosus*), dorado (*Sparus aurata*), salema (*Sarpa salpa*), yellow-headed goby (*Gobius xanthocephalus*), redmouthed goby (*G. cruentatus*), incognito blenny (*Parablennius incognitus*), and greater pipefish (*Syngnathus acus*). It is possible, that the abundance of some aforementioned bottom resident species (gobies, blennies) was so reduced in the past that they were just not recorded before. The chameleon goby *Tridentiger trigonocephalus*, endemic of the far Eastern seas, has naturalized in Sevastopol Bay. Four invasive species, freshwater by origin, were recorded in estuaries of the peninsula: far Eastern species – stone morocco (*Pseudorasbora parva*) and goldfish (*Carassius auratus*); and North American species – pumpkinseed (*Lepomis gibbosus*) and Eastern mosquitofish (*Gambusia holbrooki*).

The remaining three species are known from single findings and apparently belong to the category of accidental records.

5. MEDITERRANIZATION BARRIERS AND GENETIC ASPECTS OF SPECIES INTRODUCTION AND ESTABLISHMENT IN THE BLACK SEA

Global climate change is causing shifts in the geographical distribution of species, associated with local extinction and expansion of their distribution ranges. Natural and artificial transport pathways contribute to such redistribution of species. Transportation in ballast water is increasingly eliminating geographical barriers and separation of species.

5.1. Adaptation to local conditions

Species distribution more and more depends on whether specimens sustain transport conditions, at least passively, and then find suitable living conditions in their new environment. Within a given species and its original functional and genetic diversity, only resistant phenotypes and genotypes may survive, thereby reducing genetic diversity compared to the parent population and defining the starting point for successful settlement of suitable environments by selected, pre-adapted specimens.

The newcomers are "filtered" during the process of introduction, or after they arrive at their destination. The conditions in ballast tanks, for instance, might select particularly strong specimens that have proper characters to face the new conditions. The passage through a turbulent environment, like the Bosphorus Strait, acts also as filter.

Bottlenecks in transport to the Black Sea are set by the transport conditions in ballast water or by the acute conditions in or at the exit of the Bosphorus current system. Taking into account the hydroclimatic differences between the Mediterranean (hosting the parent population) and the Black Sea (receiving the newcomers), the physical factors that particularly challenge the survival of the specimens undergoing migration are water currents, shifts to lower salinities at the surface and lower temperatures coinciding with hypoxia and elevated CO_2 in the intermediate layer and anoxia in the depth. Furthermore, transport or migration may only be successful in a limited seasonal time window. Limiting factors not only act individually but also interact synergistically as in the case of temperature extremes, CO_2 and hypoxia, thereby exacerbating stress levels (Figure 9). Oxygendeficient (less than 80% of saturation), hypoxic (less than 30%) and anoxic conditions are typical for the coastal shelf zones of the Black Sea and the Sea of Azov in the summer period and oxygen depletion will probably become more intense in the future (Diaz and Rosenberg, 2008).



Figure 9. Organisms thermal windows: optima, limits (I) and acclimation/ adaptation (\leftrightarrow). Modified from Pörtner and Farrell (2008).

A Mediterranean species entering the Black Sea might become successful not because Black Sea conditions match Mediterranean ones, but because that species contained, in its genetic variability, the traits that allow for the colonization of the Black Sea Basin, in spite of its differences from the Mediterranean Sea. Turan (2006) reported that the amount of genetic divergence of *Mullus barbatus ponticus* in the Black Sea is high enough to be considered as a subspecies of *M. barbatus* in the Mediterranean Sea. This genetic analysis also indicated that *M. b. ponticus* could be an incipient species in the Black Sea. The seagrass *Posidonia oceanica* is a stenohaline species endemic to the Mediterranean Sea, where it normally lives at a salinity of between 36.5 and 39.5 ppt. Meinesz *et al.* (2009) reported large *P. oceanica* beds in the Marmara Sea, where salinity ranges between 21.5 and 28 ppt. They carried out a genetic analysis on these low-salinity tolerant *P. oceanica* beds, and found different signs of genetic isolation: excess of heterozygosity and a presence of fixed alleles, which are rarely found in the whole distributional range of the species.

It is important, at this point, to investigate on differences in the limits of tolerance between Mediterranean populations that became newly established in the Black Sea and those of the Mediterranean populations.

5.2. The Turkish Straits System as an acclimatization/adaptation corridor

The Turkish Strait System is a very important biological corridor for many migratory species of fish, birds and mammals from both the Black Sea and the Mediterranean Sea and it is the feeding and breeding ground for the pelagic fish of Atlantic origin during their migrations from the Black Sea to the Sea of Marmara or vice versa. Additionally, the Turkish straits form an "acclimatization zone" for transiting species, allowing those from the Mediterranean to adjust to the different environmental conditions in the Black Sea, and vice versa.

5.2.1 Physical characteristics of TSS

The Turkish Strait System (TSS) constitutes a two-layer system, where a sharp halocline of a thickness of 10-20 m separates brackish waters (22-26 psu) in the thin upper layer of the Marmara Sea (15-30 m) from the saltier waters (38.5-38.6 psu) in the lower layer throughout the year. Temperature of the upper layer varies seasonally within the range of 7-27°C whereas temperature of the lower layer remains around 14.5-15.0 °C. The relatively dense Mediterranean underflow enters into the Çanakkale Strait below the depths of 15-20 m with salinity of 38.9-39.0 psu and temperature of 16-17 °C and undergoes gradual changes along the Strait and its transition region to the western Marmara Basin. They eventually sink in the form of a dense water plume with S~38-38.5 psu and T~15.0-16 °C toward the density levels where they reside, whereas a part of it continues to flow within a narrow zone immediately below the interface. The sinking plume subsequently takes part in the renewal of the sub-halocline waters of the Marmara Sea by spreading isopycnically in the form of intrusive layers.

The underflow spends about 6-7 years in the deeper layers of the Marmara Basin (Besiktepe *et al.*, 1994). Upon reaching the Bosphorus-Marmara junction region, the lower layer waters flow into the Istanbul Strait through the submarine canyon. Thereafter, the underflow interacts with local topography at the southern and northern sill regions, becomes progressively diluted due to strong entrainment into the upper layer flow, and enters into the Black Sea junction region as a thin plume.

In terms of mixing characteristics of the Mediterranean underflow, five distinct regions are evident within the TSS: the first one occurs within the Nara section of the Çanakkale Strait where the internal hydraulic adjustment of the flow causes strong entrainment of the lower layer flow with the upper layer that then goes back to the Aegean Sea. Similar abrupt mixing occurs at the southern and northern sill regions of the Istanbul Strait. The Bosphorus-Black Sea junction region imposes further mixing on the underflow. Moreover, the wind-induced mixing within the Sea of Marmara affects the properties of the sub-halocline waters of the lower layer during autumn-winter months.

5.2.2 Persistent geographic barriers of TSS for mediterranization

Depending on the mixing and transport characteristics of the Mediterranean underflow through the TSS, Oguz and Öztürk (unpub.) recently proposed a set of successive geographic barriers that may control migration success of Mediterranean species on their way to the Black Sea. These barriers mostly apply to pelagic and benthic planktonic species and fish larvae whose transports are mostly

passive and introduced by hydro-physical conditions. The present discussion therefore excludes the migration of fish species between the Mediterranean and Black Sea ecosystems that are largely independent from such persistent hydro-physical geographic barriers.

The planktonic species and fish larvae face the first barrier in the Nara Passage zone of the Çanakkale Strait where the strong turbulence and mixing of upper and lower water masses may likely cause a part of their population to be transported back to the Aegean Sea with the upper layer flow and may introduce as well physiological shocks due to abrupt temperature change of about 7-10 °C and salinity change of about 10-15 psu. The region therefore has long been considered as an acclimatization zone for marine organisms migrating to the Black Sea (Öztürk and Öztürk, 1995).

The second barrier occurs along the junction region to the Sea of Marmara where the major part of the Mediterranean underflow sinks into intermediate and deep layers of the suboxic-anoxic western Marmara Basin. Only those individuals able to follow the narrow sub-halocline layer below the interface with sufficient oxygen (Figure 10) will be able to survive their passage.



Ecological role of the Turkish Strait System (TSS) under physical condition

Figure 10. Schematic diagram, by T. Oguz and B. Öztürk, of the physical structure of the Turkish Strait System (TSS) controlling the migration success of Mediterranean species into the Black Sea. The lower panel displays in more detail the pre-Bosphorus channel region outside the northern exit of the Istanbul Strait as well as the Bosphorus-Black Sea junction region up to the shelf break. The temperature and salinity profiles in the upper panel are typical for the Sea of Marmara. The main migration route of Mediterranean species lies immediately below the interface zone (thick sloping line) between the upper and lower layers.

Mediterranean species which manage to enter the Bosphorus encounter three successive obstacles. The first is induced by the southern sill, the second by the constriction region near the Atatürk Bridge, and the third by the northern sill at the Black Sea exit. The underflow is characterized upstream of the northern sill roughly by $S\sim35-36$ psu and $T\sim11-$ 13 °C, but more importantly its thickness of at least 30-40 m at the Aegean end of the system declined to 5-10 m at most. Entrainment process of the underflow into the upper layer that prevails excessively downstream of the sill as well as further along the shelf introduces further dilution of the underflow. When it reaches to the shelf break of the southwestern Black Sea Basin the underflow is almost indistinguishable from ambient waters and has a thickness of less than 1 m. The species which are able to survive and reach the narrow shelf zone of the southwestern Black Sea are prone to settlement and acclimatization to the Black Sea conditions. There is also a possibility that some of them can sink across the shelf break into the anoxic waters of the Black Sea together with the Mediterranean underflow. These successive physical constrains may therefore explain the low species diversity of the Black Sea (Zaitsev and Mamaev, 1997) after its connection to the Mediterranean about 7,000 years ago.

5.2.3 Temporary geographic barriers of TSS for mediterranization

While the physical constraints and bottle-necks described above along the TSS are persistent features of the system, some temporal physical features may exercise further adverse controls on the migration process. Almost every winter, under very strong northwesterly wind episodes, excessively large upper layer flow can temporally fill all depths of the Istanbul Strait with cold waters of about 5-7 °C, and temporally block the Mediterranean underflow. The abrupt mixing and sudden temperature changes between these two contrasting water masses lead to mass mortalities of commercial and immigrant fish species such as bonito, bluefish, anchovy, horse mackerel. This event is called "Orkoz" or "Ayna" by local fishermen and may even be extended into the southern half of the strait near the AnadoluHisar/Kandilli section.

To conclude, the mediterranization process is one of the subtle issues of the Black Sea ecosystem and it is likely to evolve in future decades under continuing global warming. The lack of clear understanding of this process mostly arises from the lack of systematic sampling and monitoring strategy along the TSS.

6. CLIMATE FORCING (AMO & NAO) OF BIODIVERSITY AND MEDITERRANIZATION

The magnitude and variety of climatically forced changes in the physical environment provoke substantial proximate and emergent ecological responses. The direct effects of climate change impact occur at the individual level, at various stages in the life history cycle via changes in physiology, morphology and behaviour, at population level via changes in transport processes influencing dispersal and recruitment and at community level via interacting species (e.g., predators, competitors, etc.), including climate-driven changes in both the abundance and the per capita interaction strength of these species.

6.1. Examples from plankton and fish biomass

During the period 1960-1980 the Black Sea status passed from low mesotrophy to high mesotrophy and eutrophy. The period 1960-1970 represents the Black Sea pristine conditions, with phytoplankton biomass less than 2-3 g m⁻² whereas 1970-1980 is the period of high nutrient enrichment of the system that is reflected in phytoplankton biomass by a gradual increase to more than 10 g m⁻² (Figure 11). The climate-induced changes are therefore not clearly seen due to more dominant signal of eutrophication-induced changes. However, the climate-induced changes appear to be well-marked during the 1980s and 1990s.



Figure 11. Long-term variations of summer-autumn mean phytoplankton biomass (g m⁻²) (vertical bars; after Mikaelyan, 2005), the mean CIL temperature (°C) (dots; after Belokopitov, 2005), averaged over all stations within interior basin and mean winter (December-March) sea surface temperature (SST) as an average of Hadley2, NCEP-Reynolds and Pathfinder5 data sets. The phytoplankton biomass is expressed in terms of euphotic zone integrated values.

Zooplankton biomass in the northeastern Black Sea is significantly correlated with the changes in water temperature. As shown in Figure 12, the biomass fluctuates with the annual mean sea surface temperature such that warm (cold) years attain higher (lower) biomass with clear increasing and decreasing trends of variations between cold and warm years. The corresponding phytoplankton biomass also follows the climatic changes as evidenced by close correlations between high (low) biomass and cold (warm) temperatures in Figure 11. Phytoplankton biomass has therefore out of phase variations with zooplankton biomass in regard to temperature dependence, perhaps linked with trophic cascade.



Figure 12. Long-term variations of the annual-mean edible zooplankton biomass in the northeastern basin (g m⁻²), and the mean CIL temperature (°C) (dots; after Belokopitov, 2005) averaged over all stations within interior basin and mean winter (December-March) sea surface temperature (SST) as an average of Hadley2, NCEP-Reynolds and Pathfinder5 data sets.

The sprat and anchovy stock estimates also follow closely the annual mean sea surface temperature and therefore reflect a clear signature of climatic modulations. Sprat as a cold water species attains much higher biomass during cold years and lower biomass in warm years (Figure 13). The sprat fluctuations overlap considerably with those of phytoplankton and are opposite to edible zooplankton, indicating therefore a trophic cascade pattern. Similar correlation is also evident for the sprat fat content in which a cooling (decreasing) trend coincides with increasing (decreasing) sprat fat content. In particular, sprat populations were able to maintain their highest fat content during the cold period of the 1980s. On the other hand, the anchovy stock follows an opposite trend having higher biomass during warm years.



Figure 13. Long-term variations of annual-mean basin-averaged sea surface temperature and sprat stock anomalies. The figure shows positive correlation of the changes in sprat stocks with the climatically cold years.

Climatic fluctuation may affect the relative timing of food requirement and food availability (match-mismatch). Differences in the temporal and spatial match between predator and prey may thus generate variability in the predator survival rates. The ambient conditions in the Black Sea such as water temperature and large-scale climatic and hydrographic processes generate variation in the production, distribution, and abundance of organisms. A climate-induced delay in food production could thus create a mismatch between the prey production and the predator requirements with dramatic implications for reproduction success.

6.2. Interaction with anthropogenic factors

Pollution, destruction of hydrobionts stocks, introduction of invasive alien species and habitat loss and modification were indicated by the Global Ecological Fund (GEF) as the main factors threatening the world ocean. The Black Sea is a good example.

The mass development of gelatinous plankton organisms is a characteristic feature of marine zooplankton in condition of eutrophication (Figure 14). High numbers of the scyphozoan *Rhizostoma pulmo* were observed in the coastal zone of north-western Black Sea in the late 1960s and early 1970s. The population of *R. pulmo* gradually declined back to its former levels in 1973-1974. However, almost immediately a population of another scyphozoan jellyfish, *Aurelia aurita*, became highly abundant. The exotic ctenophore, *Mnemiopsis leidyi*, unexpectedly appeared in the early 1980s, and reached a total biomass of about one billion tons (Zaitsev and Mamaev, 1997). On the other hand, the *Aurelia* population collapsed almost immediately, and the biomass of other zooplankton and ichtyoplankton decreased sharply. As a result anchovy catches dropped and commercial fishing for anchovy in the Sea of Azov came to a complete halt (Zaitsev and Mamaev, 1997).



Figure 14. Successive blooms of jellyfish in the Black Sea between 1960-1995, after sharp decline of population of the jellyfish eating mackerel. a- *Scomber scomburus*, b- *Rizostoma pulmo*, c- *Aurelia aurit*a, d-*Mnemiopsis leidyi* (after Zaitsev and Mamaev, 1997).

The Black Sea is a favourable habitat for many accidental invaders, some of which have become serious competitors for local species or even their predators. It is possible that the large volumes of phytoplankton and certain zooplankton that resulted from cultural eutrophication did facilitate the establishment of these exotics in the Black Sea (Zaitsev and Mamaev, 1997).

6.3 Interaction with fisheries

6.3.1 Fishery resources of the Black Sea

The Black Sea has a considerably limited variety of fishery resources compared to the Sea of Marmara, the Aegean Sea and the Mediterranean. Abundance and catch rate of pelagics such as anchovy, sardine, sprat, blue fish and bonito depend strongly on the recruitment success in their spawning grounds in the Sea of Marmara and NW Black Sea shelf. Turbot, whiting, red mullet, dogfish, skates, stingray, red gurnard, sole and plaice are the major demersal fish species and play an important role in the fisheries of Black Sea countries. *Rapana venosa, Venus gallina, Mytilus galloprovincialis* are the main species in demersal shellfish production

6.3.2 Development of fishing industry (1970s-2005/8)

The intensive exploitation of Black Sea fisheries started at the end of 1960s – beginning of 1970s with the increase of number of vessels and fishing efficiency. The pressure on the stocks increased until the end of 1980s with a peak total catch of 800 kt in 1988, followed by a sharp decline in the subsequent years due to introduction of the comb-jelly *Mnemiopsis leidyi*, causing high predation on eggs and larvae of economically important fish species. The decline coincides with the two-decade-warming period of climatic cycle in the region. This period also coincided with major political changes in the countries bordering with the Black Sea, when the Russian Federation, Ukraine and Georgia emerged as new states after the collapse of the Soviet Union. During this transition period, due to the financial problems, the fishing fleets of these countries were not used efficiently opening the way to an increase in the fishing effort of the Turkish fleet. From 2000 onwards, over 80% of the total Black Sea catches have been obtained by Turkey (see Figure 15). This ratio is even higher for some species, e.g. bonito, horse mackerel, whiting, red mullet, and bluefish.



Figure 15. Share of the countries in capture fish production in the Black Sea in 2007 (FAO, Statistics 2008).

The number of Turkish fishing vessels in the Black Sea is 6,700 and new entries are not permitted since 2002. On the other hand old vessels can be replaced by new ones with the same license (20% length increase for cold storage and modern life spaces).





The main fish species in the catch are anchovy, horse mackerel, whiting, bluefish, Atlantic mackerel, sea snail and baby clam (Figure 16).

6.3.3 Recent changes in catch composition of native and alien species

The sea snail *Rapana venosa* is the one of the most important alien species affecting native species of the Black Sea. It has been introduced in the Black Sea in the 1940s from the Sea of Japan by merchant vessels. The absence of any direct predators facilitated the spread of *Rapana* all over the Black Sea coasts, causing the destruction of the mussel beds, its favourite prey. However, as its meat is very popular in the Far East countries, mainly in Japan, this mollusc has been the object of commercial fishing since 1990, for exportation to overseas markets. Similarly, *M. leidyi* became the most abundant jellyfish in the Black Sea and caused the collapse of anchovy stocks (Zaitsev and Mamaev, 1997).

The Pacific mullet, *Liza haematochilus (=Mugil so-iuy)* was intentionally introduced in the Seas of Azov and the Black Sea in the period 1972-1980. Native to brackish and marine waters of the Sea of Japan, *M. soiuy* was introduced into the Azov Sea during the early 1980s by Soviet scientists (Zaitsev, 1991). This species started to reproduce in the Azov Sea and became very abundant along the south Crimean coast, before extending further (Unsal, 1992). At present, *M. soiuy* is a commercial species in the Black and Azov Seas (Shiganova, 2008). After the introduction of this species the population of native mullet declined due to high level of food competition, to the point where four of five native mullet species are currently out of the commercial list.

7. CLIMATE CHANGE PROJECTIONS

Most of the existing climate models have reproduced much weaker trend of the positive NAO index than recently observed under increasing greenhouse gas concentrations (Gillett *et al.*, 2003). Ambaum and Hoskins (2002) demonstrated quantitatively the existence of a nonlinear feedback mechanism between the NAO and the stratospheric vortex located about 20-30 km above the earth's surface over the North Pole. Scaife et al. (2005) and Rind et al. (2005) have further extended the Ambaum and Hoskins (2002) model by showing that the unexplained strengthening of the NAO can be fully simulated in a climate model by imposing observed trends in the lower stratosphere. Considering the fact that the increase in greenhouse gas concentrations cools and strengthens the stratospheric winter vortex, this process translates at the surface as stronger westerly winds that promote a positive NAO index and further warming in the North Atlantic region. Reduced stratospheric temperatures over both poles mainly in late winter and spring, when sunlight comes back to the polar night area due to the substantial reduction of lower stratospheric ozone content over the last two decades (e.g. Graf et al., 1998) also contribute to strengthening of the stratospheric winter vortex. Kodera et al. (2008) further pointed to the solar modulation of the stratospheric polar vortex, and hence promoting the positive NAO index over the Eurasia. Thus, the Eastern Mediterranean and Black Seas is expected to cool under increasing greenhouse gases which cause either to slow down the effect of global warming or to switch the regional climate into a cooling phase.

8. Research priorities and recommendations

Future research needs to address species-specific preferences and sensitivities to environmental factors, most importantly temperature, hypoxia, ocean acidification, and salinity changes, also in relation to the effect of biotic factors such as food availability. Such efforts will improve the cause/ effect understanding of ongoing change and lead to the development of reliable mechanism-based projections of future scenarios. Physiological studies of sensitivities, stress levels and functional capacities in crucial life sustaining processes need to be combined with those of phenotypic plasticity, functional genomics and population genetics.

These physiological and genetic approaches must be completed by ecological studies on the biotic interactions among species. Ecological systems are historical and are governed by both constraints (e.g. the limits of tolerance of single species) and by contingencies (e.g. the arrival of an alien predator). Constraints are predictable, but contingencies are not. According to recent estimates, the oxygen-depletion processes might be intensified in the future resulting in the overall decrease of oxygen content in the oceanic water and formation of temporal dead zones (Diaz and Rosenberg, 2008). Regarding the Black Sea it may result in increasing frequency of hypoxia in the Shelf regions (Northwestern Shelf, Anapa Shelf, Azov Sea) and in changes of the volume of the oxygenated layer of the Black Sea (Yakushev *et al.*, 2008).

The Black Sea Basin is characterized by a complex political development during the past twenty years. It embraces six States engaged in different regional forms of cooperation, but also divided on a number of issues up to a point of military confrontation. This has inevitably left its stamp on the management of marine living resources as well. After almost two decades of regional cooperation, there are still no regular stock assessments for the most important commercial species. It is hard to move on to ecosystem-based fishery management with the existing serious data gaps.

The prevailing managerial approach is the implementation of national measures (mainly input controls, such as limitation of fishing effort through licensing of fishing gear and vessels, closed

seasons). Since 2007, Bulgaria and Romania, as new EU members, have followed the Community Fisheries Policy and applied quotas for turbot and sprat. There is no international convention covering fisheries management in the whole Basin, although different drafts have been discussed at technical level for over ten years under the auspices of the Black Sea Commission. Recently, the General Fisheries Commission for the Mediterranean, GFCM, has been put forward, mainly by the EU, as a suitable body for dealing with issues arising at regional level. While the agreement establishing GFCM covers the Black Sea area, Georgia, Russia and Ukraine are not parties to the Commission, which puts certain limits to the viability of such a solution. The issue of coordinating the management of migratory species (e.g. anchovy) within the Black Sea Basin remains open and an institutional setting acceptable to all coastal countries still lies in the future.

I - Executive Summary of CIESM Workshop 39

"Climate forcing and its impacts on the Black Sea marine biota"

by

Turan C., Boero F., Boltachev A., Duzgunes E., Ilyin Y.P., Kideys A., Micu D., Milliman J.D., Minicheva G., Moschella P., Oguz T., Öztürk B., Pörtner H.O., Shiganova T., Shivarov A., Yakushev E. and F. Briand

This synthesis was written by all participants of the workshop, under the coordination of Cemal Turan and with the support of Paula Moschella. Frédéric Briand, the Monograph Series Editor, reviewed and edited this chapter along with the entire volume, whose physical production was carried out by Valérie Gollino.

1. INTRODUCTION

In welcoming the participants Dr Frédéric Briand, Director General of CIESM, remarked that Trabzon – the famed, mythical Trebizond – marked the first, long-delayed encounter of a CIESM Workshop with the Black Sea shore and that there would be many further returns to a Sea that was an essential part of the Commission scientific and geographic scope. This specific meeting would extend to the Pontic region a brainstorming exercise engaged one year earlier, with CIESM Workshop 35, for the Mediterranean ecosystem, and would be carried out in the same integrative spirit as reflected by the presence around the table of marine biologists and physicists. After presenting the two co-Chairs of the CIESM Committee on Living Resources and Marine Ecosystems, Drs Cemal Turan and Ferdinando Boero happily reunited on this occasion, he expressed his gratitude to Dr Bayram Öztürk, Turkish Representative on CIESM Board for his very efficient assistance in helping prepare the ground logistics.

1.1. Black Sea climate change and hemispherical teleconnection

The global warming observed since the end of the 19th century has been caused not only by natural climate changes on the decades-centuries scale but also by the impact of human activities on the Earth's climate system, expressed in greenhouse effect. According to IPCC (2007), mean global surface air temperature rise for the last century (1907-2006) was on average about 0.7 °C, and the trend of temperature for the last 50 years was almost twice as much (+ 0.13 °C/10 years). One of the most significant processes in the ocean-atmosphere system that influence climate fluctuations in Eurasia is the Atlantic Multi-decadal Oscillation (AMO) of sea surface temperature, with periods of 50-100 years (more often reported as 60-80 years), represented also by the low-frequency mode of North-Atlantic Oscillation (NAO) of surface pressure field (Polonsky, 2008) (Figure 1).



Figure 1. Atlantic Multidecadal Oscillation (AMO) and North Atlantic Oscillation (NAO), 5-yr running means, 1880-2005.

In general, positive NAO indexes correspond to more northern tracks of cyclones, bringing more heat/ cold in winter/ summer and more precipitations to northern Europe, whereas southern regions experience opposite conditions. Negative NAO phases mean more southern cyclone trajectories, toward the southern Europe areas, including the Mediterranean and Black seas. Estimation of climatic variations of these oscillations on a timescale over 30-years, and of related anthropogenic impacts such as the greenhouse effect and river hydraulic controls, contribute to determine long-term variability (trends and fluctuations) of the Black Sea ecosystem.

Regional atmospheric processes are under the influence of external climatic changes and they, in turn, affect processes on sea surface and in water column. The observed changes in the physical compartments determine in many respects the present and future changes of marine ecosystem state and productivity.

2. CLIMATE VARIABILITY (HYDROMETEOROLOGICAL PARAMETERS) AND ITS EFFECT IN THE BLACK SEA REGION

Based on secular observations from marine hydro-meteorological stations along the northern and eastern Black Sea shores, linear trends and long-term oscillations reveal annual, seasonal and monthly air temperature (AT) trends. Significant long-term secular linear trends of annual mean AT in most studied Black Sea regions are positive, with slopes (0.4-0.8 °C/100 years) that correspond to the secular rise of mean global surface air temperature (Ilyin and Repetin, 2006a). However, on the decadal scale, the long-term trend is interrupted by severe departures on the order of 1-3 °C (Figure 2), which corresponds to variations also seen in the sea-surface temperature (SST) as well as sub-surface (Figure 3). These decadal fluctuations agree with AMO and NAO signals (Figure 1).



Figure 2. Long-term variability of AT anomalies (°C) in Yalta (Ukraine) approximated by superposition of harmonic functions having periods 31, 41 and 62 yr.



Figure 3. Annual trends in air temperature (AT), sea-surface temperature (SST) and the winter NAO index, 1870-2006.

The uniform response of the Black Sea drainage basin to AMO/NAO can also be seen in the closeness of temporal variations in river discharge throughout the area, ranging from the Sakarya in the south, to Don in the north-east, to Danube and Dnieper in the west (Figure 4). Changes in freshwater input also have been observed (Figure 5) together with a weakening in wind activity, which is manifested as a general deceleration of horizontal circulation and vertical mixing of surface waters in the Black Sea (Ilyin, 2008b). This in turn leads to changes in the transport of heat and chemical constituents, including nutrients and pollutants, as well as a change in self-cleaning processes, such as surface water renewal by wind-driven coastal upwelling.



Figure 4. Annual discharge (5-yr running means) from the Danube (Da), Sakarya (SA), Dniepr (Dn) and Don rivers to the Black Sea.



Figure 5. Interannual variability and trends of the Black Sea fresh water budget (FWB) and its components (km³).

In addition to lowering the salinity of surface waters, increased rainfall can lower SST, especially on the eastern coasts of the Black Sea. Moreover, pollutants and nutrients brought about via increased precipitation are comparable with those derived by riverine input; in fact, the atmospheric input of nutrients is estimated in ten-thousands (nitrites, phosphates) and hundred-thousands (nitrates, sulfates, chlorides) tons per year (Chaykina *et al.*, 2008; Voitsekhovich *et al.*, 2004).

River-derived nutrient discharge of nitrogen and phosphorus to the Black Sea rose sharply in the 1950s-1960s, in response to increased agricultural activity in the Danube, Dnieper and Don watersheds. Nitrogen and phosphorus fluxes, however, declined abruptly in the late 1980s, following the economic recession which affected the former eastern block countries in that period (Figure 6). Silica discharge declined in the 1970s in part due to river damming (e.g., Iron Gates Dam; Humborg *et al.*, 1997), and shifts from siliceous (mainly diatoms) to non-siliceous phytoplankton (Petrova-Karadjova, 1984; Humborg *et al.*, 1997; Bodeanu *et al.*, 2002). Data from the NE Black Sea reveal similar trends to those observed in the NW Black Sea, but with only a slight shift in the phosphate content (Figure 7).



Figure 6. Five-year means fluvial flux of nitrogen (N), phosphorus (P) and Silica (SiO₂) to the Black Sea (data from Ludwig *et al.*, 2009).



Figure 7. Interannual changes of upper layer concentrations of inorganic species of N, P, Si in the North-Eastern Black Sea averaged for the 5-years intervals.

In the open waters, the low NO_3/PO_4 ratio in the nutricline below the euphotic zone resulted in nitrogen limited phototrophic production in the surface layers. This can be explained by intensive loss of inorganic nitrogen under suboxic conditions. According to Cociasu *et al.* (1996) and Yilmaz *et al.* (2006), the NO_3/PO_4 ratio in the euphotic zone and the upper nutricline is very low (2 - 6.5) in the open sea. The same tendency can be observed in the NE Black Sea, where the N:P ratio decreased during the last 10-15 years from 30 to 5.

One of the indicators of the Black Sea biogeochemical system recovery should be the reappearance of the nitrogen fixation. The process of production of gaseous nitrogen through denitrification and anammox is a well known feature in oxygen-deficient basins. In terms of budgeting, this loss of bound nitrogen should be compensated by nitrogen fixation (Yakushev *et al.*, 2007). Denitrification and anammox were measured in the Black Sea during the last decades (Murray *et al.*, 2003; Kuypers *et al.*, 2003), whereas N-fixation was not observed in the 1980s-1990s. In contrast, in 1950s, before the initiation of intensive eutrophication, N-fixation in the Black Sea was well-developed (Pshenin, 1963). As shown above, the low N/P ratios in the different parts of the Black Sea testify to nitrogen-limited primary production, which favors N-fixation as part of the normal functioning of the ecosystem. Recently, N-fixation was again measured in the Central Black Sea in 2003 (McCarthy *et al.*, 2007). We thus can conclude that there are present positive signs of recovery of the Black Sea ecosystem after several decades of decline in anthropogenic impact (Black Sea Commission Report, 2008).

3. COASTAL OXYGEN DEPLETION AND HYPOXIA, OXIC ZONE VOLUME

Seasonal development of low oxygen zones (oxygen concentrations below 2 mg/l, oxygen concentrations <30% saturation value) in bottom waters of the Black Sea (e.g., northwestern shelf, Anapa shelf, Sea of Azov) depends on the intensity of eutrophication as well as circulation, stratification and meteorological conditions (wind, heat flux, etc.). In the Black Sea, the development of hypoxia typically begins in June-July and attains maximum coverage in August. There is a relationship between the rate and timing of river discharge and the scale of hypoxic conditions (Berlinskii, 2003). In years with high river discharge, hence high nutrient input and organic matter production, oxygen concentrations in bottom layers are ~20% lower than in years of low river discharge.

Hypoxia is also subject to longer-term variations, and a simple correlation to environmental factors may not always hold. For instance, a two-fold increase in hypoxia occurred in the northwest shelf in the 1980s, but has since decreased in its Ukrainian sector. In contrast, no hypoxia was reported in Bulgarian waters or off other Black Sea states, other than an intensive summer anoxia in the Sea of Azov in 2001 (Yakushev et al., 2003). A long-term detailed study of the anoxic zone in the northeastern Black Sea near Gelendzhik (Podymov, 2008; Yakushev et al., 2008) (Figure 8) show that the depth of disappearance of hydrogen sulphide was characterized by values $\sigma_{\Theta}\sigma_{\Theta}=16.15$ -16.25 kg m⁻³ in 1991-1998. In 1999-2000 the shoaling of this boundary appeared. The value of this shoaling of ~5-15 m was about σ_{θ} =0.05-0.15 kg m⁻³. After the year 2000 the position of hydrogen sulphide stabilized, as also seen in ammonia, total manganese and methane (Yakushev et al., 2006). These oscillations can be connected with the corresponding winter weather conditions. For example, the two warm winters in 1998-1999 may have affected the winter formation of the oxygen-rich cold intermediate layer (CIL). These years were remarkable for the increase in SST (Figure 8), increase in temperature in the core of CIL (Oguz et al., 2006; Krivosheya et al., 2002), and shoaling of CIL in the density field (Murray et al., 2003). The decrease of intensity of CIL formation should lead to an increase in temperature and a decrease in oxygen content in its core. To check these assumptions we calculated the average concentrations of dissolved oxygen in CIL (defined as the layer from σ_{θ} =14.45 kg m⁻³ to $-\sigma_{\theta}$ =14.60 kg m⁻³) (Figure 8). In 1999-2000, when the shoaling of reluctant occurred, the oxygen content declined. The minimal concentrations were registered in 2001-2002. In 2003-2004 the oxygen content in this layer returned to values typical of the early 1990s.



Figure 8. Onsets in the density field of hydrogen sulphide (A), averaged concentration of oxygen in the CIL (in the layer σ_{θ} =14.45-14.60 kg m⁻³) (B), temperature in CIL core in the Northeastern Black Sea (data of V.G. Krivosheya); averaged temperature in the CIL core (data of the MHI oceanographic database and ARGO floats) (C) and interannual variability of the winter NAO index (crosses averaged for February-April, lines –averaged for three successive years (D). The variability in the Black Sea hydrophysical-biogeochemical system can be connected with the weather conditions change as it follows from the NAO index behaviour (Figure 8). The results obtained illustrate the mechanism of reaction of the natural system of the Black Sea on the Global Climate changes. The correlated changes in the decadal NAO index behaviour under winter weather conditions result in larger or smaller cooling of the upper layer waters. As it follows from the analyzed estimates, the changes in sea surface temperature lead to changes in winter CIL formation intensity and to oxygen renovation there. The oxygen inventory in the CIL acts as a specific accumulator that supports the consumption of oxygen for the organic matter decay and downward diffusive flux during the whole year. The interannual variations of this oxygen renovation in CIL lead to changes in the suboxic layer hydrochemical structure and, in particular in the position of the anoxic boundary in the density field. Therefore, the distribution of the chemical parameters in the density field in the Black Sea might be a good indicator of the Global Climate variations. Another factor that might affect the interannual dynamics of the hydrogen sulphide position is eutrophication. It should be emphasized that one result of 5-10 m oscillations in the anoxic boundary is a 5-10% change in the volume of the oxic waters. Such oscillations are considered vitally significant and should be studied further.

4. THE HISTORY OF BLACK SEA BIODIVERSITY

4.1 Mediterranization of the Black Sea biota

Low species diversity (i.e. low competition) combined with high habitat diversity (i.e. availability of potential niches) in the Black Sea provides favorable conditions for the introduction of alien species. Some of these species become invasive, altering the stability and functioning of the ecosystem and threatening the indigenous species. There have been increasing numbers of Mediterranean species in the Black Sea since the first records in 1920s. This is particularly true for the fish fauna. The diversity of the Black sea ichthyofaunahas increased due to the intrusion of fish from the Mediterranean Sea, a process that has been defined as "mediterranization" (Pusanov, 1967; Boltachev and Yurakhno, 2002). In addition, fish species of Indo-Pacific origin naturally migrated to the Mediterranean Sea via the Suez Canal (Lessepsian migrants) along with those introduced accidentally (via ballast waters) and intentionally (e.g. for farming purposes) further modify the Black Sea fish diversity. The water mass exchange between the two seas also facilitates the introduction of species which may become later established in the Black Sea.

Any comparison between Black Sea and Mediterranean biota is however impaired by the fact that the Mediterranean fauna is itself still incompletely known. Caspers (1957) estimated the Black Sea metazoans at ca 21% of the Mediterranean fauna. Later research in both seas showed that the Black Sea fauna is only about three and a half times poorer (see Bianchi and Morri, 2000). Comparing the Mediterranean and the Black Sea - the decrease in total number of species is paralleled by disappearance and a decline in many oceanic groups, such as Sponges, Salps, Doliolids, Pteropods, Siphonophores, Euphausiids, Nemertini, etc. These changes are undoubtedly salinity-driven. Salinity ranges from 33 to 39‰ in the Mediterranean Sea, from 17 to 22 ‰ in the Black Sea. However, the degree of faunal impoverishment is not directly proportional to salinity. Between the Mediterranean and the Black Sea, salinity drops by more than a factor two, while the number of animal species decreases by a factor 3-3.5.

Indeed, 80% of the Azov-Black Sea fauna is of Atlantic-Mediterranean origin, and its share continues to increase; only 10.4% and 9.6% of species are of freshwater and Ponto-Caspian origin, respectively. The species of Atlantic-Mediterranean origin mainly come from the Mediterranean Basin, the Lusitanian province, and the boreal zone of the Atlantic Ocean. The biota of the Black Sea shares more similarities with the biota typical of higher latitudes, that is few species with high biomass, whereas the Mediterranean Sea is characterized by many species with low biomass (Table 1).

Таха	World	Medit.	M/W(%)	BS	BS/M(%)
Phytoplankton	~4375	673	15.4	746	110.8
Red algae	5250	867	16.5	143	16.5
Brown algae	1500	265	17.7	75	28.3
Green algae	1200	214	17.8	83	38.7
Sea grasses	50	5	10	6	120.0
Total Macrophytes	12375	2024	16.4	1053	52.0
Sponges	5500	600	10.9	25	4.2
Cnidarians	11 000	450	4.1	44	9.8
Bryozoans	5000	500	10	12	2.4
Annelids	8000	777	9.7	153	19.7
Molluscs	32 000	1376	4.3	125	9.1
Arthropods	33 600	1935	5.8	288	14.9
Echinoderms	6500	43	2.2	5	11.6
Tunicates	1350	244	18.1	16	6.6
Other invert.	~13 550	~550	4.1	278	50.5
Total invert.	~116 500	~6475	5.6	946	14.6
Cartilage Fishes	1170	84	7.2	12	14.3
Bony Fishes	13 151	532	4.1	180	33.8
Reptiles	~6700	355	5.3	175	49.3
Mammals	114	21	18.4	4	19.1
Total vertebrates	21 135	992	4.7	371	37.4
Grand Total	~137 635	~7467	5.4	1317	17.6

Table 1. Numbers of marine species in the World Ocean, the Mediterranean and the Black Sea.

4.2. The diversity of Black Sea fish fauna

The current Black Sea ichthyofauna is the result of a long process started after the last junction of the Black Sea to the world ocean and continued for about eight thousand years. At present, the Black Sea only connection with the Mediterranean Sea is the Turkish Strait system, comprising the Istanbul Strait, the Sea of Marmara, and the Dardanelles. Therefore the Black Sea can be considered as the 'arm' of the Mediterranean and many of its species are common to both seas.

The Black Sea fish fauna accounts for about 200 species and subspecies, including occasional freshwater and marine fish, recorded as single individuals in the Black Sea (Svetovidov, 1964; Oven, 1993; Boltachev, 2003). However, a considerable decrease in the numbers of many native Black Sea fish is observed; some of them have not been recorded since several decades largely due to the effects of anthropogenic pressures, namely: chronic pollution, in particular eutrophication, which increases fish mortality, overfishing and poaching, the physical destruction of spawning grounds, of nursery and feeding areas, and the invasion of new hydrobionts.

According to their phylogenetics gene, ecological traits, and life cycles, in the Black Sea Basin four main fish groups can be singled out.

The fully marine fish – about 140 species and subspecies – make the core of the Black Sea ichthyofauna. The most representative species of this group, are of Atlantic – Mediterranean, tropic and sub-tropic origin. They are euryhaline and inhabit mainly the upper warmer layer in the water column. Among them, 60 naturalized completely, and formed endemic subspecies, all stages of their life cycle being spent in the Black Sea. The other species migrate regularly at the warm time of the year from different areas of the Mediterranean Basin (Vodyanitsky, 1930). Boreal–Atlantic fish are represented by 12 species, inhabiting mainly the cool subsurface layer in the warm season and penetrating the surface layer during the winter period (Svetovidov, 1964; Oven, 1993).

Brackish water fish count 22 species including species endemic of the Black Sea or species and subspecies shared with the Caspian Sea, which are autochthonous relicts of the ancient brackish-water Ponticus lake – sea (Rass, 1949). Many of these species are distributed in the brackish-coastal waters and river estuaries, mostly in the north-western part of the Sea or near the Kerch Strait.

The diadromous and semi-diadromous group includes 25 species, which are of quite ancient origin – about 1.5-2 million years. This is related with fast migrations of these fish (with the exception of the eel fish, *Anguilla anguilla*) from the northern rivers into the Pontic lake basin and then returning back to the rivers for spawning (Oven, 1993). This group is affected by the mostly negative influence of human economic activities, which result in the destruction of reproduction sites, blockage of the migration pathways in rivers and over-catches, as many species are of high commercial value, such as sturgeons, salmons and herrings.

Typical freshwater taxa count only 15 species, occasionally reaching the Black Sea Basin coastal area usually during high water in the rivers (Oven, 1993).

<u>New records in the last 20 years:</u> up till now one observes a trend of increasing arrival of exotic species into the Black Sea; often resulting in the establishment of the new species (see Tables 2 and 3). The native Black Sea ichthyofauna also registers an increase of certain commercial and/or rare species (Boltachev, 2003; Boltachev, 2009). For example, there is an increase in frequency of round sardinella (*Sardinella aurita*), bogue (*Boops boops*) and salema (*Sarpa salpa*) in Turkish costal waters, and, in the coastal zone of the south-western Crimea, of "previously endangered" species such as Black Sea salmon (*Salmo trutta labrax*), common bass (*Dicentrarchus labrax*), dotted dragonet (*Callionymus risso*), bearded umbrine (*Umbrina cirrhosa*), yellow gurnard (*Chelidonichthys lucernus*), puntazzo (*Diplodus puntazzo*) and green wrass (*Labrus viridis*) (Table 4). The sea horse (*Hippocampus hippocampus*), which practically disappeared in the middle of the 1990s, suddenly increased in abundance in 2002 and 2008 along the coasts of Crimea, the north-western part of the Black Sea and the Northern Caucasus.

Species	Origin	Presence in the 60s	Reappearance in BS	Location first record	Established in Black Sea	Abundance	Habitat	Geographic distribution	Vector	References
Sardinella aurita	Med Mar	yes	1997	Sile	yes	abundant	pelagic, Turkish coast	Atlantic- Mediterranean	natural migration	B. Öztürk
Boops boops	Med Mar	yes	1989	Sile	yes	abundant	pelagic, Turkish coast	Atlantic- Mediterranean		B. Öztürk
Thalassoma pavo	Med Mar	yes	2006	Igneada	partially	abundant	pelagic, Turkish coast	Mediterranean		B. Öztürk
Sarpa sarpa	Med Mar	yes	2001	Igneada	yes	abundant	pelagic, Turkish coast	Mediterranean		B. Öztürk
Sphyreana pinguis	Med	Vec	2004	Sile	a few	a few ind.	pelagic,	Indo-pacific	Loceone	B. Öztürk
Sphyreana sphraena	wica	yes	2005	Sile	migrant	a few ind.	Turkish coast	mgran	Lesseps	
Centracanthus cirrus	Med	no	1988	off Odessa, littoral zone of Romania, common in Turkish area	a few individuals, eggs in 1988 2 adults off Romania in 2004	a few ind.	pelagic	Mediterranean		Tsokur, 1988: Radu, 2006 (pers. com.)
Micromesistius poutassou	Med	no	1999	coastal area of Crimia, common for Turkish area	a few ind.	a few ind.	pelagic	Mediterranean, Marmara	Med Mar	Boltachev, 2006
Gobius auratus	Med	no		common for Crimea			pelagic	Atlantic- Mediterranean	Med	
Gobius cruentatus	Med	no	2007	for Crimea, Turkish area	a few ind.		pelagic	Atlantic- Mediterranean	Med Mar	Boltachev, 2006 Engin et al., 2007
Gobius xanthocephalus	Med	no	2004	for Crimea, Turkish area	a few ind.	a few ind.	pelagic		Med Mar	Boltachev, 2006 Vasilyeva and Bogorodski, 2004
Parablennius incognitus	Med	no	2005	Common for Crimea, Abhazya, Turkish area	a few ind.	a few ind.	pelagic, Turkish coast	Atlantic- Mediterranean	Med Mar	Boltachev, 2006 Bogorodskii, 2006
Zebrus zebrus	Med	no	2008	Turkish area	a few ind.	a few ind.	pelagic, Turkish coast	Atlantic- Mediterranean	Med Mar	Kovacic and Engin, 2008
Sphyraena chrysotaenia	Med	no	1999	Turkish area	a few ind.		pelagic, Turkish coast	Indo-pacific pelagic, migrant	Lesseps	Boltachev, 2006

Table 2. Exotic fish species recorded in the Black Sea.

Taxa	<1960s	1960-1970	1971-1980	1981-1990	1991-2000	2001-2009
Phytoplankton		37				
Copepoda		15	19	12	7	51
Gelatinous plankton						1
Macrophytes					26	
Benthos	1	45	30	56		5
Total	1	97	49	68	33	57

Table 3. Total number of Mediterranean plankton, algae and invertebrate species recorded in the southern Black Sea (mainly off Bosphorus).

Table 4. Historical trends of Mediterranean fish species in the Black Sea.

Species names	1920s	1930s	1940s	1950s	1960s	1970s	1980s	1990s	2000s	2010s
Sardinella aurita	+	+	+	+	+	not present	+	+	+	+
Boops boops	+	+	+	+	+	+	+	+	+	+
Thalassoma pavo	+	+	+	+	+	+	+	+	+	+
Sarpa salpa	+	+	+	+	+	+	+	+	+	+
Sphyreana sphraena	+	+	+	+	+	+	+	+	+	+
Centracanthus cirrus	-	-	-	-	-	-	-	-	+	
Micromesistius poutassou	-	-	-	-	-	-	-	-	+	+
Gobius auratus	-	-	-	-	-	-	-	-	+	-
Gobius cruentatus	-	-	-	-	-	-	-	-	+	+
Gobius xanthocephalus	-	-	-	-	-	-	-	-	+	-
Parablennius incognitus	-	-	-	-	-	+	+	+	+	+
Zebrus zebrus	-	-	-	-	-	-	-	-	-	+
Sphyraena chrysotaenia (obtusata)	-	-	-	-	-	-	-	-	+	-

The barfish (*Chromis chromis*), the lettered perch (*Serranus scriba*), the blotched picarel (*Spicara maena*) and the bogue, (*Boops boops*), are recorded again in the Black Sea. The European pilchard (*Sardina pilchardus*), though in small number, is frequently found in fixed nets and trawl catches along the whole Black Sea shelf of the Crimea. Catches of two Mediterranean migrant fishes, such as the thin-lipped grey mullet (*Liza ramada*) in 2006 and the European barracuda (*Sphyraena sphyraena*) in 2007 near Sevastopol are unique, because these species had not been encountered there since 1930 and 1950 respectively.

In the last decade, 15 fish species, new to the Black Sea ichthyofauna, or whose presence was previously doubted, were recorded in the coastal zone of the southwestern and southern Crimea. Among them, seven Atlantic-Mediterranean species: the thick-lipped mullet (*Chelon labrosus*), dorado (*Sparus aurata*), salema (*Sarpa salpa*), yellow-headed goby (*Gobius xanthocephalus*), red-mouthed goby (*G. cruentatus*), incognito blenny (*Parablennius incognitus*), and greater pipefish (*Syngnathus acus*). It is possible, that the abundance of some aforementioned bottom resident species (gobies, blennies) was so reduced in the past that they were just not recorded before. The chameleon goby *Tridentiger trigonocephalus*, endemic of the far Eastern seas, has naturalized in Sevastopol Bay. Four invasive species, freshwater by origin, were recorded in estuaries of the peninsula: far Eastern species – stone morocco (*Pseudorasbora parva*) and goldfish (*Carassius auratus*); and North American species – pumpkinseed (*Lepomis gibbosus*) and Eastern mosquitofish (*Gambusia holbrooki*).

The remaining three species are known from single findings and apparently belong to the category of accidental records.

5. MEDITERRANIZATION BARRIERS AND GENETIC ASPECTS OF SPECIES INTRODUCTION AND ESTABLISHMENT IN THE BLACK SEA

Global climate change is causing shifts in the geographical distribution of species, associated with local extinction and expansion of their distribution ranges. Natural and artificial transport pathways contribute to such redistribution of species. Transportation in ballast water is increasingly eliminating geographical barriers and separation of species.

5.1. Adaptation to local conditions

Species distribution more and more depends on whether specimens sustain transport conditions, at least passively, and then find suitable living conditions in their new environment. Within a given species and its original functional and genetic diversity, only resistant phenotypes and genotypes may survive, thereby reducing genetic diversity compared to the parent population and defining the starting point for successful settlement of suitable environments by selected, pre-adapted specimens.

The newcomers are "filtered" during the process of introduction, or after they arrive at their destination. The conditions in ballast tanks, for instance, might select particularly strong specimens that have proper characters to face the new conditions. The passage through a turbulent environment, like the Bosphorus Strait, acts also as filter.

Bottlenecks in transport to the Black Sea are set by the transport conditions in ballast water or by the acute conditions in or at the exit of the Bosphorus current system. Taking into account the hydroclimatic differences between the Mediterranean (hosting the parent population) and the Black Sea (receiving the newcomers), the physical factors that particularly challenge the survival of the specimens undergoing migration are water currents, shifts to lower salinities at the surface and lower temperatures coinciding with hypoxia and elevated CO_2 in the intermediate layer and anoxia in the depth. Furthermore, transport or migration may only be successful in a limited seasonal time window. Limiting factors not only act individually but also interact synergistically as in the case of temperature extremes, CO_2 and hypoxia, thereby exacerbating stress levels (Figure 9). Oxygendeficient (less than 80% of saturation), hypoxic (less than 30%) and anoxic conditions are typical for the coastal shelf zones of the Black Sea and the Sea of Azov in the summer period and oxygen depletion will probably become more intense in the future (Diaz and Rosenberg, 2008).



Figure 9. Organisms thermal windows: optima, limits (I) and acclimation/ adaptation (\leftrightarrow). Modified from Pörtner and Farrell (2008).

A Mediterranean species entering the Black Sea might become successful not because Black Sea conditions match Mediterranean ones, but because that species contained, in its genetic variability, the traits that allow for the colonization of the Black Sea Basin, in spite of its differences from the Mediterranean Sea. Turan (2006) reported that the amount of genetic divergence of *Mullus barbatus ponticus* in the Black Sea is high enough to be considered as a subspecies of *M. barbatus* in the Mediterranean Sea. This genetic analysis also indicated that *M. b. ponticus* could be an incipient species in the Black Sea. The seagrass *Posidonia oceanica* is a stenohaline species endemic to the Mediterranean Sea, where it normally lives at a salinity of between 36.5 and 39.5 ppt. Meinesz *et al.* (2009) reported large *P. oceanica* beds in the Marmara Sea, where salinity ranges between 21.5 and 28 ppt. They carried out a genetic analysis on these low-salinity tolerant *P. oceanica* beds, and found different signs of genetic isolation: excess of heterozygosity and a presence of fixed alleles, which are rarely found in the whole distributional range of the species.

It is important, at this point, to investigate on differences in the limits of tolerance between Mediterranean populations that became newly established in the Black Sea and those of the Mediterranean populations.

5.2. The Turkish Straits System as an acclimatization/adaptation corridor

The Turkish Strait System is a very important biological corridor for many migratory species of fish, birds and mammals from both the Black Sea and the Mediterranean Sea and it is the feeding and breeding ground for the pelagic fish of Atlantic origin during their migrations from the Black Sea to the Sea of Marmara or vice versa. Additionally, the Turkish straits form an "acclimatization zone" for transiting species, allowing those from the Mediterranean to adjust to the different environmental conditions in the Black Sea, and vice versa.

5.2.1 Physical characteristics of TSS

The Turkish Strait System (TSS) constitutes a two-layer system, where a sharp halocline of a thickness of 10-20 m separates brackish waters (22-26 psu) in the thin upper layer of the Marmara Sea (15-30 m) from the saltier waters (38.5-38.6 psu) in the lower layer throughout the year. Temperature of the upper layer varies seasonally within the range of 7-27°C whereas temperature of the lower layer remains around 14.5-15.0 °C. The relatively dense Mediterranean underflow enters into the Çanakkale Strait below the depths of 15-20 m with salinity of 38.9-39.0 psu and temperature of 16-17 °C and undergoes gradual changes along the Strait and its transition region to the western Marmara Basin. They eventually sink in the form of a dense water plume with S~38-38.5 psu and T~15.0-16 °C toward the density levels where they reside, whereas a part of it continues to flow within a narrow zone immediately below the interface. The sinking plume subsequently takes part in the renewal of the sub-halocline waters of the Marmara Sea by spreading isopycnically in the form of intrusive layers.

The underflow spends about 6-7 years in the deeper layers of the Marmara Basin (Besiktepe *et al.*, 1994). Upon reaching the Bosphorus-Marmara junction region, the lower layer waters flow into the Istanbul Strait through the submarine canyon. Thereafter, the underflow interacts with local topography at the southern and northern sill regions, becomes progressively diluted due to strong entrainment into the upper layer flow, and enters into the Black Sea junction region as a thin plume.

In terms of mixing characteristics of the Mediterranean underflow, five distinct regions are evident within the TSS: the first one occurs within the Nara section of the Çanakkale Strait where the internal hydraulic adjustment of the flow causes strong entrainment of the lower layer flow with the upper layer that then goes back to the Aegean Sea. Similar abrupt mixing occurs at the southern and northern sill regions of the Istanbul Strait. The Bosphorus-Black Sea junction region imposes further mixing on the underflow. Moreover, the wind-induced mixing within the Sea of Marmara affects the properties of the sub-halocline waters of the lower layer during autumn-winter months.

5.2.2 Persistent geographic barriers of TSS for mediterranization

Depending on the mixing and transport characteristics of the Mediterranean underflow through the TSS, Oguz and Öztürk (unpub.) recently proposed a set of successive geographic barriers that may control migration success of Mediterranean species on their way to the Black Sea. These barriers mostly apply to pelagic and benthic planktonic species and fish larvae whose transports are mostly

passive and introduced by hydro-physical conditions. The present discussion therefore excludes the migration of fish species between the Mediterranean and Black Sea ecosystems that are largely independent from such persistent hydro-physical geographic barriers.

The planktonic species and fish larvae face the first barrier in the Nara Passage zone of the Çanakkale Strait where the strong turbulence and mixing of upper and lower water masses may likely cause a part of their population to be transported back to the Aegean Sea with the upper layer flow and may introduce as well physiological shocks due to abrupt temperature change of about 7-10 °C and salinity change of about 10-15 psu. The region therefore has long been considered as an acclimatization zone for marine organisms migrating to the Black Sea (Öztürk and Öztürk, 1995).

The second barrier occurs along the junction region to the Sea of Marmara where the major part of the Mediterranean underflow sinks into intermediate and deep layers of the suboxic-anoxic western Marmara Basin. Only those individuals able to follow the narrow sub-halocline layer below the interface with sufficient oxygen (Figure 10) will be able to survive their passage.



Ecological role of the Turkish Strait System (TSS) under physical condition

Figure 10. Schematic diagram, by T. Oguz and B. Öztürk, of the physical structure of the Turkish Strait System (TSS) controlling the migration success of Mediterranean species into the Black Sea. The lower panel displays in more detail the pre-Bosphorus channel region outside the northern exit of the Istanbul Strait as well as the Bosphorus-Black Sea junction region up to the shelf break. The temperature and salinity profiles in the upper panel are typical for the Sea of Marmara. The main migration route of Mediterranean species lies immediately below the interface zone (thick sloping line) between the upper and lower layers.

Mediterranean species which manage to enter the Bosphorus encounter three successive obstacles. The first is induced by the southern sill, the second by the constriction region near the Atatürk Bridge, and the third by the northern sill at the Black Sea exit. The underflow is characterized upstream of the northern sill roughly by $S\sim35-36$ psu and $T\sim11$ -13 °C, but more importantly its thickness of at least 30-40 m at the Aegean end of the system declined to 5-10 m at most. Entrainment process of the underflow into the upper layer that prevails excessively downstream of the sill as well as further along the shelf introduces further dilution of the underflow. When it reaches to the shelf break of the southwestern Black Sea Basin the underflow is almost indistinguishable from ambient waters and has a thickness of less than 1 m. The species which are able to survive and reach the narrow shelf zone of the southwestern Black Sea are prone to settlement and acclimatization to the Black Sea conditions. There is also a possibility that some of them can sink across the shelf break into the anoxic waters of the Black Sea together with the Mediterranean underflow. These successive physical constrains may therefore explain the low species diversity of the Black Sea (Zaitsev and Mamaev, 1997) after its connection to the Mediterranean about 7,000 years ago.

5.2.3 Temporary geographic barriers of TSS for mediterranization

While the physical constraints and bottle-necks described above along the TSS are persistent features of the system, some temporal physical features may exercise further adverse controls on the migration process. Almost every winter, under very strong northwesterly wind episodes, excessively large upper layer flow can temporally fill all depths of the Istanbul Strait with cold waters of about 5-7 $^{\circ}$ C, and temporally block the Mediterranean underflow. The abrupt mixing and sudden temperature changes between these two contrasting water masses lead to mass mortalities of commercial and immigrant fish species such as bonito, bluefish, anchovy, horse mackerel. This event is called "Orkoz" or "Ayna" by local fishermen and may even be extended into the southern half of the strait near the AnadoluHisar/Kandilli section.

To conclude, the mediterranization process is one of the subtle issues of the Black Sea ecosystem and it is likely to evolve in future decades under continuing global warming. The lack of clear understanding of this process mostly arises from the lack of systematic sampling and monitoring strategy along the TSS.

6. CLIMATE FORCING (AMO & NAO) OF BIODIVERSITY AND MEDITERRANIZATION

The magnitude and variety of climatically forced changes in the physical environment provoke substantial proximate and emergent ecological responses. The direct effects of climate change impact occur at the individual level, at various stages in the life history cycle via changes in physiology, morphology and behaviour, at population level via changes in transport processes influencing dispersal and recruitment and at community level via interacting species (e.g., predators, competitors, etc.), including climate-driven changes in both the abundance and the per capita interaction strength of these species.

6.1. Examples from plankton and fish biomass

During the period 1960-1980 the Black Sea status passed from low mesotrophy to high mesotrophy and eutrophy. The period 1960-1970 represents the Black Sea pristine conditions, with phytoplankton biomass less than 2-3 g m⁻² whereas 1970-1980 is the period of high nutrient enrichment of the system that is reflected in phytoplankton biomass by a gradual increase to more than 10 g m⁻² (Figure 11). The climate-induced changes are therefore not clearly seen due to more dominant signal of eutrophication-induced changes. However, the climate-induced changes appear to be well-marked during the 1980s and 1990s.



Figure 11. Long-term variations of summer-autumn mean phytoplankton biomass (g m⁻²) (vertical bars; after Mikaelyan, 2005), the mean CIL temperature (°C) (dots; after Belokopitov, 2005), averaged over all stations within interior basin and mean winter (December-March) sea surface temperature (SST) as an average of Hadley2, NCEP-Reynolds and Pathfinder5 data sets. The phytoplankton biomass is expressed in terms of euphotic zone integrated values.

Zooplankton biomass in the northeastern Black Sea is significantly correlated with the changes in water temperature. As shown in Figure 12, the biomass fluctuates with the annual mean sea surface temperature such that warm (cold) years attain higher (lower) biomass with clear increasing and decreasing trends of variations between cold and warm years. The corresponding phytoplankton biomass also follows the climatic changes as evidenced by close correlations between high (low) biomass and cold (warm) temperatures in Figure 11. Phytoplankton biomass has therefore out of phase variations with zooplankton biomass in regard to temperature dependence, perhaps linked with trophic cascade.



Figure 12. Long-term variations of the annual-mean edible zooplankton biomass in the northeastern basin (g m⁻²), and the mean CIL temperature (°C) (dots; after Belokopitov, 2005) averaged over all stations within interior basin and mean winter (December-March) sea surface temperature (SST) as an average of Hadley2, NCEP-Reynolds and Pathfinder5 data sets.

The sprat and anchovy stock estimates also follow closely the annual mean sea surface temperature and therefore reflect a clear signature of climatic modulations. Sprat as a cold water species attains much higher biomass during cold years and lower biomass in warm years (Figure 13). The sprat fluctuations overlap considerably with those of phytoplankton and are opposite to edible zooplankton, indicating therefore a trophic cascade pattern. Similar correlation is also evident for the sprat fat content in which a cooling (decreasing) trend coincides with increasing (decreasing) sprat fat content. In particular, sprat populations were able to maintain their highest fat content during the cold period of the 1980s. On the other hand, the anchovy stock follows an opposite trend having higher biomass during warm years.



Figure 13. Long-term variations of annual-mean basin-averaged sea surface temperature and sprat stock anomalies. The figure shows positive correlation of the changes in sprat stocks with the climatically cold years.

Climatic fluctuation may affect the relative timing of food requirement and food availability (match-mismatch). Differences in the temporal and spatial match between predator and prey may thus generate variability in the predator survival rates. The ambient conditions in the Black Sea such as water temperature and large-scale climatic and hydrographic processes generate variation in the production, distribution, and abundance of organisms. A climate-induced delay in food production could thus create a mismatch between the prey production and the predator requirements with dramatic implications for reproduction success.

6.2. Interaction with anthropogenic factors

Pollution, destruction of hydrobionts stocks, introduction of invasive alien species and habitat loss and modification were indicated by the Global Ecological Fund (GEF) as the main factors threatening the world ocean. The Black Sea is a good example.

The mass development of gelatinous plankton organisms is a characteristic feature of marine zooplankton in condition of eutrophication (Figure 14). High numbers of the scyphozoan *Rhizostoma pulmo* were observed in the coastal zone of north-western Black Sea in the late 1960s and early 1970s. The population of *R. pulmo* gradually declined back to its former levels in 1973-1974. However, almost immediately a population of another scyphozoan jellyfish, *Aurelia aurita*, became highly abundant. The exotic ctenophore, *Mnemiopsis leidyi*, unexpectedly appeared in the early 1980s, and reached a total biomass of about one billion tons (Zaitsev and Mamaev, 1997). On the other hand, the *Aurelia* population collapsed almost immediately, and the biomass of other zooplankton and ichtyoplankton decreased sharply. As a result anchovy catches dropped and commercial fishing for anchovy in the Sea of Azov came to a complete halt (Zaitsev and Mamaev, 1997).


Figure 14. Successive blooms of jellyfish in the Black Sea between 1960-1995, after sharp decline of population of the jellyfish eating mackerel. a- *Scomber scomburus*, b- *Rizostoma pulmo*, c- *Aurelia aurit*a, d-*Mnemiopsis leidyi* (after Zaitsev and Mamaev, 1997).

The Black Sea is a favourable habitat for many accidental invaders, some of which have become serious competitors for local species or even their predators. It is possible that the large volumes of phytoplankton and certain zooplankton that resulted from cultural eutrophication did facilitate the establishment of these exotics in the Black Sea (Zaitsev and Mamaev, 1997).

6.3 Interaction with fisheries

6.3.1 Fishery resources of the Black Sea

The Black Sea has a considerably limited variety of fishery resources compared to the Sea of Marmara, the Aegean Sea and the Mediterranean. Abundance and catch rate of pelagics such as anchovy, sardine, sprat, blue fish and bonito depend strongly on the recruitment success in their spawning grounds in the Sea of Marmara and NW Black Sea shelf. Turbot, whiting, red mullet, dogfish, skates, stingray, red gurnard, sole and plaice are the major demersal fish species and play an important role in the fisheries of Black Sea countries. *Rapana venosa, Venus gallina, Mytilus galloprovincialis* are the main species in demersal shellfish production

6.3.2 Development of fishing industry (1970s-2005/8)

The intensive exploitation of Black Sea fisheries started at the end of 1960s – beginning of 1970s with the increase of number of vessels and fishing efficiency. The pressure on the stocks increased until the end of 1980s with a peak total catch of 800 kt in 1988, followed by a sharp decline in the subsequent years due to introduction of the comb-jelly *Mnemiopsis leidyi*, causing high predation on eggs and larvae of economically important fish species. The decline coincides with the two-decade-warming period of climatic cycle in the region. This period also coincided with major political changes in the countries bordering with the Black Sea, when the Russian Federation, Ukraine and Georgia emerged as new states after the collapse of the Soviet Union. During this transition period, due to the financial problems, the fishing fleets of these countries were not used efficiently opening the way to an increase in the fishing effort of the Turkish fleet. From 2000 onwards, over 80% of the total Black Sea catches have been obtained by Turkey (see Figure 15). This ratio is even higher for some species, e.g. bonito, horse mackerel, whiting, red mullet, and bluefish.



Figure 15. Share of the countries in capture fish production in the Black Sea in 2007 (FAO, Statistics 2008).

The number of Turkish fishing vessels in the Black Sea is 6,700 and new entries are not permitted since 2002. On the other hand old vessels can be replaced by new ones with the same license (20% length increase for cold storage and modern life spaces).



Figure 16. Production of some important fish species in the Black Sea in 2007 (FAO, Statistics 2008).

The main fish species in the catch are anchovy, horse mackerel, whiting, bluefish, Atlantic mackerel, sea snail and baby clam (Figure 16).

6.3.3 Recent changes in catch composition of native and alien species

The sea snail *Rapana venosa* is the one of the most important alien species affecting native species of the Black Sea. It has been introduced in the Black Sea in the 1940s from the Sea of Japan by merchant vessels. The absence of any direct predators facilitated the spread of *Rapana* all over the Black Sea coasts, causing the destruction of the mussel beds, its favourite prey. However, as its meat is very popular in the Far East countries, mainly in Japan, this mollusc has been the object of commercial fishing since 1990, for exportation to overseas markets. Similarly, *M. leidyi* became the most abundant jellyfish in the Black Sea and caused the collapse of anchovy stocks (Zaitsev and Mamaev, 1997).

The Pacific mullet, *Liza haematochilus (=Mugil so-iuy)* was intentionally introduced in the Seas of Azov and the Black Sea in the period 1972-1980. Native to brackish and marine waters of the Sea of Japan, *M. soiuy* was introduced into the Azov Sea during the early 1980s by Soviet scientists (Zaitsev, 1991). This species started to reproduce in the Azov Sea and became very abundant along the south Crimean coast, before extending further (Unsal, 1992). At present, *M. soiuy* is a commercial species in the Black and Azov Seas (Shiganova, 2008). After the introduction of this species the population of native mullet declined due to high level of food competition, to the point where four of five native mullet species are currently out of the commercial list.

7. CLIMATE CHANGE PROJECTIONS

Most of the existing climate models have reproduced much weaker trend of the positive NAO index than recently observed under increasing greenhouse gas concentrations (Gillett et al., 2003). Ambaum and Hoskins (2002) demonstrated quantitatively the existence of a nonlinear feedback mechanism between the NAO and the stratospheric vortex located about 20-30 km above the earth's surface over the North Pole. Scaife et al. (2005) and Rind et al. (2005) have further extended the Ambaum and Hoskins (2002) model by showing that the unexplained strengthening of the NAO can be fully simulated in a climate model by imposing observed trends in the lower stratosphere. Considering the fact that the increase in greenhouse gas concentrations cools and strengthens the stratospheric winter vortex, this process translates at the surface as stronger westerly winds that promote a positive NAO index and further warming in the North Atlantic region. Reduced stratospheric temperatures over both poles mainly in late winter and spring, when sunlight comes back to the polar night area due to the substantial reduction of lower stratospheric ozone content over the last two decades (e.g. Graf et al., 1998) also contribute to strengthening of the stratospheric winter vortex. Kodera et al. (2008) further pointed to the solar modulation of the stratospheric polar vortex, and hence promoting the positive NAO index over the Eurasia. Thus, the Eastern Mediterranean and Black Seas is expected to cool under increasing greenhouse gases which cause either to slow down the effect of global warming or to switch the regional climate into a cooling phase.

8. RESEARCH PRIORITIES AND RECOMMENDATIONS

Future research needs to address species-specific preferences and sensitivities to environmental factors, most importantly temperature, hypoxia, ocean acidification, and salinity changes, also in relation to the effect of biotic factors such as food availability. Such efforts will improve the cause/ effect understanding of ongoing change and lead to the development of reliable mechanism-based projections of future scenarios. Physiological studies of sensitivities, stress levels and functional capacities in crucial life sustaining processes need to be combined with those of phenotypic plasticity, functional genomics and population genetics.

These physiological and genetic approaches must be completed by ecological studies on the biotic interactions among species. Ecological systems are historical and are governed by both constraints (e.g. the limits of tolerance of single species) and by contingencies (e.g. the arrival of an alien predator). Constraints are predictable, but contingencies are not. According to recent estimates, the oxygen-depletion processes might be intensified in the future resulting in the overall decrease of oxygen content in the oceanic water and formation of temporal dead zones (Diaz and Rosenberg, 2008). Regarding the Black Sea it may result in increasing frequency of hypoxia in the Shelf regions (Northwestern Shelf, Anapa Shelf, Azov Sea) and in changes of the volume of the oxygenated layer of the Black Sea (Yakushev *et al.*, 2008).

The Black Sea Basin is characterized by a complex political development during the past twenty years. It embraces six States engaged in different regional forms of cooperation, but also divided on a number of issues up to a point of military confrontation. This has inevitably left its stamp on the management of marine living resources as well. After almost two decades of regional cooperation, there are still no regular stock assessments for the most important commercial species. It is hard to move on to ecosystem-based fishery management with the existing serious data gaps.

The prevailing managerial approach is the implementation of national measures (mainly input controls, such as limitation of fishing effort through licensing of fishing gear and vessels, closed

seasons). Since 2007, Bulgaria and Romania, as new EU members, have followed the Community Fisheries Policy and applied quotas for turbot and sprat. There is no international convention covering fisheries management in the whole Basin, although different drafts have been discussed at technical level for over ten years under the auspices of the Black Sea Commission. Recently, the General Fisheries Commission for the Mediterranean, GFCM, has been put forward, mainly by the EU, as a suitable body for dealing with issues arising at regional level. While the agreement establishing GFCM covers the Black Sea area, Georgia, Russia and Ukraine are not parties to the Commission, which puts certain limits to the viability of such a solution. The issue of coordinating the management of migratory species (e.g. anchovy) within the Black Sea Basin remains open and an institutional setting acceptable to all coastal countries still lies in the future.

On the recent decadal changes of the Black Sea nutrient regime and oxic/anoxic boundary position

E. Yakushev ¹, M. Chelysheva ², O. Podymov ², V. Velikova ³, V. Chasovnikov ² and V. Belokopytov ⁴

¹ Norwegian Institute for Water Researh, Oslo, Norway
² Shirshov Institute of Oceanology Southern Branch, Gelendzhik, Russia
 ³ Black Sea Commission, Istanbul, Turkey
⁴ Marine Hydrophysical Institute, Sevastopol, Crimea, Ukraine

ABSTRACT

The Black Sea is controlled by climate forcing superimposed on anthropogenic-induced fluctuations, mainly related to eutrophication, which was especially intensive in the period 1970-1990. Recent years were characterized by decrease in nutrient loads from land based sources in comparison with the 1980s and early 1990s resulting in certain positive changes in the Black Sea ecosystem state. Further, the observed alterations in Si, N and P concentrations and ratios may result in relatively stable quality change of the ecosystem (i.e. changes of shares of diatoms and coccolithophores and seasonal patterns, possible recovery of N-fixation, further improvement of the plankton community as a whole, etc.). The Black Sea hydrogen sulphide boundary oscillates in the density field with an amplitude of $\sigma_{\theta}=0.05-0.15$ kg m⁻³ depending on the climate variability, which is well related with the NAO index. The position of the sulphide boundary indicates the volume of the oxic layer in the Black Sea and plays a major role in the functioning of the Sea ecosystem. In the present paper we summarize recent assessments of the interannual dynamics of important hydrochemical parameters (mainly inorganic nutrients: phosphate (P), total inorganic nitrogen (N) and silica (Si) in the oxic layer and oxic/anoxic interface parameters) in the Black Sea during the last decades and the role of the forcing – climatic and anthropogenic.

INTRODUCTION

The Black Sea is the largest marine anoxic basin in the world. It has an oxygenated surface layer overlying a sulphide containing (anoxic) deep layer. This vertical structure has evolved because of a strong density stratification of the water column: waters with high salinity enter the Black Sea via the Bosphorus, while the upper layer waters are of riverine origin. The layers are separated by a permanent halocline. The winter mixing results in the formation of an oxygen-rich Cold Intermediate Layer (CIL) positioned above the permanent halocline (50-120 m) and characterized by a typical density ($\sigma_{\theta} = 14.5 \text{ kg m}^{-3}$). The rate of CIL formation is variable in response to changing climate.

As part of the global Ocean the Black Sea ecosystem dynamics is based on climate-induced fluctuations superimposed on anthropogenic forcing, the latter mainly related to eutrophication, which especially progressed in the period 1970-1990. The response of the Black Sea

biogeochemical system to the mentioned factors is being actively studied to ensure a proper nutrient management in the region and better knowledge on climate change (Black Sea Commission, 2008; daNUBs, 2005).

OXIC LAYER

The nutritional status of the upper layer of the Black Sea has changed significantly during the last decades with relatively stable decrease in inorganic phosphorus since 1995, increase in silica and no clear trend for nitrogen species (Figure 1, Table 1).

River-derived nutrient discharge of nitrogen and phosphorus to the Black Sea rose sharply in the 1960s and 70s in response to increased agricultural activity in the Danube, Dniepr and Don watersheds. Nitrogen and phosphorus flux, however, declined sharply in the 1990s in response to economic recession in the Eastern European countries. Shown in the Figure 2 dynamics of the total emission of N and P species to the Danube river, responsible for up to 59 % of the total river discharge to the Black Sea (Mikhailov and Mikhailova, 2008), was characterized by maximum values in the 1980s and early 1990s (Figure 2).

Table. 1. Annual trends detected in nutrient concentrations in the North-Western Shelf of the Black Sea (see monitoring sites in Ukraine, Romania and Bulgaria in Figure 1).

	Trends							
Parameter	Overall	1990-1996	1996-2003	Winter	Summer			
Ukraine								
Ammonium nitrogen	Negative	-4%	-15%	-3.1%	-1.9%			
Nitrite nitrogen	Positive	0.6%	-1.4%	2.0%	3.7%			
Nitrate nitrogen	Positive	0.5%	-6.9%	6.6%	10.5%			
Orthophosphate	4.2%	3.1%	0.7%	4.5%	5.0%			
Romania								
Ammonium nitrogen	Positive	8.7%	-5.3%	3.8%	1.5%			
Nitrite nitrogen	5.1%	2.2%	13.7%	4.3%	5.8%			
Nitrate nitrogen	3.1%	3.6%	8.7%	4.2%	5.7%			
Orthophosphate	Negative	-2.1%	-10.6%	-1.7%	-0.6%			
Silica	Positive	5.7%	6.3%	4.1%	2.0%			
Bulgaria								
Nitrate nitrogen	Positive	16.2%	63.9%	13.8%	10.1%			
Orthophosphate*	-19.3%	-	-19.3%	19.1%	-13.6%			

*Note: the pattern of orthophosphate dynamics clearly indicated 2 periods: 1990-1998 with nearly "no trend" and 1998 onwards with a clear negative trend.



Figure 1. Monitoring sites in Ukraine, Romania and Bulgaria (BSERP Report 2005: Improving the understanding of the Danube river impact on the status of the Black Sea, W. Parr, Y. Volovik, S. Nixon and I. Lipan).



Figure 2. Relative contributions of different point and diffuse sources to the emissions of (a) total nitrogen (N) and (b) total phosphorus averaged over 5 year bins (from daNUbs, 2005).

These estimates are well correlated with the observational data in the Danube river mouth region (Figure 3). Silica discharge, in contrast, declined in the 1970s due in part to river damming (e.g., Iron Gates Dam; Humborg *et al.*, 1997), with shift from siliceous (mainly diatoms) to non-siliceous phytoplankton (Petrova-Karadjova, 1984; Humborg *et al.*, 1997; Bodeanu *et al.*, 2002).



Figure 3. Long-term dynamics of Danube nutrient loads (in Kilotons) measured at Sulina, data A. Cociasu, NIMRD, Constanta, Romania.

The depletion of silica in surface waters has been found to have important impact on phytoplankton species composition – shifts from siliceous (mainly diatoms) to non-siliceous (cocolithophorides and flagellates, Figure 4) species was reported (Petrova-Karadjova, 1984; Nesterova, 1987; Bodeanu *et al.*, 2002; Moncheva and Krastev, 1997) and changes in seasonal dynamics were observed (Velikova *et al.*, 1999). Detailed analysis of the influence of these changes on the biological processes in the Black Sea is presented elsewhere (Yilmaz *et al.*, 2006; Black Sea Commission, 2008).



Figure 4. Phytoplankton populations (Bodeanu *et al.*, 2002; Mee *et al.*, 2005) and concentrations of P-PO4 and Si-SiO4 (in µM, data A. Cociasu, NIMRD, Constanta, Romania) in Romanian shallow waters.

Data from the northeastern Black Sea reveal similar trends to those observed in the NW Black Sea, but with only a slight shift in phosphate content (Figure 5).



Figure 5. Interannual changes of upper layer concentrations of inorganic species of N, P, Si in the North-Eastern Black Sea averaged for the 5-years intervals.

The analyses of hydrochemical regime changes in the North-Eastern Black Sea are based on data collected by the Southern Branch of Shirshov Institute of Oceanology (Gelendzhik) from 1980s to present. This part of the Sea is far from the influence of the Bosphorus input and Danube River inflow. Therefore, the upper layer chemical dynamics in this region should reflect "integrated" rather than local changes of the Sea.

The results obtained for 5-years averaged intervals are presented in Figure 5. The data from the North-Eastern Black Sea reveal similar trends to those observed in the NW Black Sea. However, differences are notable between these two regions: a decrease in N and Si concentrations, and a small decrease (or absence of a clear tendency) in phosphate content (Figure 5) in the NE Part are found, whereas in the NW Black Sea the decrease in phosphates is substantial in 1984-2004 and the trends for nitrogen species are not that stable though decrease has been also registered. It is worth mentioning that the share of organic N and P increased in time, both in Danube river nutrient loads (up to 90% in 2005 for P, for instance) and in western Black Sea marine waters, especially notable in 2005-2007 after the floods in the region. The latter might be well related to secondary eutrophication effects.

In the regions subjected to the influence of the Danube River, the NO_3 -N/PO₄-P ratio was 11.7 in the 1970^s and 22-23 in 1988-1992 (Cociasu *et al.*, 1996). Because of decrease of the phosphate input this ratio increased in 1995 to as high as 100. After 1996 it decreased significantly (e.g. down to 20 in 2000) due to the diminishing annual input of nitrate from the Danube river from 770,000 tons in 1991 to 108,900 tons in 2000 measured at Sulina (Yilmaz *et al.*, 2006). The NW shelf region was characterized by phosphorus limitation of primary production in 1980s-1990, but the tests completed in 2001 did not show clear P-limitation on the shelf (Yilmaz *et al.*, 2006).

In the open waters the low NO_3/PO_4 ratio in the nutricline below the euphotic zone resulted in nitrogen-limited phototrophic production in the surface layers. This can be explained by intensive loss of inorganic nitrogen under suboxic conditions. According to Cociasu *et al.* (1996), and Yilmaz *et al.* (2006) the NO_3/PO_4 ratio in the euphotic zone and the upper nutricline is very low (2 – 6.5) in the open sea. The same tendency can be observed in the NE Black Sea, where the N:P ratio decreased during the last 10-15 years from 30 to 5 (Figure 6).



Figure 6. N/P ratio seasonal dynamics at Sulina in 1990-1997 compared to 1998-2003 (NW Black Sea), data A. Cociasu, NIMRD, Constanta, Romania. (A); N/P ratio dynamics in 0-5 m layer in the NE Black Sea in 1989-2006 (B).

One of the indicators of the Black Sea biogeochemical system recovery should become the reappearance of the nitrogen fixation. The process of production of gaseous nitrogen through denitrification and anammox is a well known feature in oxygen-deficient basins. From the point of view of budgeting, this loss of bound N should be compensated by nitrogen fixation (Yakushev *et al.*, 2007). Denitrification and anammox were measured in the Black Sea during the last decades (Murray *et al.*, 2003; Kuypers *et al.*, 2003), whereas N-fixation was not observed in 1980s-1990s. By contrast, in 1950s, before the initiation of intensive eutrophication, N-fixation in the Black Sea was well-developed (Pshenin, 1963). As shown above, the low N/P ratios in the different parts of the Black Sea testify to nitrogen-limited primary production. Recently, N-fixation was again measured in the Central Black Sea in 2003 (McCarthy *et al.*, 2007).

Development of seasonally low oxygen (oxygen concentrations below 2 mg/l, oxygen concentrations < 30% saturation value) in bottom waters of the Black Sea (e.g., northwestern shelf, Anapa shelf, Sea of Azov) depends on the intensity of eutrophication as well as circulation,

stratification and meteorological variables (wind, heat flux, etc.). In the Black Sea hypoxia development typically begins in June-July and attains maximum coverage in August. There is a relationship between the rate and timing of river discharge and the scale of hypoxic conditions (Berlinskii, 2003). In years with high river discharge and hence high nutrient input and organic matter production, oxygen concentrations in bottom layers are ~20% lower than in years of low river discharge.

Hypoxia is also subject to longer-term variations, and a simple correlation to environmental factors may not always hold. For instance, a two-fold increase in hypoxia area occurred in the northwest shelf in the 1980s, but has since decreased in the Ukrainian sector of the NWS (Oguz *et al.*, 2008a,b). In contrast, no hypoxia was reported in Bulgarian waters or off other Black Sea states, other than an intensive summer anoxia in the Sea of Azov in 2001 (Yakushev *et al.*, 2003).

We thus can conclude that there are present positive signs of recovery of the Black Sea ecosystem after several decades of decline due to significant anthropogenic impact. The recently published Black Sea Commission Report (Black Sea Commission, 2008) brings much evidence of improvement of the pelagic ecosystem state in the western Black Sea, associated with reduced nutrient inputs and less frequent algal blooms, lower phytoplankton biomass (Figure 7), recovery of some macroalgal populations, increasing plankton diversity, decreasing pressure imposed by proliferations of gelatinous and other opportunistic species, and reappearance of some native trophic mesozooplankton (Figure 8), benthic and fish species.



Figure 7. Phytoplankton density and biomass in Romanian shallow waters in 1983-2007 (CBD Romanian National Report, Black Sea Commission, 2008, data Laura Boicenko, NIMRD, Constanta).



Figure 8. Long-term dynamics of mesozooplankton biomass [mg.m-3] at 3 miles off Cape Galata (Bulgarian Black Sea) during winter and spring seasons for the period 971-2007 (CBD Bulgarian National Report, Black Sea Commission 2008, data Kremena Stefanova, IO-BAS, Varna).

OXIC/ANOXIC INTERFACE

Away from the SW region, influenced by the Bosphorus Plume, redox potential decreases gradually with increasing depth and water density. In the depth range where oxic conditions change to anoxic (the redox zone), oxidized and reduced chemical species interact. These processes occur in a predictable sequence depending on the changes in redox potential (Murray *et al.*, 1995; Rozanov, 1995). The sequence of reactions is characterized by diagnostic chemical distribution. These distributions display **chemotropy** – the correspondence of vertical chemical distributions to specific density levels (Yakushev *et al.*, 2005). There have been numerous estimates of typical density levels of the onset of chemical species, depths of extrema and depths of change of vertical gradients (Vinogradov and Nalbandov, 1990; Codispoti *et al.*, 1991; Murray *et al.*, 1995; Konovalov and Murray, 2001).

We studied the changes of the position of the boundary of the anoxic zone in the density field on the base of data of regular observations received in the northeastern part of the Black Sea near Gelendzhik (more than 1,400 stations with the results of field observations from 1989 to the present (Yakushev *et al.*, 2006; 2008). As mentioned above, this part of the Sea is far from the influence of the Bosphorus input and Danube River, and the vertical structure in this region is more stable and reflects "integrated" rather, than local, changes of the sea.

Results of these calculations for monthly averaged intervals are shown in Figure 9. The values obtained slightly differ from the estimates were reported by other authors who used the visual or linear regression criteria for estimating of the onset of hydrogen sulphide (Murray et al., 1995; Volkov et al., 1997). We used the Akima spline-based method (Podymov, 2008) which we assume better as it is nonlinear and based on the objective approach for every station, which is necessary in analysis of the large data arrays.

Figure 9. Onsets in the density field of hydrogen sulphide (A), ammonia (B), total manganese (C), averaged concentration of oxygen in the CIL (in the layer $\sigma_{\theta} = 14.45 - 14.60 \text{ kg m}^{-3}$) (D), winter air temperature in Gelendzhik (E), temperature in CIL core in the Northeastern Black Sea (data of V.G. Krivosheya); averaged temperature in the CIL core (data of the MHI oceanographic database and ARGO floats) (F) and interannual variability of the winter NAO index (crosses - averaged for February-April, lines -averaged for 3 successive years) (G).



The results calculated here indicate that the depth of disappearance of hydrogen sulphide was characterized by values σ_{θ} =16.15-16.25 kg m⁻³ in 1991- 1998 (Figure 8). In 1999-2000 the shoaling of this boundary appeared. The value of this shoaling was about σ_{θ} =0.05-0.15 kg m⁻³ (corresponding to about 5-15 m at these depths). After 2000 the position of hydrogen sulphide stabilized. The same tendency can be noted in the other studied reductants – ammonia, total manganese and methane (Figure 9). The calculated vertical gradients of hydrogen sulphide, ammonium, total manganese and methane were stable in both periods (Yakushev *et al.*, 2006).

These oscillations can be connected with the corresponding winter weather conditions. For example, the two warm winters in 1998-1999 may have affected the winter formation of the oxygen-rich CIL. These years were remarkable for the increase in SST (Figure 8), increase in temperature in the core of CIL (Oguz *et al.*, 2006; Ginsburg *et al.*, 2004; Krivosheya *et al.*, 2002), and shoaling of CIL in the density field (Murray *et al.*, 2003). The decrease of intensity of CIL formation should lead to increase in temperature in its core and decrease in oxygen content there. To check these assumptions, we calculated the average concentrations of dissolved oxygen in CIL (defined as the layer from σ_{θ} =14.45 kg m⁻³ to $-\sigma_{\theta}$ =14.60 kg m⁻³). In 1999-2000, when the shoaling of reductants occurred, the oxygen content declined. The minimal concentrations were registered in 2001-2002. In 2003-2004 oxygen content in this layer returned to values typical of the early 1990s. The variability in the Black Sea hydrophysical-biogeochemical system can be connected with the weather conditions change as it follows the NAO index behavior (Figure 8).

The results obtained illustrate the mechanism of reaction of the natural Black Sea system to Global Climate changes. Correlated with the decadal NAO index behavior, changes in the winter weather condition result in larger or smaller cooling of the upper layer waters. The changes in sea surface temperature lead to changes of winter CIL formation intensity and to the oxygen renovation there. The oxygen inventory in the CIL acts as a specific accumulator that support the consumption of oxygen for the organic matter decay and downward diffusive flux during the whole year. The interannual variations of this oxygen renovation in CIL lead to changes of suboxic layer hydrochemical structure and, in particular, of position of the anoxic boundary in the density field.

Therefore the distribution of the chemical parameters in the density field in the Black Sea might be a good indicator of the Global Climate variations. Another factor that might affect the interannual dynamic of hydrogen sulphide position is eutrophication.

The main sink for oxygen is respiration of sinking particulate organic carbon (POC). Dissolved organic carbon (DOC) may also be important but much less is known about its distributions. Variability in the flux of POC (export production) is influenced by nutrient concentrations and food web structure (which are not unrelated). The late 1970s were a period of increased nutrient levels in the Black Sea (eutrophication) and this appeared to result in smaller oxygen concentration in the CIL (Konovalov and Murray, 2001).

CONCLUSIONS

Recent years were characterized by decrease in anthropogenic loads of nutrients which should bring further positive changes in the Black Sea ecosystem. The alterations of Si, N and P content and ratios may result in quality change of the ecosystem (i.e. changes of shares of diatoms and coccolithophores – restoration of the traditional domination of diatoms in the Black Sea, possible recovery of N-fixation, consequent recovery of the plankton community, etc.).

Our studies showed that the biogeochemical system of the oxic-anoxic interface is subjected to interannual changes. Surface layers ventilation with dissolved oxygen down to the depth of the CIL occurs in winter from a combination of the NW shelf and the centers of the gyres. The intensity of ventilation is determined by climate forcing which may be regulated by large scale climate formations like the NAO. This ventilation sets the upper boundary conditions for the downward transport of O_2 . Therefore, the position of the hydrogen sulphide boundary in the density field is connected with the climate variability, and well related with the NAO index.

It is necessary to stress that the direct result of the observed anoxic boundary oscillations by 5-10 m is the change of the volume of the oxic waters by approximately 5-10%, where the Black Sea oxic ecosystem exists. Such oscillations are vitally significant and should be studied in detail.

The last Black Sea Commission Report (Black Sea Commission, 2008) on the state of the Black Sea ecosystem avers that all present assessment studies indicate some gaps in our knowledge due to the absence of sufficiently comprehensive monitoring data. Especially in the present period of changing climate and variable anthropogenic load, data of biogeochemical parameters distributions in the Black Sea need to be regularly collected and analyses frequently updated to more definitively identify whether the Sea really improves in a sustainable manner or not.

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Observed long-term changes in the Black Sea physical system and their possible environmental impacts

Yuriy P. Ilyin

Marine Branch of Ukrainian Hydrometeorological Institute (MB UHMI), Sevastopol, Ukraine

Abstract

Linear trends and long-period fluctuations of meteorological and hydrophysical variables are considered by all available instrumental observations data obtained during previous decades. Obvious increase of thermal background and freshwater input were observed together with a weakening of wind activity. The last one manifests in general deceleration of horizontal circulation and vertical mixing of marine water. Water exchange through the Bosporus Strait has a tendency to yield more output of Black Sea water and less input of Mediterranean water under the climatic rise of freshwater flux.

INTRODUCTION

Global warming observed since the end of 19th century is caused not only by natural climate changes on the decades-centuries scale but also by anthropogenic load on the Earth's climate system, expressed, first of all, in the greenhouse effect. In accordance with (IPCC4 Assessment, 2007), mean global surface air temperature rise for the last century (1907-2006) was on average about 0.7 °C, and linear trend of temperature for the last 50 years was even almost twice as much ($\pm 1.3 \text{ °C}/100 \text{ yr}$).

At the same time, regional manifestations of global climate change may differ due to local geographic peculiarities, and regional anthropogenic influences may have less significance in comparison with the processes of natural climatic variability. It is known that one of the most significant processes existing in the ocean-atmosphere system and influencing on the climate fluctuations in the Eurasian region is the Atlantic Multi-decadal Oscillation (AMO) of sea surface temperature with periods of 50-100 years (more often reported as 60-80 years), represented also by the low-frequency mode of the North-Atlantic Oscillation (NAO) of surface pressure field (Polonsky, 2008). In general, a positive NAO index corresponds to more northern tracks of cyclones, bringing more heat/cold in winter/summer and more precipitations to North Europe, while the southern regions are under opposite conditions. Negative NAO phase means more southern cyclone trajectories, toward South Europe, including the Mediterranean and Black Seas. Climatic variations of these oscillations on the time scale of more than 30 years determine long-term variability (trends and fluctuations) of the Black Sea ecosystem, together with anthropogenic impacts, such as greenhouse effect and river hydraulic controls.

This work shall review the recent results on the long-term changes in physical state of the Black Sea obtained from analysis of routine observations on the shore stations network of FSU and in open-sea expeditions. Regional atmospheric processes are under the influence of external climatic changes and in turn affect processes on sea surface and in the water column. Observed changes in physical components determine in many respects the present and future changes of marine ecosystem state and productivity. Therefore the climatic variability of some principal meteorological and hydrophysical parameters in the Black Sea region is considered and then possible environmental impacts are discussed on a qualitative level.

METEOROLOGICAL CONDITIONS

Air temperature. The longest time-series of instrumental observations on the shore stations network can be produced for surface air temperature (AT), which is the most important parameter for the regional climate change studies. On the basis of secular observations on marine hydrometeorological stations of the north and east Black Sea shores, linear trends and long-term oscillations were revealed for annual, seasonal and monthly averaged AT values (Ilyin and Repetin, 2006a). These changes are in agreement with the NAO index long-term changes.

It was revealed that significant secular linear trends of annual mean AT in most studied regions are positive and correspond in their slope values to the secular rise of mean global surface air temperature. Table 1 presents slope coefficients of these trends together with mean multi-year AT values for some Ukrainian shore stations. In this and other tables, slopes statistically significant at more than 90 % probability levels are in a bold type, while those significant above 95 % probability levels are underlined. On the background of linear trends, AT variations with periods of 60-80 years were obtained by means of polynomial approximation method: a general AT increase was observed at the end of the 19th century and in the middle and at the end of the 20th century, while significant cooling took place during the periods 1910-1920 and 1970-1980.

Table 1. Mean multi-year air temperature (AT) and its linear trend slopes for the marine shore stations of Ukraine having observations duration of at least 100 years.

Station	Mean AT, °C	Trend slope, °C/100yr
Odessa	10.3	<u>0.8</u>
Ochakov	9.9	0.1
Sevastopol	12.1	<u>0.5</u>
Yalta	13.0	- 0.1
Feodosia	11.8	0.4
Averaged:	11.4	0.4

More accurate estimation of AT climatic periodicities was performed by means of spectral analysis of the longest series resolving the time-scale of AMO (stations Feodosia, Yalta and Odessa). Detrended data processing shows three climatic oscillations describing the natural variability of AT over the Black Sea north coast; their periods are 31, 41 and 62 years. In Southern Crimea (station Yalta) climatic changes seem to be the most affected by these periodic changes, while secular linear trend here is not manifested (Table 1, Figure 1).



Figure 1. Long-term variability of AT anomalies (°C) in Yalta approximated by superposition of harmonic functions having periods 31, 41 and 62 years.

In most parts of the Black Sea coast, long-period non-monotonic (quasi-periodic) changes of AT averaged for summer and winter seasons occur almost in the anti-phase: warm winter periods correspond to summer seasons with decreased temperature, and vice versa. But for all that, a secular linear trend of winter warming predominates over the summer one. Besides, a significant trend of autumn cooling is discovered for all coastal regions studied.

Wind speed and direction. The results of studying spatial features and time changes of wind over the north coast of the Black Sea for periods from 50 to 100 years confirm the fact of general wind speed decreasing during the second half of the 20th century (Repetin and Belokopytov, 2008). The main input to the total weakening of mean annual wind speed is brought by decreasing of temperate (6-9 m/s) and strong (≥ 10 m/s) winds repeatability over all regions studied, except for Novorossiysk.

Linear trends of annual wind speed were obtained as negative and significant on probability levels exceeding 95 % for all stations considered, except for Anapa (Table 2). With respect to multi-year norms, wind speed decreased by 22-51 %. This decrease occurred in all seasons, but it was most intensive in winter months. Semi-instrumental and visual observations of wind waves on the shore stations show the same trends of wave heights decreasing, which confirm total wind-wave activity weakening in the region.

Table 2. Linear trend slopes (m/s/10yr) of annual and seasonal (winter, summer) mean values of the wind speed on the shore stations of Ukraine and Russia.

Station	Period, years	Annual	Winter	Summer
Odessa	1915-2005	<u>-0.23</u>	<u>-0.27</u>	<u>-0.17</u>
Ochakov	1924-2005	<u>-0.28</u>	<u>-0.34</u>	<u>-0.25</u>
Chernomorsk	1928-2005	<u>-0.14</u>	<u>-0.19</u>	<u>-0.11</u>
Yevpatoria	1915-2005	<u>-0.08</u>	<u>-0.14</u>	-0.02
Sevastopol	1915-2005	<u>-0.12</u>	<u>-0.15</u>	<u>-0.09</u>
Cape Khersones	1915-2005	<u>-0.10</u>	<u>-0.11</u>	0.0
Yalta	1915-2005	<u>-0.06</u>	<u>-0.06</u>	<u>-0.06</u>
Feodosia	1915-2005	<u>-0.23</u>	<u>-0.23</u>	<u>-0.21</u>
Anapa	1917-2005	0.02	0.01	<u>0.07</u>
Novorossiysk	1915-2005	<u>-0.10</u>	<u>-0.11</u>	<u>-0.07</u>
Averaged:		-0.13	-0.16	-0.09

In the interannual variability of main wind directions repeatability, western and eastern winds have significant positive trends. In the northwestern part of the Black Sea, one clearly observes a tendency of repeatability rise for the west-east atmospheric macro-circulation mode and weakening of the meridional circulation type.

Precipitations on the seashore. Climatic variability of atmospheric precipitations over the Black Sea was estimated by long time-series of six Ukrainian shore stations from Odessa to Feodosia. Significant linear trends were revealed for annual precipitation sums testifying their total increase during the last 100 years (minimum 102 mm is in Odessa, NW part of the sea, maximum 167 mm is on the Cape Khersones, central deep-sea basin). Trends of interannual variability of monthly precipitation sums indicate that the intensive secular precipitation rise occurs not only in the cold season of year, but also in the warm one.

Long-term oscillations with periods of 60-70 years are detected by means of polynomial approximation of interannual variability of precipitations. Their total decreasing was observed in the last decades of the 19th century, in the period 1920-1930 and in the 1990s. The rise of

precipitations amount in the 1960s and '70s coincides with the general regional tendency of cyclonic activity in this period.

HYDROLOGICAL CONDITIONS

Water balance components. The specific water structure of the Black Sea is mainly determined by the characteristic combination of fresh water fluxes from/to atmosphere and from rivers, as well as salt water exchange with adjacent seas through the Kerch and Bosporus Straits. Fresh water budget (FWB = riverine discharge + precipitation - evaporation) depends on atmospheric processes described by variations of surface air temperature and humidity, wind speed and precipitations falling down to river watersheds and sea surface. Therefore changes of water balance (WB) components can serve as integral indicators of climate change manifestations in the Black Sea marine system.

Annual Black Sea water balance components were calculated the empirical methodology, using shore stations and open sea observations data (Altman, 1991). On the time-scales from inter-annual to inter-decadal variability, FWB together with resulting exchange flow through the Kerch Strait are the main drivers of the intensity of the Black Sea water exchange through the Bosporus Strait, which is the source of saline, oxygen-rich Mediterranean water. WB equation is used in the form dV = FWB + Qas - Qbs - Quc + Qbc, where dV indicates the Black Sea volume change; Qas, Qbs – volumetric fluxes from/to the Azov Sea to/from the Black Sea through the Kerch Strait (yearly net flow is positive); Quc, Qbc – flows of the upper and bottom currents from/to the Black Sea to/from the Marmara Sea through the Bosporus Strait (yearly net flow is usually negative on time-scales considered).

Mean values of fluxes and their linear trend slopes for the period 1945-2005 are presented in Table 3, while the interannual and climatic variability of annual fluxes is illustrated on Figure 2.

Budget component	Mean value, km³/yr	Slope, km³/yr²
Fresh water fluxes:		
Precipitations	252.6	<u>1.34</u>
River discharge	330.1	0.25
Evaporation	366.9	<u>-2.49</u>
FWB	215.7	<u>4.08</u>
Strait fluxes:		
Kerch input	48.1	-0.05
Kerch output	33.8	-0.03
Kerch rezult	14.3	-0.03
Bosporus input	167.7	<u>-1.25</u>
Bosporus output	395.8	<u>2.83</u>
Bosporus rezult	228.0	<u>4.07</u>
Sea volume change:		
Water balance	2.0	0.0
Sea level observ.	2.1	0.0

Table 3. Black Sea mean annual water budget components and their linear trend slopes for the period 1945-2005.



Figure 2. Interannual variability of the Black Sea water budget components (km³) and their linear trends.

Significant rise of precipitations and, especially, decrease of evaporation lead to FWB increasing even under the stable riverine input on climatic time-scale. With the stable water input from the Azov Sea, FWB drives the rise of output flow and the weakening of input flow through the Bosporus Strait. Interannual fluctuations and linear trends of FWB and total (output) flow from the Black Sea to the Marmara Sea are the same, which confirms the role of freshwater flux as the main driver of sea water exchange on climatic time-scale. Water balance (mean increment of the sea volume) is close to the value obtained from the observed sea level changes ($2.1 \text{ km}^3/\text{yr} = 1.6 \text{ mm/yr}$), which confirms the adequacy of the methodology used.

Water temperature at the seashore. Studies of water temperature (WT) climatic changes were performed for northern (Ukrainian) and eastern (Caucasian) coasts of the Black Sea. Calculations show that mean annual WT trends on the Ukrainian seashore are positive (Table 4). Trend slopes in the shallow Karkinit Bay (stations Khorly and Chernomorsk) and on the north-eastern coasts of the sea are significant on probability levels exceeding 90 %. On the eastern coast (stations Tuapse, Batumi) trends are negative (in Batumi, slope is significant at a level exceeding 95 %). In this region annual amounts of precipitations have a clear climatic tendency to rise. It possibly has a cooling effect on the near-shore water temperature all year. Water warming in the coastal areas studied occurs mainly in winter season, which corresponds to air temperature trends.

Station	Period, years	Annual	Winter	Summer
Odessa	1923-2005	0.03	<u>0.19</u>	-0.05
Ochakov	1926-2005	0.02	<u>0.11</u>	-0.02
Khorly	1923-2005	0.06	<u>0.17</u>	0.01
Chernomorsk	1927-2005	<u>0.09</u>	<u>0.18</u>	-0.01
Yevpatoria	1923-2005	0.05	<u>0.14</u>	0.07
Sevastopol	1923-2005	0.02	<u>0.11</u>	-0.02
C. Khersones	1923-2005	0.03	0.01	0.06
Yalta	1923-2005	0.05	0.02	0.11
Feodosia	1923-2005	<u>0.08</u>	<u>0.19</u>	0.06
Anapa	1923-2005	0.06	<u>0.11</u>	<u>0.09</u>
Novorossiysk	1924-2005	<u>0.10</u>	<u>0.31</u>	<u>-0.10</u>
Tuapse	1924-2005	-0.04	0.03	<u>-0.10</u>
Batumi	1925-1995	<u>-0.11</u>	-0.09	-0.06
Averaged:		0.03	0.11	0.0

Table 4. Linear trend slopes (°C/10yr) of annual and seasonal (winter, summer) values of water temperature on the shore stations of the northwestern Black Sea, Crimea and Caucasus.

There is no doubt that global warming influenced the Black Sea coastal water temperature rise in the 2nd half of the 20th century. It is confirmed by polynomial approximation of time-series showing the general intensive WT increase and by similar seasonal peculiarities of air and water temperature trends during the last 30 years (1975-2005). These trends can be also interpreted as climatic variability induced by the rise phase of AMO.

Open sea water temperature. Primary data on water temperature and salinity obtained during oceanographic expeditions in the Black Sea since 1910 till 2000 were used for the long-term changes analysis. The main part of these observations relates to the period 1950-1990. As the interannual variability indices, monthly values on the standard depths averaged over the "squares" 20'x30' were calculated, then transformed to anomalies from multi-year mean values and normalized on standard deviations. Annual estimates of WT and salinity anomalies were obtained by averaging for the whole Black Sea area.

Sea surface temperature in winter and summer seasons changed almost synchronously till 1975, then – in opposite phase (Figure 3). Interannual WT variability in the 0-50 m layer is similar to the winter surface temperature changes and displays a general negative tendency after 1985. In the 75-400 m water layer, long-term temperature changes are clearly expressed and, in general, they are opposite to the surface temperature tendencies. Negative anomalies predominated before 1965 and after 1990, positive ones – between these years (Figure 4).



Figure 3. Normalized water temperature anomalies on the whole Black Sea surface and their 5-year moving averages: winter (white circles, dash line) and summer (black circles, solid line).



Figure 4. Normalized annual WT anomalies (bars) and their 5-year moving averages on 150 m.

Water salinity at the seashore. Time-series of monthly and yearly averaged salinity were analyzed for shore stations reflecting the main geographical peculiarities of the Ukrainian Black Sea coast (Table 5). In the Karkinit bay (Khorly) and at the western and southern Crimea seashores (Yevpatoria, Cape Khersones, Yalta and Feodosia), negative trends significant at more than 95 % probability levels were noted for annual and monthly salinity values. Negative significant trends of annual salinity were obtained also for the North-western coast of the Black Sea (Primorskoye, Ochakov), but in Odessa only monthly trends for July, September and October were significant (0.02-0.03 psu/year). The negative trend in the Kerch Strait (Opasnoye) is determined by the significant decreasing of the Azov Sea water salinity caused by climatic change influence – precipitations rise and evaporation decrease (Ilyin *et al.*, 2009).

Table 5. Coastal water salini	y statistics fi	from Ukrainian	stations	data: mean	values an	d standard	deviation
(psu); linear trend slopes for	annual mean	n values (psu/y	/r).				

Station	Period,	Mean	Standard	Trend
Otation	years	salinity	deviation	slope
Primorskoye	1952-2005	13.47	0.96	<u>-0.02</u>
Odessa	1951-2005	14.58	0.87	-0.01
Ochakov	1957-2005	4.21	0.95	-0.02
Khorly	1957-1993	17.54	1.03	<u>-0.06</u>
Yevpatoria	1956-2005	17.94	0.26	<u>-0.01</u>
Cape Khers.	1959-2005	18.02	0.23	<u>-0.01</u>
Yalta	1952-2005	17.90	0.19	<u>-0.01</u>
Feodosia	1951-2005	17.64	0.31	<u>-0.01</u>
Opasnoye	1957-2005	12.97	0.85	<u>-0.02</u>
Averaged:		14.92	0.63	-0.02

Open sea salinity. Long-term salinity change tendencies during the second half of the 20th century have different patterns for the Black Sea upper layer (above the main pycnocline) and for the 75-400 m layer. The common feature is the presence of two sub-intervals in the period considered: 1950-1977 and 1977-2000. Surface layer salinity before 1977 had mostly positive anomalies, after 1977 – negative ones (Figure 5a). Interannual salinity changes in the main pycnocline layer were expressed even more clearly and their change tendencies are, in general, opposite to the surface salinity rate: before 1977 negative anomalies were predominant, after – positive ones (Figure 5b).



Figure 5. Normalized annual water salinity anomalies (bars) and their 5-year moving averages (line) (a) on the whole Black Sea surface and (b) at 150 m depth.

Since no significant trend could be revealed for the whole Black Sea salinity because of irregular spatial and temporal data distribution, analysis of all available observational data near the two key sources of fresh and saline water input was performed in order to construct time-series and describe the long-term variability of water salinity during the second half of the 20th century within the riverine and Mediterranean water plumes expanding over the Black Sea shelf (Ilyin, 2008a).

Significant long-term negative trends of surface water salinity were fitted for July data in the central part of the NW shelf, and for August data in the near-Danube region. At the same time, long-term north-western wind intensification was observed in the period 1950-2000 near the Danube delta for yearly mean values as well as for summer monthly mean values. This effect enhances the riverine water transport in southward and south-eastward directions after the spring water input from the main rivers, while river discharge did not change significantly.

By using all salinity data for 1960-2000 sampled in the bottom water layer of the near-Bosporus shelf, the Mediterranean water plume patterns were studied for all seasons. Long-term variability of the plume statistics demonstrated significant changes between decades. Some increase from the '60s to '70s, followed by significant decrease in the '80s and '90s was obtained for bottom salinity and probabilities of its high values observation. These results were compared with, and explained by, freshwater budget component changes as the climate variability manifestations in the Black Sea.

Rim Current. Seasonal and interannual variability of the Black Sea water geostrophic circulation is reflected in correspondent changes in the deep basin's surface topography. It is known that large-scale sea surface topography has average spatial tendency of rising at the shores and lowering in central deep-water regions, which is conditioned by the cyclonic character of water circulation. Maximal slopes of sea level in the direction from the deep water towards the seashore correspond to alongshore flow of the Main Black Sea Current or the so-called Rim Current (RC).

For the study of long-term changes in the RC intensity, oceanographic data sampled on standard sections across the stream were used (Ilyin, 2008b). On the basis of vertical distributions of water temperature and salinity, dynamical heights were calculated and their slopes on section tracks estimated. Then time-series of these parameters were constructed for the period 1959-1995, when oceanographic work on standard sections was executed with different regularity.

The most systematic and durable data set exists for the cross-section to SW from Cape Khersones across the north-western branch of the RC (Crimea Current) flowing in general direction to the west, along the continental slope. Significant negative linear trends of surface dynamic heights and slopes were revealed for this section testifying of long-term tendencies of RC weakening and its displacement to the north, closer to the shelf-break. These tendencies are different according to the seasons (decreasing the most in winter and spring seasons, less in autumn and insignificant in summer). Less surface slopes mean less cross-stream pressure (and water density) gradients and therefore less geostrophic current speed. From 1959 till 1995, dynamic slopes and current speed decreased on average almost twice from their initial values.

Deceleration of the RC's Crimea branch corresponds to long-term intensification of yearly averaged western wind components acting in the opposite direction to the current, while total weakening of wind's relative vorticity in the region was registered. Intensive cyclonic wind vorticity predominated in the 1950-60s and was later lower in magnitude and variable in sign vorticity values.

Together with other indicators of the regional marine climate change (temperature and precipitations rise, wind activity and evaporation weakening, salinity decreasing), observed features of geostrophic current weakening may have some environmental consequences.

POSSIBLE ENVIRONMENTAL IMPACTS

While discussing observed long-term changes in physical components of the Black Sea ecosystem, some preliminary general (qualitative) assumptions can be advanced.

First of all, regional climate changes seem to be due to not only anthropogenic global warming but also natural variations in climatic system described by AMO and NAO indices fluctuations on time scales of decades and centuries.

During the last decades, a clear increase of temperature and freshwater input was observed, together with a weakening of the wind activity. The latter results in general deceleration of horizontal circulation and vertical mixing of marine water. It leads to changes in heat transport and chemical constituents in marine water (including nutrients and pollutants), as well as alteration of self-cleaning processes, such as surface water renewal by means of wind-driven coastal upwelling.

Evidence of water temperature rise under atmospheric forcing tends to suggest that more heatloving biological (Mediterranean?) species will expand in the Black Sea, while current desalination tendencies due to rise in freshwater input (more precipitation and less evaporation) can lead to opposite results – expansion of fresh- and low-saline water inhabitants.

As a result of more abundant rainfalls, a lowering of water temperature is possible in some regions, especially at the eastern coasts of the Black Sea. It can also promote alterations in biological indicators of marine ecosystem. Moreover, pollutants and nutrients falling down with precipitations can contribute to additional contamination of marine water because their amount is comparable with the riverine input. Thus, atmospheric input of nutrients is estimated in ten-thousands (nitrites, phosphates) and hundred-thousands (nitrates, sulfates, chlorides) tons per year (Chaykina *et al.*, 2008; Voitsekhovich *et al.*, 2004).

Finally, water exchange through the Bosporus Strait tends towards more output of Black Sea water and less input of Mediterranean water under the climatic rise of freshwater flux. Probably, this is not a promoting factor for the "mediterranization" of the Black Sea ecosystem.

Recent trends in fluvial discharge to the Black Sea

John D. Milliman¹, Wolfgang Ludwig², Albert J. Kettner³ and Kehui Xu⁴

 ¹ School of Marine Science, College of William and Mary, Gloucester Point, USA
² Centre de Formation et de Recherche sur l'Environnement Marin, CNRS/Université de Perpignan, France
³ CSDMS, INSTAAR, University of Colorado, Boulder, USA
⁴ PDepartment of Marine Science, Coastal Carolina University, Conway, USA

ABSTRACT

Rivers discharging into the Black Sea drain 2.4 million km² of land area, approximately five times the surface area of the Black Sea itself (0.46 million km²). Basin-wide runoff averages 140 mm/yr, but individual basin runoff ranges from <100 (Ukrainian and Russian rivers) to 1,000-1,500 mm/yr (Georgian rivers). Historically, the Danube, Dniepr and Don Rivers have discharged nearly 70% (285 km³/yr) of the >400 km³/yr of water reaching the Black Sea. As with runoff, the mountainous rivers draining Georgia and northern Turkey have the highest sediment yields (200-500 t/km²/yr), but because of their small drainage basins, these rivers historically contributed much less sediment (19 million tons per year (Mt/yr)) than the larger northern rivers (~85 Mt/yr).

Interannual variations in water and sediment discharge reflect climatic shifts related to the North Atlantic Oscillation (NAO) and Atlantic Multidecadal Oscillation (AMO), whereas changes in the fluvial discharge of nutrients in large part reflect the agricultural economy of the region as well as the effects of river damming. Deliveries of water, and particularly sediment, to the Black Sea have changed since 1950 due to increased damming and irrigation. Although freshwater discharge has decreased only slightly, available data suggest a shift in seasonal patterns, with less discharge during late winter-early spring, and greater summer-autumn discharge.

INTRODUCTION

The Black Sea is a classic estuarine marginal sea, freshwater, largely derived from river runoff, flowing out as surface water through the Bosporus, and Mediterranean Sea water flowing in via an undercurrent. The degree to which the Black Sea is drainage-basin dominated is reflected by the fact that rivers flowing into the Black Sea drain about five times more surface area than the surface area of the Black Sea itself ($2.4 \text{ vs. } 0.46 \times 10^6 \text{ km}^2$). In contrast, the ratio of drainage basin to sea area of the Mediterranean Sea is ~2.2.

Many of the data cited in this paper (see Table 1) come from the encyclopedic report by Jaoshivili (2002), who also included many small rivers as well as all the major rivers draining into the Black Sea. Here, however, we limit ourselves to rivers 2,000 km² or greater in area. Many of the data from Turkish rivers come from Hay (1994). We also have utilized data from the Global River Data Centre (GRDC) as well as data from other sources as summarized in Milliman and Farnsworth (2010).

Table 1. Black Sea rivers with drainage basins larger than 2,000 km²; river locations shown in Figure 1. The collective basin areas of these rivers (2.3 x 106 km²) represents 96% of the estimated 2.4 x 106 km² draining into the Black Sea. Because of incomplete data, numbers in italics may represent pre- or post-dam discharges. Data for Jaoshvili (2002), Hay (1994), GRDC, and Milliman and Farnsworth (2010).

River	Country	Basin Area	Runoff	Pre-dam Q	Post Q	Sed. Yield	Pre-dam Qs	Post Qs	Yrs Data	End Date
		(10 ³ km ²)	mm/yr	km³/yr	km³/yr	t/km²/yr	Mt/yr	Mt/yr		
Low-Runof	ff Northern	Rivers								
Danube	Romania	820	260	210	210	82	67	25	80	2000
Dniepr	Ukraine	560	94	44	42	4	2,3	0,8	56	2006
Don	Russia	420	69	29	21	15	6,3	1,9	110	1990
Dniestr	Ukraine	72	130	9,3	9,3	42	3	0,49	105	1985
Yuzhny Bug	Ukraine	64	53	3,4	2,8	3	0,2	0,2	20	1984
Kuban	Russia	58	220	13	13	140	8,4	8,4	89	1998
Ingul	Ukraine	9,7	62	0,6	0,6	13	0,13	0,13		1987
Subtotals		2000		310	300		87	37		
Low-Runof	ff Southern	Rivers								
Kesilirmak	Turkey	79	96	7,6	7,6	215	17	0,44	12	1986
Yesilimak	Turkey	65	110	7,2	7,2	290	19	0,19	12	1986
Sakarya	Turkey	57	98	5,6	3,6	190	11	3,8	36	1999
Sumav	Turkey	23	190	4,4	4,4					
Filyos	Turkey	13	240	3,1	3,1	285	3,7	0,1	11	1986
Kamchea	Bulgaria	5,3	130	0,7	0,7	210	1,1	0,46		1979
Karasu	Turkey	2,9	210	0,6	0,6	14	?	0,04	11	1987
Harsit	Turkey	2,6	310	0,8	0,8	200	0,52	0,52		
Subtotals		245		30	28		52	5,5		
High-Runo	ff Southea	stern Rivers								
Choruh	Georgia	22	410	9	9	370	8,2	8,2	12	1986
Rioni	Georgia	13	1000	13	13	530	7,6	3,7	20	1984
Inguri	Georgia	4,1	1500	6	1,6	440	1,8	0,13		
Kodori	Georgia	2	1950	3,9	3,9	410	0,82	0,82		
Subtotals		41		32	27		18	13		
Totals		2300		372	355		150	55		

The data in Table 1, however, by no means should be considered as inclusive or complete. Only four of the listed rivers (Danube, Don, Dniestr and Kuban) are represented by more than 40 years of data, whereas 2/3 of the rivers are represented by 12 years or less of data. Given this short-term available data set, we can assume that some of the water and sediment discharge data shown in Table 1 reflect either pre- or post-dam values; without a more complete data set it is difficult to know which.

BLACK SEA RIVERS

As shown in Table 1 and Figure 1, rivers draining into the Black Sea range greatly in size, runoff and sediment yield. Based on their physical dimensions as well as their collective runoff and sediment yield character, the rivers can be separated into three categories: low-runoff, low sediment yield northern rivers; low runoff, moderate sediment yield southern rivers; and high runoff, high sediment yield southeastern rivers.

1) By far the biggest rivers are those entering the Black Sea from north (Figure 1); the Danube alone accounts for 1/3 of the collective Black Sea drainage area. If one adds the Dniester and Don, these three rivers account for 2/3 ($1.8 \times 10^6 \text{ km}^2$) of the total land area draining into the Black Sea. Including other Ukrainian and Russian rivers, the total land area exceeds $2 \times 10^6 \text{ km}^2$. Four of the seven northern rivers listed in Table 1 are characterized by runoff less than 100 mm/yr, the Don's natural runoff being only 69 mm/yr. With headwaters in relatively wet Alps and Caucasus mountains, respectively, the Danube and Kuban Rivers are the only northern rivers whose runoffs exceed 200 mm/yr (260 and 220, respectively). Because of their large basin areas, however, large northern rivers historically have collectively discharged ~310 km³/yr of water to the Black Sea, more than 80% of the basin-wide total (Table 1). The Danube alone discharges more than half (210 km³/yr) of the fluvial water reaching the Black Sea. Because many northern rivers drain low-lying terrain, they tend to have low sediment yields, the average being only 43 t/km²/yr, but because of their collective size, prior to dam construction these rivers account for about 80% of the sediment reaching the Black Sea, ~87 million tons (Mt) per year (Table 1).



Figure 1. Black Sea drainage basin, showing the locations of the 19 rivers presented in Table 1.

2) Most Turkish rivers in the south also have low runoffs, the average (120 mm/yr) being slightly lower than the northern rivers. The three largest rivers, the Kesilirmak, Yesilimak, and Sakarya (collective drainage basin area of ~200,000 km²) have a cumulative runoff of ~100 mm/yr, and a pre-dam annual discharge of 20 km³/yr. Because Turkish rivers drain mountainous terrain, their historic sediment yields have been much higher (230 t/km²/yr) than the northern rivers, but due to their relatively small drainage basins, before dam construction they collectively discharged ~50 Mt/yr of sediment to the southern Black Sea (Table 1), more than half the total of the northern rivers although draining an order of magnitude less area.

3) Rivers with the highest runoffs and sediment yields are found along the southeastern Black Sea, specifically in Georgia and northeastern Turkey. Average runoff is 780 mm/yr, five to six-fold higher than other Black Sea rivers. Discounting the Choruh River (410 mm/yr), average runoff for the southeastern rivers is much higher, ~1,500 mm/yr. Due to their small cumulative areas (41,000 km²), however, total pre-dam discharge to the Black Sea was only 32 km³/yr. Most of these rivers drain mountains with elevations approaching or exceeding 3,000 m; in contrast, the Don and Dniepr Rivers to the north have maximum elevations of 180 and 330 m, respectively. Because of their high runoff and high elevations, as well as being tectonically active, the average sediment yield of the southeastern Black Sea rivers reaches 430 t/km²/yr. Collectively their pre-dam annual sediment discharge was 18 Mt/yr (Table 1).

TEMPORAL VARIATIONS: CLIMATIC FORCING

Although there is some evidence for that El Niño-Southern Oscillation has some influence on precipitation and water discharge in southwestern Turkish rivers (Karabork and Kahya, 2009), the prime climatic drivers in controlling river discharge to the Black Sea are the North Atlantic Oscillation (NAO), superimposed on the longer-term Atlantic Multidecadal Oscillation (AMO). This forcing can clearly be seen in long-term discharge patterns of the Danube River (whose headwaters lie in the Alps, more than 1,000 km to the west), the Dniepr River in the north, and the Sakarya River in the south. Between 1950 and 2000, all three rivers showed pronounced low runoffs in the early 1970s and, particularly, in the early '90s, coincident with positive NAO and low AMO indices; high runoffs in the mid '60s, late '70s and late ''90s, in contrast, coincided with negative NAO and high AMO indices (Figure 2). During the periods of low runoff, discharge from Black Sea rivers was as much as 25-30% less than during periods of high runoff (Figure 2).



Figure 2. Annual runoff of the Danube, Dniepr and Sakarya Rivers (above) compared to North Atlantic Oscillation (NAO) and Atlantic Multidecadal Oscillation (AMO) indices, 1950-2000.

TEMPORAL VARIATIONS: CHANGES DUE TO DAMMING

Beginning in the middle of the past century many Black Sea rivers were dammed, in part for hydroelectric power and flood control (e.g., Danube) but, particularly in those areas with lesser amounts of precipitation for irrigation (e.g., Don in the north, Sakaraya in the south). At present most rivers flowing into the Black Sea are partially or extensively dammed. Mean annual pre-dam discharge from the 19 Black Sea rivers larger than 2,000 km² in area was 372 km³/yr (Table 1). If one includes smaller rivers, the mean annual total should have approximated 400 km³/yr. For many of the rivers cited in Jaoshvili (2002), however, it is not clear whether listed discharges represent pre- or post-dam values.

Because of the lack of long-term temporal data (see Table 1), it is difficult to judge the presentday discharge of Black Sea rivers. The Danube and Dniepr appear to have similar discharges to their pre-dam values, whereas the Don and Sakarya have lower discharges. A contrast between the Danube and Don is seen in Figure 3, where the temporal trend in Danube discharge coincides with basin-wide precipitation, whereas Don discharge between 1901 and 1990 decreased by ~20%, primarily in response to dam construction in the late 1940s, despite a slight increase in basin-wide precipitation. Much of the stored water on the Don and other low-runoff has been ultimately used for irrigation. We anticipate that present-day post-dam cumulative discharge is somewhat less than 375 km³/yr (Table 1), the decreased discharge reflecting water lost through evapotranspiration via irrigation and evaporation of reservoir water, but without better data this is only a guess.



Figure 3. Long-term temporal trends of annual runoff (R) and basinwide precipitation (P) in the Danube (above) and Don (below) Rivers, 1901-2000. Precipitation data from Climate Research Unit, University of East Anglia.

A better estimate can be made for the effects of sediment storage due to damming. Nearly every Black Sea river has a lower present-day sediment load than it had prior to damming. The mean cumulative sediment discharge of the Danube, Dniepr, Don and Dniestr Rivers is presently ~28 Mt/yr, compared to pre-dam loads of ~78 Mt/yr (Table 1). The low-runoff southern rivers have been even more impacted, the mean annual sediment loads decreasing by nearly an order of magnitude, from ~50 to 5 Mt/yr (Table 1). Collectively, the Black Sea rivers presently discharge only about 30% the amount of pre-dam sediment; a more thorough dataset might actually show an even greater sediment loss.

CHANGES IN SEASONAL DISCHARGE

Figure 4 shows the temporal trends in seasonal discharge of four Black Sea rivers. In two of them, the Don and Sakaraya, discharge has declined appreciably; in the other two, the Danube and Dniepr, discharge has remained more or less constant. With the exception of the Danube, there has been a decrease in late winter-early spring discharge; and with the exception of the Sakaraya, there has been an increase in late summer to late autumn discharge. We assume that this relates to the seasonality when water is trapped or released; similar trends are seen in the Po River, where water trapped in reservoirs is released in summer for irrigation (Kettner and Syvitski, 2008). We also note that peak discharge occurred in April-May; now it occurs in March-April (Figure 4), reflecting earlier snow melt similar to that seen elsewhere. (e.g., western North America; Stewart *et al.*, 2005).



Figure 4. Seasonal changes in discharge from the Danube, Dniepr, Don and Sakarya Rivers, pre- and postdam construction. Even though annual discharge from the Don and Dniepr decreased considerably, late summer and autumn discharge actually increased, the result of basinwide water usage. Sakarya River data from Isik *et al.* (2008); other data from GRDC.

TEMPORAL VARIATIONS: CHANGES IN LANDUSE

Black Sea rivers have experienced some major landuse changes in recent years. As seen in Figure 5, discharge of nitrogen and phosphorous increased sharply in the 1960s in response to increased use of artificial fertilizers in agriculture. One result was that by the 1980s biological production in the Black Sea was no longer phosphorous-limited (Ludwig *et al.*, 2009 and references therein). Phosphorous and nitrogen levels remained more or less constant until the early '90s, when, with the collapse of the former Soviet Union, fertilizer use in agriculture decreased, leading to a 40% decrease in phosphorous discharge (Figure 5).



Figure 5. Silicate, nitrogen and phosphorus discharge from Black Sea rivers, 1963-1998. Data from Ludwig *et al.* (2009).

Increased retention of fluvial waters behind dams, on the other hand, led to a decrease in silicate discharge in the late 1960s (Figure 5), reflecting increased diatom production in dam reservoirs. This decrease, combined with increased discharge of phosphorus and nitrogen (Figure 5) mean that silica became a limiting nutrient. The silicate to phosphorous ratio decreased by nearly 50% from the mid-'60s to late '80s (Figure 6). The decline in silicate and the increased nitrogen/silicate ratio may explain the decreasing diatom production coincident with increasing dinoflagellate production, and a corresponding increase in hypoxia in northern Black Sea shelf waters (Humborg *et al.*, 1997).



Figure 6. Ratio of silicate to phosphorous discharge from Black Sea rivers, 1963-1998. Data from Ludwig *et al.* (2009).

CONCLUSIONS

While the rivers discharging into the Black Sea are relatively well documented, we still lack longterm data for many of them, particularly those draining the southern and southeastern parts of the region. How much discharge has changed – and whether these changes are also manifested in seasonal changes – are still not well delineated. With the data at hand, however, we can conclude that while water discharge to the Black Sea has changed little over the past 50 years – mostly reflecting interannual shifts in regional precipitation – winter/early spring discharge seems to have declined due to river damming and irrigation, whereas late summer and autumn discharge has increased. A far greater change is seen in discharge of suspended sediments (a 60-70% decrease, perhaps more) due to damming, in changes in nutrient fluxes in response to damming (decreased silicate discharge) and in changes in regional agriculture (decreased phosphorous and nitrogen).

Origin and evidence of climate variability on physically-driven changes in the Black Sea

Temel Oguz

Institute of Marine Sciences, Middle East Technical University, Erdemli, Turkey

1. INTRODUCTION

Temporal scales of natural variability of the earth's climate system cover a broad range from seasonal cycles to inter-annual patterns, inter-decadal cycles such as the North Atlantic and Pacific Decadal oscillations, and to multimillenial-scale changes such as glacial inter-glacial transitions. Over the past several centuries, human activities (such as fossil fuel burning and deforestation) have become an additional, important component of the climate system. According to the recent Assessment Report of the Intergovernmental Panel on Climate Change, warming of the global climate system in response to increasing rate of anthropogenic production of greenhouse gases is unequivocal. Anthropogenic climatic forcing is mediated primarily by greenhouse gas (predominantly CO2) emissions. Together, elevated CO2 and the resultant increases in global mean temperature have already started resulting in a cascade of physical and biochemical changes in marine systems.

The aim of this paper is to highlight key changes in the Black Sea abiotic properties with particular emphasis on linkages between the North Atlantic Oscillation (NAO), climate change and physical properties of the Black Sea. They serve as a background material for the assessment of climate-induced changes in Black Sea ecosystem properties. We first provide a brief overview of the NAO dynamics in connection with the global warming. This issue is critical because the hydro-meteorological and biogeochemical properties of the Black Sea are largely controlled by the NAO. The way in which the NAO is affected by future climatic changes will also govern the Black Sea ecosystem. We then relate the long-term changes in the sea surface temperature, the net freshwater input into the basin, and the sea level anomaly, and the subsurface oxygen concentrations to the change in winter NAO index. We finally provide a brief summary of future projections based on various scenarios deduced from the ensemble model forecasts for Europe.

2. Dynamics of the North Atlantic Oscillation in connection with anthropogenic climatic forcing

During boreal winters, the climate in large parts of the Northern Hemisphere is under the influence of the NAO. It constitutes the dominant mode of tropospheric variability in the North Atlantic region including the east coast of North America and Europe with extensions to Eurasia. The NAO is characterised by a meridional oscillation of mass between two major centres of action over the subtropical Atlantic (the Azores High) and near Iceland (the Iceland Low). The NAO is closely associated with the strength and direction of the north Atlantic storm tracks as well as with precipitation and temperature over Europe. The difference of normalized sea level pressures between the Azores High and Iceland Low (e.g. between two stations at Gibraltar and Iceland) is often used to construct the NAO index time series (Hurrell, 1995). Alternatively, hemispheric definitions can be used, derived by projecting SLP onto an Empirical Orthogonal Function (EOF) pattern, for instance of November-April monthly SLP northward of 20°N (Thompson and Wallace, 1998). The latter is often referred to as the Arctic Oscillation index, or Northern Hemisphere Annular Mode index. However, since these all represent essentially the same phenomenon, and to avoid confusing readers, we refer to the former as a "station-based" NAO index, and the latter as an "EOF-based" NAO index. During winter months with a positive NAO index, i.e. with an enhanced north-south pressure gradient over the north Atlantic, northern Europe is in general characterized by warm and wet conditions and eastern-southeastern Europe (the Eastern Mediterranean and Black Seas) by dry conditions. The opposite holds for months with a negative NAO index.

Over recent decades the winter index of the NAO has exhibited an upward trend, corresponding to lowered surface pressure over the Arctic and increased surface pressure over the subtropical North Atlantic. Most climate models have shown that the natural forcings unlikely account for a substantial component of the recently observed positive NAO index trend (Gillett *et al.*, 2003). In order to explain the observed increase in the winter NAO index, several mechanisms driven by anthropogenic and/or natural forcings on the NAO (e.g. greenhouse gases, stratospheric ozone, tropospheric sulphate aerosol, volcanic aerosol, and solar irradiance changes) have been examined by climate models.

Figure 1 shows the evolution of winter NAO index based on seven climate model simulations (using a similar scenario) under increasing greenhouse gas concentrations. Though there are large inter-model variations depending on the details of the model physics, they generally show a decrease in pressure over the Arctic region, and some increases at lower latitudes. Such patterns project onto the positive (westerly) phase of the NAO. Thus, the winter NAO index shows a positive trend in all seven climate models. Though the magnitude of this trend is highly model-dependent, the consistency in the sign of the change provides some confidence that the circulation response to greenhouse gas forcing is likely to be an enhancement of the westerly circulation in the north Atlantic sector.



Figure 1. The observed NAO index (solid line) and the average (dashed line) of the NAO indices from seven climate model simulations under increasing greenhouse gas forcing (1% per annum compounded increase in CO2 after 1990), together with an envelope containing the individual model simulations (grey shading). All series have been smoothed with a 30-year low-pass filter. The NAO index is the scaled principal component time series associated with each model's leading EOF of the Atlantic-sector SLP field (defined during the control run of each model). Taken from Gillett *et al.* (2003).

Ambaum and Hoskins (2002) quantified by a model the existence of a nonlinear feedback mechanism between the NAO and the stratospheric vortex located about 20-30 km above the earth's surface over the north pole. An increase in the NAO index leads to a stronger stratospheric vortex that eventually causes lowering of the surface pressure over the North Pole intensifying the NAO index. Thus, according to the Ambaum and Hoskins (2002) model, the stratosphere acts as an integrator of the NAO index. Walter and Graf (2005) also indicated the importance of

including the state of the polar vortex strength in any study of the variability over the North Atlantic.

Scaife *et al.* (2005) and Rind *et al.* (2005) have further extended the Ambaum and Hoskins (2002) model by showing that the unexplained strengthening of the NAO can be fully simulated in a climate model by imposing observed trends in the lower stratosphere. They indicated that, despite having little effect on global mean warming, downward coupling of observed stratospheric circulation changes to the surface can account for the majority of change in regional surface climate over Europe and North America. Considering the fact that the increase in greenhouse gas concentrations cools and strengthens the stratospheric winter vortex (Cubash *et al.*, 2001), this process translates at the surface as stronger westerly winds that promote a positive NAO index and further warming in the North Atlantic region. Then, because of the reverse modality of the NAO, the Eastern Mediterranean and Black Seas are expected to cool, which cause either a slow down of the effect of global warming or to switch of the regional climate into a cooling phase.

Reduced stratospheric temperatures over both poles mainly in late winter and spring, when sunlight comes back to the polar night area due to the substantial reduction of lower stratospheric ozone content over the last two decades (e.g. Graf *et al.*, 1998) also contribute to strengthening of the stratospheric winter vortex. Kodera *et al.* (2008) further pointed to the solar modulation of the stratospheric polar vortex, and hence the Northern Hemisphere winter trends. The linear trends of DJF-mean SLP for 1958/1959 to 2004/2005 calculated using NCEP/NCAR reanalysis data (Kalnay *et al.*, 1996) for 16 high solar (HS) winters (Figure 2) are characterized by a seesaw pattern similar to a NAO between the polar and midlatitudes, which is most prominent over the Euro-Atlantic sector. A decrease of polar pressure is related to a stronger stratospheric polar vortex at 50 hPa. Twenty-one winters are classified as LS winters: they exhibit a weak regional Icelandic Low–Azores High seesaw confined over the North Atlantic Ocean.



Figure 2. Linear trends of DJF mean SLP for Low Solar (LS) and High Solar (HS) winters in the NH ($20^{\circ}N$ - $90^{\circ}N$). Contour interval is hPa/10-year, and color indicates the statistical significance of trends according to the Mann-Kendall test. Winters are classified as HS or LS depending on whether the activity is higher or lower than the mean value \pm 0.25 standard deviation. Taken from Kodera *et al.* (2008).

It was recently found that the centers of action of the winter NAO variability shifted spatially eastward after the late 1970s. Such an eastward shift altered its relationship with some climate variables (e.g. surface air temperature, sea ice export, cyclone activity, heat flux, etc.) over the North Atlantic and surrounding regions (Jung *et al.*, 2003). Lu and Greatbatch (2002) argued that this shift may be related to the change of the North Atlantic storm activity. Luo and Gong (2006) pointed out that the eastward shift is probably due to an increase in the strength of the zonal mean westerly winds in the North Atlantic region. Ulbrich and Christoph (1999) suggested the likely role of anthropogenic climate change for the winter NAO pattern shift.

3. PHYSICALLY-DRIVEN CHANGES IN THE BLACK SEA

Sea surface temperature: long-term Black Sea winter-mean air and sea surface temperature anomalies since the 1870s as well as the annual-mean SST anomaly after the 1950s (Figure 3) indicate a cooling phase up to 1910, followed by an approximately 1.0 °C warming trend during 1910-1970, roughly 1.5 °C cooling during the next 20 years (up to 1993), and an equally strong warming trend afterwards during 1994-2002. The latter warming trend brought temperatures back to their levels at the beginning of the 1970s, indicating that the Black Sea did not experience any warming after 1970. A significant correlation of the winter-mean SST with the May-November mean temperature of the Cold Intermediate Layer below the seasonal thermocline (Figure 4) suggests persistence of the winter cooling signature well below the surface layer and during the rest of the year.



Figure 3. Long-term changes of the Black Sea winter-mean and annual-mean sea surface temperature anomalies, the winter-mean air temperature anomaly, and the winter-mean North Atlantic Oscillation index.



Figure 4. Winter mean SST versus May-November mean temperature of the Cold Intermediate Layer (CIL). The CIL is defined by the layer with temperatures less than 8°C below the mixed layer.

The cooling trend after 1970 up to the mid-1990s is related to strengthening of the NAO in the positive phase (Figure 3) which implies colder, drier and more severe winters in the Black Sea-Eastern Mediterranean Sea region and wetter, milder and warmer winters over northwestern Europe and the Eastern North Atlantic Ocean (Hurrell, 1995). How much of the cooling in the Black Sea during the 1980s is associated with natural mode of variability in NAO or is contributed by the impacts of increasing greenhouse gas concentrations in the upper atmosphere is not known. The existing regional models do not incorporate indirect effects of the greenhouse gases and aerosol forcings and/or incorporation of statospheric processes on the NAO variability, and may therefore provide misleading results for the Black Sea.

Water budget: on the basis of available data since the 1920s (Ilyin and Repetin, 2006b), the total river discharge and precipitation into the Black Sea showed weak but opposite trends that compensate each other so that their sum remains uniform at ~550 km³ y⁻¹ (Figure 5). Evaporation varied slightly around 400 km³ y⁻¹ up to the mid 1970s (except 15% increase in the 1940s), and then decreased steadily to ~300 km³ y⁻¹ during the subsequent 15 years of cooling phase and stabilized at this value afterwards. The net freshwater flux into the sea therefore revealed an increasing trend from ~120 km³ y⁻¹ in the early 1970s to ~300 km³ y⁻¹ in the mid-1990s with additional fluctuations of ~100 km³ y⁻¹ superimposed on this trend. Its difference from the temporal volume change of the sea (which in fact may be calculated by the sea level data) implies a nearly two-fold change in the net outflow from the Black Sea into the Bosphorus during the second half of the 1990s with respect to the 1960s.



Figure 5. Long-term variations of the river discharge, precipitation, evaporation (km³ y⁻¹), and the net water flux computed as the sum of precipitation and river discharge minus evaporation for the Black Sea.

Sea level anomaly: it is a prominent feature of global warming and of large scale atmospheric systems in regional seas. Sea level change provides the best response of the physical climate to atmospheric forcing, because the link includes an overall response of the changes in the surface atmospheric pressure through the inverse barometer effect, water density changes in response to temperature and salinity variations (steric effects), precipitation, evaporation and river runoff. The detrended sea level anomaly (SLA) time series (Stanev and Peneva, 2002), as an average of the measurements at twelve coastal stations around the Black Sea, oscillates within the range of 10 cm (Figure 6). Its higher (lower) values 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 thermo-steric effect. The sea level anomaly is positively correlated with the net freshwater input into the sea and negatively correlated with the winter NAO index (Figure 6).



Figure 6. Long-term variations of the net water input (km³ y⁻¹), sea level anomaly and winter-mean NAO index.

The annual-mean tide-gauge data show a high degree of consistency with the altimeter SLA data as well. They both exhibit a rising trend of 3 cm y⁻¹ from 1993 to mid-1999 followed by -3.0 cm y⁻¹ declining trend for 07/1999-12/2003, which is consistent with the cooling phase indicated by the winter SST data. When monthly variations of the SLA are resolved, the linear trend of rise increases to 20 cm during 1992-1999 that was roughly 3 cm higher than the estimate based on the coastal tide gauge data (Tsimplis and Josey, 2001; Stanev and Peneva, 2002). Good agreement between the monthly SLA changes and the Danube discharge rates suggest the predominant role of the latter on the basin-scale sea level oscillations.

Subsurface oxygen concentration: Figure 7 displays the long-term annual-mean oxygen concentration changes of the layer between $\sigma_t \sim 14.45$ and 14.6 kg m⁻³ sigma-t surfaces (roughly the base of euphotic zone) as well as the average temperature of the Cold Intermediate Layer during May-November. They are based on the data compiled from all deep stations in the eastern basin (Yakushev *et al.*, 2005). The subsurface oxygen concentration reflects an increasing trend, from 170 μ M to $\sim 300 \mu$ M during the 1980s and the early 1990s, of the high phytoplankton production but follows a decreasing trend afterwards as phytoplankton production decreases. This is opposite to the expectation of their rather an opposite type variation due to high oxygen consumption in more productive years. In fact its positive correlation with CIL temperature (or the annual-mean, winter-mean surface temperatures) indicates an overwhelming role of climate through a more efficient ventilation of the subsurface layer during severe winters, with cold temperatures and more intense vertical mixing of the surface layer. On the contrary, DO concentration decreases during warm years reflecting a more limited ventilation process.



Figure 7. Long-term variations of annual-mean dissolved oxygen concentration at 14.5 kg m⁻³ sigma-t level, and the mean CIL temperature during May-November.

4. CLIMATE CHANGE PROJECTIONS FOR THE BLACK SEA

Giorgi and Lionello (2008) recently provided a new assessment of future climate change projections over the European region as obtained from the 17 Multi Global Model Ensemble (or MGME) models. Figures 8 to 10 show the ensemble average change in seasonal sea level pressure (SLP), precipitation and surface air temperature for the A1B scenario for the period 2071-2100 compared to 1961-1990. In DJF, the models show an increased SLP and thus increased anticyclonic circulation, centered over the central Mediterranean (Figure 8). In the other seasons, the area of increased SLP extends from the northeastern Atlantic to central Europe and the Mediterranean. The main effect of this circulation change pattern is a northward shift of the Atlantic storm track, with a deflection of storms north of the Mediterranean region into higher latitude areas. We also note that increased high pressure and anticyclonic conditions generally lead to greater stability and thus conditions less favorable to storm generation.

SLP change (mb, 2071-2100 minus 1961-1990), MGME ensemble average, A1B scenario



Figure 8. MGME ensemble average change in sea level pressure (SLP) for the four seasons, 2071-2100 minus 1961-1990, A1B scenario. Units are mb. DJF is December-January-February, MAM is March-April-May, JJA is June-July-August, SON is September-October-November.



Precipitation change (%, 2071-2100 minus 1961-1990), MGME ensemble average, A1B scenario

Figure 9. MGME ensemble average change in precipitation for the four seasons, 2071-2100 minus 1961-1990, A1B scenario. Units are % of 1961-1990 value.


Temperature change (C, 2071-2100 minus 1961-1990), MGME ensemble average, A1B scenario

Figure 10. MGME ensemble average change in surface air temperature for the four seasons, 2071-2100 minus 1961-1990, A1B scenario. Units are °C.

As a consequence of these changes in the circulation patterns, the Mediterranean region exhibits a general reduction in precipitation, while the northern European regions show an increase in precipitation (Figure 9). The area of precipitation reduction has a maximum northward extension in the summer, encompassing most of the western European continental areas, consistently with the SLP pattern, which presents the largest positive values over the northeast Atlantic in this season. In JJA, MAM and SON essentially the entire Mediterranean region and most of Western Europe show a pronounced decrease in precipitation. In winter the transition area between positive and negative precipitation change moves southward and crosses the northern Iberian, Italian and Balkan peninsulas. In the east–west direction the largest precipitation reduction occurs over the western and eastern Mediterranean, partly in association with local topographical features (such as the Iberian Plateau and Atlas mountains in the west and the Balkan peninsula in the East), with a more irregular inter-seasonal behavior in the east.

Concerning air temperature (Figure 10), the Mediterranean region exhibits a warming maximum in summer. In winter and spring, the maximum warming magnitudes are found over continental northeastern Europe, at least partially in response to reduced snow cover there. In the fall the warming is more equally distributed throughout the European land areas. In general the mitigating effect of the Mediterranean Sea and the reduced warming over the sea areas is present in all seasons.

Figures 8 to 10 thus give us an overall picture of increasingly drier and warmer conditions over the Mediterranean in the future climate scenarios, with this pattern being particularly pronounced in the summer season. The patterns of SLP, precipitation and temperature change shown in Figures 8 to 10 are similar for different greenhouse gas forcing scenarios. They are similar in shape but may change in magnitudes: the higher the forcing the larger the magnitude of change.

Ongoing "mediterranization" process in the Black Sea

Murat Sezgin¹ and Ahmet E. Kideys²

¹ Faculty of Fisheries, Sinop University, Akliman, Sinop, Turkey ² Commission on the Protection of the Black Sea Against Pollution, Besiktas, Istanbul, Turkey

ABSTRACT

Since its last connection to the World Oceans through the Bosphorus 7,000 years ago, the Black Sea has been a natural recipient of Mediterranean species with a process named as "mediterranization" of the Black Sea. However, recent studies indicate an increase in the rate of new Mediterranean species arriving and establishing in the Black Sea over the last decade. This trend must have been contributed by the elevated seawater temperatures reported and is expected to continue over the coming years.

The Black Sea is the youngest sea of the world and hence probably the most vulnerable to anthropogenic impacts as its ecosystem is unlikely to have reached equilibrium yet. The last connection, which is through the narrow and shallow Istanbul (Bosphorus) and Canakkale (Dardanelles) straits, to the seas and oceans was established only about 7,000 years ago. A gradual salinisation of this once freshwater lake created a distinct two-layer zonation in salinity with a thin layer (max 200 m) of less saline (18%0) light waters at the surface and Mediterranean affected, more saline, heavy waters (22%0) deeper lying. Due to absence of vertical exchange of waters, these deep waters down to 2,200 m lack oxygen and hence the Black Sea contains the largest anoxic waters of the planet.

One of the most important questions for marine biologists nowadays is to forecast how climate change will impact a marine ecosystem. To understand the possible responses of the ecosystem, it is important to know how that system behaved in the past under different conditions that inherently also includes climatic oscillations.

During alternation between freshwater and marine conditions, the majority of the entire fauna and flora of the Black Sea changed. For example while transforming from the Tethys Ocean (in Tertiary period; 2-65 Myr ago) to Sarmatic Sea (in the Miocene; 6-26 Myr ago), much of the endemic fauna disappeared, however typically oceanic animals such as whales, manatees and seals continued to dwell in the very low saline waters of the Sarmatic Sea for a long time, before they too disappeared (Zaitsev and Mamaev, 1997). The Neoeuxian Lake, the predecessor of the modern Black Sea, had a salinity of 5-7 and was inhabited by brackish water fauna and flora, some of which still surviving in areas of low salinity. These "Pontian relicts" include the bivalves *Dreissena, Adacna, Monodacna*, the polychaetes *Hypania* and *Hypaniola*, the crustaceans *Pontogammarus* and *Paramysis*, and the fish kilka (*Clupeonella*), many species of goby, sturgeons and herrings. Succession in salinisation could be understood, among others, from the occurrence of certain stenohaline species, such as the coccolithophorid *Emiliania huxleyi* in sediment cores; this species

first appeared in the Black Sea between 1,600-3,100 years ago when the salinity reached 11 (Hay *et al.*, 1991).

At present, 80-85% of the fauna and flora is made up by Mediterranean species, the rest by freshwater and Ponto-relict species. Compared to the Mediterranean, much reduced number of species occur in the Black Sea, but the number of adapting species is increasing gradually, a process known as "mediterranization". It is interesting to note that several Mediterranean species (e.g. the copepods *Calanus* and *Centropages*, the arrowworm *Sagitta*) have changed considerably to be classified as new species after adaptation to the specific conditions of the Black Sea.

Kovalev *et al.* (1998) suggested that the process of natural invasion and acclimatisation was more intensive during the period of fast increasing salinity. During the last centuries, in condition of stable salinity, establishment of Mediterranean species is less marked.

Occurence and distribution of species in any sea including the Black Sea are primarily determined by seawater temperature and salinity. It is expected that a warming of air and seawater temperatures will result in increased diversity of pelagic or benthic marine life in the Black Sea, with adverse effects limited mainly to declines in abundance or loss of a small number of native species. Changes to a minority of biotopes might occur in the long term.

According to Oğuz (2005), long term winter mean temperature data in the Black Sea indicated synchronous oscillations with 8 to 10 years periodicity. Despite observed exceptions, there is a long-term increase trend in temperature with a value of 0.2 °C.

The Black Sea and other seas are getting warmer in response to increased atmospheric carbon dioxide, a result of human activities. However, distinguishing environmental stress due to climate change from that due to human pressure is often difficult (Bianchi and Morri, 2000). Additionally, anthropogenic and climatic actions can combine their effects on changing natural marine biota.

Non-native species in the Black Sea are separated in two categories: Mediterranean immigrants and far-sea species. Climate changes may facilitate both of these invasion types. In this paper we concentrate on Mediterranean immigrants.

There is no doubt that the biota of the Black Sea is changing. Mediterranean influx, human action and present climate changing jointly favour the occurence and the spread of Mediterranean originated species and alien species. The so-called "mediterranization" of the Black Sea has to be considered as due to the combination of these three factors. To understand the effect of the "mediterranization" of the Black Sea, it is essential to start monitoring biodiversity at a large scale.

The Turkish Strait systems are the major biological corridors for pelagic and benthic forms migrating between the Mediterranean and the Black Sea. These straits allow the acclimatization of certain species of Mediterranean origin penetrating to the Marmara Sea and Black Sea. Depending on the temperature increase, "mediterranization" of the Black Sea fauna is in progress and immigration of new species will occurs. The new immigrants may be misperceived to increase productivity and biodiversity. However, in longer term, they will disturb native species and nature balance.

The earliest information about invasion of Mediterranean planktonic animals is reported by Zernov (cited in Kovalev *et al.*, 1998) who suggested that the cladoceran *Penilia avirostris* penetrated and acclimatised in the Black Sea in the early 1900s. Mediterranean plankton is believed to be transported via the Lower-Bosporus flow. Kovalev *et al.* (1998) lists over 60 Mediterranean copepod species that were reported in the Black Sea since (see also Shiganova, this volume). Some of these species occur in abundance as far as the Crimean coasts. Recently Selifonova *et al.* (2008) reported the first appearance of another 33 Mediterranean copepod taxa in samples obtained from the western Black Sea in 2001.

Benthic organisms, especially long lived and sessile organisms, are good indicators of ecological pressures in marine ecosystems because they are adapted for living on or in particular bottom types, and respond relatively rapidly to natural and anthropogenic stress.

The number of reported benthic immigrants are increasing in the Black Sea. A new example is a caridean shrimp *Paleamon longirostris*. This species was previously known from the eastern Mediterranean coasts including the Aegean Sea and the Sea of Marmara (Kocataş and Katağan, 2003). It has been reported recently for the first time in the Black Sea (Sezgin *et al.*, 2007).

In August 2003 Asterias rubens (Echinodermata) was reported for the first time as well in the Black Sea (Karhan *et al.*, 2007). After being first reported from the Bosphorus Strait in 1996 this alien starfish has invaded the Sea of Marmara and is now extending its range of distribution to the Black Sea (Albayrak, 1996). *A. rubens* feeds mostly on Molluscs. Since, its preferred food, the blue mussel *Mytilus galloprovincialis*, occurs in very large populations along the coasts of the Black Sea, the expansion of this new alien species in the Black Sea will not be limited by food supply. Competition between *A. rubens* and native starfish *Masthasterias glacialis* is also possible (Karhan *et al.*, 2007). Other recently recorded Echinodermata species in the Black Sea are *Amphiura filiformis*, *Asterina gibbosa* increasing number of alien species of this phylum is a clear indication of salinity change. Growing numbers of a thermophilic (requiring high temperatures for normal development) sea urchin species *Arbacia lixula* in the northern Aegean Sea and Marmara Sea are perceived as preliminary signs of faunal shifts in these seas as a result of climatic change.

Besides Echinodermata, certain fish species act as indicators of global warming. Seawater temperature is a major factor in fish distribution as it plays a direct role in reproduction process. Besides fish are very sensitive to seawater temperature during their pre-adult stages (i.e. larva and juvenile). Fish like sardine, bogue and salema are abundant in the Mediterranean Sea but were rare in the Black Sea and Marmara Sea until 20 years ago. Now they begin to be exploited in western Black Sea regions such as off Igneada.

A major characteristics of species entering the Black sea from the Mediterranean is the fact that these species dwell in saline and warm waters. For example, the introduction of species like conger, barracuda or john dory in this sea shows that the distribution of thermophilic species is extending.

With its relatively higher salinity (22%o) and warmer temperatures, the Marmara Sea is in a way an acclimatisation area before passing to the Black Sea. Some species found only in the warm and more saline southern Mediterranean regions are now increasingly appearing in the Marmara Sea. For example the ornate wrasse *Thalassoma pavo* is now seen in the Marmara Sea (TUDAV, 2008). It will not be a surprise to see this species soon in the Black Sea.

Black Sea countries are building more dams to produce energy from rivers as well as to keep ever decreasing water resources under control. Building more dams on the major rivers, coupled with lower precipitation in the Black Sea region, is expected to cause faster elevation of salinity. The introduction of many new species and the alteration of food webs in the Black Sea, especially through the "mediterranization" process, is thus expected to be more pronounced in coming years.

Studying climate change effects on marine ectotherms and ecosystems: physiological concepts for a cause and effect understanding

Hans-O. Pörtner

Alfred Wegener Institute, Bremerhaven, Germany

ABSTRACT

The effects of climate on marine ectotherms and their ecosystems in a specific environment, like the Black Sea ecosystems, need to consider the levels of abiotic factors effective in those environments as well as their variability. The interaction of factors also requires consideration. A cause and effect understanding beyond empirical observations supports a more accurate, mechanism based projection of ecosystem effects and quantitative scenarios. In a climate context in general, increasing hypoxia events and progressive carbon dioxide accumulation are trends, which co-occur with thermal changes. These trends will also affect the Black Sea, especially where such interactions already shape ecosystem structure and set limits to ecosystem distribution. This chapter briefly outlines the physiological principles of temperature, hypoxia and CO₂ effects and interactions and thereby identifies research questions to be addressed in Black Sea environments. Here changing salinities may also play a role. For analyses of the complex interactions and effects of various environmental factors at ecosystem level, concepts elaborated for the effect of individual factors need to be integrated in order to achieve more realistic estimates of sensitivity to environmental change. Progress in recent years has identified ways of how such integration may occur and can be implemented (e.g. Pörtner and Farrell, 2008). The principles and their integration operate similarly across animal phyla. Those principles which provide a link between physiology and ecology and support an understanding of ecosystem level processes are emphasized.

TEMPERATURE DEPENDENT NICHE DIMENSIONS: PHYSIOLOGICAL PRINCIPLES

Oxygen and capacity limited thermal tolerance

Ecosystem changes elicited by anthropogenic impacts at local scales as well as by global climate change have opened our eyes to the need for an understanding of the mechanistic background of such changes. Which characters render a species sensitive to climate and which ones cause losses in abundance? What is driving selected species to extinction at local or larger scales? A twist in the interpretation of available knowledge is suitable to start identifying the physiological dimensions of the environmental niche in which a species or one of its specific life stages live. Such dimensions result from the consideration of performance characters in relation to both biotic and abiotic characters. In the context of climate change effects on marine ecosystems the underlying thermal physiology plays a key role. Recent insight into the mechanisms of thermal adaptation and limitation opens a perspective for a unifying cause and effect understanding of climate change effects on aquatic ectotherms.

As a general principle, aerobic scope limited by temperature and insufficient oxygen supply at both sides of the thermal window sets the scope for performance in animals, with an optimum at upper pejus temperature (e.g. Pörtner and Knust, 2007; Pörtner and Farrell, 2008). According to recent insight, performance capacity largely relates to aerobic capacity, the capacity of ventilatory and circulatory systems to supply sufficient oxygen for covering physiological costs above maintenance. This statement relates to repeated findings that thermally limited oxygen supply capacity sets the width and positioning of thermal windows on the temperature scale. These findings led to the concept of oxygen and capacity limited thermal tolerance in aquatic species (Figure 1).



Figure 1. Conceptual model of how ocean warming, hypoxia and acidification as interacting stressors shape the thermal window of performance of a species, population or life stage, based on the concept of oxygen and capacity limited thermal tolerance (after Pörtner, 2002; Pörtner and Knust, 2007). Optimized oxygen supply to tissues between low and high pejus temperatures (top) combined with the kinetic stimulation of performance rates by warming supports temperature dependent performance and a functional optimum (i.e. an optimum of aerobic scope) close to upper pejus temperature (bottom). This reflects functional capacity in ecosystem level processes such as competition, foraging, immune response, growth and behaviours. Ambient hypoxia and elevated CO₂ levels both cause a narrowing of thermal windows and possibly, lower performance optima through lower functional capacities and reduced systemic oxygen tensions (green arrows). The graph depicts acute performance levels and limitations in response to short term temperature fluctuations. On longer time scales, changing temperatures elicit acclimatization as a limited shift of performance optima and limits on the temperature scale (horizontal arrows). Low and high limits of thermal acclimatization (vertical lines) delineate the thermal niche of a species, seen in long term processes like growth and development. Note that the passive tolerance range is a relevant component of the niche in some cases when it is exploited under extreme conditions, e.g. in invertebrates of the intertidal zone.

Initially, studies of temperature-dependent oxygen supply, mode of metabolism and associated mechanisms of thermal adaptation in marine invertebrates and fishes across latitudes suggested a role of oxygen supply in thermal limitation. Early evidence came from studies in marine invertebrates (annelids, sipunculids) which showed transition to anaerobic mitochondrial metabolism at both low and high ends (called critical temperatures) of their thermal window (Zielinski and Pörtner, 1996; Sommer *et al.*, 1997). Work in bivalves and fishes demonstrated the onset of anaerobic succinate formation at high temperatures (van Dijk *et al.*, 1999; Pörtner *et al.*, 1999; Peck *et al.*, 2004). A more recent example confirmed the onset of anaerobic metabolism at low and high temperature extremes in cephalopod mantle tissue (Melzner *et al.*, 2006). The

transition to mitochondrial anaerobiosis was shown to result from the development of progressive hypoxemia in arterial haemolymph of a crustacean towards both sides of the thermal window, with an optimum range of maximum body fluid Po_2 in between (Frederich and Pörtner, 2000). Once the critical Po_2 of oxygen diffusion into cells and mitochondria was reached, mitochondria started to respire anaerobically.

Overall, evidence of temperature-induced hypoxemia in fish builds on relatively few examples, with the study by Lannig *et al.* (2004) reporting temperature-dependent venous oxygen tensions, and the study by van Dijk *et al.* (1999) identifying the transition to anaerobic metabolism. Pörtner and Knust (2007) and Pörtner *et al.* (2001; 2008) integrated these findings with those of temperature-dependent growth. The study by Mark *et al.* (2002) as well as Lannig *et al.* (2004) indicated a limited capacity of cardio-circulation to respond to warming beyond a certain limit, the pejus limit, while temperature-dependent oxygen demand increased. Current knowledge indicates that excess ambient oxygen improves resistance to warming by shifting pejus limits (Weatherley, 1970; Mark *et al.*, 2002; Pörtner *et al.*, 2006, cf Figure 1). According to these findings hypoxemia elicits the first levels of thermal limitation, through a limitation and then reduction in aerobic scope and performance.

All of these findings formed the basis of the concept of oxygen and capacity limited thermal tolerance as depicted in Figure 1. With it came the conclusion that in a systemic to molecular hierarchy of thermal tolerance the whole organism would experience functional limitations first through systemic oxygen limitations which would then cause functional limitations or biochemical stress events at tissue, cellular or molecular levels (Pörtner *et al.*, 2001; 2002, Figure 1). Thermal windows shift through acclimatization or, on evolutionary time scales, adaptation at genomic levels. Both involve adjustments through gene expression at the level of energy metabolism capacities, both aerobic (Guderley, 2004; Hardewig *et al.*, 1999; Lucassen *et al.*, 2006) and anaerobic (Nathanilides, 1996; Pörtner, 2002; Zakhartsev *et al.*, 2004).

In aquatic, specifically marine environments, the emerging knowledge of these principles supports explanations of regime shifts, shifts in biogeography, changes in species interaction and in food web structure (Pörtner and Farrell, 2008). First evidence for ecological impact of heat induced within organism oxygen limitation came from a study in eelpout (Zoarces viviparus) in the North Sea, where the species exists at the limit of its acclimatization capacity, i.e. on the warm side of their thermal niche. Species abundance in the Wadden Sea falls upon exposure to extreme summer temperatures. This occurs in the same temperature range where growth performance decreases. Large individuals are affected most by the heat stress. The study by Pörtner and Knust (2007) showed the link of thermally limited cardio-circulatory performance and aerobic scope to the onset of reduced growth performance and abundance in the natural environment, the German Wadden Sea. The study also shows that the species does not grow beyond a thermally set size limit in this area. This matches the observation in cod, where between juveniles and adults, thermal windows are narrowest in the larger specimens (Pörtner et al., 2008). The narrowest thermal windows would in fact be expected in larval stages and in spawning adults, once the latter are required to cover the oxygen demand of large egg or sperm masses (Pörtner and Farrell, 2008). These two may be those life stages reflecting the sensitive bottlenecks at ecosystem level. Another suitable example is the spawning migration of mature salmon in the Pacific Northwest which is progressively constrained by rising summer temperatures. Oxygen supply limitations during muscular exercise of migrating salmon play a key role in thermal limitation and the inability of the salmon to reach their spawning grounds in warming rivers (Farrell et al., 2008). Furthermore, recent examples among invertebrates and their life stages confirm the wider applicability of these concepts. The distribution and vertical zonation of Mediterranean bivalves follows their resistance to thermal stress. Oxygen limitation under thermal stress elicits or contributes to further responses along the stress axis, involving signaling events and the heat shock response (Anestis et al., 2007; 2008). These results support a general model of stress response including the concept of oxygen and capacity limited thermal tolerance as elaborated for fishes (Kassahn et al., 2009). A generalized picture emerges of the systemic to cellular responses to thermal stress in marine ectotherms. Applicability of these principles in early life stages was demonstrated in larval stages of Crustaceans (Storch et al., 2009). Within the scope of their work comparison of species populations in a latitudinal cline confirmed that the width of thermal windows is narrower in animals with a low level of energy turnover. Further work in oysters demonstrated that pollution causes enhanced costs in aerobic metabolism of oysters. The resulting load on oxygen supply capacity causes a reduction in heat tolerance (Lannig *et al.*, 2008; Sokolova and Lannig, 2008).

PHYSIOLOGICAL BACKGROUND OF HYPOXIA AND CO₂ TOLERANCE IN MARINE ORGANISMS Hypoxia tolerance

The problem of environmental hypoxia has been treated independently of temperature. The conceptual framework developed needs to be looked at in more detail before attempting to integrate it with concepts developed for other stressors like temperature. In the context of organismic requirements for ambient oxygen and of the associated levels of hypoxia sensitivity, the concepts of oxyconformity, oxyregulation, and the critical PO₂ have been revisited considering systemic and cellular processes in declining ambient oxygen tensions from an integrative point of view (Pörtner and Grieshaber, 1993). It has been recognized early that animals may show different patterns of oxygen consumption in response to changes in ambient PO_2 . Some keep their oxygen consumption more or less constant in a wide range of PO₂ and are called oxyregulators. Others reduce their oxygen uptake with decreasing oxygen tensions and have, consequently, been termed oxyconformers. Intermediate responses exist (Mangum and van Winkle, 1973) which do not support such clear categorization which is nonetheless useful to identify metabolic patterns of oxyconformity and the underlying mitochondrial mechanisms. Circumstantial evidence for the presence of an alternative mitochondrial oxidase (cytochrome o) exists in lower marine invertebrates, e.g. sipunculids, annelids or bivalves (Pörtner et al., 1985; Buchner et al., 2001; Tschischka et al., 2000). This oxidase might represent an ancient mechanism of oxygen detoxification used in animals which live in hypoxic environments. Only these aerobic oxyconformers, which display oxyconformity at cellular and mitochondrial levels should be considered as "true" oxyconformers, whereas the progressive drop in oxygen consumption seen during extreme hypoxia in both oxyconformers and oxyregulators is caused by oxygen supply being insufficient to completely cover energy demand. Variable intracellular oxygen levels drive variable rates of oxygen consumption in oxyconformers, whereas this rate remains constant above the Pc in oxyregulators. However, aerobic oxyconformers can be behavioral oxyregulators, once they manage to keep oxygen levels in their water burrow or in their body fluids constant through compensatory adjustments in ventilatory (and circulatory) efforts. Irrigation of worm burrows in the sediment or ventilation of gill chambers in bivalves may in fact involve apparent oxyregulation in these animals. By keeping oxygen in their body fluids at minimal levels (e.g. Massabuau, 2001) they could minimize the extent to which oxygen detoxification by cytochrome o is necessary. Variable ventilatory capacities might thus explain the variable responses elaborated by Mangum and van Winkle (1973).

The terms oxyconformity and oxyregulation have been defined for quiescent animals which display baseline or "standard" metabolic rate. Standard metabolic rate (SMR) is defined as the lowest rate of oxygen consumption for oxyregulators, "which would be obtained when all organs were absolutely at rest". The data available for several oxyregulators suggest that this rate is maintained down to the critical PO_2 below which anaerobiosis starts (see below). This clear physiological definition of SMR excludes the "perturbing" effect of spontaneous muscular activity on the pattern of oxygen consumption during hypoxia. SMR is analysed (1) by correcting for the influence of spontaneous activity during long term measurements, (2) by extrapolating to zero activity during analyses of aerobic metabolism at various activity levels, or (3) by determining metabolic rate at or slightly above the Pc, to exclude the effect of oxyconformity mechanisms. However, focusing on standard metabolic rate may not be satisfying, as animals need to perform and be active at ecosystem level so that the analysis falls short of sufficiently providing ecosystem level implications. Nonetheless, for a principle comparison of the responses of oxyconformers and oxyregulators to progressive hypoxia the concept of standard metabolic rate is relevant. According to a simple model the different patterns of conformity and regulation and associated metabolic transition phases can be analysed and some ecosystem level implications elaborated (Figure 2). Hypoxia sensitivity of the organism also changes with the levels of activity which cause an increase in metabolic rate and an upward shift of the Pc.



Figure 2. Graphical presentation of a model used for the comparison of the physiological responses of oxyconforming and oxyregulating animals in declining oxygen tensions (modified after Pörtner and Grieshaber, 1993). For the sake of clarity, oxygen consumption rates and critical oxygen values are compared in absolute terms, neglecting the fact that standard metabolic rates are variable between species and individuals. Pc_M is the critical PO_2 below which anaerobiosis starts, Pc_R is the critical PO_2 of constant aerobic metabolic rate. SMR is the standard metabolic rate, the minimum metabolic rate in complete aerobiosis (at Pc_M), excluding locomotory activity. An increase in oxygen consumption may occur in oxyregulators below Pc_M (see text). An aerobic oxyregulator is able to maintain SMR at PO_2 values above Pc_M , Pc_M equals Pc_R . However, it is able to increase metabolism to a maximum rate during phases of aerobic exercise. Maximum aerobic metabolic rate is reached by full exploitation of energy turnover capacity (high energy consumption and associated production). Maintaining this maximum leads to higher levels of Pc (Pc_{max}) and thus, enhanced hypoxia sensitivity than at SMR. In contrast, an aerobic oxyconformer regularly exceeds SMR once exposed to high ambient oxygen levels and passively exploits its aerobic scope above Pc_M , $Pc_R > Pc_M$.

The concept of a critical PO_2 was introduced to characterize hypoxia sensitivity as the oxygen tension below which an oxyregulating animal is no longer able to maintain its rate of oxygen consumption independent of the ambient oxygen tension and starts to exhibit a decreasing rate of oxygen uptake. This definition is not applicable to quantify hypoxia sensitivity in all animals including oxyconformers. Recent studies that include an analysis of anaerobic processes at different oxygen tensions demonstrate that this critical PO_2 is not only characterized by the transition from an oxygen independent to an oxygen dependent pattern of oxygen consumption, but also by the onset of an anaerobic energy metabolism. Thus the failure of oxyregulation as well as the onset of anaerobiosis coincide, due to insufficient capacity for oxygen uptake and transport via the blood (Pörtner and Grieshaber, 1993). This extended concept of the critical PO_2 (i.e. the ambient oxygen tension below which water oxygen concentration becomes limiting and anaerobic metabolism is needed to cover resting energy demand) becomes applicable in both oxyregulatoring and oxyconforming species. Combined analyses of changes in the overall rate of oxygen consumption, in oxygen transport via the body fluids, and in the transition from aerobic to anaerobic energy production are required to unequivocally establish the critical PO_2 .

Anaerobic ATP production processes are located in the cytosol and within mitochondria leading to the formation of either lactate (opine) or succinate. These metabolites may, in most cases, be suitable cytosolic and mitochondrial markers of an anaerobic metabolism. However, muscular activity may lead to pyruvate and lactate or opine accumulation when mitochondria are still performing aerobically. This emphasizes the relevance of analyzing mitochondrial processes in quantifying hypoxia sensitivity. For example, long term incubation of oxyconforming *Sipunculus nudus* below the Pc demonstrated that succinate accumulation occurred before the opines were formed as glycolytic end products. Consequently, anaerobic glycolysis became involved in resting individuals of this species only when oxygen supply fell to an extent which did no longer allow

(all of) the mitochondria to produce energy by aerobic means. This observation presents strong evidence that the animals exhibited their minimal aerobic metabolic rate at the critical PO_2 . As a corollary, the metabolic rate at the Pc can be seen to represent the standard metabolic rate (SMR) of both oxyregulating and oxyconforming organisms. Furthermore, oxyregulators are able to maintain low metabolic rate (SMR) at PO_2 -values higher than Pc (Pc_M in Figure 2), whereas the oxygen consumption of "true" oxyconformers increases above Pc. These animals show a second critical PO_2 (Pc_R in Figure 2), above which the elevated rate of oxygen uptake finally remains constant.

Further observations characterize the Pc. On systemic and cellular levels, the transition from aerobic to anaerobic energy metabolism is either linked to the pronounced decrease or even increase in oxygen consumption, the latter as a result of a stimulatory response elicited by e.g. lactate accumulation (Pörtner *et al.*, 1994; Pinz and Pörtner, 2003). This again eliminates uncertainty in quantify hypoxia sensitivity in oxyregulators. The critical oxygen tension is also characterized by the critical reduction of oxygen transfer via the blood or other body fluids. In those animals, able to tolerate long-term exposure to hypoxia, overall energy expenditure continues to fall below the critical PO₂. Furthermore, the Pc increases with organisational complexity, from cellular to complex organisms because mechanisms causing additional limitations of oxygen provision become involved:

(1) In a cell diffusion limitation of oxygen in the membrane and the cytoplasm together with the rate of mitochondrial respiration and, perhaps, the clustering of mitochondria in areas of high energy needs define the point at which the oxygen concentration finally becomes limiting and anaerobiosis commences.

(2) At tissue level, capillary PO_2 (in animals with closed circulatory systems) or bulk venous PO_2 (in animals with an open circulatory system) are key parameters in determining whether oxygen provision is sufficient for the individual cell. The maintenance of the pressure head for sufficient oxygen supply depends upon the rate of perfusion, the density of the capillaries and on blood oxygen transport.

(3) For the whole organism the required pressure head, i.e. the Pc will also depend upon the structures and functions of the gas exchange organ and the circulatory system, and upon the O_2 affinity of the pigment and its regulation. These mechanisms alleviate the main problem that body surface to volume ratios are low and unfavorable for oxygen diffusion at large body sizes.

A summary of the different patterns discussed for regulators and conformers leads to a simple model (see Figure 2) where, generally, oxygen consumption at the Pc is equivalent to standard metabolic rate, even when considering that a potential increase in oxygen uptake below the Pc may occur as a response linked to the onset of anaerobic metabolism. SMR or Pc vary between species and their life stages as well as between individuals of the same species according to body size. SMR and Pc may even be variable in an individual animal according to its physiological state under the prevailing endogenous and exogenous conditions. For example, long term acclimatization to hypoxia may occur, so that the critical PO₂ and SMR may be lower for individuals of the same species exposed to hypoxia as compared to those exposed to higher oxygen tensions. Once an animal displays a metabolic rate higher than SMR such as during activity, the Pc of aerobic metabolism will rise and reach a high Pc_{max} at maximum metabolic rate (see Figure 2).

From an integrative point of view these concepts of hypoxia sensitivity have become relevant in the context of thermal limitation and its role in understanding climate change effects on marine ecosystems. Temperature and hypoxia would traditionally be considered as different environmental factors, with specific implications for whole organism functioning. As outlined above, however, studies of temperature-dependent oxygen supply, mode of metabolism and associated mechanisms of thermal adaptation in marine invertebrates and fishes across latitudes have suggested a role of oxygen supply in thermal limitation. Development of the respective concept of oxygen and capacity limited thermal tolerance in marine water breathers, however, has revealed how temperature and hypoxia are intertwined and become effective at ecosystem level (Pörtner and Knust, 2007; Pörtner and Lannig, 2009). Thermal stress causes systemic hypoxemia at both ends

BOOK IN STOCK

of the thermal window. Temperature-dependent oxygen supply capacity sets the width of thermal window of an animal (Figure 1). Thermally induced hypoxemia and associated stress and signaling mechanisms likely shape acclimation responses at various, molecular to whole organism levels (e.g. Kassahn *et al.*, 2009). Thermal adaptation affects SMR and the cost of maintenance as well as energy budget of an organism.

The integration of the concepts of thermal and hypoxia sensitivity leads to new insights and perspectives relevant for hypoxia tolerance (Figure 3). These aspects require investigation in future research. The thermal optimum also reflects improved hypoxia tolerance. Close to upper pejus temperature the capacities of ventilatory and circulatory systems to provide oxygen to tissues are maximal and, accordingly, PcM results minimal. The positive balance between oxygen supply capacity and oxygen demand is maintained during cooling to lower pejus temperature. Cooling lowers the capacity for oxygen supply but also metabolic rate and provides elevated solubilities and levels of ambient oxygen. Hypoxemia setting is due to thermal limitation below both lower and upper Tp's causes a rise in Pc, thus indicating progressive reduction of hypoxia tolerance at the borders of the thermal window. At both critical temperatures, the Pc is maximal and becomes equivalent to ambient oxygen tensions (e.g. Zakhartsev et al., 2003). As a corollary, the speciesspecific thermal window and the temperature sensitivity of Pc reflect the temperature dependence of hypoxia sensitivity and also the integration of thermal and hypoxia sensitivities. These relations require consideration of analyses of hypoxia resistance. Conversely, hypoxia and other stressors like carbon dioxide (see below) will affect thermal tolerance limits and also the processes involved in thermal acclimatization and adaptation, which counteract thermally-induced hypoxemia and thereby also improve hypoxia tolerance. The specialization of whole organism functioning on limited temperature ranges emerges as a key element explaining current observations of climate change effects on ecosystems. As a perspective, the operation of species and their sensitivity to environmental factors including hypoxia may in fact best be understood if analysed on a matrix of temperature dependent performance.



Figure 3. Conceptual model of how ocean warming and hypoxia interact based on the concept of oxygen and capacity limited thermal tolerance (simplified from Figure 1). Optimum aerobic scope close to upper pejus temperature also reflects optimum hypoxia tolerance, due to optimal oxygen supply capacity causing Pc to be minimal. Hypoxia sensitivity is enhanced at thermal extremes when oxygen supply capacity falls in relation to oxygen demand, and the Pc rises towards its maximum (cf. Figure 2), indicated by the onset of anaerobic metabolism at ambient, even normoxic oxygen tensions.

Tolerance to ocean acidification

In the case of CO_2 -induced ocean hypercapnia and acidification, present effects on marine ecosystems may still be so small that evidence for changes in the field is largely lacking. Future scenarios indicate that marine life forms are threatened by the specific or synergistic effects of factors involved in these processes. Identification of the mechanisms through which temperatureand CO_2 -related ocean physicochemistry affect organism fitness, survival and success, is crucial for this research sector. Available knowledge suggests unifying physiological principles of CO_2 effects, across animal groups and phyla (Pörtner *et al.*, 2004; 2005a,b; Pörtner, 2008), by adopting thermal windows of optimized performance as a basic character defining species fitness and survival. Ocean acidification likely affects especially lower marine invertebrates, which are characterized by a low capacity to compensate for disturbances in extracellular ion and acid–base status and sensitivity of metabolism to such disturbances. Available data suggest that one key consequence of these features is a narrowing of thermal tolerance windows, as well as a reduced scope for performance at ecosystem level (Pörtner and Farrell, 2008). These changes in bioenvelopes may have major implications for the ranges of geographical distribution of these organisms and in species interactions.

SYNOPSIS

As a corollary, the examples discussed in the present paper are in line with the general contention that aquatic fauna and their life stages specialize on climate and associated temperature variability. The related temperature windows are underlying the observed sensitivities to climate induced temperature extremes, primarily due to decrements in performance, i.e. the capacities to forage, migrate, grow or reproduce. So far, these generalized conclusions derive from limited evidence based on relatively few examples in temperate waters (cf. Pörtner and Farrell, 2008). Further evidence is needed to assess to what extent the limits of the thermal niche of a species (which includes the limits of acclimation capacity) match those of its niche realized at ecosystem level.

Species specializing on different climates likely do so for the sake of energy savings and efficiency (Pörtner, 2006). Available evidence suggests that more agile species, thanks in part to better oxygen supply systems, are more eurythermal and accordingly, would cover wider ranges of geographical and thermal distribution (Pörtner, 2002; Peck et al., 2009). Cold stenothermal species display low levels of energy turnover and a high level of growth efficiency (e.g. Heilmayer et al., 2004; Pörtner *et al.*, 2005a,b). Multiple stressors (abiotic factors like CO_2 , hypoxia, toxicants, biotic factors like limited food availability, predation pressure or competition) may narrow the thermal window of aerobic performance (or thermal niche) and lower the performance maximum (see below). In case of abiotic factors this may occur through temperature-induced hypoxemia being exacerbated by ambient hypercapnia or hypoxia (Metzger et al., 2007; Pörtner and Farrell, 2008). In fact, as temperature has pervasive effects on all levels of biological organisation, synergistic effects by other stressors may be seen to occur on a thermal matrix of performance. Changing window widths of temperature-dependent performances would therefore be a key aspect to be considered in a climate change context. Furthermore, a species' thermal niche will include a threshold of minimum performance required to ensure competitiveness at ecosystem level. There are currently no analyses available which have determined such temperature-dependent limits or the required levels of minimal performance.

Loss of aerobic scope may not only be caused by unfavourable abiotic conditions like extreme temperatures, elevated CO_2 levels or ambient hypoxia. Such loss may also arise via lower food availability as well as unfavourable shifts in energy budget through limited energy availability overall or through excessive energy demand of foraging. Competition might add further costs and exploit a significant fraction of energy budget, possibly at the expense of growth performance, developmental rate, and reproductive output or of the capacity to exert combinations of these "activities" fueled by residual aerobic scope. Again, the fact that growth, development, and reproduction need to operate above a minimum rate may add to the narrowing of the thermal niche.

A conceptual framework for the Black Sea?

Along with the concept of oxygen and capacity limited thermal tolerance, a mechanistic framework emerges which is suitable to guide the collection and interpretation of data on climate change effects at species and ecosystem levels and to avoid misinterpretation of effects and underlying principles. It also supports the development of more reliable, mechanism-based projections into the future than with the mathematical modelling of empirical data alone. This framework may in fact help to parameterize the respective models addressing climate change effects on ecosystems. Mechanism-based projections based on physiological knowledge are therefore proposed as reliable tools to predict the change in the performance and fitness of individual species and their lifestages as well as in species interactions.

The Black Sea is characterized by large seasonal temperature oscillations, surface water freshening and nutrient input from rivers. It went through a severe phase of winter cooling (2°C on average) in the eighties and nineties. Winter low SS temperatures reached down to about 5°C in the north. The late nineties saw a warming trend, associated with freshening due to enhanced precipitation, and a disappearance of the cold intermediate water layer usually formed during winter. Ecosystem and biodiversity shifts were described and projected by Oguz *et al.* (2003), Oguz and Gilbert (2007) and Tokarev and Shulman (2007). Cause and effect in those trends would become accessible with appropriate experimental studies and mechanism based modelling along the principles developed in the present study.

Trend on increasing Mediterranean species arrival into the Black Sea

Tamara Shiganova¹ and Bayram Öztürk²

¹ P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences, Moscow, Russia ² Faculty of Fisheries, Istanbul University, Turkey

The flora and fauna of the present-day meromictic Black Sea, which was formed under conditions of relatively low salinity combined with the existence of an anoxic zone beneath the upper oxygencontaining layer, is distinguished by a low species richness and by a low species diversity in most of the taxonomic groups represented. Meanwhile, it features a rather high productivity, particularly in near-shore regions, a high abundance of mass species, and a richness of fish resources.

The Black Sea biota is composed for 80% by species of Atlantic-Mediterranean origin, and for 10.4% and 9.6% species of freshwater and Ponto-Caspian origin, respectively. One may add an arctic assemblage, which is extremely poor and mainly contains flora (Mordukhai-Boltovskoi, 1969). The dominant group from Atlantic-Mediterranean origin comprises species of Lusitanian province, and of the boreal Atlantic Ocean. Species with Lusitanian origin belong to warm water species and inhabit the upper layer of the Black Sea. Species of Atlantic boreal origin belong to moderately cold water species. They have clear features of cold-water relicts. Among them one finds mainly benthic, demersal and pelagic species, which live in the cold intermediate layer and below down to the boundary of anoxic layer. Only the most eurythermal of them may rise to the surface layers.

In addition to salinity, qualitative impoverishment of the Black Sea biota is due to the absence of deep-water species at depths greater than 125-200 m.

At present, the total number of species recorded in the Black Sea is relatively small and stands at 3,774 spp. Of these 1,619 are fungi, algae, and higher plants; 1,983 are invertebrates, 180 are fish, and four are sea mammals-dolphins (Zaitzev and Alexandrov, 1998).

In the 20th century, especially in its second half, under the influence of climatic and anthropogenic factors, significant changes have occurred in the diversity of the flora and fauna of the Black Sea. Among the most pronounced anthropogenic factors, we note:

- regulation of the runoff of major rivers;
- increase in the supply of dissolved mineral forms of phosphates and nitrates from large rivers accompanied by reduced silicate supply. This resulted in a decrease in the Si : P and Si : N ratios, which are important for the functioning of phytoplankton;
- increase in the supply of organic matter from the Danube River, which caused mass development of mixotrophic algae;
- changes in the composition of phytoplankton species and their proportions: domination of dinoflagellates instead of domination of diatoms, significant growth in the phytoplankton biomass and outburst in the development of harmful algae;
- subsequent eutrophication;

BOOK IN STOCK

- corresponding increase in the primary production: twofold on the average over the entire sea and tenfold in its northwestern part;
- subsequent outbursts of native gelatinous species such as *Aurelia aurita* and *Noctiluca scintillans*; - deterioration in the condition of spawning and feeding areas of fishes;
- high pressure of fishery resulted in decreasing stocks of large pelagic fishes migrants from the Aegean and Marmara Seas and dolphins;
- invasion of non-native species, some of which negatively affected the communities in which they introduced or replaced native species.

The classical scheme of the functioning of a balanced ecosystem in an inland basin is based on a "top-down control" against predators that descends from large pelagic fishes and mammals to small pelagic fishes and below to zooplankton (when large edible zooplankton dominates) and algae (when diatoms dominate).

As a result of the man-induced changes that affected the Black Sea ecosystem by the end of the 1980s, it evolved into a mesotrophic or eutrophic (in its northwestern and the western parts) basin with disturbed functioning, which was favorable for the development of gelatinous plankton.

The occasional and sometimes intentional introduction of non-native species of animals and plants is a global phenomenon that concerned the Black Sea as well, which received non-native species (both marine and brackish) of different origins.

Alltogether 156 (or 171?) species were established, which belong to different taxonomical groups (Figure 1).



Figure 1. Donor areas of the non-native species and their share (%) in the Black Sea.

The disturbance of the Black Sea has favored the establishment of new gelatinous representatives of macroplankton such as the predatory warm-water ctenophore *M. leidyi*. Within the heated zone of the surface layer of the Black Sea it found conditions optimal with respect to the temperature, salinity, and productivity. Under these conditions, it became capable of developing a high activity (intensity of the metabolism and, hence, the feeding and growth rates) and reached extremely high abundances. After the *M. leidyi* invasion, cascading effects occurred at the higher trophic levels, from a decreasing zooplankton stock to collapsing planktivorous fish and dolphins (bottom-up). Similar effects occurred at lower trophic levels: from a decrease in zooplankton stock to an increase in phytoplankton, relaxed from zooplankton grazing pressure (top-down) and from increasing bacterioplankton to increasing zooflagellata and ciliates (Shiganova *et al.*, 2004).

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Ten years later another warm-water ctenophore *Beroe ovata* – a natural predator on *M. leidyi* – was introduced with ballast waters from the same source area (coastal area of north America) and established. This resulted in population decrease of *M. leidyi* and the ecosystem began to recover trophic web at all levels (Shiganova *et al.*, 2000; 2003).

In addition during last decades, Black Sea temperature increased both in the surface, mixed and cold intermediate layers (Figure 2), which facilitated the population increase of thermophilic species and their northward expansion from the Mediterranean. Until recently new Mediterranean species have been recorded temporally or permanently mainly in the near-Bosporus region. Therefore, they are usually not regarded as established non-native species. But if we take into account only established species, their share in the total numbers of non-native species consists of 36%. Since 1960s (and certainly earlier) the Bosporus Strait delivered many Mediterranean species from different taxonomic groups. But selected Mediterranean taxa (phyto-, zooplankton, benthic and fish species) are more and more often recorded also off northwestern and northeastern coastal areas. At present, this process is facilitated by rising temperature. Species that penetrated beyond the Bosporus reached the centre, southwest, southeast and northeast, moving with the currents or lenses of Mediterranean water. Others, released with ballast water, increased especially around harbor areas.



Figure 2. Rising water temperature from1990 till 2007 (data of Lab. Hydrophysics of Southern branch of SIO RAS).

As a rule, invaders remain rare or are abundant only in definite years, which suggests a high stability of the communities of the Black Sea with respect to establishment of non-native species and/or that conditions of the Black Sea (with low salinity and low winter temperature) are not favorable.

MICROPLANKTON

Microplankton elements are Mediterranean tintinnids, first found in the northwestern Black Sea in 2002 (Polikarpov *et al.*, 2003).

Phytoplankton

Mediterranean phytoplankton species new for the Black Sea are recorded year after year, and their numbers keep increasing. A significant number of species native to the Mediterranean colonize the Bosporus region (Table 1). Some of them might survive only in this area where salinity is higher than in other regions of the Black Sea. Examples include the diatoms *Fragillaria striatula* and *Thalassiothrix frauenfeldii*, the coccolithophorid *Calyptrosphaera incriase* and the peridinean *Ceratium macroceros*, recorded since the beginning of the 1960s at a salinity of 34‰ and a temperature of 14°C. These conditions significantly differ from the Black Sea (Georgieva, 1993). However, some other newcomers of the 1960s and early 1970s were found not only near the Bosporus but also near Crimea (Table 2) (Kuzmenko, 1966; Senichkina, 1973; Kovalev *et al.*, 1998).

Table 1. Mediterranean phytoplankton species found near the Bosporus in the Black Sea (Georgieva, 1993).

	T °C	S‰
Amphidinium conradi (Conrad) Schill.	7.44	18.38
A. mannanini Herd.	10.79	18.18
A. vigrense Wolosz	10.79	18.18
Biddulphia alternans (Bail.)V. H.	7.70	19.34
Ceratium furca var. eugrammum (Eht.) Jorg.	18.67-24.97	16.44-18.39
<i>C. fusus var. seta</i> (Eht.) Jorg.	7.80	18.39
C. hexacantum f. aestuarium (Schrod.) Schill.	7.81	18.39
C. hexacanthum f. contortum (Lemm.) Jorg.	7.80	18.39
C. massiliense (Gourret) Jorg	7.81	18.39
C. teres Kof.	-	-
C. trichoceros (Eht.) Kof.	10.79	18.18
C. tripos var. atlanticum Ostf.	7.81	18.39
Coccolithus pelagicus (Walich.) Schill.	7.55	18.20
Cochlodinium citron Kof. et Sw.	7.39	18.50
Eucampia cornuta (Cl) Grun	8.40	19.78
Gymnodinium paradoxum Schill.	-	-
G. pygmaeum Leb.	10.79	18.18
Oxytoxum parvum Schill.	7.41	18.33
<i>O. variabile</i> Schill	23.98	15.73
<i>O. viride</i> Schill.	8.88	20.32
Peridinium sinaicum Matz	18.82	18.36
Pronoctiluca acuta (Lohm.) Schill.	9.14-9.85	18.57-18.96
<i>P. pelagica</i> Pavill	7.64	-
Pyrocystis hamulus Cl.	13.20	17.20
P. fusiformis (W.Th.) Mur.	9.51	21.42
P. pseudonoctiluca (W.Th.) Schill.	6.52	18.40
Rhabdosphaera stylifera Lohm.	8.74	20.14
Rhizosolenia styliformis Brightw	17.13	17.59
Syracosphaera coronata Lohm.	7.44	17.98
S. cornifera Schill. (Helladosphaera)	16.10	17.98
S. quadricornu (Anthosphaera) Schill.	8.74	29.14
S. spinosa Lohm.	7.31	18.52
Thalassiothrix mediterranus Pavill	7.89	19.13
Total 33 species		

Species name	Origin	First record in Black Sea	Location of first record	Establish- ment	Abundance	Geographic distribution	Tolerance limits	Vector	Reference
A- Phytoplankton									
Dinophyceae Alexandrium pseudogonyaulax (Biecheler) Horiguchi ex Yuki et Fukuyo	Mediterranean	2001-2002	Odessa Bay	established	abundant, potentially toxic	Mediterranean, eastern Atlantic	euryhaline, euryterm	shipping	Terenko, 2003
Gessnerium mochimaensis Halim 1967	Mediterranean	1991	Varna Bay	established?	not abundant	Mediterranean, tropical and subtropical Atlantic	marine, Tropical, subtropical	shipping	Moncheva et al., 1995
Cochlodinium polykrykoides Margalef	Mediterranean	2001,2002	Varna Bay, north- eastern Black Sea	established	abundant	Mediterranean, eastern Atlantic	subtropical	shipping	Terenko, 2003; Vershinin et al., 2004
Gyrodinium cf.aureolum Hulburt	Mediterranean	2002	Varna Bay	established?		Mediterranean, eastern Atlantic	subtropical	shipping	Terenko, 2003
Gymnodiniaceae Gymnodinium sanguineum Hirasaka=Gymnodinium splendens Lebour	Mediterranean	2000	Off Crimea, Bulgarian coast, Odessa Bay	established	abundant	Mediterranean	subtropical	shipping	Senecheva, 2002
G. blax Harris	Mediterranean?	1998	Odessa Bay	established?		Mediterranean?		shipping	Terenko, Terenko, 2000
G. lacustre Stein	Mediterranean?	1999	Odessa Bay	established?		Mediterranean?		shipping	Terenko, Terenko, 2000
Amphidinium acutissimum Schill	Mediterranean?	1999	Odessa Bay	established?		Mediterranean?		shipping	Terenko, Terenko, 2000
A. lanceolatum Schrod	Mediterranean?	1996	Odessa Bay	established?		Mediterranean?		shipping	Terenko, Terenko, 2000
A. larvale Lindem	Mediterranean?	1999	Odessa Bay	established?		Mediterranean?		shipping	Terenko, Terenko, 2000
A. vigrense Wolosz	Mediterranean?	1995	Odessa Bay	established?		Mediterranean		shipping	Terenko, Terenko, 2000
Ceratium furca var.eugrammum (Her) Jorg.	Mediterranean?	1999	Odessa Bay	established?		Mediterranean?		shipping	Terenko, Terenko, 2000
C. longirostrum Gourr.	Mediterranean?	1999	Odessa Bay	established?		Mediterranean?		shipping	Terenko, Terenko, 2000
Cochlodinium geminatum (Schutt)	Mediterranean?	1998	Odessa Bay	established?		Mediterranean?		shipping	Terenko, Terenko, 2000
Spatulodinium pseudonoctilca (Pouchet) Cachon et Cachon	Mediterranean	2002	Odessa harbour	established?	a few ind.	Mediterranean, North Atlantic	temperate	shipping	Terenko, 2003
Dinophysis odiosa (Pavillard) Tai & Scogsberg (=Protodinophysis odiosa Pavillard Loeblich III= Phalacroma odiosa Pavillard	Mediterranean	2001;	Northern Black Sea	established		Mediterranean	subtropical	shipping	Senecheva, 2002
Talassionemataceae Lioloma pacificum (Cupp) Hasle (=Thalassiotrix mediterranea var. Pacifica Cupp)	Mediterranean	2001; 2002-2003	coastal waters of Sevastopol, Odessa Bay	established	abundant off Sevastopol, Odessa	Mediterranean, North Atlantic	subtropical	shipping	Senecheva, 2002; Alexandrov, 2004
Сем. Bacillariaceae Pseudo-nitzschia inflatula Hasle (=Nitzschia infantula Hasle)	Mediterranean	1999-2001	coastal waters of Sevastopol, Odessa	established		Mediterranean	subtropical	shipping	Senecheva, 2002
Sceletonema subsalsum (Cleve)?	Mediterranean?	1993	coastal waters of Romania	?		Mediterranean? North Atlantic	temperate	shipping	Alexandrov, 2004
Bacillariophyceae Protoraphidiaceae Asterionellepsis glacialis Cleve et Molle (= Asterionella japonica (Castracane) F.E.Rount 1990)=Asterionella glacialis Castracane B- Macrophytes	Mediterranean	1968	coastal area of Sevastopol	established		Mediterranean	eurythermal	shipping	Senicheva, 1971
Ulvaceae Lamour.ex Dumort Enteromorpha kylinii Bliding	Mediterranean	1990	coastal area of Turkey	established		Mediterranean, Northwest Atlantic	temperate	penetration? shipping?	Bavaru et al.,1991; algaebase

Table 2. Mediterranean algal species recorded in the Black Sea: A- Phytoplankton; B- Macrophytes.

<i>Ulva curvata</i> Kutz. De Toni	Mediterranean	early 1990s	coastal area of Turkey	established	Mediterranean, northern Atlantic	subtropical	penetration? shipping?	Aysel, 1995; algaebase
U. fasciata Delile	Mediterranean	early 1990s	coastal area of Turkey	established	Mediterranean, global	subtropical, tropical	penetration? shipping?	Aysel, 1995; Taskin et al., 2008
Cladophorales Haeckel Cladophoraceae Wille <i>Cladophora flexuosa</i> (O.F.Muller) Kulz	Mediterranean	early 1990s	coastal area of Turkey	established	Mediterranean, northern and southern Atlantic, Pacific	temperate	penetration? shipping?	Aysel, 1995; Taskin et al., 2008
C. lehmanniana (Lindenb)	Mediterranean	early 1990s	coastal area of Turkey	established	Mediterranean, South Africa	subtropical	penetration? shipping?	Aysel, 1995, Guery, 2001
C. pellucida (Huds.) Kutz	Mediterranean	early 1990s	coastal area of Turkey	established	Mediterranean, South Africa	subtropical	penetration? shipping?	Aysel, 1995; Guery, 2001
C. prolifera (Roth.) Kutz.	Mediterranean	early 1990s	coastal area of Turkey	established	Mediterranean, Western Indian Ocean	subtropical	penetration? shipping?	Aysel, 1995; Guery, 2001
Cystoseira compressa (Esper) Gerloff et Nizamuddin f.compressa	Mediterranean	early 1990s	coastal area of Turkey	established	Mediterranean	subtropical	penetration? shipping?	Aysel, 1995; Guery, 2001
<i>C. corniculata</i> (Wulf.) Zanard	Mediterranean	early 1990s	coastal area of Turkey	established	Mediterranean	subtropical	penetration? shipping?	Aysel, 1995; Taskin et al., 2008
<i>C. schiffneri</i> Hamel =C.discors (L.)	Mediterranean	early 1990s	coastal area of Turkey	established	Mediterranean, Adriatic	subtropical	penetration? shipping?	Aysel, 1995; Ribera et al.,1992
Sargassaceae Kutz. Sargassum acinarium (L) C.Ag.=S.Ag.f.linifolium (Turn.)C.Ag.	Mediterranean	early 1990s	coastal area of Turkey	established	Mediterranean, Atlantic	subtropical	penetration? shipping?	Aysel, 1995; algaebase
S. hornschuchii C.Ag.	Mediterranean	early 1990s	coastal area of Turkey	established	Mediterranean	subtropical	penetration? shipping?	Aysel, 1995; algaebase
Rhodophycea Ceramiales Oltm Antithamnion heterocladum Funk	Mediterranean	early 1990s	coastal area of Turkey	established	Mediterranean	subtropical	penetration? shipping?	Aysel, 1995
Ceratium flaccidum (Kutz.) Ardiss	Mediterranean?	early 1990s	coastal area of Turkey	established	Mediterranean	subtropical	penetration? shipping?	Aysel, 1995
C. tenerrimum (G.Martens) Okamura var Tenerrimum	Mediterranean?	early 1990s	coastal area of Turkey	established	Mediterranean	subtropical	penetration? shipping?	Aysel, 1995
Compsothamnion thuyoides (Sm.) Nageli	Mediterranean	early 1990s	coastal area of Turkey	established	Mediterranean,north Europe	temperate	penetration? shipping?	Aysel, 1995
Dasyaceae Kutz. Dasya ocellata (Gratel.) Harv	Mediterranean	early 1990s	coastal area of Turkey	established	Mediterranean	subtropical	penetration? shipping?	Aysel, 1995
Neosiphonia elongella (Harv.)M.S.Kim et I.K.Lee=Polysiphonia elongella Harv.)	Mediterranean	early 1990s	coastal area of Turkey	established	Mediterranean	subtropical	penetration	Aysel, 1995; Garreta et al., 2001
Polysiphonia deusta (Roth) Spreng	Mediterranean	early 1990s 2001	coastal area of Turkey	established	Mediterranean	subtropical	penetration	Aysel, 1995
P. paniculata Mont.	Mediterranean	early 1990s	coastal area of Turkey	established	Mediterranean, Atlantic	subtropical	penetration? shipping?	Aysel, 1995; Garreta et al., 2001; Taskin et al., 2008
P. stricta (Dillw.) Grev.=P.urceolata (Lightf. Ex Dillw.) Grev.)	Mediterranean?	early 1990s	coastal area of Turkey	established?	Mediterranean? Northwest Atlantic		penetration? shipping?	Aysel, 1995
<i>P. subulata</i> (Ducl.)P.Crouan et H.Crouan = <i>P. violacea</i> (Roth) Grev.	Mediterranean	early 1980s	coastal area of Turkey	established	Mediterranean	temperate	penetration	Dimitrova- Konaklieva, 1981 Aysel, 1995; Garreta et al., 2001
P. tenerrima Kutz	Mediterranean	early 1990s	coastal area of Turkey	established	Mediterranean	subtropical	penetration	Aysel, 1995
P. tripinnata J. Ag	Mediterranean	early 1990s	coastal area of Turkey	established	Mediterranean	subtropical	penetration	Aysel, 1995; Karacuha et al., 2007

Kuzmenko (1966) recorded *Dynophysis schuttii* Murr. et Whitt. and *Podolampas spinifer* Okatumura, previously unknown in the Black Sea but typical of the Mediterranean, off the southern coast of the Crimea at a salinity of 18-18.5‰. In the early 1990s, *Katodinium rotundatum* (Lohm) Fott, *Achradina sulcata* Lohm., and *Pronoctiluca* sp., appeared in shallow water off Yalta. *Distephanus octonarius* var. *Polyactis* (Jorg) Gleser and *D. speculum* var. *Septenarius* Jorg, previously unknown in the Black Sea were also discovered off Crimea area (Senichkina, 1993). In all, 37 representatives of Mediterranean phytoplankton were registered in subsurface waters of the Bosporus region (Table 1) (Georgieva, 1993). Many of these species, such as *Syracosphaera*

cornifera, Ceratium furca var. *eugrammum, Pyrocystis hamulus, Pronoctiluca acuta* etc., were recorded not only in the waters originated from the Sea of Marmara and Mediterranean but also in typical pelagic Black Sea waters.

Not all species found recently can be considered as newcomers as some of them were discovered after more detailed examinations of ancient Black Sea samples. Thus in coastal northwestern Crimea, long-term observations (1968-2002) brought to light new species for the Black Sea, such as the diatoms *Asterionellapsis glacilis, Chaetoceros tortissimus, Thallassiosira nordenskioeldii, Lioloma pacificus, Pseudonitzschi inflatula*, two subspecies of *Chaetoceros*, and the dinophyte *Dinophysis odiosa*, as author assumed they arrived from the Mediterranean (Senicheva, 2002).

During the last years a large number of Mediterranean species, new to the Black Sea, were found around the ports (Table 2) (Alexandrov, 2004; Moncheva, 1995; Terenko and Terenko, 2000; Terenko, 2003; Senicheva, 2001).

In early August 2001 the Mediterranean *Chaetocerus tortissimus*, *Cochlodinium polykrikoides*, and *Alexandrum* sp. were recorded in the coastal area of northeastern Black Sea (coastal Bolshoi Utrish). *Cochlodinium polykrikoides* reached a biomass of ca 500 µg.l⁻¹ (Vershinin *et al.*, 2004). It was observed also in Odessa Bay in 2002 (Terenko, 2003).

Altogether 11 Mediterranean species of phytoplankton were found recently in areas far from Bosporus; 10 more species found in the Black Sea are considered as species probably Mediterranean origin (Table 2).

ZOOPLANKTON

High numbers of holozooplankton species are dispersed with Low-Bosporus current into the Black Sea and are found off the Bosporus. Among them, 54 species are Copepoda. All of them were recorded along the southern Black Sea but none of them became abundant (Table 3).

Reference*	1	2	3	4	5	6
Species						
Calanus gracilis Dana		+				
Calanus minor Claus				+		
Calanus tenuicornis Dana					+	
Calocalanus pavo Dana	+	+	+	+	+	
Calocalanus pavoninus Farr.	+		+			
Calocalanus plumatus Shmel.		+		+		
Calocalanus plumulosus Claus					+	
Calocalanus (tenuis?) Farr.			+			
Candacia athiopica Dana		+				
Centropages typicus Kroyri				+		+
Clausocalanus (Brady)		+		+		+
Clausocalanus arcuicornis (Dana)	+	+	+			
Clausocalanus mastigophorus (Claus)				+		
Clausocalanus parapergens Frost, Flem		+				
Clausocalanus paululus Farr.		+	+	+		
Clausocalanus pergens Farr.		+		+		+
Corycaeus clausi F. Dahl	+		+			
Corycaeus flaccus Giesbr.	+		+			
Corycaeus furcifer Claus	+	+	+		+	
Corycaeus latus Dana		+		+		
Corycaeus limbatus Brady				+		
Corycaeus sp.	+		+	+		
Corycaeus typicus Kroger	+		+	+		

Table 3. List of Mediterranean Copepoda found in the Black Sea prior to 1998 (with additions after Kovalev *et al.,* 1998).

Corycella gracilis Dana		+				
Corycella rostrata Claus				+		
<i>Corycella</i> sp.	+		+			
Ctenocalanus vanus Giesbr					+	+
Eucalanus sp.					+	
Euterpina acutifrons Claus	+	+	+	+		
Lucicutia flavicornis Claus			+			
Lucicutia gemina Farr				+		
Macrocetelia gracilis Dana		+				
Mecynocera clausi Thompson				+	+	
Micsetelia gracilis Dana	+	+	+	+		+
<i>Oithona</i> sp.		+	+			+
Oncaea subtilis Giesbr.					+	
Oncaea conifera Giesbr.	+		+	+	+	
Oncaea curva Sars		+				
Oncaea dentipes Giesbr.	+	+	+	+		+
Oncaea media Giesbr.		+				
Oncaea mediterranea Claus	+		+	+	+	
Oncaea minuta Gieshr.	+	+	+	+		+
Oncaea similis Sars		+	+	+		
Oncaea subtilis Giesbr.		+				
Oncaea venusta Philippi					+	
Paracalanus aculiatus Giebr.					+	
Paracalanus nanus Sars				+	+	
Paroithona parvula Farr.					+	
Phaenna spinifera Claus					+	
Pleuromamma abdominalis Lubb				+		
Pleuromamma gracilis Claus				+		+
Pleuromamma sp.		+				
Scolecithrix danae Lubb		+				
Temora stylifera Dana				+		
Total 54 species						

***References:** 1- Pavlova, 1964; 1965; Pavlova and Baldina, 1969; 2- Kovalev *et al.*, 1976; 3- Kovalev, 1971 4- Kovalev *et al.*, 1987; 5- Porumb, 1980; 6- Kovalev *et al.*, 1998.

In the last decade, some 50 additional species of Mediterranean and Marmara Sea Copepoda were found in the southern Black Sea (Zagorognya *et al.*, 1999; Tarkan *et al.*, 2005): they may be considered as regular migrants arrived with Mediterranean water masses.

Recently the compass jellyfish *Chrysaora hysoscella* was recorded in pre-Bosporus area (Öztürk and Topaloglu, 2009), following its 2000 record in the Sea of Marmara (Inanmaz *et al.*, 2003) and now this stinging species is also found into the Black Sea. This species has not been a threat yet, but is beginning to increase its area of distribution. This species is planktophagous, consuming a range of planktonic animals (<http://www.nhm.ac.uk/nbn>).

In the northeastern Black Sea off Gelendzhik three species of Mediterranean Copepoda were recorded: *Euchaeta marina, Rhyncalanus nasutus, Pleuromamma gracilis* and one species of Ostracoda: *Philomedos globosa* (Musaeva, pers. comm.). *E. marina* and *P. gracilis* have already been found off Bosporus (Kovalev *et al.*,1998), two others were recorded for the first time. Most probably they were brought with ballast waters but did not get established as they were not found in following years.

In the coastal waters off Crimea, the numbers of non-native planktonic species observed all of Mediterranean origin keep increasing. To date, it is not clear whether all will be capable of establishment. Among them, one finds the harpacticoids *Amphiascus tenuiremis*, *A. parvus*, *Leptomesochra tenuicornis*, *Idyella palliduta*, *Ameiropsis reducta*, and *Proameira simplex*, the

planktonic copepods *Oithona brevicornis, O. plumifera, O. setigera, Clausocalanus arcuicornis,* and *Scolecetrix* sp.. Species of the family Clausidiidae, *Rhincalanus* sp. and *Oncaea minuta* – were found off Crimea in the area of Smeinyi Island. Some species were represented by few specimens or single individuals (Zagorodnya and Kolesnikova, 2003). But we cannot yet consider them as established species, although some of them were rather abundant.

In 2005-2006 the species of Copepoda *Oithona brevicornis* reached a very high abundance (in autumn 42,667 ind.m⁻³ in the central part of Sevastopol Bay. Since the middle of September until the end of 2006 *O. brevicornis* comprised from 70% to 96-97% of total mesozooplankton. Most probably this species is establishing now in the Black Sea (Altukhov and Gubanova, 2006; Gubanova and Altukhov, 2007). *O. brevicornis* was recorded also off Novorossiisk, Tuapse (Seliphonova, 2009).

In May-June 2001 during the R/V Knorr cruise 33 Mediterranean species of Copepoda were recorded in the western Black Sea. All of them were found in good conditions in water with low salinity (Seliphonova *et al.*, 2008).

Overall more and more Mediterranean subtropical species of mesozooplankton are recorded in the Black Sea outside the Bosporus area, most probably they were brought with ballast waters, but now we may consider only *Oithona brevicornis* as established species (Table 4).

Species name	Origin	First record in Black Sea	Location of first record	Establishment	Abundance	Habitat	Geographic distribution	Tolerance limits	Vector	Reference
Scyphozoa Pelagiidae <i>Chrysaora hysoscella</i> (Linne, 1766)	Mediterranean	July 2009	off Bosphorus	a few ind.	a few ind.	marine and brackish	Mediterranean, Northeast and southern Atlantic, Marmara	subtropical, temperate	expansion	Inanmaz et al., 2003 Öztürk and Topaloglu, 2009 in press
Echinodermata Arbacia lixura	Mediterranean	2007	Canakkale Strait, later Marmara Sea	locally	not abundant	rocky, muddy area of Turkish coast	Mediterranean	subtropical	not known	Öztürk, 2006
Echinodermata Asterias rubens	Mediterranean	1996, 2003	off Bosphorus	locally	not abundant	marine benthic	Mediterranean	subtropical	expansion, shipping?	Albayrak, 1996; Karhan et al., 2007
Echinodermata Amphiura filiformis	Mediterranean	recently	off Bosphorus	locally		marine benthic	Mediterranean	subtropical	expansion, shipping?	Sergin, Kideys, 2009
Echinodermata Asterina gibbosa	Mediterranean	recently	off Bosphorus	locally		marine benthic	Mediterranean	subtropical	expansion, shipping?	Sergin, Kideys, 2009
Bivalvia <i>Mytilus edulis</i> Linne, 1758	Mediterranean	2001	Odessa Bay	single individuals	single ind.	marine benthic	Mediterranean North Atlantic	subtropical	expansion	Alexandrov, 2004
Bivalvia Mytilus trossulus ? Gould, 1850	Pacific Ocean		Odessa Bay	single individuals	single ind.	marine benthic	West Pacific	subtropical, temperate	ballast waters	Alexandrov, 2004
Anadaridae <i>Anadara demiri</i> (Piani, 1981)	Mediterranean	1968	Black Sea near Bosphorus and north- western Black Sea	established	abundant	marine benthic	Mediterranean, Aegean	subtropical	natural expansion	Öztürk,1998 Turkey Country report
Anadara cornea (Reeve, 1844)	Mediterranean, introduced from Indo- Pacific		Southern and off Bosphorus	established		marine benthic	Aegean (non- native), Southern Atlantic, Indo- Pacific	subtropical, tropical	expansion	Öztürk,1998
Cirripedia Balanidae Balanus amphitrite?	Mediterranean	2001	Odessa Bay		a few ind.	marine benthic	Mediterranean, Northern Atlantic		shipping	Alexandrov, 2004
Polychaeta Capitellidae <i>Capitellethus dispar</i> (Ehlers, 1907)	Northeast Atlantic, Indo-pacific, Mediterranean?	1972	off Bosphorus		a few ind.	marine demersal	Mediterranean Northeast Atlantic and Indo-West Pacific	temperate	shipping	Alexandrov, 2004
Crustacea Decapoda Paleamon longirostris H. Milne-Edwards	Eastern Mediterranean, Marmara Sea	2005	off Bosphorus	few ind.	few ind.	marine	Mediterranean, Marmara Sea, Eastern Atlantic, the Baltic Sea	temperate- subtropical	expansion	Sezgin et al., 2007
Crustacea Decapoda Sirpus zariquieyi Gordon, 1953	Mediterranean	2000	off Bosphorus	few ind.		marine	Mediterranean, Aegean, Marmara Sea	subtropical	shipping?	Zaitsev and Ozturk, 2001
Copepoda Oithonida <i>Oithona brevicornis</i> Giesbrecht, 1891	Adriatic Sea? Mediterranean?	2002	Sevastopol Bay	established	abundant	marine euryhaline	Adriatic Sea Mediterranean, North Atlantic	subtropical, temperate	ballast waters	Gubanova, Altukhov, 2006

Table 4. Mediterranean invertebrate species recorded in the Black Sea.

BENTHOS

Via Bosporus penetrate many larvae of benthic animals. Some of them may find a proper substratum and settle. If density of individuals is high, they may create self-reproducing population.

Among benthic species which penetrated from the Mediterranean and now live in the near Bosporus area there are representatives Gastropoda. According to their origin they may be subdivided: five Mediterranean (*Scissurella laevigata, Proneritula westerlundi, Alvania cimex, Doto paulinae, Calmella cavolinii*), eleven - Mediterranean-boreal (*Diodora graeca, Calliostoma granulatum, Aporrhais parpelicani, Turritella communis, Lunatia fusca, Trophonopsis muricata, Tritonalia erinacea, Tritia incrassata, Cylichnina cilindracea, Philine quadripartita, Leiostraca glabra*), two - Mediterranean - Lusitanian (*Payraudeutia intricata, Mitrella scripta*) (Chukhchin, 1984).

Area of distribution: twenty two species of Mediterranean Bivalvia are limited off Bosporus. Among Anisopoda also two species *Leptochelia mergellinae* Smith and *Pontotanais borceai* Bacescu occur off Bosporus (Makkaveeva, 1979).

Thirty Mediterranean species of Polychaeta were recorded off the Bosporus area. Among them already in the 1960s two Polychaeta species *Sternaspis scutata* and *Ophiothrix tragilis* were found. In addition among Mediterranean species which occur near the Bosporus area of the Black Sea: three Ophiuroidea species, one Echinoidea species, one Asteroidea species, one Scaphopoda species, eleven Ostracoda species, eight Echinodermata species (Kiseleva, 1979).

The numbers of Mediterranean species off Bosporus area keep increasing.

During the last decades some species which occurred earlier only off Bosporus area began to penetrate in other areas of the Black Sea. Three species of Amphipoda (*Synchelidium maculatum, Megamphopus cornutus, Monoculodes gibbisus*) were found in the near Bosporus area, off the western shores of Crimea and of Caucuses. Cirripedia *Verruca spengleri* that occurred previously only off Bosporus was found in high abundance in the coastal area of Crimea even in 1950s (Aykubova, 1948).

Among similar species recorded far from the southern part of the Black Sea we may mention Amphipoda *Colomastix pusilla* recently found in the northwestern area of Crimea and near Kerch Strait (Revkov *et al.*, 2003). Representative of Isopoda *Gnathia bacescoi* also occurred only near Bosporus but since 1969 was recorded in the coastal area of Crimea (Zaitsev and Alexandrov, 1998). Representative Pantopoda *Anoplodactylus petiolatus*, recorded earlier off Bosporus in 1986, was found in the coastal area of Crimea near Yalta at the depths 10-20 m in community *Chamelea gallina* (Sergeeva, 1992). Three Bivalvia species, found earlier only off Bosporus were recorded in a few numbers in the coastal areas of Crimea. Among them *Clausinella fasciata*, *Hiatella rugosa* (Revkov *et al.*, 2003) and *Acanthocardia tuberculata* were found near Kerch straight (Terent'ev,1998).

In 2001 live individuals of juveniles of one more gastropod *Neptunea arthritica* (Bernardi, 1857) (Gastropoda, Buccinidae) were recorded in Kamyshevaya Bay (Sevastopol, Crimea). They were probably brought in an ova laying. *Neptunea arthritica* is a Far East species, predator which can live in brackish waters. Establishment of this species may create deteriorations in the benthic communities of the Black Sea (Shadrin *et al.*, 2002).

In 2001 two new non-native Bivalvia species were found in the Odessa Bay: *Mytilus edulis* and *Mytilus trossulus* (Alexandrov, 2004). *M. edulis* probably was brought with ballast waters from the Mediterranean, where it is used for aquaculture in Spain and Italy shores mainly. Probably the Pacific species *Mytilus trossulus* was brought with ships from Far East Russian areas, where it is a main cultivated species (Table 4) (Suprunov and Makarov, 1990).

Thus numbers of Mediterranean benthic species in the near Bosporus area are increasing more than other groups and some of these species appear also in the north-western Black Sea. Such systemic groups as Echinodermata are represented now with more and more species (Table 4).

Mention should be made to species, that arrived from the Adriatic Sea, because conditions of the north Adriatic are closer to the Black Sea. There are only few of them: *Anadara inaequivalvis* and *Crassostrea gigas*. None of them is native to the Adriatic Sea. *A. inaequivalvis* was brought to the Adriatic Sea from the coastal waters of the Philippine Islands. After arrival into the Black Sea *A. inaequivalvis* became a natural widespread component of the coastal communities. *C. gigas* entered the Black Sea from the Adriatic, where it had been brought from the Sea of Japan (Skarlato and Starobogatov, 1972). It occurs in few numbers. Attempts have been made to cultivate it in oyster farms in the northeastern Black Sea, using special methodology (Zolotarev, 1996).

MACROPHYTES

The list of macrophytes of the Black Sea was published in 1975. It now counts 38 additions. The most significant change is the almost twofold increase in the number of *Cladophora*, *Ulva*, *Ceramium*, *Polysiphonia*, *Cystoseira* and *Sargassum*; many of them play a key role in the bottom communities of the Mediterranean (26 species) (Table 2). Most are thermophilic and indicators of the transition zone between the boreal and tropical domains (Milchakova, 2002).

The greatest number of species probably penetrated with currents, and became established in nearshore waters of the Anatolian coast. Their proportion reaches 26% of the total number of macrophytes. Among them, green Chlorophyceae, brown Fucophyceae, and red Rhodophyceae are represented by ten, five, and twelve species, respectively (Aysel and Erdugan, 1995).

Off the coasts of Rumania and Bulgaria, six new Cladophora among other green algae were brought with ballast water but their origin is uncertain (Bavaru *et al.*, 1991; Milchakova, 2002).

In 1990, in Odessa Bay, the near-shore euryhaline brown *Desmarestia viridis* was found for the first time in the Black Sea. By winter 1994/1995, *D. viridis* had already become a major presence in the near-shore zone of the bay. In recent years, *D. viridis* has spread over to the northwestern Black Sea (Minicheva, 2007a). This species was most probably brought with shipping from the north Atlantic, and it is also species which was introduced into the Mediterranean in the coastal zone of France (Minicheva and Eremenko, 1993).

FISHES

Some Mediterranean fishes perform regular feeding and/or spawning migrations to the Black Sea. This refers, first of all, to valuable large predator species: the Mediterranean-Atlantic horse mackerel *Trachurus trachurus trachurus* (Linnaeus), the Atlantic bonito *Sarda sarda* (Bloch), the bluefish *Pomatomus saltatrix* (Linnaeus), the Atlantic mackerel *Scomber scombrus* (Linnaeus), and the Mediterranean mackerel *S. japonicus colias* Gmelin.

The swordfish Xiphias gladius Linnaeus, the blue-finned tuna Thunnus thynnus thynnus (Linnaeus), the Mediterranean picarel Spicara moena, and the European pilchard Sardina pilchardus used to visit and even spawn in the western and northwestern parts of the sea (Svetovidov, 1964; Gordina and Bagnyukova, 1992). In the 1970s-1980s, the abundance of migrating species significantly decreased and most of the species virtually stopped entering the Black Sea. In recent years, the conditions for fattening have improved, owing to increase in the stock of small pelagic fishes after the *Beroe ovata* invasion that controlled *M. leidvi* abundance. As a result, some Mediterranean species reappeared both in the western part of the sea (the mackerels, the bonito, and the bluefish) (Abaza et al., 2006) and in its northwestern part (the horse mackerel, the bonito, the bluefish, the Mediterranean picarel Spicara moena (L), the European pilchard Sardina pilchardus (Walbaum), the green wrasse Labrus viridis (Linnaeus), and triplefin Triptervgion tripteronotus (Risso) (Boltachev, 2006). In addition, starting from 1999, their feeding area expanded and new Mediterranean fish species appeared; for example, in the near-shore waters off Crimea, the dorado Sparus aurata Linnaeus, the salema Sarpa salpa (Linnaeus), and the thicklipped gray mullet *Chelon (= Mugil) labrosus* (Risso) appeared and intensely reproduced (Table 6) (Boltachev, 2006).

Species name	Origin	First record in Black Sea	Location of first record	Establishment	Abundance	Habitat	Geographic distribution	Tolerance limits	Vector	Reference
Cnidaria, Scyphozoa Rhisostomea Cassiopea andromeda	Mediterranean	_	Marmara	established	abundant	Aegean Sea	entered into Mediterranean via Suez Canal		Lessepsian Mediterranean, expansion	Ozgur, Ozturk, 2008
Scyphozoa Pelagiidae Chrysaora hysoscella (Linne, 1766)	Mediterranean	August 26, September 18, 2000	Bay of Erdek (southern Mediterranean	established locally	not abundant	central part of Marmara and near Istanbul off Bosphorus in July 2009 fist record of the Black Sea				Inanmaz et al., 2003 Öztürk and Topaloglu, 2009 in press
Trachimedusa Liriope tetraphylla	Mediterranean	2005	Coastal area off Dardanelles	established	abundant	Marmara Sea	Mediterranean	marine, subtropical	expansion	Yilmaz, Yuksek, 2009
Echinodermata Arbacia lixura	Mediterranean		Caanakkale Strait, Marmara Sea	locally	not abundant	Turkish coast of Marmara Sea	Mediterranean	subtropical	Aegean Sea	Öztürk, 2006
Echinodermata Asterias rubens	Mediterranean	1996	off Bosphorus	locally	not abundant	marine species		subtropical	shipping?	Albayrak, 1996; Karhan et al., 2007
Asterias rubens	Mediterranean	2007	Black Sea	established	not abundant	marine species	Mediterranean, Marmara	subtropical	expansion	Karhan et al., 2007
Erugosquilla massavensis Kossmann, 1880	Indian Ocean	2002	Sea of Marmara	a few	not abundant	marine	Indian Ocean	tropical	Suez Canal	Katagan et al., 2004

Table 5. Mediterranean and Indo-Pacific invertebrates recorded in the Sea of Marmara.

Table 6. Mediterranean fishes species recorded in the Black Sea.

Species name	Origin	First record in Black Sea	Location first recorded	Establish- ment	Abundance	Habitat	Geographic distribution	Tolerance limits	Vector	Reference
Clupeidae Sardinella aurita Valenciennes	Mediterranean, Marmara	1997	along the shores of Crimea, Turkish coast, Sile	migration increased	increase abundance	marine, brackish water species; pelagic	Eastern Atlantic, Mediterranean	subtropical	migration	Boltachev, 2006; Fishbase, FAO; Ozturk, 2006
Gadiformes Gadidae <i>Micromesistius</i> <i>poutassou</i> (Ricco)	Western Mediterranean,Atlantic?	1999	coastal area of Crimea; off Turkey	a few ind. present in Turkish waters for many years	a few ind. off Cape Aiya, common for Turkish area	marine, bathy- pelagic	western Mediterranean, North Atlantic: Barents Sea, along the African coast to Cape Bojador	boreal	migration	Boltachev, 2006; Fishbase, FAO; Ozturk, 2006
Mugilidae Chenon labrosus (Risso)	Mediterranean	1999	Crimean coast; southern Back Sea	increase in abundance, established	migration	demersal; catadromous	Mediterranean, Eastern Atlantic	subtropical	migration	Boltachev, 2006; Fishbase, FAO
Liza ramada (Risso)	Mediterranean	1950, 2007	Crimea, north- western Black Sea	increase in abundance	migration	marine, pelagic	Mediterranean, eastern Atlantic	subtropical	migration	Boltachev, 2009; Fishbase, FAO
Labridae Thalassoma pavo (L)	Mediterranean, Marmara	2006	Igneada	migration	migration	marine, reef- associated; marine; depth range 1-150 m	Mediterranean, eastern Atlantic, Marmara	subtropical	migration	Fishbase, FAO; Ozturk, 2006
Sparidae <i>Sarpa sarpa</i> (L)	Mediterranean, Marmara	2001	extension	migration	increase in abundance	marine, pelagic	Mediterranean, Eastern Atlantic	subtropical	migration	Fishbase, FAO, Ozturk, 2006
Sparidae Sparus aurata (L)	Mediterranean		Crimean coast	migrant, increase presence in the Black Sea	increase in abundance	marine and brackish	Mediterranean, Marmara	euryhaline eurythermal	migration	Fishbase, FAO, Boltachev, 2006

Sparidae Boops boops (L)	Mediterranean, Marmara	1989	Turkish coast, Sile; population increased and distribution extended	migration	migration	demersal marine	Atlantic- Mediterranean	subtropical	migration	Fishbase, FAO Ozturk, 2006
Umbrina cirrosa (Linnaeus, 1758)	Mediterranean	1962, 1999	Northestern Black Sea	a few, rare occurred in the Black and Azov Seas	reappeared	demersal; brackish; marine	Eastern Atlantic: Bay of Biscay and Gibraltar to southern Morocco, including the Mediterranean	subtropical	migration	Pashkov, 2005; Fishbase
Centracanthidae Centracanthus cirrus Raffinesque	Mediterranean	1988	off Odessa, littoral zone of Romania, Turkey area	a few individuals, eggs in 1988 2 adults off Romania in 2004, common in Turkish area	increase in abundance	marine, bentho- pelagic	Mediterranean, Marmara, Eastern Atlantic	subtropical	migration	Tsokur, 1988; Radu, 2006 (pers. com.)
Centracanthidae Spicara maena (L)	Mediterranean		off Bulgaria, Crimea, Caucasus	migrant, increased presence in the Black Sea	increase in abundance	marine, neretic	Eastern Atlantic, Mediterranean	marine, subtropical	migration	Svetovidov, 1964; Salekhova, 1979; Salekhova et al., 1989
Gobiidae <i>Gobius auratus</i> Risso	Eastern Mediterranean		common for Crimea, Turkish area		established	saltwater, marine, demersal	Eastern Mediterranean, Adriatic Sea, Atlantic	subtropical	shipping? migration?	Gordina, 1967; Fishbase
Gobiidae G. cruentatus	Mediterranean		off Crimea, Turkish area		established?	marine, demersal; In the Medi- terranean found in eel- grass beds	Mediterranean, Atlantic, Marmara	subtropical	shipping? migration?	Boltachev, 2006; Fishbase
Gobiidae G. xanthocephalus	Mediterranean		off Crimea, Turkish area		established	marine	Mediterranean, Atlantic, Marmara	marine, subtropical	shipping? migration?	Boltachev, 2006; Ozturk, 2006
Gobiidae Tridentiger irigonocephalus (Gill, 1859)	Pacific		Sevastopol Bay			demersal; brackish; marine	Pacific Ocean	temperate	shipping, ballast waters?	Boltachev, 2009;
Blenniidae Parablennius incognitus Bath, 1968	Mediterranean		common for Crimea, common for Turkish area		established	demersal; marine, between algae in shallow, rocky, littoral areas	Mediterranean, Marmara, Eastern Atlantic	marine, subtropical	migration?	Boltachev, 2006; Fishbase
Syngnathidae Syngnathus acus L.	North Atlantic		Crimean coast			lives amongst seaweed or sea-grass at depths down to 20 m	around the coasts of Britain and Ireland	temperate	migration? shipping?	Boltachev, 2006

Previously, in contrast to the gilthead bream, the thick-lipped gray mullet had never been recorded in the northwestern part of the Black Sea. For the first time, a juvenile of *Chelon labrosus* was caught in October 1981 in Donzulav Bay. In October 1983, shoals of the thick-lipped gray mullet consisting of 10-15 fishes were observed in the waters off Sevastopol (Salekhova, 1987). Starting from 1999, the thick-lipped gray mullet has been repeatedly found in the areas off Sevastopol. A specimen of the salema off the Crimea was first noted in 1999 (Boltachev, 2006). At present, its abundance in this region is rapidly increasing.

The dorado is often recorded as single specimens or minor shoals in Balaklava Bay and adjacent near-shore waters. Probably, the dorado and the salema may stay for overwintering now in the coastal waters off Crimea (Boltachev, 2006).

The Mediterranean umbrine *Umbrina cirrosa* was once found in the Black Sea Biosphere reserve in 1962 (Tkachenko, 1994). In summer 1999, one female with eggs was caught again in Pshada Bay (Pashkov, 2005).

All the above-mentioned species are seasonal Mediterranean migrants rather than invaders into the Black Sea. Among the non-native species, three species of fishes previously not encountered in the Black Sea were found in the coastal waters of Crimea. They include two specimens of the barracuda *Sphyraena pinguis* that were caught with a bottom trawl in Balaklava Bay in August 1999. This is an Indian-Pacific species, which penetrated as a Lessepsian migrant via the Suez Canal to the eastern Mediterranean including the Aegean Sea in 1931 and ultimately reached the Black Sea. This species is increasing area of distribution in the Mediterranean and became commercial species (Boltachev, 2009). Two individuals caught were identified as *Sphyraena obtusata* as well, but after very detailed analyses they were determined as *S. pinguis* (Boltachev, 2009). Another record concerns the Indian-Pacific species *Sphyraena obtusata*, a Lessepsian migrant that penetrated into the Mediterranean recently only in 1992 (Table 7). This species is not abundant, occuring rarely in the Mediterranean. A few individuals were found off the Bosporus area (Öztürk, 2006).

Species name	Origin	First record in Black Sea	Location of first recorded	Establishment	Abundance	Habitat	Geographic distribution	Tolerance limits	Vector	Reference
Sphyraenidae Sphyraena obtusata Cuvier	Indo-Pacific, Red Sea, Mediterranean	1999	Turkish area Şile	a few ind.	migrant, a few ind.	pelagic, marine	Indo-Pacific, Red Sea and East Africa to Samoa, migrate to eastern Mediterranean	marine, brackish; tropical	Lessepsian migrant	Fishbase, FAO, Öztürk, 2006
Sphyraenidae Sphyraena pinguis Gunter,1874	Indo-Pacific, Mediterranean	2004	coastal area of Crimea	a few ind.	a few ind. a few ind.	pelagic, marine	Indo-pacific pelagic, migrant	marine, tropical	Lessepsian migrant	Boltachev, 2009
Gobiidae Tridentiger irigonocephalus (Gill, 1859)	Pacific Ocean		Sevastopol Bay			demersal, brackish; marine	Pacific Ocean	temperate	shipping, ballast waters?	Boltachev, 2009
Tetraodontidae Lagocephalus spadiceus (Richardson, 1845)	Mediterranean, Pacific Ocean	2008	Çanakkale, the Sea of Marmara	a single ind.	a single ind.	demersal; marine, also brackish waters	Indo-West Pacific: Australia. Introduced (Lessepsian) in eastern Mediterranean	subtropical	Lessepsian migrant	Tuncer et al., 2008

Table 7. Indo-Pacific fish species recorded in the Black Sea.

A specimen of the northern blue whiting *Micromecisthis poutassou* 15.7 cm long was caught in January 1999 at a depth of 60 m off Balaklava (Crimea). It is a typical Atlantic-boreal species widely spread in the Mediterranean basin, including the Aegean Sea and the Sea of Marmara; most probably, it penetrated from the Mediterranean Sea. Blue whiting performs long-lasting migrations; it is known as a stenohaline eurythermal species dwelling at salinities no less than 33‰, but was first encountered at a salinity of 18‰. There are two ways of explanation of the appearance of the above two species in the Black Sea: fishes might migrate from the Sea of Marmara or the Mediterranean Sea or, which seems more probable, might be brought with ballast waters.

The third species is the coral-dwelling butterfly fish *Heniochus acuminatus*. A specimen 76 mm long was caught by a net in Balaklava Bay in October 2003. It is a typical tropical Indian-Pacific species and the conditions of Balaklava Bay are hardly favorable for it. This fish was most probably delivered with ballast waters (Boltachev, 2006).

In recent years, in the waters off Rumania, *Centracanthus cirrus*, which probably also penetrated from the Mediterranean Sea, was observed. To date, it has significantly increased its abundance and now represents a commercial fish in the littoral zone of Rumania (Abaza *et al.*, 2006) and off the Turkish coast (Öztürk, 2006). In the central part of the sea, its developing eggs were first found in June 1982 (Tzokur, 1988).

The golden goby *Gobius auratus* Risso, first found in the communities of near-shore macrophytes off Crimea and recently in the northeastern part of the sea may also be referred to as a Mediterranean invader (Nadolinsky, 2004). Two more Mediterranean species of Gobiidae *G. cruentatus* and *G. xanthocephalus* were recorded recently off Crimea and Turkish area (Boltachev, 2006; Öztürk, 2006).

Another indo-Pacific Gobiidae *Tridentiger irigonocephalus* was recorded off Crimea and Turkish areas (Boltachev, 2009). Representatives of Gobiidae are small species; it is probable that they were brought with ballast waters, particularly in the case of *Tridentiger irigonocephalus*.

One more indo-Pacific species recorded in the Turkish area of the Black Sea is the half-smooth golden pufferfish *Lagocephalus spadiceus* in 2008 (Tuncer *et al.*, 2008).

In the last years the Mediterranean species *Parablennius incognitus* became common in Turkish area and appeared off Crimea (Öztürk, 2006; Boltachev, 2009 and this volume). Among other species *Syngnathus acus* L. was recently found off Crimea (Boltachev, 2009 and this volume). Its origin is not clear. Probably it was brought from the northern Atlantic Ocean with ballast waters.

DISCUSSION

During the second part of the 20th century the Black Sea became the main recipient area for nonnative temperate and warm water marine and brackish water species which arrived from different donor areas. Euryhaline and eurythermal species of Atlantic origin became abundant, often forming large populations. In turn most of these established species affected other seas of the Mediterranean basin and the Caspian Sea (Shiganova and Dumont, unpubl. data).

Since the end of 1980, with the beginning of warm period, more and more warm-water species of different origin have established in the Black Sea.

During the last decades a new trend has appeared. The Mediterranean species which have always penetrated into the Black Sea with Low Bosporus current and could live only off Bosporus area began to disperse with the currents or survive ballast waters release in other areas of the Black Sea. Earlier they could not settle due to low temperature, particularly in winter, but now with increasing temperature the share of these non-native species of Mediterranean origin is gradually increasing.

Organisms driven with currents and ballast waters represent phyto- and zooplankton, macrophytes, benthic or demersal organisms, and fishes. These species as a rule have subtropical and in some cases even tropical origin (Tables 1-7). None of them became very abundant; their greater number still occur only in the near-Bosporus and southern parts of the Black Sea where salinity is higher. Selected species migrated to the near-shore regions off Bulgaria, Rumania, and the Crimea also with currents or via ship ballast waters (Tables 8, 9).

	<1960s	1960- 1970	1971- 1980	1981- 1990	1991- 2000	2001- 2009
Phytoplankton		37				
Copepoda		15	19	12	7	51
Gelatinous plan	nkton					1
Macrophytes					26	
Benthos	1	45	30	56		5
Fish					9	5
Total	1	97	49	68	42	62

Table 8. Mediterranean species found in the southern Black Sea (mainly off Bosphorus).

Table 9. Mediterranean species found in the northwestern and western Black Sea.

	prior to 1991	1991-2000	2001-2009
Phytoplankton	_	23	11 (+10)
Copepoda			47
Gelatinous plankton			
Benthos			12
Fish	—	9	
Total		32	70 (+10)

The appearance of species of Indo-Pacific origin is a new event for the Black Sea.

Shift from fish to gelatinous plankton

The most significant events were the arrival of two warm water ctenophores: *Mnemiopsis leidyi* and *Beroe ovata*. The first affected all trophic web of ecosystem and became the main driver of the Black Sea ecosystem functioning. The stocks of most of commercial fish greatly dropped (Shiganova *et al.*, 2003; 2004). Arrival of the second species induced the recovery of the Black Sea ecosystem. But then *Mnemiopsis leidyi* spread from the Black Sea to the Sea of Marmara, the Aegean Sea and recently in further areas of the Mediterranean with ballast waters (Shiganova *et al.*, 2001; Shiganova and Maley, 2009; Galil *et al.*, 2009).

Recent years marked a new trend: the arrival of gelatinous species from the Mediterranean. Several Mediterranean jellyfishes have penetrated the Sea of Marmara, notably *Chrysaora hysoscella*, *Cassiopea andromeda*, Trachimedusa *Liriope tetraphylla*. In 2009 *C. hysoscella* was recorded for the first time in the Istanbul Strait and the Turkish part of the Black Sea (Öztürk and Topaloglu, 2009). This is a temperate planktivorous species and it cannot be excluded that it will establish in the Black Sea if salinity conditions allow.

Northward extension, increase abundance and change phenology

Significant range northward extensions have been recorded for Mediterranean fishes, with seasonal migrations in the Black Sea. Some of them have changed phenology: they used to spend a short period of warm seasons in the Black Sea for spawning/ and feeding but now some of them stay longer in the Black Sea, intensively reproduce and even most likely stay for overwintering. This was not observed earlier (the dorado *Sparus aurata*, the salema *Sarpa salpa*).

Arrival and establishment of Mediterranean species

We may consider that nine Mediterranean species of fish were most likely established in recent years in the Black Sea (Table 6). But we still cannot consider most of phytoplankton and zooplankton species, which were recorded both in the southern and northwestern areas of the Black Sea, as established. The main reasons are low salinity and cold winters. Among Copepoda only temperate *Oithona brevicornis* has established. Among phytoplankton 11 species have established: there are mainly representatives of Dinophyceae, which develop in spring and summer and are capable to produce cysts in unfavorable conditions. *Gymnodinium sanguineum* is among them: it lives in upwelling and is therefore tolerant to low temperatures (Table 2).

Most benthic species and macrophytes may be considered as established species in the southern Black Sea and in other parts as well.

Thus there is a progressing trend of arrival of Mediterranean species into the Black Sea both with the currents as natural expansion and with ballast waters. Most of these species arrived in previous years, but relatively low temperature and low salinity prevented their establishment. Now with rising temperature some species can establish. First of all benthic species that inhabit at depths where salinity is higher, especially in the southern part of the Black Sea. Due to intensification of shipping (Table 10), particularly between Mediterranean and Black Sea countries (62% of vessels in Novorossiysk harbor arrived from the Mediterranean countries – Matishev *et al.*, 2005) the numbers of species released with ballast waters also increased. Some of these species began to establish in the vicinity of harbors.

Year	Number of vessels	Mean volume of ballast waters	
1938	4500	7500	
1985	24 100	105,500	
1996	49952	156,057	
2001	56000	110,000,000	
2002	47283	103,897,121	
2003	46936	102,943,762	
2004	54564	116,342,089	
2005	54794	115,298,453	
2006	53721	78,987,432	

Table 10. Numbers of vessels crossing the Bosphorus Strait and mean volume of released ballast waters (Matishev *et al.*, 2005; Ozturk, 2006).

The total numbers of Mediterranean species found only in the southern Black Sea comprise 240 species. At present time it is difficult to determine exactly how many of them might be included in the list of established species. We consider as established among them 23 species of macrophytes. Zoobenthic species, which are most probably, would be established as well in future, we have not included in the list of established species. Species found in the northwestern and western Black Sea comprised 84 species. Among them we consider 33 species as established: 10 species of zoobenthos, 11 species of phytoplankton, 3 species of microplankton (fam. Tintinnidae) and 9 fish (Table 9). This process is ongoing and these numbers probably omitted certain species which were recorded recently and locally.

In the Black Sea the total established non-native species (without all near Bosporus Mediterranean species) from all areas account for about 4% of the native biota (Figure 1).

By comparison, in the Mediterranean Sea, the fraction of established non-native species (see CIESM Atlas on line) is between 6 and 7% of the native biota (about 12,000 species). Black Sea biodiversity is about 3,5 times less than in the Mediterranean. The numbers of established non-native species decrease in the same proportion for these seas. So, the basin appears capable to accept the numbers of non-native species in proportion equal natural biodiversity (Shiganova and Dumont, in press).

The most euryhaline and eurytermal non-native species from other areas did spread or were brought with ballast waters from the Black Sea into the Sea of Azov and the Caspian Sea where they could establish. None of the Mediterranean species spread from the Black Sea farther to these seas. The only exception concerns three species of Tintinnidae, which were found in the Sea of Azov. The reason is a low salinity of these seas (low than 15‰, the boundary of mesohaline water, which is important for biota).

Not all non-native Mediterranean species are harmful for the Black Sea ecosystem with the exception of gelatinous species. The rising of the numbers of species, abundances and areas of distribution of gelatinous plankton – both native and invaders – are the most dramatic events for Mediterranean, Sea of Marmara and the Black Sea. Expansion of gelatinous species from the Mediterranean to the Sea of Marmara and after that farther to the Black Sea is a particular threat for their ecosystems. Continuation of expansion of the aggressive Black Sea invader *Mnemiopsis leidyi* in different areas of the Mediterranean Sea is also cause for much concern.

Estimating the possibility of mediterranization of the marine flora of the Black Sea – a morphofunctional approach

Galina G. Minicheva

Odessa Branch Institute of Biology of Southern Seas, National Academy of Sciences of Ukraine

ABSTRACT

A comparative assessment of the ecological activity of phytoplankton and phytobenthos in the northwestern Black Sea (NWBS) and the Mediterranean Basin is made with the help of morphofunctional analysis. It shows that the mean specific surface S/W values which illustrate the intensity of the participation of vegetative populations in the primary-production process for NWBS macrophytes are twice higher than for the Mediterranean Basin. For highly functional phytoplankton algae, average S/W values for NWBS communities are at least 30% higher than for Mediterranean. The factors forming a barrier for penetration of Mediterranean species into the NWBS have been ranked as follows: 1st factor – level of nutrients; 2nd – salinity; 3rd – temperature and 4th – stream of solar energy on the water surface. A high level of salinity and temperature is also a significant barrier. A potential pattern for possible macrophyte aliens penetration has been created for a mediterranization scenario of the NWBS. It includes a high ecological activity (S/W $-30-100 \text{ m}^2 \text{ kg}^{-1}$), cold-loving species tolerant to low salinity (up to 12 %), tolerating significant salinity and temperature fluctuations. Desmarestia viridis is an exotic species for the Adriatic Sea. In the early 1990s it entered the NWBS and became the dominant winter phytocoenosis. The biological features of this macrophyte correspond to the pattern of potential aliens entering the NWBS.

METHODOLOGY OF THE MORPHOFUNCTIONAL APPROACH

The founders of the morphofunctional ecology of seaweeds are Diana and Mark Littler, American researchers of the Department of Botany of the National Museum of Natural History in Washington who initiated these studies in the late 1970s. They demonstrated the relation between the morphological form and productivity of macrophyte algae in the Caribbean basin based on the functional form of macrophytes (Littler and Littler, 1980). Meanwhile the morphofunctional approach was being developed at the Institute of Biology of Southern Seas, National Academy of Sciences of Ukraine in Sevastopol, under the guidance of Dr. Kirill Khailov. The Sevastopol school studies metabolic processes as a regulation mechanism of the morphological form of macrophytes (Khailov and Parchevsky, 1983). The main objective of the morphofunctional approach for the Odessa school (Department of Morphofunctional Ecology of Aquatic Vegetation of the OB IBSS, headed by the author) is to obtain a wider possibility for evaluating phytobenthos and phytoplankton with the help of indices of active algal surfaces (Minicheva, 1998).

Methodology of morphofunctional approach of estimation of water vegetation underlies a holistic approach. The main idea is that quantitative dependence exists between morphological parameters of aquatic vegetation and abiotic factors influencing the production process. For example, if there is an increase in nutrients in the ecosystem, small thinly branched filamentous algae will replace a large forms with thick laminated thallus. The principal methodical achievement of the morphofunctional approach is that the morphofunctional structure of the species, which is expressed in the specific surface (S/W), serves as its ecological activity (EA) coefficient. That index illustrates the intensity of the primary production process for species with different morphological structure. The EA of marine flora expressed quantitatively is one of the paths of solving the issue of ecological identification of biological diversity (Table 1).

Species diversity	System of binary nomenclature (K.Linnaeus, 1761)	Theory of «r» and «k» selection (P. MacArthur, E. Wilson., 1967)	Coefficient of ecological activity of species (G. Minicheva, 1990)
•	Spirulina tenuissima	r - species	1200
*	Oscillatoria viridis	r - species	424
+	Kylinia virgatula	r - species	270
*	Pilaiella littoralis	r - species	140
*	Urospora penicilliformis	r - species	110
*	Cladophora albida	r - species	85
*	Polysiphonia denudata	k - species	56
*	Ceramium elegans	k - species	26
\$	Cystoseira barbata	k - species	9
\$	Fucus serratus	k - species	3

Table 1. Stages in biological and ecological identification of species diversity.

The concept of EA of species is useful to understand how the floristic structure of aquatic vegetation reacts to changes in the fluxes of matter and energy passing through the ecosystem. For example under high nutrient input, only those species with a high EA will remain in the community structure. Therefore, in a eutrophic ecosystem the seaweeds with the highest S/W values (small, short cycle, thinly branched species) will dominate. Vice versa the species with lower S/W values (large, perennial forms with a thick thallus) will be inhibited and will be the first to disappear from the structure of plant communities.

For practical application of the morphofunctional approach when studying aquatic vegetation, the estimation algorithms of the indices based on parameters of the active surface of unicellular and multicellular algae have been elaborated (Minicheva *et al.*, 2003). The main indices are:

- Population specific surface (S/W)p gives the area of the surface through which the population to carry out metabolism with the aquatic environment $(m^2.kg^{-1})$, used for estimating the EA of species with a difference morphological structure;
- Community surface index SIcm reflects the area of the vegetation developing per square meter of sea bottom (for phytobenthos unit) or per a cubic meter of the water column (for phytoplankton m^{-1}), used for estimating the intensity of the production process in ecosystems of different trophic status.

Possibilities of the morphofunctional approach:

- On the basis of the morphological portrait of aquatic vegetation it is possible, to compare the EA of the autotrophic link and the trophic status of ecosystems with different floristic composition (Minicheva, 1996; 1998a). In 2004 in Odessa an international workshop (Black Sea Ecosystem Recovery Project) was conducted where the methods of evaluating the trophic status were passed on to participants of six Black Sea riparian states. A unified evaluation was carried out for assessing the comparative state of eutrophication along the Black Sea coast.
- Using the numerical EA species coefficients it is possible to predict changes in the floristic composition and in the structural-functional organization of communities of benthic vegetation during changes in the trophic status of the ecosystem. It is quite possible in the new conditions to determine species which may become potential alien species or perspective resources. For the northwestern Black Sea the time necessary for restoring the *Cystoseira* and *Phyllophora* communities that were degraded under eutrophication, the corridors of EA for possible alien species and the potential resource species for creating processing technology has been determined (Minicheva, 1990; 1993; 1996; 2007b).
- Using the morphofunctional parameters it is possible to describe quantitatively the response of the phytobenthos community and phytoplankton to **local** (coastal hydrotechnical constructions, recreation, discharges, etc.), **regional** (changes in water quality in the aquatic basin) and **global** (climatic) influence of factors. The optimum exposure of phyto-overgrowths on coastal hydrotechnical constructions for restoring water quality in the coastal zones with a high anthropogenic load has been revealed. The potentiel force of response of autotrophic communities to climatic changes has been also determined. The high stability of communities of coastal macrophytes and phytoplankton in the northwestern Black Sea to possible fluctuations of climatic factors is also shown (Minicheva, 2005; 2006; Minicheva *et al.*, 2008b).

COMPARATIVE ANALYSIS OF FACTORS OF THE BLACK AND MEDITERRANEAN SEAS PRODUCTION PROCESSES

The variability of both geographical-climatic and anthropogenic factors influence the development of the floristic structure, biomass, production characteristics and morphological portrait of the vegetation. To compare the window of conditions in which the flora of the Black and Mediterranean seas develops, the mean values and variability of temperature, light, salinity and nutrients in different areas were analyzed (Figure 1). The mean values and variability (oscillation coefficient, VR, %) of these factors were estimated according to published data (Marine Atlas of the Atlantic and Indian oceans, 1950-1966; Mediterranean Targeted Project II, 1997-1998) and statistical methods (Vasnev, 2001). A preliminary comparative analysis of different areas of the Mediterranean-Black Sea basin showed the following laws governing the production processes:

- the smallest difference of mean values and oscillation between Black and Mediterranean Seas was noted for light (stream of solar energy) (see Figure 1a);
- the northwestern Black Sea (NWBS) is the coldest for comparative areas, with a 3 fold higher oscillation of sea water temperature (see Figure 1b);
- the salinity is 2 fold lower of the Black Sea in contrast to the Mediterranean. In its northwestern part which receives the runoff of three large European rivers (Danube, Dniester, Dnieper) the oscillation is on two orders higher than in the Mediterranean (see Figure 1c);
- in the NWBS the level of nutrients is 6-7 fold higher, but the oscillation, related not only to geographical and climatic factors but also to biological processes, is similar for both (see Figure 1d).



Figure 1. Comparative analysis of mean values and oscillation (VR) of factors determining the development of vegetation in different parts of the Mediterranean and Black Seas basins.

These relations allow to make a ranking of factors determining the corridors of conditions of development of aquatic vegetation in both basins and the possibility of mediterranization or vice versa "pontization" (Pontus Euxinus, ancient name of Black Sea) of the marine flora. For determining the ratios of mean values and oscillation of factors influencing the aquatic vegetation, the southern Aegean Sea and the northwestern Black Sea were selected. The first factor determining the barrier of penetration of Mediterranean vegetation into the NWBS is a significantly higher level of nutrients (1:7,5). The second factor – a lower salinity (2,7:1) and third – a lower temperature (1,7:1) (Figure 2). The mean values of the stream of solar energy on the water surface are almost similar for both areas (1,2:1) (see Figure 2). In this way it is possible that during mediterranization of the NWBS, small, short cycled, thinly branched (high S/W values) cold loving algal species of the Mediterranean Basin, tolerant to low salinity (up to 12‰), can enter the NWBS.



Figure 2. Ratio of average values of abiotic factors for the southern Aegean Sea and northwestern Black Sea.

The degree of oscillation of factors for developing vegetative communities is as significant as their mean values (Minicheva *et al.*, 2008b). On degree of oscillation the salinity is the first factor for determining the entry of new species in the NWBS - 1:572 (Figure 3). The ratio of temperature oscillation in the southern Aegean Sea and NWBS is 1:3,6. In the northwestern area the fluctuations of light on the water surface and of nutrients are not much higher than in the Aegean Sea (see Figure 3). A mediterranization scenario for the aquatic vegetation of the northern Black Sea, can only involve species sustaining low levels of salinity and temperature and with a very high tolerance to salinity and temperature oscillations.



Figure 3. Ratio of oscillation coefficients (VR) of abiotic factors for the southern Aegean Sea and the northwestern Black Sea.

PRELIMINARY EVALUATION OF THE ECOLOGICAL ACTIVITY OF MEDITERRANEAN MACROPHYTES

The development of macrophytes in conditions of high eutrophication leads to an adaptive response increasing the rate of consumption of nutrients via decrease in diameter and thickness of laminated structures of the thallus (Minicheva, 1996). Because of this, one and the same species which develops in different conditions can have different (S/W)p. A preliminary EA evaluation of exotic macrophytes in the Mediterranean Sea (preview of CIESM Atlas of Exotic Species in the Mediterranean Vol. 4 Macrophytes, in press), showed that their (S/W)p was on average 5-25% lower than the same species developing in the northwestern Black Sea (Minicheva, 1998b) (Table 2). This may be ascribed to the higher trophic status of the NWBS in contrast to the Mediterranean Basin.

Table 2. Comparative analysis of the ecological activity of macrophytes in the Mediterranean Sea and species inhabiting the Black Sea.

Species	Ecological activity (specific surface of population), (S/W)p, m ² .kg ⁻¹	
	Mediterranean Sea	Black Sea
Pylaiella littoralis (Linnaeus) Kjellman	136,2	157,5
Punctaria tenuissima (C. Agardh) Greville	25,0	22,7
Desmarestia viridis (O.F. Müller) J.V. Lamouroux	72,7	78,0
Padina sp.	18,0	19,4
<i>Ectocarpus siliculosus</i> var. <i>hiemalis</i> (P.L. Crouan & H.M. Crouan) Foslie	187,9	178,9
Scytosiphon dotyi M.J. Wynne	11,1	27,04
Acrochaetium sp.	404,5	496,2
Porphyra yezoensis Ueda	55,0	63,1
Antithamnion sp.	92,6	116,2
Ceramium sp.	25,0	26,0
Apoglossum gregarium (E.Y. Dawson) M.J. Wynne	26,2	28,9
Gracilaria arcuata Zanardini	11,2	14,4
Grateloupia sp.	6,2	8,2
<i>Hypnea</i> sp.	6,0	17,9
Nemalion vermiculare Suringar	5,04	4,6
Lomentaria hakodatensis Yendo	10,9	9,3
Chondria sp.	13,8	28,6
Laurencia sp.	11,2	13,9
Polysiphonia sp.	17,9	60,0
Cladophora sp.	45,0	47,8
Codium sp.	7,5	8,5
Ulva sp.	21,1	36,3

Macrophyte samples taken along the Adriatic coast (Dubrovnik, October 2003) allowed the first analysis of Mediterranean macrophytes using the morphofunctional approach. Macrophytes were sampled at seven sites near Dubrovnik and Lukrum Island. According to 1,200 measurements of morphological parameters, (S/W)p coefficients were estimated. The analysis confirmed that the morphological portrait of the seaweed is sensitive to local differences in the conditions for development. The highest EA of communities was noted for those developing on the public beaches of Dubrovnik, followed by communities in Lukrum Island facing the city. The lowest EA was observed in communities located on the open side of Lukrum Island, i.e. in its cleaner area which was less subject to anthropogenic eutrophication.

According to preliminary evaluation the functional activity of NWBS macrophytes communities exceeds more than twice that of the Adriatic Sea. This is due to the higher level of eutrophication.
Similarly, recent eutrophication episodes in the northern Adriatic Sea, led to the replacement of the *Fucus, Cystoseira, Sargassum* community by ephemeral (short cycled) species (Munda, 1993; 2008). This completely conforms to the laws of nature in which EA species with high (S/W)p values replace low functional that do not withstand competition. On average the species of genus *Fucus, Cystoseira, Sargassum* surface are $3-12 \text{ m}^2\text{.kg}^{-1}$. In short cycled species this value may rise to 50-150 m².kg⁻¹. Since the level of nutrients is the first barrier between the two basins, a eutrophication scenario of the Mediterranean Sea, could bring about a pontization of the Mediterranean flora with Black Sea species having high values of specific surface. According to another scenario the entry of EA species can continue to occur from the Atlantic and Indo-Pacific in trophic areas of the Mediterranean Basin and the Black Sea. A similar case was observed for the alien brown seaweed *Desmarestia viridis* which had a high level of introduction in the northern most trophic areas of the Mediterranean. Sea (northern Adriatic Sea) (CIESM Atlas of Exotic Species of Macrophytes in the Mediterranean, in press), and in the 1990s in the NWBS. The specific surface of *Desmarestia viridis* ((S/W)p = 80 m².kg⁻¹) at the time of entry corresponded ideally to the level of eutrophication at that period in the NWBS (Minicheva and Eremenko, 1993).

The level of nutrients and salinity are more significant barriers than temperature in the exchange of marine flora of both basins. The scenario for mediterranization of Black Sea flora as a result of global climatic change seems less probable than further invasion of small, short cycled algae (overgrown with slime) of larger areas of the Mediterranean Basin.

THE PRELIMINARY COMPARATIVE ANALYSIS OF THE PHYTOPLANKTON STRUCTURE OF THE BLACK AND MEDITERRANEAN SEAS

The elaboration of a number of phytoplankton indices of active surfaces allows to apply the morphofunctional approach to communities of planktonic algae (see Table 3) (Zotov, 2006). Depending on the dimensions and the geometric form of the cell, each taxonomic section of phytoplankton has a certain EA value. The sequence of EA of phytoplankton is started by dinophytes and ended by blue-green algae with maximum values of specific surface of the taxonomic section – (S/W)ts (Figure 4).

Organization level	Specific surface index	Surface index
Cell	Specific surface of the cell (S/W)c	-
Uniform-sized cell group	Specific surface of the uniform-sized cell group (S/W)uni.c.gr	-
Population	Population specific surface (S/W)p	Population surface index SIp
Community	Community specific surface (S/W)cm	Community surface index SIcm
Region floristic grouping	Floristic grouping specific surface (S/W)fg	Phytoplankton surface index SIphp
Taxonomic section	Taxonomic section specific surface (S/W)ts	Taxonomic section surface index SIts

Table 3. Morphofunctional indices of phytoplankton.



Figure 4. Main phytoplankton taxa arranged by EA.

Comparing the taxonomic structure of the phytoplankton of the northwestern Black Sea and the Mediterranean reveals a significant similarity of species diversity - 629 and 643, respectively, and of taxonomic structure (Zotov, 2006; Vadrucci *et al.*, 2007) (Figure 5).



Figure 5. Comparative analysis of the taxonomic structure of the NWBS and Mediterranean phytoplankton.

When comparing the integral EA of phytoplankton of the two areas, considering the percentage contribution of each taxonomic section and average (S/W)ts value, then the laws governing the morphofunctional differences are linked with the conditions of the habitat (Figure 6). The NWBS has a more simple community structure. The first three taxonomic groups (*Bacillariophycea*, *Dinophycea*, *Chlorophycea*) make up 84% of all cells, and the cells average S/W value makes up 926,6 m².kg⁻¹. In the Mediterranean area, the taxonomic structure is smoother (see Figure 6). The same three dominating groups (*Bacillariophycea*, *Dinophycea*, *Chlorophycea*) make up 61%, with a mean S/W value of 652,5 m².kg⁻¹.



Figure 6. Comparative analysis of NWBS and Mediterranean phytoplankton EA.

The life form phytoplankton (unicellular algae) has an EA a few magnitudes greater than phytobenthos (macrophytes). Preliminary evaluation has shown that the functional activity of NWBS macrophytes more than twice exceeds that of the Mediterranean Basin (Adriatic Sea). For phytoplankton the difference does not exceed 30%.

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Early signs of "mediterranization" and climate change in the Black Sea

Dragoş Micu¹ and Valentina Todorova²

 ¹ National Institute for Marine Research and Development "Grigore Antipa", Constanta, Romania
² Bulgarian Academy of Sciences, Institute of Oceanology, Sofia, Bulgaria

"Mediterranization" defines here the process through which the Black Sea ecosystem acquires a more Mediterranean-like character, both in terms of fauna and flora and of its functioning.

At present around 80% of the Black Sea fauna and flora are of Mediterranean origin. In the distant past (Karangat period, 100,000 yrs b.p.) the Black Sea was even more Mediterranean-like, but this situation was reversed towards the end of the Wurm glaciation.

It is easy to assume that global warming of the climate will lead to increased temperatures and salinity of the Black Sea, thus accelerating the mediterranization process. But is it really? The workings of Earth's climate are not simple nor readily understandable. While warming of the climate over the vast landmasses surrounding the Black Sea may be more clearly perceived, it is still unclear how climate change is influencing the Black Sea properly. Recent research in different areas of the Black Sea gives mixed signals.

Studies of the interannual variability of sea surface temperature in the Black Sea (Ginzburg *et al.*, 2008) and of the impact of climatic changes on its hydrological structure (Piotukh *et al.*, 2008) have shown a positive trend of mean basin-averaged SSTs of about 0.06°C per year between 1982-2007. However, within this period the character of temperature changes and SST trends were significantly different: negative trends of mean annual SSTs in 1985-1993, marked rise of SST in 1993-2001 (over 2 °C), and a tendency to its decrease (under the continued global warming) after 2001. The trend of winter SSTs in the Black Sea over a longer period (1957-2002) was small and negative, of about -0.008 °C per year (see Ilyin, this volume).

The SST variability penetrates in depth and is reflected in the temperatures of the Cold Intermediate Layer (CIL). The cooling caused by the negative trend of winter SST is strongly expressed throughout the CIL and even penetrates in the permanent picno-halocline to a depth of 150 m. In turn, the warming signal is expressed only in the upper layers of the CIL (30-50 m). It appears that until now climatic changes have resulted in an increase of the "cold reserve" of the CIL.

An increasingly cold CIL coupled with an increase in mixing is very likely to produce a cooling of Black Sea surface waters as a response to climate change. This general cooling trend can be overridden or strengthened in certain areas due to locally specific situations.

In general, the shallow waters in the immediate vicinity of the coasts are more likely to become very warm during summer, regardless of the general cooling trend. Strong vertical stratification and

bottom anoxia are likely to appear locally, especially if discharge of nutrient-rich continental waters also occurs in the area. A good example is the northwestern shelf, where the mean annual SST in coastal waters (Odessa) increased by 1.7 °C during 1998-2008. There, during the last 5-7 years, the phytoplankton community has seen an increase of the percentage of thermophilic microalgae (tropical and subtropical species) and a decrease of psychrophilic (arctic-boreal) species (Derezyuk and Medinets, 2008). Also, a study on small pelagic fish from the northwestern shelf during the last decade (Shulman, 2008) shows a deterioration of psychrophilic sprat condition, while thermophilic anchovy fared much better. The fragile recovery of the northwestern shelf benthic ecosystem is very likely to come to an abrupt end if the warming tendency continues in this area.

A continuation of the present trend of increasing in a duration and intensity of the westerly and northerly winds is likely to produce more upwelling events along the steeper western and northern coasts of the Black Sea, with a corresponding increase in intensity and duration of cooling of surface waters near these coasts. This situation will permit the access of more cold-tolerant Mediterranean fauna and flora.

The southern coast has been until now the most Mediterranean-like and will most probably continue to be even more so. A more intense mediterranization of this region will occur especially if the global sea level rise will lead to a rise in the level of the Mediterranean. If the inflow of Mediterranean water through the Bosphorus becomes greater than at present, this will result not only in intensified mediterranization of the southern Black Sea coast, but also in an extension of mediterranization in the adjacent southwestern and southeastern corners of the Black Sea.

To summarize, cooling and increased mixing of open-sea waters is to be expected over the whole Black Sea basin, while coastal waters may follow or not this general trend, depending on locally important factors:

- increased mediterranization is to be expected along the southern coast and possibly the southwestern and southeastern corners;
- more intensified cooling and prolonged upwelling along the western and northern coasts which, together with an increase in salinity, could allow for more ingression of cold-tolerant Mediterranean species;
- warming, strong vertical stratification and recurrence of anoxic events on the northwestern shelf, an area most definitely not prone to mediterranization.

Climate warming poses a threat to an unique aspect of the Black Sea ecosystem: the Zernov's *Phyllophora* field.

During the last decade, the increase in water transparency and accumulation of nutrients in sediments over the northwestern shelf has caused succession in the structure of seaweed communities of Zernov's *Phyllophora* field (Minicheva *et al.*, 2008a). As a result, small species of filamentous algae, which have 40 times higher biological activity than *Phyllophora*, have started to replace it. Recent observations (Minicheva, 2007b) suggest that *Phyllophora* and the filamentous algae compete seasonally, with perennial *Phyllophora* dominating in winter but being outcompeted in summer (Minicheva, this volume).

Climatic change could also induce the desertification of the vast steppes which border the Black Sea to the north. This could reduce river runoff but increase erosion and sediment load of these waters, leading in turn to more turbidity and sedimentation on the northwestern shelf. If the northwestern shelf ecosystem evolves as we foresee here, with more summer phytoplankton blooms and recurrence of anoxic events, Zernov's *Phyllophora* field is most likely going to disappear.

In contrast the smaller *Phyllophora* field recently discovered (Todorova and Micu, 2008) off the southern Bulgarian coast might be enhanced if our forecast for the western coast proves is verified.

Changes features in ichthyofauna in the coastal sea waters of the Crimea in the last decade

Alexander Boltachev

Institute of Biology of Southern Seas, National Academy of Science of Ukraine, Sevastopol, Ukraine

ABSTRACT

141 species, 90 genera, 50 families of fish species registered in the Black Sea, have been seen near the Crimean shores. For the last decade 15 species were registered here for the first time. They comprise seven Atlantic-Mediterranean species dispersed along the Crimean coasts by now, one endemic species of the Far Eastern Pacific Ocean (chameleon goby *Tridentiger trigonocephalus*) naturalized in Sevastopol Bay, four invading species, freshwater in origin, settled permanently occur in the estuary zones of the peninsula; the remaining three species are known from single findings and apparently belong to the category of accidental visitor. In recent the number of registrations of rare Atlantic-Mediterranean species also increased. At the same time the stocks of the main commercial species are slowly recovering from their recent collapse.

Key words: ichthyofauna, mediterranization, human impact, alien species

The dynamics of Black Sea ichthyofauna formation has continued for about eight thousand years after the last joining of the Black Sea with the World Ocean. According to the last data it accounts for about 200 species and subspecies, including both marine fish and occasional freshwater (Svetovidov, 1964; Boltachev, 2003; FNAM, 1984-1986; FAO, 1987). Marine fish – about 140 species and subspecies - make the base of the ichthyofauna. The Atlantic-Mediterranean tropical and subtropical euryhaline species dominate among them. They inhabit mostly the upper layer. Sixty of them completely acclimatized, and formed endemic subspecies; all stages of their life cycle are connected with the Black Sea. The others migrate regularly at the warm time of the year for fasting from other areas in the Mediterranean Basin. (Vodyanitsky, 1930). Boreal-Atlantic fish is represented with more than ten species, inhabiting at the warm time mainly the cool subsurface layer and entering the surface layer in the winter period (Svetovidov, 1964). Diversity of the Black Sea ichthyofauna, as a rule, increases due to intrusion of fish from the Mediterranean Sea ("mediterranization") in recent decades (Puzanov, 1967; Boltachev and Yurakhno, 2002). In addition, fish originating from the Indian Ocean, coming to the Mediterranean Sea through the Suez Canal and further north to the Black Sea, as well as artificially introduced species make part of this group.

The group of brackish water fish accounts for 22 species, endemic or common with the Caspian Sea, which are autochthonous relicts of the ancient brackish-water Ponticus lake – sea (Rass, 1949). Many of these species are distributed in the brackish coastal waters and river estuaries, mostly in the northwestern part of the Black Sea and near of Kerch Strait.

The group of diadromous and semi-diadromous comprises 25 species and is of quite ancient origin – about 1.5-2 million years (Oven, 1993). It is connected with fasting migrations of these fishes (with the exception of the eel fish, *Anguilla anguilla*) from the northern rivers into the Pontic lake basin and fish, going up the rivers for spawning.

The last group is formed by typical freshwater species (14-16), occasionally coming from rivers to the coastal marine zone, usually during high water in the rivers.

In the first stages of Black Sea taxonomic studies a number of researchers noted high species abundance in the Crimean coastal zone flora and fauna, if compared with the other basin regions (Kiselevich, 1922). This is connected to the geographical location of the peninsula, spreading to the south about to the middle of the sea, to difference in abiotic and biocenotic factors, width of the shelf etc. Across the small length of the peninsula from north to south (about 180 km) considerable differences in hydrologic characteristics of the coastal zone can be traced. Near northern and northwestern shores of Crimea, water freezes in winter and heats up to 27°C in summer; water salinity in the Karkinitsky Gulf decreases at the surface to 1.6 ‰, while near the southern coast interseasonal temperature changes are the least for the region – from 7°C in winter to 26°C in summer; variations of salinity here are not inconsiderable and its average magnitudes are in the limits of 18 ‰. Thus, the Crimean coastal zone can be considered as a model region from the point of view of general tendencies of biocenotic changes taking place at the Black Sea shelf, depending on habitat conditions and anthropogenic impact.

According to our records and the pertinent literature, fish of 141 species, 90 genera, 50 families can be found in the coastal and shelf Black Sea seawater zones of Crimea (Table 1).

			Ecological group						
			1	Marine	fish		Brackish	Diadromous	Fresh-
Nº	Families	Species		b	с	d	relicts	and semi – diadromous fish	water fish
1	2	3	4	5	6	7	8	9	10
1	Squalidae	Squalus acanthias L.		+					
2	Rajidae	Raja clavata L.		+					
3	Dasyatidae	Dasyatis pastinaca (L.)	+						
4	Acipenseridae	Acipenser gueldenstaedti colchicus (non Marti)						+	
5		Acipenser nudiventris Lovetzky*						+	
6		Acipenser stellatus Pallas						+	
7		Acipenser sturio L.*						+	
8		Huso huso (L.)*						+	
9	Clupeidae	Alosa caspia nordmanni Antipa						+	
10		Alosa caspia tanaica (Grimm)						+	
11		Alosa kessleri pontica (Eichwald)						+	
12		Alosa caspia paleostomi (Sadowsky)						+	
13		Alosa fallax nilotica (Geoffroy StHilaire)						+	
14		Clupeonella cultriventris cultriventis (Nordmann)					+		
15		Sardina pilchardus (Walbaum)							
16		Sardinella aurita Valenciennes	+						
17		Sprattus sprattus phalericus (Risso)		+					
18	Engraulidae	Engraulis encrasicolus ponticus Aleksandrov	+						
19		Engraulis encrasicolus maeoticus Pusanov	+						
20	Salmonidae	Salmo trutta labrax Pallas*						+	
21	Anguillidae	Anguilla anguilla (L.)						+	
22		Conger conger (L.)	+						
23	Cyprinidae	Carassius auratus (L.)							+
24		Pseudorasbora parva (Temminck et Schlegel)							+
25	Gadidae	Gaidropsarus mediterraneus (L.)		+					
26		Merlangius merlangus euxinus (Nordmann)		+					
27		Micromesistius poutassou (Risso)		+					
28	Ophidiidae	Ophidion rochei Müller	+						
29	Poeciliidae	Gambusia holbrooki (Girard)							+

Table 1. List of fish in the Crimean coastal zone of the Black Sea.

1	2	3	4		6	7	8	9	10
30	Atherinidae	Atherina boyeri bonapartii Boulenger	+						
31		Atherina mochon pontica Eichwald	+						
32		Atherina hepsetus L.	+						
33	Belonidae	Belone helone euxini Günther	+						
34	Zeidae	Zeus faber L							
35	Gasterosteidae	Gasterosteus aculeatus I		+					
36	Syngnathidae	Naronhis onhidion taras (Bathke)	+						
27	Synghatinuae	Superathys abaster Bisso	·						
20		Syngnathus abuster Kisso	- T						
20		Syngnainus acus L.	-						
39		Syngnathus schmitati Popov	+						
40		Syngnathus tenuirostris Rathke	+						
41		Syngnathus typnie argentatus Pallas	+						
42		Syngnathus variegates Pallas	+						
43		Hippocampus hippocampus (L.)	+						
44	Sphyraenidae	Sphyraena pinguis Günther			+				
45		Sphyraena sphyraena (L.)	+						
46	Mugilidae	Chelon labrosus (Risso)	+						
47		Liza aurata (Risso)	+						
48		Liza haematocheilus (Temminch et Schlegel)				+			
49		Liza ramada (Risso)	+						
50		Liza saliens (Risso)	+						
51		Mugil cephalus L.	+						
52	Serranidae	Serranus scriba (L.)	+						
53	Moronidae	Dicentrarchus labrax (L.)*	+						
54		Morone saxatilis (Walbaum, 1792)	+						
55	Centrarchidae	Lepomis gibbosus (L.)							+
56	Percidae	Stizostedion lucioperca (L.)						+	
57	Pomatomidae	Pomatomus saltatrix (L.)	+						
58	Carangidae	Trachurus mediterraneus ponticus Aleev	+						
59	Curungiane	Trachurus trachurus trachurus (I_)	+						
60	Contracanthidae	Spicara flavuosa Bafinesque	+						
61	Centracantinuae	Spicara magna (L.)	+						
62		Spicara maena (L.)							
62	Sparidaa	Poors boors (L.)	т 						
05	Sparidae	Boops boops (E.)	-						
64		Diploaus annuaris (L.)	+						
65		Diplodus puntazzo (Cetti)*	+						
66		Diplodus sargus (L)	+						
67		Pagellus erythrinus (L.)	+						
68		Sarpa salpa (L.)	+						
69		Sparus aurata L.	+						
70	Sciaenidae	Sciaena umbra L.	+						
71		Umbrina cirrosa L.*	+						
72	Mullidae	Mullus barbatus ponticus Essipov	+						
73	Chaetodontidae	Heniochus acuminatus (L.)			+				
74	Pomacentridae	Chromis chromis (L.)	+						
75	Labridae	Ctenolabrus rupestris (L.)	+						
76		Labrus viridis L.*	+						
77		Symphodus cinereus (Bonnatterre)	+						
78		Symphodus ocellatus Forsskål	+						
70	<u> </u>	Symphodus roissali (Risso)	+						
80		Symphotus (1850)							
00		Symphotus uncu (L.)							
81	A	Symphoaus rostratus (Bioch)	+						
82	Ammodytidae	<i>Gymnammoaytes cicerellus</i> (Katinesque)		+					
83	Trachinidae	Trachinus draco L.	+						
84	Uranoscopidae	Uranoscopus scaber L.	+						

1	2	3		5	6	7	8	9	10
85	Scombridae	Sarda sarda (Bloch)	+						
86		Scomber japonicus colias Gmelin	+						
87		Scomber scombrus L.							
88		Thunnus thynnus (L.)	+						
89	Xiphiidae	Xiphas gladius L.	+						
90	Gobiidae	Aphia minuta (Risso)	+						
91		Benthophiloides stellatus (Sauvage)					+		
92		Gobius auratus Risso*	+						
03		Gobius hurduidis Kasso	+						
04		Cobius cabitis Pallas	+						
94		Cobius coolitis i allas							
95									
96		Gobius niger Jozo L.	+						
9/		Gobius ophiocephalus Pallas	+						
98		Gobius paganellus L.	+						
99		Gobius xanthocephalus Heymer et Zander	+						
100		Knipowitschia caucasica (Berg)					+		
101		Knipowitschia longecaudata (Kessler)					+		
102		Mesogobius batrachocephalus (Pallas)					+		
103		Neogobius cephalargoides Pinchuk					+		
104		Neogobius eurycephalus (Kessler)					+		
105		Neogobius fluviatilis (Pallas)					+		
106		Neogobius kessleri (Gunther)					+		
107		Neogobius melanostomus (Pallas)					+		
108		Neogobius platyrostris (Pallas)*					+		
109		Neogobius ratan rattan (Nordmann)					+		
110		Neogobius syrman (Nordmann)					+		
111		Pomatoschistus marmoratus (Risso)	+						
112		Pomatoschistus minutus elongatus (Canestrini)	+						
113		Pomatoschistus pictus adriaticus (Malm)	+						
114		Proterorhinus marmoratus (Pallas)					+		
115		Tridentiger trigonocephalus (Gill)				+			
116	Callionymidae	Callionymus pusillus Delaroche*	+						
117		Callionymus risso Le Sueur*	+						
118	Blenniidae	Aidablennius sphynx (Valenciennes)	+						
119	Dieminuue	Blennius ocellaris I	+						
120		Commoblennius galerita (L.)	+						
120		Linonhrus adriaticus (Steindachner et Kolombatović)	+						
121		Lipophrus duranteus (Stemacemer et Rotomoatovie)	+						
122		Parablannius incognitus (Both)	+						
123		Parablannius sanavinoloutus (Dallo)	- +						
124		Parablemius sanguinoienius (Panas)	T						
123		Taraotennius teniacularis (Brunnich)	+						
120	T	Parablennius zvonimiri (Kolombatović)							
127	1 ripterygildae	Tripterygion tripteronotus (Risso)							
128	Scorpaenidae	Scorpaena porcus L.							
129	i riglidae	Aspitrigla cuculus (L.)							
130	Dathidaa	Chelidonichthys lucernus (L.)							
131	Dotnidae	Arnoglossus kessleri Schmidt*							
132	scopnthalmidae	Pseud maxima maeotica (Pallas)		+					
133		<i>Pseua maxima torosa</i> (Rathke)		+					
134	DI	Scophthalmus rhombus (L.)		+					
135	Pleuronectidae	Platichthys flesus luscus (Pallas)		+					
136	Soleidae	Solea nasuta (Pallas)	+						
137	Balistidae	Balistes carolinensis Gmelin	+						

1	2	3	4	5	6	7	8	9	10
138	Gobiesocidae	Diplecogaster bimaculata euxinica Murgoci	+						
139		Lepadogaster candollei Risso	+						
140		Lepadogaster lepadogaster lepadogaster (Bonnaterre)	+						
141	Lophiidae	Lophius piscatoris L.*	+						

Remark:

a - Atlanto-Mediterranean warm water fish;

b – Boreal-Atlantic fish;c – Indo-Pacific fish;

d – Far-East Pacific fish;

* - species, put into the "The Red book of Ukraine" (1994).

Marine fish make the base of the region fish community (78.0 %): tropical and subtropical 94 species Atlantic-Mediterranean, 12 Boreal-Atlantic, 2 Indo-Pacific and 2 Pacific (Table 1 and Figure 1). The Far-east haarder (*Liza haematocheilus*) is the only completely naturalized species of several valuable commercial fishes, that were artificially introduced into the Black and Azov Seas. In recent years this species distributed into the areas of the Mediterranean Basin.

There are 14 species of brackish water autochthonic relicts – common kilka (*Clupeonella cultriventris cultriventis*) and gobies (Gobiidae). Besides, 13 diadromous and semi-diadromous fishes-sturgeons (Acipenseridae), herrings (genus *Alosa*), Black Sea salmon (*Salmo trutta labrax*), European pike-perch (*Stizostedion lucioperca*) inhabit the Crimean waters. It must be mentioned that the spiny sturgeon (*Acipenser nudiventris*) and Atlantic sturgeon (*A. sturio*), included into this list, have not been recorded for over 50 years near the Crimean or Ukrainian shores. Freshwater fishes are represented by four species; all of them are aliens for the inner water reservoirs of the Crimea, and three of them were registered in the estuaries for the first time. It is possible that the list of freshwater species is not complete, as we lack recent information about ichthyofauna composition in the brackish part of the Karkinitsky Gulf.



Figure 1. Ecological structure of ichthyofauna in coastal Black Sea water of the Crimea.

The first signs of negative changes in the ichthyofauna diversity and food fish stocks in the Black Sea and near Crimea in particular were noted at the end of the'60s, and by the beginning of the '90s the general condition of the ecosystem was evaluated as catastrophic (Rass, 2001). This was a consequence of human activity: chronic pollution, physical destruction of biotopes, overfishing, introduction of aggressive species – aliens with ballast waters, overregulation of rivers flows, etc.

For example, the number of fish species in the coastal zone of Sevastopol in 1990 decreased almost two times compared with 1980 – from 84 to 45 (Oven, 1993). Most valuable fish species lost their fishery importance – sturgeons, bonito (*Sarda sarda*), Atlantic mackerel (*Scomber scombrus*), bluefish (*Pomatomu saltatrix*), grey mullets (Mugilidae), some species of herrings (Clupeidae), etc. Fishing of one of the most abundant species – horse-mackerel (*Trachurus mediterraneus ponticus*)

stopped by the middle of the '90s and anchovy (*Engraulis encrasicolus*) catches diminished by about two orders of magnitudes. Black Sea sprat (*Sprattus sprattus phalericus*) became the main fishery species at the Black Sea shelf of Crimea, making 94-98% of general catches. Some 20 species appeared as being threatened and were included into the "Red book of Ukraine".

From about 1998 up to the present time one observes near Crimean coasts some positive tendency in the restoration of the specific diversity of the native Black Sea ichthyofauna, with appearance of new species and increase of quantitative characteristics of some valuable for fishing and rare species.

From 2001 one observes an increase in the stock of the Black Sea horse-mackerel, and in 2003 it was again included into the list of fishery items. Anchovy and young bluefish have been wintering the last years near the Southern coast of Crimea up to Sevastopol, and the golden mullet (*Liza aurata*), leaping grey mullet (*L. saliens*), common grey mullet (*Mugil cephalus*) and sometimes the haarder comes to the bays in the vicinity of Sevastopol. In the warm season adult bluefish and bonito may be found in trawl catches. The numbers of garfish (*Belone belone euxini*) is increasing both in the Black Sea and the Sea of Azov near Crimea.

When evaluating modern state of the Crimean coast ichthyofauna, registration of findings of species rare for the region is of interest. For example, in the coastal zone of the southwestern Crimea they mark an increase in frequency of occurrence of such "Red book" species as the Black Sea salmon (*Salmo trutta labrax*), common bass (*Dicentrarchus labrax*), dotted dragonet (*Callionymus risso*), bearded umbrine (*Umbrina cirrhosa*), yellow gurnard (*Chelidonichthys lucernus*), puntazzo (*Diplodus puntazzo*) and green wrass (*Labrus viridis*). Sea horse (*Hippocampus hippocampus*), which practically disappeared in the middle of the '90s, jumped in abundance in 2002 and 2008 along the coasts of Crimea, the Black Sea northwestern part and the Northern Caucasus as well.

The barfish (*Chromis chromis*), lettered perch (*Serranus scriba*), the blotched picarel (*Spicara maena*) and bogue (*Boops boops*) are again found in the sea. The round sardinella (*Sardinella aurita*) recently fished out in Sevastopol bays, is the solitary specimen lately known in the Crimean water. The European pilchard (*Sardina pilchardus*) though in small number, is frequently found in fixed nets and trawl catches along all the Black Sea shelf of Crimea. Catches of two Mediterranean migrant fishes, such as the thin-lipped grey mullet (*Liza ramada*) in 2006 and the European barracuda (*Sphyraena sphyraena*) in 2007 near Sevastopol are unique, because the first species have not been met here since 1930 and the second one since 1950.

15 fish species, new for the ichthyofauna of this region as well as for the Black Sea as a whole, or whose presence here was previously doubted, were registered during the last decade, just in the coastal zone of the southwestern and southern Crimea.

Among them, seven Atlantic-Mediterranean species have acclimatized at present along the Crimean coasts: thick-lipped mullet (*Chelon labrosus*), dorado (*Sparus aurata*), salema (*Sarpa salpa*), yellow-headed goby (*Gobius xanthocephalus*), red-mouthed goby (*G. cruentatus*), incognito blenny (*Parablennius incognitus*), and greater pipefish (*Syngnathus acus*). It is possible that the number of some aforementioned bottom resident species (gobies, blennies) was small in previous years, and they were just not considered before. Note also the complexity of their catch and identification. The endemic of the far eastern seas (chameleon goby *Tridentiger trigonocephalus*) has naturalized in Sevastopol Bay. Four invading species, freshwater in origin, were recorded in the estuary zones of the peninsula: far eastern – stone morocco (*Pseudorasbora parva*), goldfish (*Carassius auratus*); and north american – pumpkinseed (*Lepomis gibbosus*) and eastern mosquitofish (*Gambusia holbrooki*).

The remaining three species are known only from single findings and apparently belong to the category of accidental. The Atlantic-Boreal species blue whiting (*Micromesistius poutassou*) was caught near Balaklava (Cape Aiya), and two specimens of the Indo-West-Pacific red barracuda (*Sphyraena pinguis*) and pennant coralfish (*Heniochus acuminatus*) were caught in Balaklava Bay.

The red barracuda, a Lessepsian migrant, was first found off the coasts of Palestine in 1931 and is rather abundant at present in the eastern part of the Mediterranean Sea and in the Aegean Sea (Golani *et al.*, 2002). The pennant coralfish and chameleon goby are most likely related to ballast waters of commercial vessels, and discovery of blue whiting and red barracuda is quite possible as a result of their migrations.

Black Sea fisheries and climate change

Naciye Erdogan¹, Ertug Duzgunes² and Hamdi Ogut²

¹ Ordu University, Fatsa Faculty of Marine Sciences, Turkey ² Karadeniz Technical University, Faculty of Marine Sciences, Trabzon, Turkey

ABSTRACT

Biodiversity and total biomass of major fish species have already been reduced in the Black Sea, due to environmental pollution, overfishing and other anthropogenic effects. To make it worse, introduced species have increased in abundance and diversity as well, leading to increased food competition and predation, thus putting more pressure on native stocks. Sea water temperature is one of the most important key factor having a direct effect on the physiological wellbeing of aquatic organisms. Any important fluctuations in the temperature will put tremendous pressure on organisms at or near their physiological limits, by challenging organisms' energy budget to survive. When aquatic organisms fail to adapt to new conditions, they will be forced to migrate to more favorable conditions or die; adaptation will be unsuccessful. Moreover, increases in water temperature may change traditional migration patterns of migratory pelagic, e.g. south to north migration of anchovy in Black Sea. More research is needed to determine the association between the type and level of change in the abiotic factors and the type and level of physiological and/or behavioral response in especially economically important stocks.

Key words: global warming, climate change, fisheries, Black Sea.

INTRODUCTION

Effects of global warming/climate change on fisheries

Fisheries is one of the most sectors most threatened by global warming as livestock production and grains and other crops could decrease substantially due to the drought, leading to produce more from the sea. Billions of people rely on fish as an important protein source and more than 200 million people are employed in fisheries related sector worldwide (WWF, 2008).

There is strong scientific evidence of negative effects of global warming on fisheries (Cushing, 1982; Beukema *et al.*, 1990; Beamish, 1995; Hays *et al.*, 2005; Roessig *et al.*, 2004; Kojiri *et al.*, 2008). The reaction of fish can extend from physiological adaptation to major migrations to more suitable environments, driven by shifts in diversity, timing of seasonal peaks and abundance of prey items, or increased cost of homeostasis at a given location as well (Beaugrand *et al.*, 2002; Hays *et al.*, 2005; Richardson and Schoeman, 2004).

Higher water temperatures could affect fish and fisheries in various ways (Reid *et al.*, 1997). First of all, through physiological, behavioral and genetical adaptations. Growth as mentioned above is the first to be affected (Fivelstad *et al.*, 2007). Elevated temperatures accelerate the loss of hypo-osmoregulatory capacity in Atlantic salmon (Handeland *et al.*, 2004). The same study emphasized that temperature influences the development and loss of smolt characteristics in both strains, and

has long-term effects on post-smolt performance in seawater. More surprisingly in a recent study, the growth of a common coral-reef fish *Acanthochromis polyacanthus* was found to be strongly affected by the elevated water temperatures due to climate change (Munday *et al.*, 2008). However, effects of temperature on organisms at individual and population levels are very complex, due to the fact that temperature influences the organism as well as other factors affecting the organism. Impaired breeding, for example, is one of the most apparent outcomes of insufficient growth. Decreased growth, especially in larval fish, may cause very low levels of survival or high variation in larva production (Chong *et al.*, 2004). On the other hand, as a direct effect of temperature, breeding efficiency of cold water fish due to the high temperatures will be diminished and will be expressed as low egg and sperm quality.

Migratory reactions of fish populations to increasing temperatures are becoming more apparent for many aquatic species (Quero *et al.*, 1998). Migration of fish into cooler areas could generate serious problems due to the fact that food webs will be reformed in response to the newcomers. It is likely that food in the new area will not support both newcomers and old settlers. Thus, competing abilities will determine which fish will be able to survive. It should be noted that if any change occurs in the migratory behavior of a prey fish, it will be reflected in their predators as well.

FISHERIES IN THE BLACK SEA

Fisheries is an important sector for the Black Sea countries as a major source of employment and economical returns. More than 298 millions persons live in the Black Sea countries and around 17 millions inhabit on the coastline (Table 1). Ukraine and Turkey have the longest coastlines offering advantages in fisheries to these countries. Total fish production exceeded 750,000 tons in 2007 with an increase of 72 % comparing with 2000 data (Table 1, Figure 1). The majority of the production belongs to Turkey (661,153 tons, 89%), followed by Ukraine and Russian Federation (Figure 2).

Table 1. Some demographic and fisheries data of the Black Sea countries.

Bulgaria	Georgia	Romania	Russian Federation	Turkey	Ukraine
7965	5177	22387	144082	70318	48902
714	650	746	1159	6700	6800
354	310	225	800^{2}	1329	2782^{2}
11000	3000	13000	3051000^3	644000	229000^{3}
2843	2837	1824	24922	342455	63161
1261	360	436	2912	7308	2300
	Bulgaria 7965 714 354 11000 2843 1261	BulgariaGeorgia79655177714650354310110003000284328371261360	BulgariaGeorgiaRomania7965517722387714650746354310225110003000130002843283718241261360436	BulgariaGeorgiaRomaniaRussian Federation79655177223871440827146507461159354310225800²110003000130003051000³2843283718242492212613604362912	BulgariaGeorgiaRomaniaRussian FederationTurkey7965517722387144082703187146507461159670035431022580021329110003000130003051000364400028432837182424922342455126136043629127308

¹ 2000 demographic data; ² Including Azov Sea; ³ Includes high seas fisheries.



Figure 1. Marine fish catch in the Black Sea countries.



Figure 2. Share of the countries in fish catch in the Black Sea in 2007.

The number of fishing vessels is around 14,500 and half of the Black Sea fishing fleet is operated by Turkey (Table 1). In terms of fishing effort, Turkey is more efficient due to the number of big sized trawlers and purse seiners (up to 64 m overall length; more than 800 vessels) that make up about 10 % of the Turkish Black Sea fishing fleet (TSA, 2008).

Historically, fish catches did rapidly increase after 1970, mainly due to subsidizes provided by Turkish Government to the fisheries sector after the Fisheries Law enacted in 1971. Most of the wooden vessels were replaced with the steel ones, lengths of the vessels and fishing nets increased, long ranged fish finders and navigation instruments provided, and fish meal and oil plants were established with the support given to the industry. Due to ecological impacts, fish stocks collapsed in 1988-89 fishing season and 60-70% of the production sharply decreased. After 1992, a recovery period did start and the production reached its earlier peak level in 2007 (Figure 3) with the major input of anchovy into production.



Figure 3. Production of some important fish species in the Black Sea in 2007.

Anchovy plays an important role in the food web and fish production in the Black Sea. Any impact on anchovy stocks like pollution in spawning grounds, extreme environmental parameters above or under tolerance limits, overfishing and high predation rates may affect its future productivity and abundance. According to the 2007 data anchovy production has reached over 35,700 tons in Turkey. There is no data from Ukraine, Russian Federation and Georgia except Turkey. The data from Turkey suggests that total anchovy catch is around 40,000 tons (including the catch of purse-seiners from Turkey operating off the Georgian coasts).

Production of all fish species showed the same increase and decline trend as national overall production trend (Figure 2). Production of all species increased till the collapse period (1988-89), and then declined sharply. There are some recent signs of slight recovery. Majority of the production has been obtained from anchovy, followed by horse mackerel, whiting, sea snail, baby clam, mackerel and blue fish (Figure 4). In case of western shelf, the spiny dog fish also has an importance for the fisheries of Romania and Bulgaria.



Figure 4. 2007 production of some important species in the Black Sea.

Black Sea fisheries are very important for Turkey. More than 80% of the production comes from the Black Sea (59% from the Eastern and 21 % from the Western Black Sea) (Figure 5).



🗆 Eastern Black Sea 🗈 Western Black Sea 🖻 Marmara 🖻 Aegean 🖽 Mediterranean

Figure 5. Marine production of Turkey by the seas (tons).

While counting the highest marine production rates among Black Sea countries, annual fish consumption per capita in Turkey overall is very low. The mean rate 7-8 kg per capita is half of the world consumption rate (16 kg) and 25 % of EU rate (25 kg). Annual fish consumption rate is much higher, ranging between 75-80 kg, in the coastal cities of Turkey.

Mariculture is progressing in the Black Sea. There are a number of companies, all located in Persembe Bay (Ordu), Yomra (Trabzon) and Rize and their production in marine cages reaches up to 5,000 tons.

POTENTIAL IMPACTS OF CLIMATE CHANGE ON BLACK SEA FISHERIES

Biodiversity and total biomass of major economical fish species have been reduced already in the Black Sea in the last forty years, due to environmental pollution, overfishing and other anthropogenic effects. To make it worse, the number of invasive species is increasing as well, putting more pressure on domestic stocks.

It should be noted that fisheries resources have been already damaged by overfishing and pollution. Additive pressure by global warming could be very damaging. Decreases and irregularities in rainfalls may affect nutrient input to the Black Sea through rivers creating chain reaction from bottom to top of the food web.

Biodiversity in the ecosystem could be seriously affected. Composition of species in the commercial catch has decreased, comparing with that of the 1970s. Brown meager, bogue, Mediterranean mussel, oysters and gurnard and sturgeons were all endangered and sea bream is extinct in Turkish coastal waters. The number of introduced species has increased (i.e. *Rapana thomasiana, Mnemiopsis leidyi, Anadara cornea, Mugil soiuy*) due to transportation by merchant vessels, favorable environmental conditions and absence of predators.

In recent years, warming has affected migration patterns of anchovy leading to a shortening of fishing season. Before the 1990s main anchovy fishing season was between November to February but just after collapsing the season was limited to early January. Further temperatures over 15-16°C, prevents schooling even in the main fishing season. Although there is anchovy in the sea, it becomes more difficult to catch them with the purse seines.

All these observations are supported by the analysis of daily sea surface temperature time series (Turkish State Meteorology Service). Figure 6 shows that sea surface water temperature changed in the anchovy fishing season from 1960 to 2007. All monthly figures show a similar pattern indicating that warming of sea water started in the late 1980s.



Figure 6. Giresun station surface sea water temperatures from November to February during 1985-2007.

On the other hand, the number of days with optimum temperatures of 9.5-14.5°C has considerably increased in the same period (Figure 7). There is a good correlation between number of days with optimum temperature and fish catch. It should be noted that if the anchovy season gets shorter, all fishing effort will be deployed in this limited season, impacting on the fish stocks.



Figure 7. Optimal fishing days (9.5-14.5°C) total anchovy production from 1970 to 2006.

Warming may encourage introduced species over local species. For example, after the introduction of the Pacific Mullet (*Mugil soiuy*) that migrates to Turkish waters from May to June, the production of five local species has decreased and then some of these species disappeared due to high food competition. At present, along the Turkish Black Sea coast four of five local mullet species are losing commercial importance due to pacific mullet.

In the region, cold water species (e.g. rainbow trout) aquaculture both in land based ponds and marine cages have increased substantially. Some anticipated problems observed in the last decade are: 1) decreased efficiency in breeding (low egg and sperm quality, shift in spawning time), 2) increased disease frequency and occurrences (e.g. white spot disease in freshwater and vibriosis in marine cages), 3) longer growing period for sea bass in marine environment. Should the environmental temperature increase further, sea bass will replace rainbow trout in sea cages. Possible sea bream giving large numbers of mortalities to winter syndrome disease could be an alternative species as well if minimum water temperature of sea water increases to 10°C from 8°C in the region.

Introduced species

Increasing maritime traffic among international waters, increased water temperatures and favoured the extension of certain species. Of the 650 species presently living in the Mediterranean, 90 were determined to be introduced. Fifty-nine of the introduced came through Suez Channel.

There is accumulating evidence that gelatinous zooplankton populations have increased in recent years in the world (Link and Ford, 2006; Kawahara *et al.*, 2006). Overfishing, eutrophication, and species introductions have been suggested to favor jellyfish populations (Shiganova, 1998; Parsons and Lalli, 2002; Lynam *et al.*, 2005; Attrill *et al.*, 2007; Purcell, 2005). There have been two jellyfish introductions in the Black Sea: (*Mnemiopsis leidyi* during early 1980s and *Beroe ovata* late 1990s). Both species adapted to the Black Sea ecosystem efficiently. *M. leidyi* is blamed for the collapse of fisheries in the Black Sea. Similarly profound impacts have also been documented by many other authors (Brodeur, 1998; Purcell and Arai, 2001; Daskalov, 2002). They respond to any such environmental changes as algal blooms due to the fact that Jellyfish species are very

opportunistic. Limited algal blooms in the Black sea could be the results of inhabiting large population of jellyfish. However, as expected in the future the Black Sea ecosystem became very fragile, and large fluctuations in the fisheries could be expected in the future.

Due to increased complaints of fishermen, there are studies undergoing to determine causative agent and potential impacts on the ecosystem. The first findings indicate that such phenomenon (white colored mucilage secretion) is probably the reason of an algal agglomeration similar to those observed in the Adriatic and western Mediterranean Sea. Such unexpected events as exotic phytoplankton blooms, which prevent light penetration and oxygen circulation, though very rare in the Black Sea comparing to other parts of the world seas (Feyzioglu and Ogut, 2005), it should be expected to occur more frequent in the coming decades due to irregularities in the climate.

There have been very few studies dealing with introduced species and global change together. One study carried out by Stachowicz *et al.* (2002) found strong evidence in responses of ascidians (sea squirts) to interannual temperatures. Introduced species were trying to recruit earlier than the native species. In Turkey, it is agreed that spread and successful invasion of the whelk (*Rapana tomasiana*) in the whole Black Sea ecosystem took place by the ballast waters of the merchant ships.

Native species

The frequency of algal blooms around the coastal waters of Turkey has been relatively low (Feyzioglu and Ogut, 2005). However, with the warming of water temperature, the frequency of harmful algae (native or introduced) reports will increase in the near future. As mentioned above, new introduced species of harmful algae and native algae blooms are expected to occur more often.

Majority of the production comes from anchovy fishing off the Turkish coasts of the Black Sea. Fishing starts from central northern coast of Turkey and continues towards eastern coastal areas. Water temperature is a key factor determining when fish enters the Turkish coastal areas and when fishing starts to be economically worthwhile. Water temperature should drop to the 16-17 °C in order anchovy to form schools. Delayed entrance of anchovy will limit the duration of the fishing season as well. In the future if water temperature continues to increase, anchovy stock may not migrate to warmer waters off Turkish coast and may prefer not to migrate for foraging, since in their spawning habitats water may also become warmer due to the global warming. It was well documented in the Pacific Ocean that anchovy and sardine populations respond to the increased climatic temperatures. In the warmer regimes, sardine population increased whereas in the cooler cycles anchovy population increased (Chavez *et al.*, 2003). Similar trends were also documented for the salmon as reviewed by Hare and Francis (1995). Over the decades, high and low production levels were observed with the interventions. Climatic temperatures were also linked to the observed variation in the production. Such periods for any fish species is very important to know, manage, protect and increase production while conserving fragile stocks at high risk periods.

Large portion of the remaining is expected to be destroyed in the upcoming decade as well. In the Mediterranean Sea, soft corals (Gorgons) are very common. In recent years, a mass mortality was observed. They first become whitish and then they die due to the tissue necrosis. Martin *et al.* (2002) reported that mortality was caused by three different vibrio species and tissue necrosis only occurred at high temperatures (23°C). This was specifically linked to the acidification due to the increased water levels and temperatures. Similarly, serious levels of damage in the soft corals (Gorgons) in the Mediterranean and Aegean Sea thought to be linked to the increased water level and temperatures.

RECOMMENDATIONS

As any other country, Turkey has to take radical measures to protect her invaluable natural resources. As an important step, Turkey has the signed Kyoto Protocol in 2008. Research programs should be designed to consider effects of global warming. Endangered species should continue to be listed and protected. More research should be carried out on stock assessment of economically important fish species and conservative measures should be taken to protect aquatic resources when necessary.

It is an accepted fact that it is difficult to foresee the type, level and extend of the impacts of global warming on biodiversity and on organisms. Most reports depend on observational studies, not allowing conclusions. Multidisciplinary approaches should be employed combined with the application of modeling techniques, so as to understand complex ecological. Only such approaches may offer some practical solutions for urgent cases.

In short, global warming and related climate change has serious impacts on biodiversity. More effort should be made by <u>all Riparian countries</u> to determine controllable variables having effect on Black Sea ecosystem. More scientific data from holistic studies (multidisciplinary, ecosystem based) are needed for evaluating the dynamics of this system for better risk assessment strategies (modeling the dynamics among ecosystem, pollution and fisheries). Fishing pressure should be balanced according to the capacity of marine living resources. Environmental friendly fishing methods and gears should be encouraged.

Economic aspects of climate change adaptation in Black Sea coastal areas

Aleksandar Shivarov

Varna University of Economics, Bulgaria

ABSTRACT

Climate change exerts long term pressure on the already precarious state of the Black Sea environment. The last episode of mismanagement of the sea in the second half of the twentieth century demonstrated that overlooking the needs of the natural environment carries substantial economic costs. It is necessary therefore to identify the most vulnerable areas and sectors of the coastal societies impacted. The analysis is conducted within the Drivers – Pressures – State – Impacts – Responses (DPSIR) conceptual framework. Major economic effects can result from rising sea level, increasing occurrence of extreme weather events and possible changes in migratory and behavioural patterns of commercially exploited fish species. The need for adaptation calls for coordinated steps at a regional level and involvement of all stakeholders on the national and local levels for the design and timely implementation of suitable actions in response to climate change.

INTRODUCTION

During the past two decades, the Black Sea has been a case study in mismanagement of a large marine ecosystem. Overfishing, nutrient pollution and introduction of exotic species are the main causes of environmental degradation in the sea. Substantial international efforts have been mobilised to stave off the crisis. At present there are signs of recovery of the coastal ecosystems, mainly due to the restructuring of economic activities since the late 1990s (Black Sea Commission, 2008). There are also precarious indications that the sea is moving towards a new stable state, different from the conditions prevailing until the 1960s. The future development path of the ecosystem will depend on its response to the long term climate changes and pressures from the economies in the sea basin and foremost from the coastal countries.

In the last century, considerable temperature increases have been observed at a global scale; the warming trend has significantly intensified over the last five decades. As the Intergovernmental Panel on Climate Change (IPCC, 2007a) stated in its Fourth Assessment Report, warming of the climate system is unequivocal and it is expressed in the increase of global average air and ocean temperatures, widespread melting of snow and ice, and rising sea level. The warming tendency throughout Europe is even more pronounced: the average temperature has increased 1.3°C and 1.0°C for the European land area and European land and ocean area respectively, comparing the trend towards 2008 with pre-industrial times. Europe has warmed slightly more than the global average (i.e. 0.9°C and 0.7°C for land and land and ocean respectively). Considering the European land, nine of the twelve years between 1997 and 2008 were among the warmest since the beginning of instrumental measurements in Europe, with 2007 as the warmest year (1.5°C higher than pre-

industrial), closely followed by 2000, 2006 and 2008 (EEA, 2009). During the last quarter of the twentieth century, temperature trends are higher in Central and North-eastern Europe and in mountainous regions, while lower trends are found around the Mediterranean. An intensification of rainfall is observed in most parts of the continent, even in some areas which are becoming drier, a trend that couples with a surge in the number of extreme weather events (Munich Re, 2008).

There is a broad consensus that the average sea level increased from the nineteenth to the twentieth century, and the total rise in the past century is estimated to be around 0.17 m (IPCC, 2007b). The increase of sea level in the Black Sea basin was by 2.5 mm annually over the last 60 years (Tsimplis *et al.*, 2004), compared to a global average of 1.8 mm per year from 1961 to 2003 (IPCC, 2007b). Mikhailov and Mikhailova (2008) point out that the sea level increase is in the range of 2.0-4.0 mm per year for the Black Sea. This marks a rate higher than the global average and exceeding the level in the Atlantic Ocean (1.7 mm/year) and the Mediterranean (1.1-1.3 mm/year). Actually, recently published data by Guinehut and Larnicol (2008) based on satellite observations for the period October 1992-May 2007 record even higher values – a 7.5 mm/year sea level rise in the Black Sea. It is precisely this relative sea level change that causes concern among coastal managers (IPCC, 2007b).

The IPCC projects an increase in sea level of 0.35 m by 2100 due to thermal expansion, caused by global warming (IPCC, 2007b). Best estimates of temperature increase range from 1.8 to 4°C across different scenarios, and expected sea level changes vary from 0.28 to 0.43 m. Recent EEA (EEA/JRC/WHO, 2008) assessments indicate that IPCC sea level rise estimates could be too low, because of the risk of more rapid changes than assessed so far in the Greenland ice sheet. Therefore the upper values of the quoted ranges are not to be considered the upper bounds for sea level rise. There are suggestions that impact analysis should explore additional sea level rise scenarios of +50% the amount of global mean rise, plus uplift or subsidence, to assess the full range of possible change (Hulme *et al.*, 2002). While sea level rise is a gradual process, the coast is exposed to the increased risks of flooding, erosion, and saltwater intrusion due to extreme weather events such as storms and heavy rains.

CONCEPTUAL FRAMEWORK

The interaction between natural and social systems has been increasingly analysed through the framework of Driving forces – Pressures – State – Impacts – Responses (DPSIR). It enables to trace the links between social phenomena exerting pressure on the environment (Driving forces); stresses that human activities place on the environment (Pressures); the condition of the environment (State); consequences from environmental degradation including economic costs (Impacts) and available policy responses. This approach has also been applied to the study of the Black Sea. Mee (2005) proposed a modified framework, including institutional barriers (Figure 1).



Figure 1. DPSIR Framework (Source: adapted from Mee, 2005).

The first attempts for monetary evaluation of the consequences from the expected climate changes date from the beginning of the 1990s. Economists face two main obstacles – uncertainty, associated with the evaluation of physical impacts, and methodological problems related to regional estimates.

First, an economic evaluation requires a fine knowledge of physical impacts. This knowledge is still limited, starting from the impact of human induced emissions on the global climate and reaching the effects on natural systems and society. Besides, these processes are developing on a vast time scale with substantial lags between causes and effects. Thus, there is a lot of room for uncertainty regarding the future impacts and their monetary value.

Second, even though there is an established and growing body of literature on the measurement of environmental and natural resource values, the transfer of estimates from one location and time setting to another is still strongly debatable. The application of cost-benefit analysis in evaluating the positive and negative impacts also remains an expensive and time-consuming task. Yet economic assessment is now a tool for policy makers to gauge the expected effects and act towards reducing the negative impacts while taking advantage of the positive ones.

COST OF CLIMATE CHANGE

Primary examples of major recent studies are the Stern Review (2007) and the latest assessment of Nordhaus (2008). The Stern Review estimates that under the baseline scenario (with relatively high emissions and including market and non-market impacts and catastrophic risk) the loss in GDP per capita by 2200 will range from about 3 to 35%, with a central estimate of 15%. Nordhaus provides lower estimates, with a best guess on the economic damages from climate change with no interventions in the order of 2.5% of world output per year by the end of this century, and by nearly 8% of global output in 2200.

Total costs attributed to climate change can be viewed as the sum of three classes of costs. These are costs associated with mitigation, adaptation measures and residual damage. Mitigation covers actions towards diminishing the emissions of greenhouse gases: examples are carbon taxes and the "cap-and-trade" system developed by the European Union. Adaptation measures include e.g. coastal protection, improved water management and adoption of new or more resistant crops in agriculture. Inevitably, certain stretches of land and some production and consumption practices will have to be abandoned – they are classified as residual damage.

There is a trade-off between these three categories, both between mitigation and adaptation costs (the higher the investments aiming to reduce the concentration of greenhouse gases at global level, the lesser the necessity of adaptation measures and vice versa), and between the sum of mitigation and adaptation costs and the residual damage (the higher the investments in mitigation and adaptation, the lesser the costs associated with the residual damage and vice versa) (Figure 2).



Figure 2. Total costs of climate change.

From a cost-efficiency perspective, the problem is to choose the optimal level of mitigation and adaptation that minimise the total costs arising from climate change. From an economic viewpoint, the abatement effort should be balanced against the ability of natural and human systems to adapt to the ensuing changes. The choice of adaptation degree remains to a large extent outside the scope of economics, especially concerning natural systems. Thus, the economic approach can assist the decision-making process in outlining the available trade-offs, but it cannot substitute the process itself. The approaches to the expected impacts are inevitably influenced by the existing uncertainty surrounding the physical processes and their effect on the socio-economic phenomena.

ECONOMIC IMPACTS OF SEA LEVEL RISE

The most important aspects of climate change affecting the coastal zone and its development are sea level rise and increased surface temperatures. While there are other impacts, for instance increased water scarcity, droughts, increased probability of fires and shifts in energy consumption, they are not limited to the coast. Sea level rise is seen as a main threat, as its effects are straightforward and clearly negative. It could have substantial impact on river deltas and low coastal zones which are often densely populated and with highly developed infrastructure – and often burdened with conflicting and overlapping interests. The process is exacerbated by increased coastal erosion and the risk of floods caused by storm surges and heavy rainfall. Most existing studies focus on forecasts of global average sea level which do not give a detailed picture of local conditions. Currently, there are few studies discussing the impacts of climate change on Black Sea communities.

The risk of floods and economic loss will affect various industries. Sea level rise can bring about changes in the coastal ecosystems that could be on such a scale that the countries in the region will be unable to pursue proactive coastal defence strategies embracing all vulnerable areas. A one meter increase in sea rise level could lead to flooding of river deltas and coastal lakes and wetlands in the Black Sea basin (Tingle, 2006). Among the seriously threatened areas are the Danube delta, the Dniester estuary, the deltas of Kuban (Sea of Azov), Rioni and Kizilirmak (UNECE, 2008; UNDP Georgia, 2007; Mikhailov and Mikhailova, 2008). The chain of coastal lakes and wetlands (*limans*), extending along the Ukrainian coast and south of the Danube delta along the Romanian coast up to Shabla and Durankulak lakes in Bulgaria, are also under the risk of being engulfed by the sea. There is a risk of flooding of low lying areas such as the north-western rim of Burgas Bay, including the Sunny Beach tourist resort in Bulgaria (Palazov *et al.*, 2007). The above estimates do not take into account tectonic processes and the effects of coastal erosion that combine with sea level rise.

The economic impacts of rising sea level will stem from the mix of adaptation measures. These could include better protection of ports against storms, possible need for upgrading of port facilities due to higher sea level, protection or relocation of major industrial facilities located on the coast (e.g. refineries, chemical plants) and relocation of transport infrastructure running presently by the sea-front (panoramic roads) or through wetland areas threatened by prolonged or permanent flooding. Certain resort areas may also become threatened by increasing sea level due to their location. The extent of the growing natural hazards will require prioritisation of projects and will inevitably lead to abandoning vast stretches of coastline to the forces of the sea.

Response to sea level rise

The responses to sea level rise can be found in three main strategies: protection, accommodation and retreat (Nicholls, 2007; OECD, 2008):

- Protection reduces the risk of the event by decreasing the probability of its occurrence. Aims to protect the land from the sea so that existing land uses can continue, by constructing hard structures (e.g. seawalls) as well as using soft measures (e.g. beach nourishment).
- Accommodation increases society's ability to cope with the effects of the event. This strategy implies that people continue to occupy the land but make some adjustments (e.g. elevating buildings on piles, growing flood- or salt-tolerant crops).
- Retreat reduces the risk of the event by limiting its potential effects. This strategy involves no attempt to protect the land from the sea. In an extreme case, the coastal area is abandoned.

A summary of the major physical impacts and examples of potential adaptation responses is presented in Table 1.

Physical impact	S	Examples of adaptation responses (P – Protection; A – Accommodation; R – Retreat)					
1. Inundation,a. Surge (sea)flood and stormb. Backwaterdamageeffect (river)		Dikes / surge barriers (P) Building codes / floodwise buildings (A) Land use planning/hazard delineation (A/R)					
2. Wetland loss (and change)		Land use planning (A/R) Managed realignment / forbid hard defences (R) Nourishment / sediment management (P)					
3. Erosion (direct and indire	ect change)	Coast defences (P) Nourishment (P) Building setbacks (R)					
4. Saltwater intrusion	a. Surface waters b. Groundwater	Freshwater injection (P) Change water abstraction (A)					
5. Rising water tables and impeded drainage		Upgrade drainage systems (P) Polders (P) Change land use (A) Land use planning / hazard delineation (A/R)					

Table 1. Physical impacts and potential adaptation responses to sea level rise.

Source: Nicholls, 2007, p. 7.

An initial benchmark of the total costs from sea level rise for Central and Eastern Europe amounts to US\$500 million per year (Tol, 2002). It comprises adaptation costs, formed by protection measures and damage from dry land and wetland loss. This estimate can be compared to 0.02% of GNP on an annual basis (OECD, 2008). To put this in perspective, a study of Black Sea wetlands using data for 35 sites, including the value of fish, reed harvesting, grazing and nutrient retention found that the total value was in the range from US\$314 million to 514 million per year (Gren, 1996). These values correspond to \$190 and \$312 per ha respectively. The figures are consistent with a more recent review of several dozen coastal valuation studies that estimate the median values for coastal goods and services such as recreation, water quality, commercial fisheries and biodiversity in the range from \$200 to \$500 per ha per year (Brander *et al.*, 2003).

Nicholls (2007) covers two categories of adaptation costs: beach nourishment and sea dike construction, and outlines the necessity of substantial rise in investments compared to no sea level rise. Under a business-as-usual scenario, annual beach nourishment costs in Eastern Europe should amount to US\$10 million per year for 2030 and reach US\$14 million at the end of the century, which is over a hundredfold increase compared to a scenario with no sea level rise. The investments in constructing and maintaining sea walls remain the most substantial part equalling US\$494 million in 2030 and reaching \$838 million in 2130. The costs of sea flood damages are in the range of 80 to 86 million dollars annually for the period 2030-2130. It is worth mentioning here that adaptation costs to sea level rise, compared to other climate change parameters that react on a shorter time span.

OTHER EFFECTS OF CLIMATE CHANGE

Further effects of climate change may be expected in the fisheries sector as a result of increased sea surface temperature. There are already observations of shortening fishing season for anchovy off the Turkish coast, where the species forms the bulk of commercial catch (for further details see Erdogan *et al.*, this volume). This is supported from sightings of the species wintering near the southern coast of Crimea in recent years (Boltachev, this volume). Sea surface temperature is a key environmental factor, conditioning the behaviour of anchovy i.e., its migration and schooling patterns. Disruption of the existing patterns would affect directly nearly 20,000 fishermen employed in the Turkish Black Sea fishing sector and more people in the processing industry. While the sector accounts for less than one per cent of the country's GDP, it generated \$273 million

in 2007 only from export of fishery products (Turkish Statistical Institute, 2008). Most affected would be the population on the Turkish coast, since over 80% of fish catch in the Black Sea is attributed to this country, and about half of the whole Black Sea capture production is concentrated in the south-eastern Black Sea, turning the area around Trabzon a focal point for the industry.

The eastern Black Sea coast of Turkey is home also to a thriving aquaculture industry, based mainly on rainbow trout farmed both on land and in sea cages. Raising temperatures during the last decade have increased the frequency of disease outbursts, decreased breeding efficiency and shortened the growing season. These events have pressed for a shift to farming of new species more suitable to the changing conditions. It seems that European seabass will replace the trout (Erdogan *et al.*, this volume). While this could be a solution for the local economy, it remains burdened with the inherent problems of culturing predator species. The farming of predators exerts further pressure on fish stocks for feeding the farmed species and can hardly be considered a sustainable practice.

Coastal tourism is another important sector that may expect negative impacts from rising summer temperature and decreasing demand during the traditional summer season. For instance, during the last few years the share of income from coastal tourism in Bulgaria has represented around 7-8% of GDP. This puts it among the most important branches in the economy of the coastal regions. Monetary estimates about the effects of climate change on this sector in three coastal regions in Bulgaria and Romania are expected from the EU funded CLAVIER project (Mishev and Mochurova, 2008).

The health impacts from the regional warming trends are not adequately assessed yet. The general projections for Europe however point at increasing mortality risk by between 0.2 and 5.5% for every 1°C increase in temperature above a location-specific threshold. A different type of risk to public health driven by climate changes comes from the spreading of vector-borne diseases. Particular attention is due to the tiger mosquito (*Aedes albopictus*), a transmitter of a number of viruses, which has substantially extended its range in Europe over the past fifteen years and is projected to extend it further. The Black Sea coastal regions are considered very likely areas of possible establishment between 2010 and 2030 (EEA *et al.*, 2008).

DEMOGRAPHIC CHANGES

Besides the direct physical impacts of climate change that will affect coastal regions, there are also socio-economic processes that will spur the need for adaptation. Among the most evident is demographic change. In the coming decades, there will be a gradual shift of population southwards. In 2005 less than half of the total population living in the Black Sea coastal regions (Eurostat NUTS2 level for Bulgaria, Romania and Turkey and corresponding administrative units for Georgia, Russia and Ukraine, bordering the coast and falling within the Black Sea watershed) was concentrated along the Turkish coast. If nation-wide UN projections are extended to regional level, the population on the coast will undergo a slight increase, reaching a peak in 2040 when it will be just 6% larger compared to 2005. While the total population on the coast is expected to remain relatively stable, there will be a change in the centre of gravity and by the end of the period 60% of the whole population will be condensed along the southern shore (Figure 3).



Figure 3. Population distribution in the Black Sea coastal regions, million people. The calculations are based on data from the Population Division of ESA/UN, 2008 and on national statistics.

We can tentatively suppose that this will lead to deteriorating conditions in the southern part of the basin, which will simultaneously be exposed to higher sea water temperatures as a result of climate change and growing anthropogenic pressure. The double stress may lead to perturbations in the coastal ecosystem and declining fish stocks. If nowadays the area of highest concern in environmental terms is the north-western shelf, in the next decades we may expect rising problems along the Turkish coast. This coastal zone will be less affected by rising sea level due to its higher elevation, but the overall situation will be exacerbated by growing population and increase of pressure on the environment. Further conflicts may arise over the use of freshwater resources and its impact on the ecosystems (see Milliman and Kettner, this volume). This calls for timely land and sea use planning and the establishment of viable institutions that are capable of tackling the challenges.

CONCLUSION

The most important impacts of climate change affecting the Black Sea coastal regions are sea level rise and extreme weather events. They will require substantial adaptation efforts from all coastal countries and timely planning at the national level. Since sea level will continue to rise by at least 3 mm per year during this century, irrespective of mitigation measures, the main trade-off remains between adaptation and acceptance of land loss. A preliminary benchmark for the Black Sea region estimates that required adaptation costs start from US\$500 million annually. A combined precautionary and proactive approach to adaptation can provide sustainable and far-sighted solutions and is advisable as countries develop their policies. In reality the adaptation costs are likely to be higher than the estimated range.

The adaptation strategies will inevitably be linked to non-climate factors such as socio-economic development of the coastal regions. The expected shift in the population southwards probably will call for additional measures along the Turkish coast to alleviate the increased anthropogenic pressure on the sea environment. The parallel changes in the physical and socio-economic environments will require a holistic approach to the complex issues of coastal management and the involvement of all stakeholders.

There are still many knowledge gaps regarding the expected impacts of climate change on the coastal areas due to the low spatial resolution of most existing projections. It is hard to speak of ecosystem based approach to fishery management when there are no regular stock assessments for the most important commercial species. The economic valuation of the effects for the region is itself complicated due to the dispersed and often difficult to access statistical data on the local units along the coast. Initial attempts to describe the main socio-economic characteristics of coastal regions have been launched by the European Union (Eurostat, 2009). However, they naturally do not cover the northern and eastern rim of the Black Sea. There is also a pronounced need for more researchers working in the field of environmental and natural resource economics in the Black Sea region, in order to achieve a better understanding of the interplay between the environment and the people on the seashore.