



**GLOBAL CHANGE AND ECOSYSTEMS**  
6<sup>th</sup> Framework Programme No 515234

**IASON:International Action for the  
Sustainability of the Mediterranean  
and Black Sea Environment**

**Coordinator: Hellenic Centre for Marine Research, Greece**

**Overall Synthesis on Ecosystem Functioning  
(WP2)**

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(D2.1)*



Project no.: 515234  
Project acronym: IASON

Project title: International Action for Sustainability of the Mediterranean and Black Sea  
EnvirOnmeNt

Instrument: Specific Support Action

Thematic Priority: 6.3 GLOBAL CHANGE AND ECOSYSTEMS

**Deliverable 2.1**  
**Overall synthesis on ecosystem functioning**

Due date of deliverable: February 2006  
Actual submission date: August 2006

Start date of project: 1<sup>st</sup> January 2005

Duration 18 months

Organisation name of lead contractor for this deliverable: Hellenic Centre for Marine Research  
(HCMR)

<b>Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)</b>		
<b>Dissemination Level</b>		
<b>PU</b>	Public	<b>X</b>
<b>PP</b>	Restricted to other programme participants (including the Commission Services)	
<b>RE</b>	Restricted to a group specified by the consortium (including the Commission Services)	
<b>CO</b>	Confidential, only for members of the consortium (including the Commission Services)	

## D2.1: Overall synthesis on ecosystem functioning

### Introduction

This report is made of two main parts, one dealing with the physical features of SES, the other with their bio-ecological conditions. The synthesis of the often separate approaches leads to the definition of a complex scenario, along with hints about the future research trends that should be pursued to face an unprecedented period of dramatic physical and biotic change, leading to management decisions based on expert advice.

### **Section 1: Physical Overview of SES**

The Mediterranean and Black Sea system has a surface of  $2,9 \times 10^6$  km<sup>2</sup> and a volume of  $4,238 \times 10^6$  km<sup>3</sup>, with a mean depth of 1429 m. Due to its relatively small volume, this marine system exhibits a high sensitivity both to climate change (naturally or humanly driven) and to pollution. The Mediterranean Sea has a surface area of about  $2,5 \times 10^6$  km<sup>2</sup>. The Black Sea, with a surface area of  $0,4 \times 10^6$  km<sup>2</sup>, is approximately one-fifth of the surface area of the Mediterranean. It has a total volume of  $0,547 \times 10^6$  km<sup>3</sup>, and a maximum depth of around 2200 m (Sverdrup et al. 1947).

The time scale for renewal of the waters of the Mediterranean is about 70 years (Ovchinnikov et al., 1985), with differences among the various sub-basins, quite small indeed when compared to a time-scale of a few thousand years characterizing the World Ocean. Residence times for the Black Sea have been estimated to vary from less than 10 years in the upper-middle pycnocline to more than 400 years in the intermediate layer (500–650 m), probably exceeding 1000 years at the deepest layers (Ünlüata et al., 1990; Murray et al., 1991, 1998; Ivanov and Samodurov 2001). Thus, due to its small volume, the system of the two basins is characterized by very small inertia to climatic variability, thus possibly acting as an index of such variability.

We still lack the understanding that would allow us to predict how the system will respond in the future decades, under the stresses by the expected climatic changes.

This section aims at merging the current findings (reviewed by Malanotte-Rizzoli, 2003; Tintoré et al., 2005; Tsimplis et al., 2006) with older knowledge, providing distilled information on the current state of the thermohaline and sub-basin scale circulation of the two Seas and of their variability, proposing improvements on currently established monitoring networks and suggesting possible hazards and threats for the stability of the current ecosystem.

### **The forcing**

The atmosphere exchanges heat, water and momentum with the sea. The exchange of heat and water, highly depending on the wind conditions, generates density gradients driving the thermohaline circulation that, to a large degree, determines the ecological character of each basin. The exchange of momentum drives the wind-forced circulation, which partly imposes sub-basin scale circulation features.

Basin-wide evaporation estimates in the Mediterranean Sea range from  $2250$  km<sup>3</sup> yr<sup>-1</sup> to  $3925$

km<sup>3</sup> yr<sup>-1</sup> (corresponding to an evaporation density of 0.92-1.57 m yr<sup>-1</sup>), while precipitation from 775 to 1375 km<sup>3</sup> yr<sup>-1</sup> (corresponding to 0.31-0.55 m yr<sup>-1</sup>).

Similarly, the Black Sea exhibits a small deficit in its vertical exchanges of fresh water with the atmosphere, with the evaporation (~300-450 km<sup>3</sup> yr<sup>-1</sup>, or 0.75-1.12 m yr<sup>-1</sup>) slightly exceeding precipitation (~200-300 km<sup>3</sup> yr<sup>-1</sup>, or 0.50-0.75 m yr<sup>-1</sup>).

Thus, both basins experience a net water deficit in their interaction with the atmosphere. The river run-off closes the water budget in such a decisive manner as to determine the contrasting thermohaline and ecological character of the two basins.

The net annual riverine input to the Mediterranean Sea has been estimated to range between 250 and 500 km<sup>3</sup> yr<sup>-1</sup>, with the more recent studies converging to the smaller values, a fact probably identifying anthropogenic intervention.

The Adriatic Sea is the only region where the gains of freshwater by precipitation and runoff exceed losses by evaporation. The North Aegean could also be considered as one of these areas, if the Black Sea inflow is taken into account as runoff.

The corresponding riverine contribution to the freshwater budget of the Black Sea is estimated to range between 270 and 340 km<sup>3</sup> yr<sup>-1</sup>, a value larger than the overall precipitation and comparable to the overall evaporation of the basin. When divided by the surface area of the Black Sea, it corresponds to a water addition of 0.85 m yr<sup>-1</sup>, an amount much greater than the corresponding estimates for the Mediterranean. This value is of the same order as E and larger than P in the Black Sea, and two-three times larger than E-P, and thus critical in providing the Black Sea with a water surplus.

## ***The response***

### **Exchange flows, Thermohaline circulation, water types and masses**

The water budget of the two seas, as described above, is revealing regarding the nature of their thermohaline circulation and their resulting ecological character. An excess of evaporation over precipitation characterizes both the Mediterranean and the Black Seas. However, the riverine contribution in the Black Sea is of the same order as each of the atmospheric components, and much larger than their difference. Thus, it shifts the fresh-water budget on an annual scale to a water surplus. In comparison, the riverine inputs in the Mediterranean are too small to overcome the water deficit caused by the excess evaporation over the precipitation on the basin. The Mediterranean is a typical concentration basin, and the Black Sea is a textbook example of a dilution basin.

The Strait of Gibraltar controls the exchange of the Southern European Seas (SES) with the Atlantic, and thus the World Ocean. In the upper layer warm and relatively fresh (S~36.2) Atlantic water enters the Mediterranean Sea, while in the lower-layer cold, highly saline (S~38.5) Mediterranean water flows toward the Atlantic Ocean.

The other two straits of major interest are the Bosphorus and Dardanelles Straits, connecting the Mediterranean proper and the Black Sea.

The Turkish Straits System (hereafter: TSS) connects the Mediterranean proper with the Black Sea, and is comprised of two long channels (or Straits), the Dardanelles and the Bosphorus Straits, and the Marmara Sea between them. As mentioned before, the Black Sea has a surplus of water and the Mediterranean Sea a deficit, thus the TSS is characterized by a surface flow of light, low-salinity Black Sea waters towards the Mediterranean, and subsurface flow of highly-saline Mediterranean waters toward the Black Sea. Despite the fact that the exchange through the TSS system is estimated to be about 100 times smaller than the Gibraltar exchange, the significance of the connection between the two Seas is not only critical for the maintenance of the current thermohaline and biogeochemical functioning of

the Black Sea.

The Bosphorus sill depth is 36 m; the mean salinity of the surface and subsurface flow is 19 and 37 respectively; the mean position of the interface is well represented by the 20ppt isohaline.

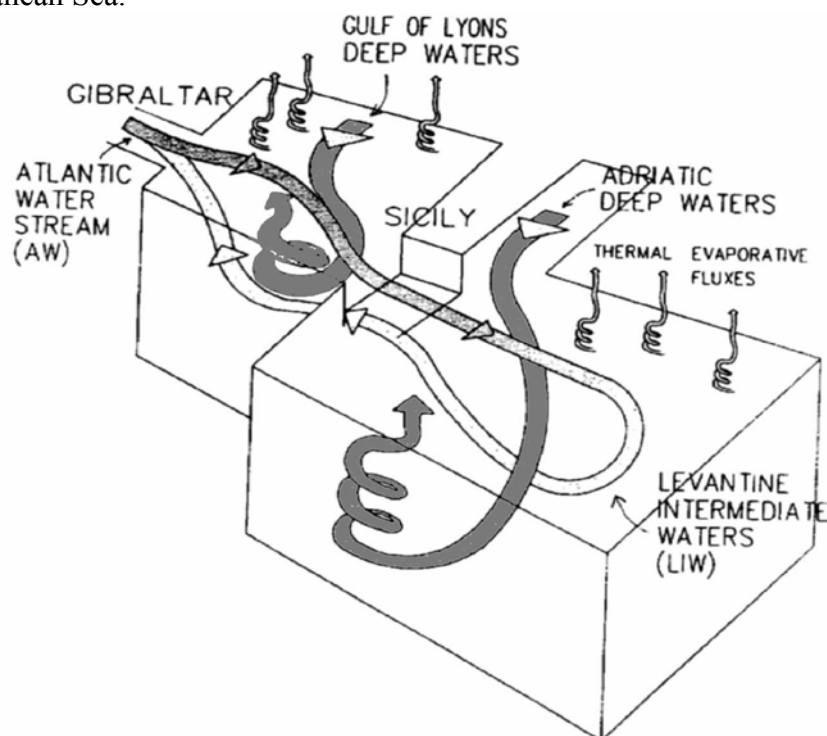
The Dardanelles Strait (sill at 8 m) has not been studied as extensively as either Gibraltar or Bosphorus. The flow is again two layered: the characteristics of the subsurface current Mediterranean water range at temperatures 13-17°C and salinities 38.5-39. The temperature and salinity of the surface layer exhibit a seasonal cycle, and are modified by entrainment of Mediterranean water from below.

## **Thermohaline Circulation of the two basins**

### **Thermohaline circulation of the Mediterranean proper**

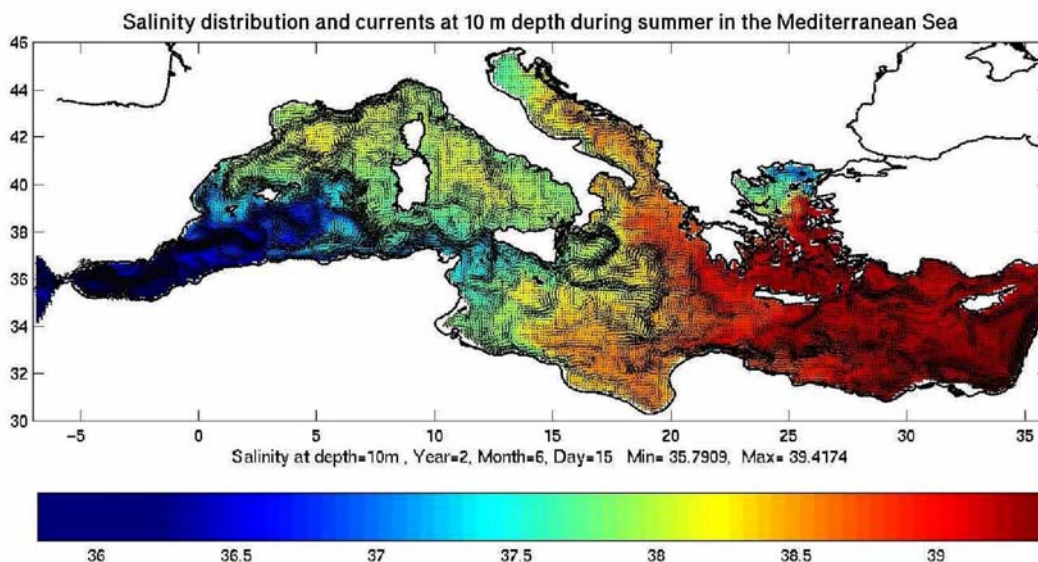
The different freshwater budget of the two Seas dictates the different thermohaline circulation and biogeochemical character of the basins. As a concentration basin, the Mediterranean exhibits highly oxygenated deep waters due to the short residence time resulting from the high rate of formation of high-density waters. The Mediterranean Sea heat exchange with the atmosphere exhibits a very strong north-south gradient. Thus, the three northernmost extremities of the Mediterranean, i.e. the Gulf of Lyons, Adriatic and Aegean Seas, exhibit winter heat-loss maxima that reach  $200 \text{ W m}^{-2}$ . This fact, combined with the mean cyclonic circulation of the Mediterranean Sea, determines the sites of formation of the bottom waters of the Mediterranean Sea.

As



mentioned in the previous chapter, the main source of new water for the Mediterranean is the surface inflow from Gibraltar, forming a water mass identified as Atlantic Water, AW. This

water, entering the Alboran Sea, starts a long journey along the North Africa coast following the generally cyclonic flow around the Mediterranean coasts. As it remains at the surface, this water mass is directly subjected to the net evaporation over the Mediterranean, resulting to a rise of the AW salinity. Another process further contributing to the salinity rise of the AW is the lateral mixing with higher-salinity surface waters to the north, through eddies formed by the unstable Algerian Current. At the western part of the Sicily Strait, the Algerian Current bifurcates into one component that remains in the Western Mediterranean Sea, following a mean cyclonic path along the western coast of Italy and the French Riviera, and another component that crosses the Sicily Strait to enter the Ionian Sea. The AW that remains in the Western Mediterranean forms there a large pool of Atlantic water, considered the source of the Western Mediterranean Intermediate Waters (WIW). This water mass, characterized by maximum salinities of 38.3, is formed during winter off the northern shores of the Western Mediterranean and follows the general cyclonic circulation within the Western Mediterranean below the AW. In summer, it lies between the AW and LIW water masses, at depths 85-350m.



Thus, along the eastward route along the North African coast, the salinity of the Atlantic Water rises from about 36.5 in Gibraltar, to 37.0-37.5 in the Strait of Sicily. Along the path of the AW branch that enters the Eastern Mediterranean, further evaporation and lateral mixing occurs, thus the salinity continues to rise to 38.6 in the Cretan Passage and 39.1-39.3 in the eastern extremities of the Levantine Sea. The volume flux of the eastward flow crossing the Sicily and Cretan Straits remain at about 1 Sv, however the quantity of the original Atlantic Waters entering the Ionian and Levantine basins is much reduced by the above processes.

The Levantine Intermediate Water occupies the layers between about 200 and 500 m in the Eastern Mediterranean, and can be identified by the salinity maximum, reaching about 38.95-39.05 in the Levantine. After its formation, the LIW travels westwards, undergoing diffusion of its properties through the mesoscale turbulence in the Ionian. A branch of LIW enters the Adriatic Sea, providing the necessary excess salt for the subsequent formation of the very dense Adriatic Deep Water (ADW). The main part of LIW remains in the Ionian Sea and, when reaching the Sicily Strait, it is characterized by a salinity of about 38.75.

The LIW reaches Gibraltar with a mean salinity ranging between 37.75 and 38.43, and forms



the major part of the Gibraltar undercurrent feeding Mediterranean Outflow, which influences the salinity and stratification of the whole North Atlantic Ocean.

The Levantine water is possibly the dominant water mass of the Mediterranean. However, in studying the Mediterranean ecosystem, it only occupies the upper-intermediate layers of the Sea. The deep layers are occupied by denser waters, of higher oxygen content. The regions of formation of the deep waters of the Mediterranean are the same northern extremities of the Sea that exhibit the winter heat-loss maxima: the Gulf of Lyons, the Adriatic and the Aegean Sea.

The main source of deep water for the Eastern Mediterranean, excluding a well-documented interval between 1987 and 1995, is the Adriatic Sea. The water-mass occupying the deep layers of the Eastern Mediterranean, called the Eastern Mediterranean Deep Water (EMDW), is a fairly homogeneous characterized by potential temperature around 13.6 and salinity 38.7. Water from Aegean origin exiting the Cretan Straits has been identified forming lenses at intermediate depths, just below the LIW layer and was named Cretan Intermediate Water (CIW).

In the Western Mediterranean, the layers below the WIW and LIW are occupied by the Western Mediterranean Deep Water (WMDW) water mass (major site of formation of the waters occupying the layers below the LIW, is the Gulf of Lyons. The dense water formation takes place during winter storms in the Gulf of Lyons, when the strong, cold and dry Mistral forces large amount of heat-loss and evaporation on the surface layers of the sea. Heat-loss is the dominant factor in the buoyancy loss of the surface layer, and determines the depth of convection.

### **Thermohaline circulation of the Black Sea**

One branch of the thermohaline conveyor belt that was not mentioned above, due to its small magnitude relative to the large volume fluxes, of the order of 1 Sv, characterizing the Mediterranean Sea thermohaline circulation, is the exchange with the Black Sea. As we mentioned above, the two Seas exchange mass and properties through the Turkish Strait System. The Mediterranean Sea provides about 32000 m<sup>3</sup> s<sup>-1</sup> Mediterranean water (0.03 Sv) of high-salinity water to the TSS, and receives about 0.04 Sv of water from the Black Sea, modified through mixing at Nara Passage. However, due to the filtering (through mixing) at the Dardanelles and Bosphorus Straits, the Black Sea receives only about 0.01 Sv of modified Mediterranean water (of salinity about 38.5), and provides a little less 0.02 Sv of its own surplus waters (salinity about 18) to the TSS. The Black Sea is a dilution basin, due to the large magnitude of its riverine input of freshwater. Thus, the dense water entering through the Bosphorus Strait forms filaments that flow down the continental slope as density currents, undergoing entrainment of a volume 3-6 times larger. The Mediterranean waters entering the Black Sea do not penetrate deeper than the upper 400-600, and their direct effect contributes to the lateral ventilation of the Black Sea, through enrichment with oxygen-rich waters. However, this undercurrent is also responsible for maintaining the current high stratification and thus, in the long run, the anoxic character of the deep layers of the Black Sea established after the connection with the Mediterranean about 7500 years before present. This deep layer, composed partly of high salinity water of Mediterranean origin, is characterized by very high densities relative to the overlying water layers, originated in the Black Sea. Thus, the stratification of the top of the deep layer of the Black Sea is permanent, with small excursions of its depth depending on the freshwater budget and the severity of the meteorological forcing in the Black Sea, and the surface circulation is essentially de-coupled from the stagnant deep layer, characterized by residence time-scales reaching a few thousand years. The only

convective activity recorded in the deep layers is associated with geothermal activity, maintaining a very thick (400-500 m) deep convective layer.

The upper layers of the Black Sea, above the 200-250 m deep oxic-anoxic interface, exhibit their own thermohaline circulation. The surface of the Black Sea is characterized by extremely low salinities ( $S \sim 18$ ), maintained by the freshwater surplus due to the large riverine input component of the freshwater budget. This layer is only about 20 m thick. Below this layer, there is the Cold Intermediate Layer (CIL), characterized by temperatures less than  $8^{\circ}\text{C}$ , occupying the depths between 30 and 60 m near the central regions of the Black Sea, and deeper at the edges. This layer represents the densest water ( $\sigma_t$  reaching  $15.5 \text{ kg m}^{-3}$ ) formed by winter convection processes locally in the Black Sea, through direct interaction of the surface layer with the atmosphere. The levels of dissolved oxygen are high at the top of the CIL, but fall rapidly with depth to become undetectable at its bottom. Hydrogen sulphide does not rise immediately with the depletion of dissolved oxygen. Below CIL there is a thin (about 20 m) water layer where both dissolved oxygen and hydrogen sulphide remain at levels below detection. This layer is called the Sub-Oxic Layer.

The formation of CIL waters takes place in winter over the extended northwest shelf of the Black Sea, thus, through shelf formation. Due to their low density relative to the Black Sea deep waters, the dense CIL waters formed do not sink to the bottom of the Black Sea, but are transported laterally by the main cyclonic circulation to extend throughout the whole basin. While the CIL can be ventilated at the northwest shelf, the SOL remains isolated from the atmosphere.

Another scenario for the ventilation of the CIL layer envisages the cyclonic circulation of the Black Sea as facilitating the ventilation of the CIL layer through the reduction of the surface layer thickness in the middle of the two Black Sea main gyres. This could act as a preconditioning for the dense-water formation during cold storm outbreaks.

## ***Variability and trends***

### **Natural and anthropogenic variability of the forcing**

The variability of the several forcing factors of the system can be described as natural and anthropogenic. However, the boundaries between these two cannot always be well-defined. For example, while it is straightforward to include the reduction of riverine freshwater discharge to the sea due to river damming as anthropogenic, it is not so clear when we consider the possible reduction of rainfall over the sea or the riverine catchment areas. In any case, the purpose of this report is not to classify whether the recorded trends and variability are anthropogenic or not, but just to review the currently recorded interannual variability, and attempt to isolate mean trends (in the time-scale of the last 50-100 years) from pentadal-decadal interannual variability. High frequency and seasonal variability will not be included in our review, as we are interested in interannual changes and assessments.

We will examine the recorded variability in the heat, freshwater and momentum forcing of the Mediterranean and Black Sea basins.

### **Variability of the thermal forcing**

Studies based on gridded data identified a significant annual warming trend of about  $0.75 \text{ }^{\circ}\text{C yr}^{-1}$  over the entire Mediterranean land areas through the 20<sup>th</sup> century. The warming trends were higher at the beginning and the end of the century, and also for winter and summer



values. However, the eastern Mediterranean has experienced different trends than the Western part of the basin. While the western Mediterranean experienced a monotonic warming trend, reaching the eastern Mediterranean experienced cooling. The trends have not been constant either. The summer air temperature records for the 1900-1949 period reveals that warming was experienced in the western basin, while a cooling trend over 1900-1949 was only prevalent over Libya and Egypt. Regarding winter temperatures, during the period 1900-1949 a general cooling was recorded in the central basin but a warming in the east and west. During the 1950-1999 period the eastern basin experience cooling and the western basin warming. For the period 1950-1993, a decrease of sea surface temperatures was also recorded in the Eastern Mediterranean.

Satellite-obtained Black Sea SST for the period 1982-2000 recorded a general warming trend of  $0.09\text{ }^{\circ}\text{C yr}^{-1}$  of the annual mean Black Sea SST. In relation to the thermohaline circulation variability, winter mean SST minima were recorded in the years 1985, 1987, 1992 and 1993, and maxima in the years 1984, 1988, 1995 and 1999. After 1994, winters have been warm. The air-sea exchange over the Black Sea for the period 1979-1993, as provided by the ECMWF atmospheric model, did not identify any statistically significant trends over the analyzed period.

### **Variability of precipitation and evaporation**

Recent precipitation over the Mediterranean Sea showed a significant decrease in the annual precipitation over the 20<sup>th</sup> century. A similar negative trend was found for winter precipitation. In general, precipitation fields over the Mediterranean exhibits high spatial variability.

NCEP re-analyses reveal that winter precipitation has decreased by 20% in the second part of the twentieth century over the whole Mediterranean. This decrease occurred mostly during the period late 1970s to early 1990s. Interestingly, while the Mediterranean rainfall decreases, the extreme daily rainfall exhibits an increasing trend.

While the precipitation over the Black Sea does not reveal any significant trend, the evaporation shows a significant decreasing trend since the mid-twentieth century, possibly due to global change.

### **Variability of runoff**

The interannual variability of river runoff in the Mediterranean Sea in the 20<sup>th</sup> century was estimated to be about 60% of the climatological long-term mean, while decadal variations are of the order of 20%. The interannual variability of riverine outflow (connected to the NAO-correlated precipitation) is correlated to the NAO index. This correlation decreases especially in the southeast Mediterranean, where ENSO has been suggested as affecting the Nile stream flow.

Regarding the Black Sea, a mean trend of  $-2.2\pm 1.3$  over the period 1954-1997 has been estimated. This trend is very small, especially considering the impact possibly deriving from the damming of major Black Sea rivers in the 1950s-1960s.

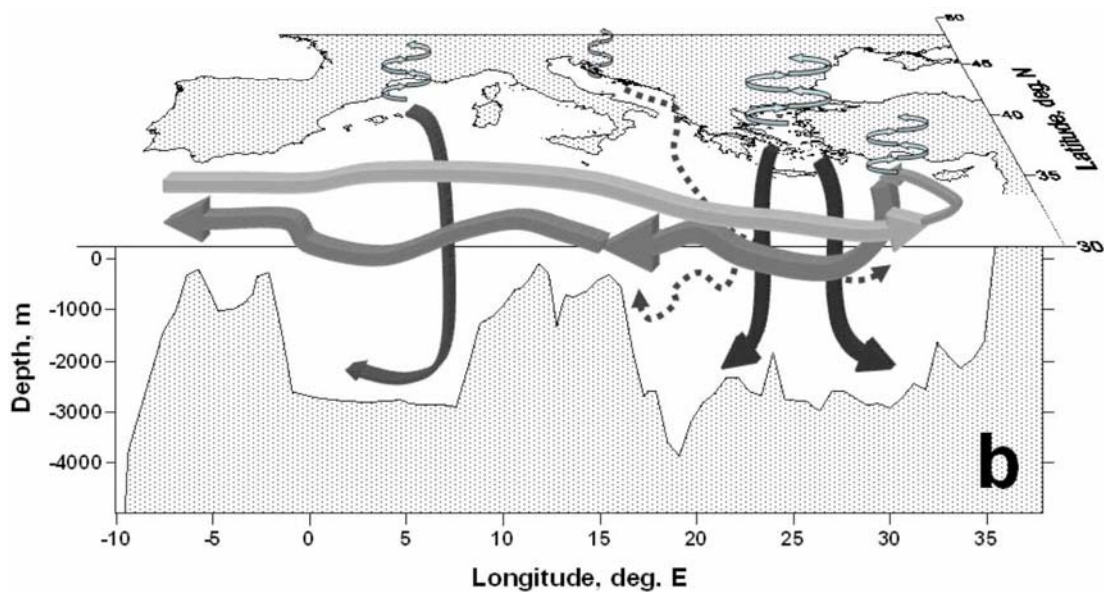
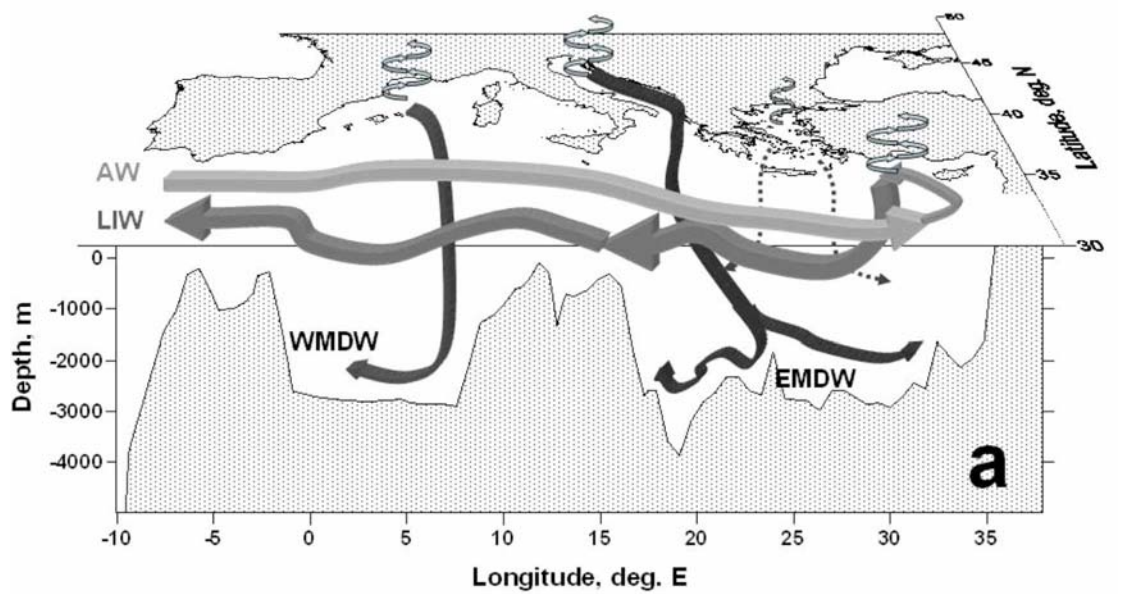
## **Response of hydrographic properties, vertical structure and thermohaline circulation**

### **Variability of the Mediterranean Sea hydrography and thermohaline circulation**

Until the mid-seventies, the conventional wisdom was that the Sea is in steady state, at least for time-scales of the order of 100-1000 years. Studies on observed trends over the period 1959-1997 for the deeper layers certified that the deep waters are not in steady state and that the temperature and salinity of the WMDW water mass increased at a rate of  $3.5 \times 10^{-3} \text{ }^\circ\text{C yr}^{-1}$  and  $1.1 \times 10^{-3} \text{ yr}^{-1}$  respectively. At the same period, the temperature and salinity of the intermediate waters increased at the higher rates of  $6.8 \times 10^{-3} \text{ }^\circ\text{C yr}^{-1}$  and  $1.8 \times 10^{-3} \text{ yr}^{-1}$  respectively. These changes were detected also in the deep waters of the Western Mediterranean, as well as in the Levantine Intermediate Water. While the WMDW temperature and salinity started rising in 1955, the LIW exhibits warming trends since 1909. They went further to attribute the changes of the WMDW water mass to the salinity increase of the LIW. Furthermore, they attributed the LIW salinity rise to anthropogenic changes in the freshwater budget of the Eastern Mediterranean Sea through river damming, especially after the construction of the Asswan dam on the Nile. However, it has been argued that the river damming was not enough to account for the observed salinity changes, so that a contribution of reduced freshwater input from the Black Sea was necessary, through a reduction of its own freshwater budget due to an increase of evaporation and damming of the Central/Eastern European rivers. More recently, it has been suggested that the damming of the Nile river could account only for about 45% of the salinity increase of WMDW, increasing surface and intermediate water salinity trends being caused by a local reduction of precipitation in the Western Mediterranean due to increasingly positive values of the North Atlantic Oscillation index from 1960 to 1990, as well as damming the river Ebro.

More recently, several studies surprisingly showed that the upper waters of the Eastern Mediterranean exhibit a cooling trend from about 1950, while the salinity trend of the surface waters of both the Eastern and the Western Mediterranean basins is positive.

While the Western Mediterranean exhibits a rather continuous trend of its hydrographic properties towards more warm and saline values, with the main features of its thermohaline structure and circulation remaining stable, the Eastern Mediterranean showed a major shift in its thermohaline circulation in the early 1990s. As mentioned in a previous chapter, before the mid-1990s the source of the Eastern Mediterranean Deep Waters was considered to be the Adriatic Sea. However, comparison of two zonal transects performed in 1987 and 1995 along the Eastern Mediterranean by the F.R.S.Meteor, showed that the Adriatic-originated waters filling the bottom waters of the Levantine and Ionian Seas had been raised by denser, more oxygenated and more saline water that could be traced to the Aegean Sea. This observation allowed producing an estimated minimum volume flux of 1 Sv for seven years (1987-1995), required to produce such a salinity anomaly in the deep layers of the Mediterranean. This observation amounted to a major shift in the thermohaline circulation of the Eastern Mediterranean, since it meant that the main contributor to the EMDW water mass would (at least during its occurrence) be the Aegean Sea and not the Adriatic. This phenomenon was called Eastern Mediterranean Transient (EMT). Fig. A shows the “normal” formation of Mediterranean Deep Water in the Gulf of Lions and in the Northern Adriatic. Fig. B shows the Transient, when, instead of the Northern Adriatic, it is the Aegean to feed the Eastern Mediterranean deep water.



The evolution of the waters was followed from their formation in the Aegean Sea, to the spilling and their propagation into the deep Ionian and Levantine basins. The outflow of dense waters (Cretan Deep Water, CDW) from the Straits of the Cretan Arc was estimated to about a mean value of about 0.5 Sv with a range of 0.3 Sv, reaching maximum values of 1 Sv based on current measurements. By the late 1990s, the export of very dense water in the Aegean Sea was diminished; water is still being exported from the Straits of the Cretan Arc, but it only sinks to a depth between the LIW and EMDW layers of the Eastern Mediterranean. Furthermore, there is evidence that the Adriatic Sea, fed with high-salinity water of Cretan origin, is now returning to its role as the dominant formation site for the Eastern Mediterranean EMDW water mass. The changes can be summarized as (i) a salt redistribution within the water column of the Eastern Mediterranean (a net salt flow from the surface to the

deep layers) and (ii) a net salt gain throughout the water column.

Several scenarios have been proposed in regards to the origin and causes of the EMT. The scenarios range from a change in the local freshwater balance over the Aegean Sea, a series of anomalously cold winters during that period, a salinity increase of the AW entering the Ionian Sea, and blocking of the AW from entering the Levantine and Aegean Seas due to mesoscale circulation, a change in the pattern of the winter wind-field over the Eastern Mediterranean for the period of 1980-1993, a reduction of the buoyancy forcing by the Black Sea and subsequent triggering of the event by formation in the North Aegean in 1987, the erosion of the Cretan Sea pycnocline combined with long term anthropogenic salinity rise due to river damming.

All the above scenarios contribute to the same results, but none can fully explain the magnitude of the EMT. Furthermore, they are not mutually exclusive: The change of wind-stress fields observed in the 1980-1993 period could be directly related both to the change of surface circulation in the Ionian Sea, blocking AW from entering the Levantine and Aegean Seas, and to the observed precipitation decrease (and possible rise of evaporation) over the Aegean Sea. The possible interrelation of several forcing factors point to the possible examination of the variability of large-scale atmospheric features and teleconnections in order to shed more light into the EMT phenomenon.

### **Variability of the Black Sea hydrography and thermohaline circulation**

The Black Sea, due to the shallowness of its thermohaline conveyor belt and its small size, is much more sensitive to variability of the heat and freshwater forcing, and its ecosystem has undergone major crises in the 1980s and 1990s, possibly related to physical forcing of the sea. The major issue concerning the variability of the Black Sea thermohaline circulation and associated vertical structure was the degree to which the massive dam building by Soviet Union in the 1950s and 1960s could influence the freshwater budget of the basin, to a degree potentially catastrophic for the vertical stability of the water column and potentially the ecosystem. It has been suggested that a continuation of the major dam-building projects could significantly alter the thermohaline circulation of the Sea, by intensifying the CIL production at the NW shelf which, when combined with the Mediterranean effluent, could erode the H<sub>2</sub>S layer and lead to a warming of the water column. A significant rise of the oxic-anoxic interface occurred between 1975 and 1988, probably due to a man-made reduction in freshwater inflow into the Black Sea, without discounting possible natural variability. The dissolution of the Soviet Union, and possibly the environmental concerns mentioned above, caused a cessation of dam construction projects, and thus the projected reduction of the river flows was not realized. For the period 1954-1997, a trend of  $-1.46 \text{ mm yr}^{-1}$  (as equivalent sea-level change) due to river runoff has been estimated. This trend is not large, and opposing the P-E trend ( $1.73$ , following the NCEP  $\text{mm yr}^{-1}$  climatology). Thus, there is no sign of a potential large-scale change of the vertical structure of the Black Sea due to anthropogenic changes of the riverine forcing.

Thus, it appears that any variability in the atmospheric or riverine forcing of the Black Sea has remained in the thin upper oxygenated layers (the BSW and CIL layers, and possibly the SOL layer). A recent study of the interannual variability of the satellite-derived SST fields over the Black Sea for the period 1982-2000, estimated a general trend of the seasonal mean SSTs to cool during all seasons except summer for the period 1982-1991 and to rise at faster rates in the period 1991-2000. Maybe this surface cooling trend should be compared with a



respective cooling trend of the Eastern Mediterranean surface waters during the period 1950 to late 1980s. Four winters of weekly mean SST minima, the winters of 1985, 1987, 1992 and 1993, were identified. These were winters where CIW formation was expected to be intensified, accelerating the thermohaline conveyor belt of the Black Sea. The residence time of CIW waters was estimated to about 5.5 years. Three of the above four mentioned winters of minimum weekly SST in the Black Sea, the winters of 1987, 1992 and 1993, were the periods when the major dense water formation events took place in the Aegean Sea, triggering (in 1987) and intensifying (in 1992 and 1993) the EMT.

The phase-agreement of the Black Sea and the Aegean regarding the long-term trends of SST evolution, as well as the timing of dense water formation in these adjoined seas, suggests: a) that the thermohaline circulation of the Black Sea and the Aegean respond in phase to large-scale atmospheric features, possibly connected to teleconnections; b) that the exchange between the two Seas may be amplifying this phase agreement of the thermohaline circulation.

Regarding (b), the Black Sea water inhibits dense water formation in the North Aegean by forming a surface insulating layer. During the dense water formation periods, the surface salinity in the Turkish Straits System is expected to rise due to vertical convection and mixing with underlying saltier waters, either in the Black or Marmara Seas. In fact, such high surface salinity values, reaching 33, were observed in the Marmara Sea during winter 1987, a year of formation in both Seas. Thus, the buoyancy input by the Black Sea to the Aegean is expected to be reduced during such periods. As a result, the surface insulation of the North Aegean is expected to be reduced during years of increased CIW production in the Black Sea, and dense water formation in the Aegean will be facilitated.

## Teleconnections

Large-scale atmospheric features and teleconnections are known to significantly affect the Mediterranean climate. The presence of sapropels in successive horizons of the Eastern Mediterranean sediments is a witness of the complete disruption and reversal of the thermohaline circulation of the basin, that took place several times in the past. Sapropel formation was synchronous with periods of intensification of the east African monsoon, paced by astronomical forcing. The increased humidity over eastern Africa led to enhanced discharge of the Nile river. Furthermore, insulation maxima periods coincide with increased precipitation over the northern Mediterranean. Sapropel formation therefore occurs during periods of generally more humid climate leading to a positive water balance in the eastern Mediterranean.

In modern times, since the onset of the current climatic conditions about 11500 ago, there has been no catastrophic change of such a large scale as complete disruption and reversal of the Mediterranean and Black Seas' thermohaline circulation. However, that does not mean that the climate has been stable. Since the onset of the Holocene, there have been at least 6 periods characterized by significant rapid climate change. These periods were often associated with disruption of the human civilization and loss of lives. Most of the Holocene climate shifts can be attributed to solar variability and long-term insolation changes. The direct relation between solar forcing and the climatic conditions in the Mediterranean show a relation between solar irradiance and atmospheric  $^{18}\text{O}$  content in Mediterranean sapropels. Such changes in solar radiation affect the moisture balance and major large-scale climatic phenomena, like the El-Niño Southern Oscillation (ENSO). The ENSO variability affects the weather over the Mediterranean and the Black Sea. A correlation between autumn and spring precipitation over

the western Mediterranean and ENSO has been found. However, ENSO (and, thus, the oceanic circulation and sea-surface temperature variability) is related to the timing of appearance of another teleconnection, even more related to the Mediterranean and Black Sea climate in decadal time-scales, the North Atlantic Oscillation.

The North Atlantic Oscillation (NAO) is most related to the Mediterranean climate, especially precipitation. The NAO index (defined as a normalized difference between the sea-level pressure in the region of the Azores and Iceland) is highly correlated to precipitation over western Mediterranean and Central/Eastern Europe. The period between 1960 and the mid-1990s was characterized by a tendency of the NAO index to increase, which amounted to higher precipitation in Northern Europe and lower precipitation in the Mediterranean. Thus, the recorded trends of the salinity and temperature in the Western Mediterranean Sea have been attributed to the increased NAO values over the 1960-mid-1990s period.

The NAO/precipitation negative correlation is high and significant over the Western Mediterranean, but less so over the Eastern basin. More recently, a high correlation of the North Sea Caspian Pattern (defined as the midtropospheric geopotential height difference between North Sea and Caspian Sea regions) with the heat and momentum exchanges over the western Black Sea and Aegean Sea has been shown.

Understanding how teleconnections may influence the thermohaline circulation of the basins is crucial, in assessing the projections made by forecasting models for the climate under various climate change scenarios.

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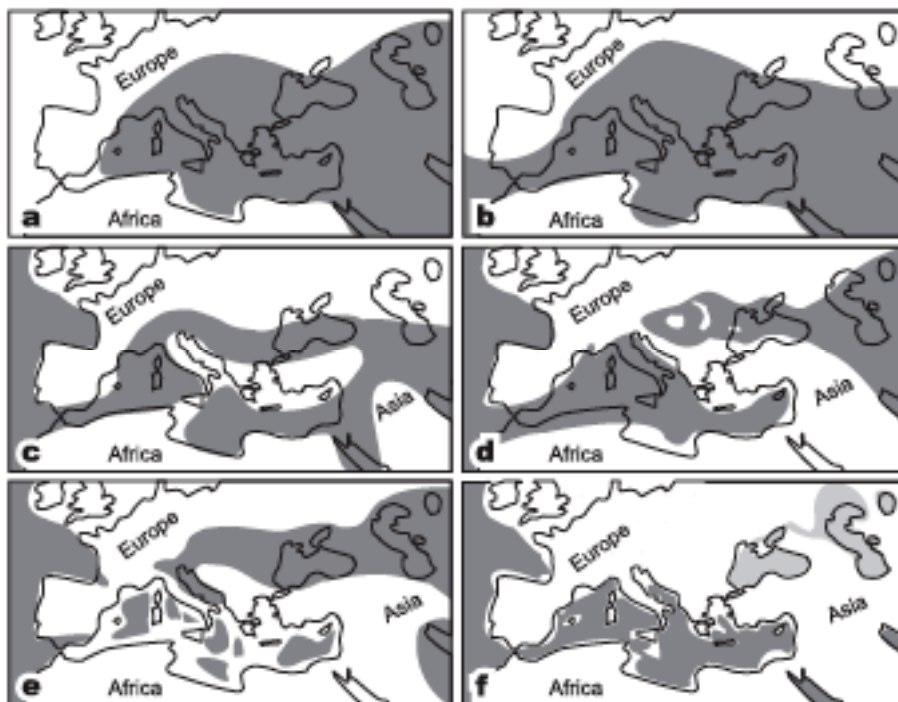
## Section 2: Biodiversity and ecosystem functioning in the Eastern Mediterranean and in the Black Sea.

The global scale changes that are affecting the planet (see previous section) are likely to significantly impact the biota (Chapin et al. 1997). The projected increase in temperature (global warming) would affect the distributions of both thermophilic and thermophobic biota. The projected increase in the frequency of extreme events would favour opportunistic species (including aliens species), able to take advantage of erratic opportunities of success (CIESM, 2002).

The Mediterranean Sea and the Black Sea, due to their small size may advance our knowledge of the impacts of Global Change on marine systems, and, indeed, may serve as the proverbial ‘miner’s canary’ to the world ocean.

### *Peculiarities of SES*

The temperatures of the shallow waters of the Mediterranean Sea are tropical in the summer and temperate in the winter, the southeastern part being the warmest. The Mediterranean biota has been mostly derived from post-Messinian Atlantic colonisation (5MYA) through the Gibraltar Strait, and is biased by an ecological founder effect linked to the characteristics of the source biota (see Bianchi and Morri, 2000, for a review).



The major phases in the geological evolution of the Mediterranean Sea (land white, sea stippled) were: (a) Triassic, 220 my BP; (b) Cretaceous, 120 my BP; (c) Oligocene, 30 my BP; (d) Miocene, 10 my BP; (e) late Miocene (Messinian Stage), 6 my BP; (f) late Pleistocene (Würm glacial), 20 000 y BP. Plate movement is neglected to represent land masses in their relative position of today.

The perceived faunal impoverishment of the easternmost basin of the Mediterranean has been attributed to the limited access through the narrow and shallow straits of Gibraltar and the Siculo-Tunisian sill, the relatively recent recolonization after the Messinian crisis, to Quaternary climatic fluctuations and to the sea's extreme oligotrophy (Fredj 1974, Yacobi et al. 1995). Sarà (1985) proposed that the high temperature and salinity prevailing in the Levantine Basin made it unsuitable for many Atlanto-Mediterranean taxa, and the present Atlanto-Mediterranean organisms are presumably at the limit of their ecological tolerance.

## **SES biodiversity**

The number of macroscopic species hitherto recorded from the Mediterranean Sea exceeds 8500 (Bianchi and Morri 2000), the Black Sea hosts about 500 species (Zenkevitch, 1963), many are in common with the Mediterranean Sea.

Numbers of species of macroscopic marine organisms in the world ocean and in the Mediterranean Sea.

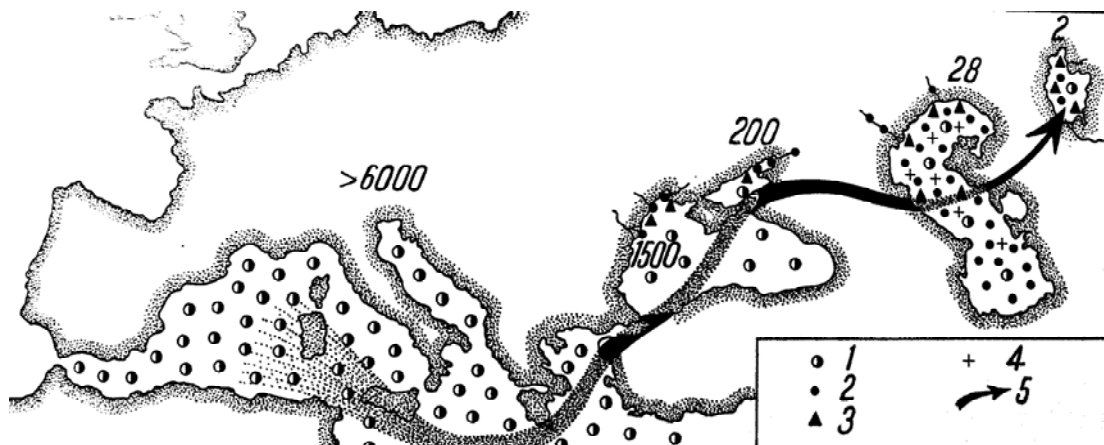
Taxa	World	Medit.	M/W(%)	BS
Red algae	5250	867	16.5	143
Brown algae	1500	265	17.7	75
Green algae	1200	214	17.8	83
Sea grasses	50	5	10.0	6
Total plants	8000	1351	16.9	307
Sponges	5500	600	10.9	25
Cnidarians	11 000	450	4.1	44
Bryozoans	5000	500	10.0	12
Annelids	8000	777	9.7	153
Molluscs	32 000	1376	4.3	125
Arthropods	33 600	1935	5.8	288
Echinoderms	6500	143	2.2	5
Tunicates	1350	244	18.1	16
Other invert.	~13 550	~550	4.1	278
Total invert.	~116 500	~6575	5.6	946
Cartilag. Fishes	850	81	9.5	
Bony Fishes	11 500	532	4.1	180
Reptiles	58	5	8.6	0
Mammals	114	21	18.4	4
Total vertebrates	12 522	639	5.1	184
Grand total	~137 000	~8565	6.3	468

The bulk of SES biodiversity is represented by the Mediterranean biota. The Black Sea, however, is not simply a subsample of the Mediterranean. Its peculiar features led to the development of original communities, leading to a unique blend of biodiversity.

The biodiversity of SES' habitats has been extensively studied, culminating in the seminal synthesis by Pérès and Picard (1964), updated and refined by Bellan-Santini et al. (1994). The

physiognomy of habitats and communities has been categorized in many different ways, but is lacking a single, comprehensive classification.

Biodiversity erosion has been of serious concern since the Rio Convention on Biodiversity, but, paradoxically, the academic research of biodiversity has been neglected, due to misguided funding allocations. Efforts at listing biodiversity (e.g. Costello et al., 2001) often lacked rigorous scientific analysis of the data, resulting in flawed species and habitat type lists.



A general pattern in biodiversity distribution in SES is the impoverishment of the Mediterranean flora and fauna from the west to the east. The numbers are the total amounts of species, symbol nr 1 is the Mediterranean fauna, 2 is the Caspian fauna, 3 is the Fresh-water fauna, 4 is the Arctic immigrants, 5 is the direction of migration.

The Black Sea is an arm of the Mediterranean, and many of its species are common to both seas, but it is of distinct character, owing to its physical and historical conditions that produced a marked lower diversity. The biota of the Black Sea reflect situations that may be found at higher latitudes: few species with high biomasses each, whereas the Mediterranean is characterised by many species with low biomasses each.

These figures derive from research in the first two thirds of the past century, when it was common wisdom that the Eastern part of the Mediterranean was poorer than the Western one. This has been hypothesized, as mentioned earlier, with the founder effect of the Atlantic fauna after the opening of Gibraltar. The warmer conditions of the eastern basin were not conducive for the establishment of a temperate-boreal contingent. Another reason for this low diversity, however, might have been the scant biological exploration of the Eastern and Southern part of SES. In other words, the number of species is lower because the research effort has been lower, or is it really lower (see Arvanitidis et al. 2002)? A definite answer to this question is now impossible, since the basin underwent severe changes in the last third of the last century, with a great enrichment of the fauna of the southern basin, due to the influx of many “alien” species. This change in a local biota is probably the greatest biogeographical transition in recent times (Galil and Zenetos, 2002).

## **Recent changes in SES biodiversity**

The opening of the Suez Canal allowed the arrival of tropical species in the Mediterranean. They rapidly became established in the Levantine basin, occasionally reaching as far west as the Sicilian strait and even in the Western basin. Furthermore, an increasing contingent of autochthonous southern Mediterranean species has been lately expanding their distributions northwards, in response to the warming of surface waters throughout the basin. To document this dramatic change, the International Commission for the Scientific Exploration of the Mediterranean Sea (CIESM) published an Atlas of the exotic fish species that entered the Mediterranean in recent years (Golani et al. 2002). Out of 100 species of alien fish, 98 are considered thermophilic. The two alien boreal species that entered through the Strait of Gibraltar remain confined to the Alboran Sea. Similarly, the species list of the CIESM Atlases covering both crustacean decapods (Galil et al. 2002) and molluscs (Zenetos et al. 2003) are evident of the great preponderance of thermophilic aliens.

In a reversal of the historical trend, the easternmost basin of the Mediterranean has been recently “exporting” alien Erythrean biota to the central and western basins (tropicalisation), whereas the southern native biota expands northwards (meridionalisation) (CIESM, 2002).

The functioning of the Mediterranean system was considered to be regulated by the regular sequence of two main marine seasons in the surface waters, with a peak of phytoplankton production after the cold season storms and the increase of solar radiation, and another, smaller one at the end of the warm season. This scheme has been disrupted by global change, and the tendency towards warming (resulting into both meridionalisation and tropicalisation) is only one of the aspects linked with the changing conditions. The other face of the medal is the enhancement of the extremes, sometimes with extremely cold winters, leading to fish mass mortalities (Guidetti et al. 2002). These perturbations can reach also the deepest waters of the basin, as recently demonstrated by the study of the impact of the Eastern Mediterranean Transient on deep-sea biodiversity (Danovaro et al. 2001).

## **The fish-jellyfish transition**

Throughout the world ocean, industrial fisheries are depleting the populations of large top predators, in a phenomenon known as “fishing down the food web” (Pauly et al. 1998; CIESM, 2000). This concept describes the impoverishment of the higher levels of food webs, with man impact being focused on lower levels. In parallel with the decimation of the predatory fish we witness the emergence of large jellyfish populations (Mills, 2001). Gelatinous predators also occupy top positions in food chains, feeding on large species when they are represented by their eggs, larvae and juveniles. Furthermore, gelatinous predators feed upon crustacean plankton, the food of fish larvae and juveniles. They are, thus, both predators and competitors of large fish, impairing their recruitment (CIESM, 2001).

SES have been and are subjected to the blooms of several gelatinous plankton species.

### **Gelatinous plankton in the Black Sea and the story of *Mnemiopsis***

In view of jellyfish dynamic and impacts, the temporal subdivision of the history of the Black Sea is: (i) a pristine period, with *Rhizostoma pulmo* prevalence (60-70-ies); (ii) period of *Aurelia aurita* expansion (70-80-ies); (iii) late 80s-90s - recognized as “*Mnemiopsis* era” (iv)

a contemporary phase- the period after 1997, when the ctenophore *Beroe ovata* reached the Black Sea (Kamburska et al, 2002).

In the coastal area (north-western shelf), crustacean zooplankton biomass was high in the 1960s, decreasing apparently during the 80-ies, beginning of 90-ies, normally related to the deterioration of ecological conditions in this region since 1986 and to *Mnemiopsis* grazing pressure thereafter (Shiganova, 1997). Changes of most common species were best expressed by the alteration of the copepoda/cladocera species dominance.

In offshore areas the dominant species *Pseudocalanus elongatus*, *Calanus euxinus* and *Sagitta setosa* decreased 10 to 100 fold. A common feature of the entire Black Sea was the increase of the total zooplankton biomass, but mainly on the account of opportunistic species *Noctiluca scintillans* and the gelatinous species *Pleurobrachia pileus*, and *Aurelia aurita* (Zaitsev and Polischuk, 1984).

Since mid-90ies, changes in the communities species composition, pattern of seasonal dynamic and diversity were reported, despite of *Mnemiopsis* interannual fluctuations suggesting signs of recovery of zooplankton communities (Kideys, 2002).

Four species of gelatinous animals are common in the Black Sea, two indigenous scyphozoan medusae (*Rhizostoma pulmo* and *Aurelia aurita*) and two ctenophores (the indigenous *Pleurobrachia pileus* and the invader *Mnemiopsis leidyi*).

*Rhizostoma pulmo* is most common in coastal areas and is the least abundant among gelatinous animals of the Black Sea, although in the late 1960s - early 1970s high abundances were reported. *Aurelia aurita* typical in polluted inshore waters, reached peak values (over 1 kg m<sup>-2</sup>) during the 1980s and a total biomass for the entire sea calculated at 300-500 million tons, decreasing after the outburst of *M. leidyi* in 1989. A significant negative correlation between the number of *M. leidyi* and the biomass of *A. aurita* (n=14, r= -0,80, p=0.005) was observed (Shiganova et al., 1998). Following the decrease of *M. leidyi* in 1995-1996 the *A. aurita* biomass again started to increase.

Since its introduction into the Black Sea, *M. leidyi* manifest successful naturalization in the ecosystem – from few specimen detected in 1986- 1987, in spring 1988 large numbers of ctenophore were recorded in various parts of the Black Sea – 20 to 60 g m<sup>-2</sup> and a biomass in the central part as high as about 1 kg/m<sup>-2</sup> (Vinogradov et al. 1989). In August of 1989 the biomass of ctenophore in the coastal areas of the sea and in the north-western shelf exceeded 3 kg/m<sup>-2</sup> (maximum-5,2 kg m<sup>-2</sup>), and in the open area was about 1,5 kg m<sup>-2</sup>. In the summer 1990, in several coastal zones (Anapa and Bulgaria) its biomass amounted to 10 to 12 kg m<sup>-2</sup>, and up to 1,5-3 kg m<sup>-2</sup> in the open areas. After 1990 the biomass of *M. leidyi* decreased almost steadily until 1993 when it dropped to its lowest value (0.05 kg m<sup>-2</sup>) since the beginning of its outbreak. In 1994 a high biomass (2.7 kg m<sup>-2</sup>) in the open sea in August-September was found and remained at a moderate level of 1-1.5 kg m<sup>-2</sup> in 1995 and 1996. *Mnemiopsis* was suggested one of the key factors for the adverse changes in the planktonic community structure, leading to the collapse of fisheries in the whole basin (Mutlu, 2001; Shiganova, 2001).

After *Beroe ovata* introduction a new phase in *Mnemiopsis* development in the Black Sea with a very pronounced year-to-year variability and a general decreasing trend suggesting a successful predator prey – control.

Based on the ctenophore abundance and interaction pattern, the classification into “poor”, “normal” or “rich” years was adopted for the Black Sea ecosystem. Based on data of 1999-2002 in comparison to long-term trends, the positive changes recorded in mesozooplankton performance along the Bulgarian coast are explained as adjustment to the prey-predator mode of the exotic couple *Mnemiopsis-Beroe* not ignoring other environmental factors. Various factors have been reported to contribute to the variability of zooplankton spatio-temporal



distribution and abundance, the anthropogenic impacts being considered among the key forcing factors. Pollution (e.g. oil pollution) was reported as a possible reason for the observed decrease in the zooplankton in the upper water layers by affecting the early stages in the life cycle of zooplankton and fishes in particular, which are very sensitive to pollution.

As it often happens in nature, events do not occur as a consequence of single causes, and it is the confluence of multiple events that result in a given situation. Factual observation on *Mnemiopsis* food preferences, however, clearly show that this ctenophore feeds on fish eggs and larvae and on their food. Its arrival in an already impacted system might have triggered and facilitated the rapid decline of the fish populations.

In the Aegean sea, *Mnemiopsis* was firstly recorded in the Saronikos Gulf during late spring-summer 1990 (45-75 ind. m<sup>-2</sup>). Since then its abundance was decreasing until 1996, and after this year became rare in the area (Shiganova *et al.*, 2001). However, swarms were recorded in other areas of the Aegean Sea. I

The presence of *Mnemiopsis* in the Aegean is mainly attributed to the Black Sea water entrance into the northern Aegean Sea.

Recent unpublished experimental work suggests that reproduction rate of *Mnemiopsis* is highest in the Black Sea and lowest in the Aegean Sea, although weight specific reproduction is highest in the Caspian Sea and lowest in the Aegean Sea. The lower reproduction rate in the Aegean Sea was attributed to both the lower prey concentration (mesozooplankton) and the higher salinity in the area. The respiration rate was also lower in the Aegean and the Caspian Seas than in the Black Sea, which is probably related with the different osmoregulation resulted by the great differences in salinity.

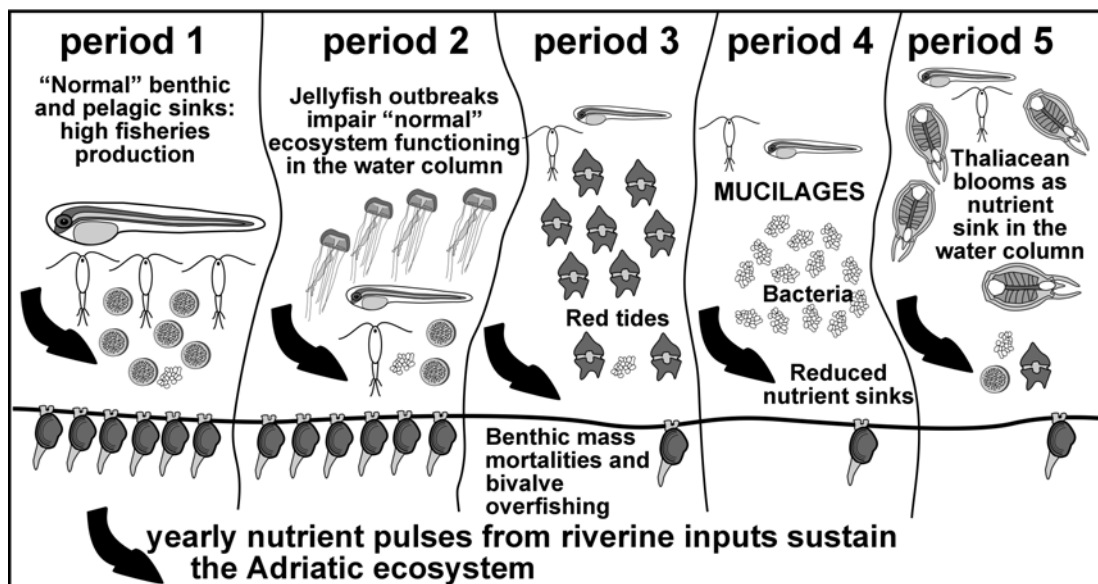
### ***Pelagia* and the history of the Adriatic Sea**

The Adriatic has always been very productive, especially in its northern part, with high fish and shellfish production. The nutrient input of the Po river, and of other rivers, fuelled an efficient trophic web that led to a much flourishing economy. In the early Eighties, *Pelagia noctiluca*, a Mediterranean-resident scyphozoan, became so abundant to clog fishing nets in almost no time, impairing their efficiency. The scientific community was not ready to study such a phenomenon: many scientists tackled that problem just due to sudden fund availability, with no prior experience on gelatinous organisms. A better understanding of the impact of *Pelagia* on ecosystem functioning might be inferred by comparing the situation of the Adriatic with that of the Black Sea, a few years later. *Mnemiopsis* did not contribute to the collapse of fisheries because it clogged fishing nets but, instead, because it ate fish eggs and larvae, and also the crustacean zooplankton that fish larvae and juveniles feed upon. The local scientific community had a chance to better appreciate the phenomenon in respect to what happened in the Adriatic for *Pelagia*. It is highly probable that the impact of *Pelagia* outbreaks was similar to that of *Mnemiopsis*. Both are gelatinous, opportunistic predators, both went through outbreaks and, furthermore, *Pelagia* is larger than *Mnemiopsis* and is a powerful stinger. If the blooms of *Mnemiopsis* depleted the fish stocks of the Black Sea by predation and competition, it is probable that the outbreaks of *Pelagia* had similar effects on the Adriatic ecosystem. But we will never know, since research did not focus on this aspect, also because *Pelagia* suddenly disappeared. After the *Pelagia* years, dinoflagellate outbreaks occurred, leading to red tides. The study of red tides was totally uncoupled from the study of jellyfish blooms, even if both cases involve opportunistic species that monopolized the standing biomass, subtracting ecospace to all other species. The causal link leading from jellyfish to dinoflagellate outbreaks is a tenuous one, and cannot be tested anyway. It has been



hypothesised, however, that the ecological vacuum left by the *Pelagia* years was filled by opportunistic dinoflagellates that had resting stages in the Adriatic sediments, waiting for a good opportunity to hatch. The Adriatic red tides led to anoxic crises that led to mass mortalities. The benthic stocks of bivalve molluscs (as well as other filter feeders like ascidians and sponges) became depleted. Fishermen, to cope with stock depletion, increased their efficiency in extracting bivalves from the sediments by shifting from artisan to industrial (hydraulic dredges) devices. The depletion of benthic filter feeders was further enhanced. After all this, mucilages arrived. Mucilages are probably due to nutrient processing by bacteria. Bacteria (and also particulate organic matter) are fed upon by mucous filter feeders like bivalves and ascidians, so that the absence (or the great reduction) of their populations (a veritable nutrient sink) probably left space just to bacteria to perform their metabolic activities on the available carbon.

Casual observation showed that when there are extensive outbreaks of pelagic tunicates (very efficient, mucociliary filter feeders) mucilages do not occur. A possible explanation for this is that the benthic sink is replaced by the planktonic one.



Adriatic ecological history can be divided into five main periods: Period 1: Nutrient pulses sustain diatom production that, in its turn sustains zoobenthic filter feeders and zooplankton, this one sustaining nekton. In this period the Adriatic fisheries yields are very high. Period 2: several years of outbreaks of *Pelagia noctiluca* have a strong effect on the communities in the water column, removing zooplankton and fish larvae. Period 3: the reduction of pelagic nutrient sinks, due to *Pelagia* outbreaks, leaves space for opportunistic dinoflagellates, leading to red tides in the water column and to benthic mass mortalities. The reduction in fisheries yields leads to increased fishery effort (for instance with hydraulic dredges). Both pelagic and benthic nutrient sinks are reduced. Period 4: In the absence of relevant nutrient sinks, nutrient pulses are used by bacteria that produce mucilages as a side effect of their metabolism. Period 4: Blooms of pelagic tunicates filter phytoplankton (including bacteria) and restore, albeit temporarily, the pelagic nutrient sinks.

This "historical" reconstruction of Adriatic ecology shows what might be gained by careful inspection and monitoring of biodiversity changes in this basin and, most probably, in any other basin. The composition of biodiversity, in terms of species evenness, can greatly alter

ecosystem functioning and the unexpected events of a given period (e. g. mucilages) might be the product of a chain of events triggered by other, equally unexpected, events (e. g. jellyfish outbreaks).

All this, besides providing an ultimate explanation of the mucilage phenomenon (supplementing the proximate one linked to bacterial metabolism), also provides management advice, since the restoration of an efficient benthic carbon sink is a prerequisite for the establishment of the “normal” situation, even though the Adriatic might never go back to the conditions of 30 years ago but, instead, might reach another more or less stable point. Another variable to insert in this picture is the arrival of the exotic bivalve *Tapes philippinarum* that, in recent years, established extremely successful populations, possibly restoring at least a part of the benthic sink.

The above reconstruction is completely hypothetical, but it provides an explanation of events whose occurrence has been investigated only in the proximate mechanisms. The most obvious example is the explanation of red tides with nutrient availability. Nutrients are necessary for the development of red tides, but they are not sufficient.

### ***Rhopilema* in the Eastern Mediterranean (and *Olindias* in Tunisia)**

The south-eastern basin has been suffering since the late 1970s from annual jellyfish blooms caused by a previously unknown species, *Rhopilema nomadica*, that became rapidly established and built populations that impact significantly both fisheries and tourism (Galil et al. 1990). This species, though first described from the Mediterranean, is in fact an Erythrean alien (of Red Sea origin, entering through the Suez Canal), and is known to occur in the red Sea and along the east African coast, though not forming there as huge shoals as in the Levantine basin. Every summer since the 1980s, *Rhopilema* is a constant (and irritating) component of the Eastern Mediterranean gelatinous plankton, with great ecological impacts. Apparently, however, the species has not yet expanded beyond the Levantine basin. Two other alien tropical jellyfish are known from the Levant: *Cassiopea andromeda*, rapidly expanding in the eastern basin, especially in bays, and *Phyllorhiza punctata*, which appears occasionally nearshore.

Gelatinous plankton is often overlooked by “classical” plankton studies, mainly focused on crustaceans. It is not surprising, thus, if information on this component of plankton is scant. The first study on the gelatinous plankton of Tunisia, for instance, reported recent recurrent blooms of *Olindias phosphorica* (a hydromedusa that can reach 6 cm in diameter) that disturb fisheries and tourism (Yahia et al., 2003).

The fish-jellyfish transitions described above are apparently unrelated, at least from the point of view of possible successful strategies of the single species. The concurrent success of gelatinous species, as already suggested, is probably due to the decline of their direct competitors: large fish.

## **Erythrean alien Species in the Mediterranean Sea**

The Mediterranean Sea is exceptionally susceptible to biological invasions. The principal vectors of introduction are, in descending order of importance, passage through the Suez Canal, mariculture and shipping (CIESM, 2002). Alien macrophytes, invertebrates and fish are found in most coastal habitats in the Mediterranean. Some invasive species have outcompeted or replaced native species locally, some are considered pests or cause nuisance, whereas other invaders are of commercial value. The rate of marine bioinvasions has

increased in recent decades; collectively they have significant ecological and economic impacts in the Mediterranean. However, little has been done to evaluate the risk posed by each vector, or to minimize the risk of introducing additional alien species.

The Erythrean invasion through the Suez Canal has contributed the largest number of alien species in the Mediterranean amounting to over 80% of the records of alien fish (Golani et al. 2002), decapod crustaceans (Galil et al. 2002) and molluscs (Zenetos et al. 2003). Despite impediments such as the canal's length, shallowness, turbidity, temperature and salinity extremes, hundreds of Erythrean species traversed the Suez Canal and settled in the Mediterranean, forming thriving populations along the Levantine coasts, with some invaders extending their range as far west as Tunis, Malta and Sicily. They exert a significant impact on the local biodiversity and ecosystem function.

Erythrean species, in fact, can replace their congeners almost completely, as it happened with the Indo West Pacific starfish *Asterina burtoni* in respect with the autochthonous *Asterina gibbosa*, whose populations along the Israeli declined in coincidence with the rapid increase of its Erythrean congener. Similarly, in the same geographical area, the Erythrean killifish, *Aphanius dispar* replaced *A. fasciatus* along the Mediterranean coast of Israel; the Erythrean mytilid *Brachidontes pharaonis* replaced the native mytilid *Mytilaster minimus*; the Erythrean limpet, *Cellana rota*, replaced the native Mediterranean limpet, *Patella caerulea*; the native penaeid prawn, *Melicertus kerathurus*, commonly caught by trawlers along the Israeli coastal shelf on sandy or sandy mud bottoms, is now replaced by Erythrean penaeid prawns; the Erythrean snapping shrimps *Alpheus inopinatus*, and *A. audouini* are more common in the south-eastern Levantine rocky littoral than the native *A. dentipes*, and *A. rapacida*, much more common than the native *A. glaber* on the muddy bottoms of the shallow shelf; the Erythrean dragonet, *Callionymus filamentosus*, has replaced the native callionymids *C. pusillus*, and *C. risso*, along the Levantine upper shelf; the populations of the Erythrean narrow-barred mackerel, *Scomberomorus commerson*, have greatly increased in the 1980s, coincidentally with the decline in the populations of the one-time common native meager, *Argyrosomus regius*, to the point where the latter is rarely encountered along the Israeli coast.

Competitive displacement may also modify bathymetric ranges in populations of Erythrean and indigenous species. The native red mullet, *Mullus barbatus* and the native hake, *Merluccius merluccius* were both displaced into deeper, cooler waters by their respective Erythrean competitors, *Upeneus moluccensis* and *Saurida undosquamis*. Similarly the Erythrean mantis shrimp, *Erugosquilla massavensis*, displaced the native Spottail mantis shrimp, *Squilla mantis*, into deeper waters.

The changes caused by Erythrean alien species have gone beyond local decimation or replacement of native species, or modification of their ranges, some Erythrean invasives have altered the native food web. The two Erythrean siganid fish that settled in the Mediterranean: *Siganus rivulatus* and *S. luridus*, were first recorded off the coast of Israel in 1924 and 1955, respectively. Both species formed thriving populations along the Levant coast and are found as far west as Tunisia. An analysis of gut contents of siganids, in conjunction with the spatial and seasonal composition of the local algal community at one rocky site off the Israeli coast, showed that their diet has also a significant impact on the structure of the local algal community: it seems that by feeding selectively they have nearly eradicated some of their favorite algae locally. The multitudinous siganids have replaced native herbivorous fish: "... along the Lybian coast, *S. rivulatus* seems to outcompete *Boops boops*, reducing the abundance of the latter, since both species feed upon algae.... Quite likely, the same is true for the S.E. Aegean Sea". Likewise, along the Lebanese coast, it has replaced the native *Sarpa salpa*, that had been abundant in trawl catches early in the 20th century. The siganids comprise a third of the fish biomass in rocky habitats along the Israeli coast, and 80% of the

abundance of the herbivorous fish in shallow coastal sites in Lebanon. Prior to the arrival of the siganids in the Mediterranean, there were few herbivorous fish and their role in the food web off the Levantine rocky habitats had been negligible. The algal contribution to the web was mainly through the decomposers. The algivorous siganids increased the rate large amounts of algal material were recycled (in hours through the fish gastrointestinal system rather than weeks or months of decomposition).

### **Phantom aliens in the Mediterranean**

Boero et al. (2005) argue that the number of aliens that reached the Mediterranean Sea might be much higher than presently perceived. The examples of two hydromedusan species are used to exemplify this situation. *Clytia linearis* was first described (as *C. gravieri*) during the first biological exploration of the Suez Canal, in 1938. The second record from the Mediterranean dates back to the early Fifties and, since then, it became the most common littoral hydroid of the basin, even if it has never been labelled as an alien species. Another species of the same genus, *Clytia hummelincki*, reached the Mediterranean at the end of the last century and is now rather frequent and abundant in the Adriatic, Ionian and Thyrrenian Seas (the only ones where it had been searched for). Both species produce medusae and might have an impact on ecosystem functioning by predating on fish larvae and on their food, just as *Mnemiopsis leyidi* did in the Black Sea. These animals are rather inconspicuous and only expert taxonomists can recognize their presence. Since taxonomic expertise is rapidly vanishing throughout the world, chances are good that many successful aliens of small size simply pass unnoticed, in spite of potentially great impacts (the ecological importance of a species is not proportional to its size).

### **Red tides, Harmful Algal Blooms, and Mucilages**

Red tides, Harmful Algal Blooms in general, and mucilages occur when nutrient loads become high, an environmental state labelled as eutrophication (Vollenweider et al. 1992). These phenomena are rather frequent in the Mediterranean, as shown above for the story of the Adriatic. Other cases are well documented in the Aegean Sea coastal waters, the periodicity of red tide phenomena are sporadic and irregular. In the Saronikos Gulf, strong red tide events accompanied by fish death occurred during 1977-1983 as well as in 1987 and they were caused by the toxic dinoflagellate species *Gymnodinium breve*. A list of red tides phenomena (from the early 1980 to 1995), the blooming species (30 species) and their relation to anthropogenic eutrophication in the Saronikos and Thermaikos gulfs was presented in Moncheva et al. (2001). A detailed review on the occurrence of mucilage phenomena (associated with diatoms) in Hellenic coastal waters during 1982-1994 is given by Gotsis-Skretas (1995).

Thermaikos Gulf is an area where HABs are recorded frequently. Dinoflagellates were the dominant blooming species from 1996 and among them was the toxic species *Dinophysis cf. acuminata*, a DSP causative (Diarrhoeic Shellfish Poisoning), with substantial socio-economic impact in the area (economic losses of ~3 million Euros every year).

### **The drivers of change**

Both the Mediterranean and the Black Seas are undergoing rapid change. The Mediterranean biota is obviously responding to a rise in temperature, so showing precociously what will

presumably happen to the rest of the world ocean where, due to greater water masses, the change will take longer to become so evident. The Black Sea is showing the impact of an invasive alien species on a species poor basin.

Both basins are presently characterised by high biomasses of gelatinous plankton, heavily impacting on fish communities and on tourist activities.

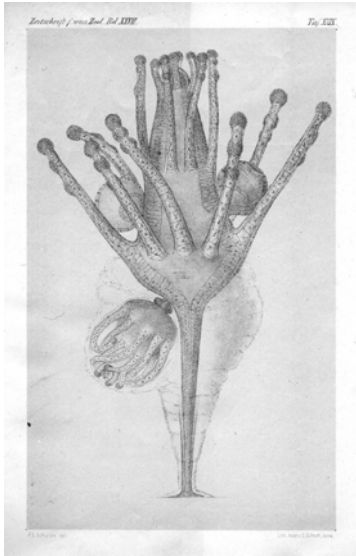
The sharp decrease in top predators in marine food chains is well documented by fisheries' reports, and disregarding the consequences, fisheries continue fishing from ever lower rungs of marine food webs (often to feed aquacultured top predators). The top positions in marine food webs are being taken by opportunistic species that do not feed on adult but on larval prey and that are able to shrink their populations when resources are not available and to build up enormous populations when conditions are favourable. These predators are gelatinous: cnidarians and ctenophores are replacing big fish at the top of marine food chains. This tendency is already realised in both the Black Sea and the Eastern part of the Mediterranean, where we can observe a condition that will possibly become the rule in many parts of the world ocean.

### **Species extinction (as seen through the Hydrozoa)**

A common concern about biodiversity is the increase in extinction rates at a global level, especially due to human activities. The media report on this phenomenon extensively and it is quite normal to hear or read that, at present, we are in the midst of a biodiversity crisis that is similar to the one that led to the disappearance of dinosaurs! It is undeniable that man had (and has) a great impact on terrestrial communities, causing the extinction of many species of large vertebrates and even of invertebrates. The same impact, however, is rather difficult to prove for the marine fauna and flora. The Mediterranean area is impacted by human activities since millennia and should be the most sensitive one to human action. If one asks the name of even a single marine species that became extinct from the Mediterranean, the answer is "we do not know". There are several threatened species, like the monk seal, the red coral, and a few others (if compared to the rest of the Mediterranean biota), but no documented case of species extinction is available from the basin (Boero, 2003). Is this due to overamplification of environmental problems, and we are worrying for nothing? Or, maybe, there are species that became extinct and we simply do not perceive their absence? If we look at the reports on marine biodiversity, what we see is exactly the opposite: species numbers increase! A list of Mediterranean Antho- and Leptomedusae made in 1958 by Picard (intended for an unpublished volume of Faune de France) included 191 species. Boero and Bouillon updated the work in 1993, listing 346 records, and in 1997, Boero *et al.* listed 379 species (see Bouillon *et al.* 2004 for a review). So, if we consider the literature, the number of Mediterranean hydrozoan species doubled in less than fifty years! The same is true for almost all marine groups. Of course this is due to the addition of the newly recorded species to the ones that were already present in the former lists: we always report on what we find and not on what we do not find! Boero and Bouillon did not find all the species that Picard listed, they simply took Picard's list and added to it all the new records from the Mediterranean. The problem is: are all these species still there? How can we realize that an inconspicuous species became extinct? We would do well to compare present-day lists (based on present collections) with old lists deriving from comparable sampling effort (though sampling efforts are often incomparable).



The problem of documenting possible extinction might be tackled from another angle. Is there a place in the Mediterranean that is conducive to local species extinction and that is hosting a biodiversity that bears some originality in respect to the rest of the basin? The answer is: the Northern Adriatic. The Northern Adriatic has climatic features that are similar to those of northern seas, and also its biota are similar to those of Northern latitudes. The main driver for



this are the northern winds that cause temperatures as low as 5 °C in the winter! The brown alga *Fucus virsoides* is the trademark of this area and it is endemic to this part of the Mediterranean. It is probably strictly related to *Fucus spiralis*, a species living in the Atlantic. How many species contribute to the originality of the Northern Adriatic? The answer is not easy. Many of these species have been described long time ago and, maybe, nobody found them again because nobody looked for them. Benovic et al. (1987) noticed a decrease in hydromedusan diversity after the *Pelagia* years, but this tendency soon became inverted and the situation went back to “normal”. In 1876, however, Schulze described a new hydroid species, *Tricyclusa singularis*, from the Gulf of Trieste. The main feature of this species is the presence of three rings of tentacles on the hydranth column, a very distinctive character that led to the erection of a new family to accommodate the species.

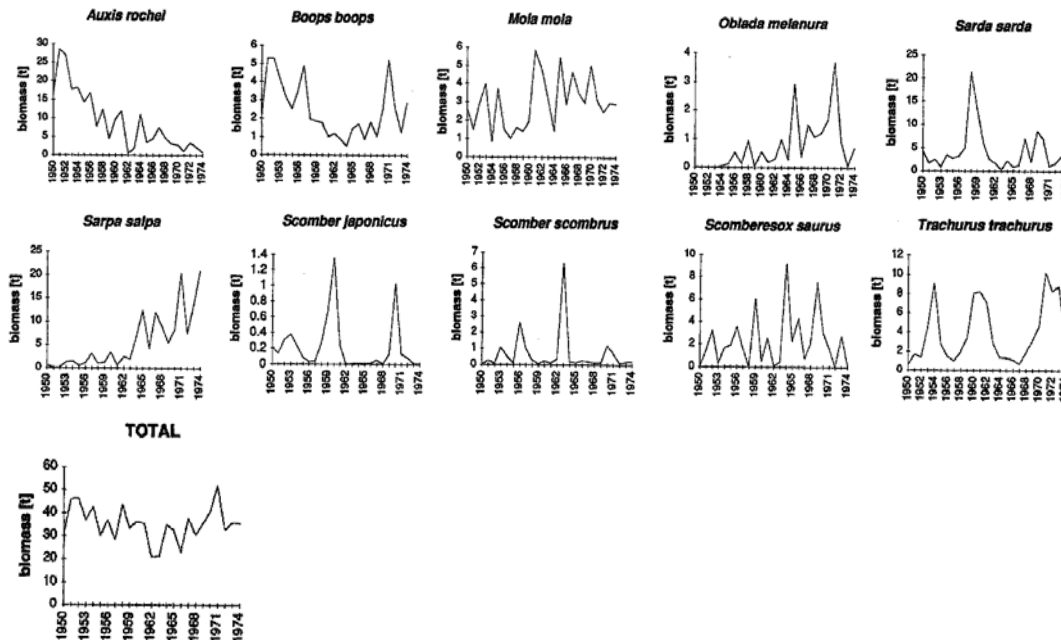
After its discovery, *Tricyclusa* has never been recorded again from the Mediterranean, but has been found repeatedly in Brittany (even though it is not sure that the Atlantic species is identical with the Mediterranean one)! The explanation for these patterns of distribution might be that, after the opening of Gibraltar, the basin was colonised by Atlantic species of temperate affinity and only later the climate exerted a selection of species and also led to speciation events that produced the present-day biodiversity of the basin. The remnants of these early colonizers are to be found in the part of the basin that is more similar, in climatic features, to the sites of origin of the species that entered from Gibraltar. In case of global warming, it is reasonable to hypothesise that the species that will be more affected will be the ones with boreal affinity. The compilation of a list of species that have been recorded only from the Northern Adriatic might lead to the hypothesis that they should be under stress, and maybe even extinct from the basin, due to the current temperature increase. The fact that *Tricyclusa singularis* has not been reported since 1876, for instance, suggests that the species might be extinct. A strong sampling effort from the Northern Adriatic, aimed at finding the species recorded in the past, might lead to the identification of a group of species that are presumably extinct or, at least, endangered.

## Biodiversity and ecosystem functioning in a changing world

Ecosystem functioning is often intended as the efficiency of biogeochemical cycles (Naeem and Wright, 2003). If we accept this meaning, it is obvious that biodiversity has nothing to do with ecosystem functioning (see Boero et al. 200 for a review). Rare species are the bulk of biodiversity and their bearing on biogeochemical cycles is often negligible (unless they are keystone species). The carbon budget, or the biomass yield, of a basin might remain stable, but the species composition of the biota might change considerably. The species composition of the biota is very important in providing good and services to our species. Identical biogeochemical cycles might lead to a large production of fish biomass or, in alternative, to a



large production of jellyfish biomass. The cycles of both carbon and phosphorous might result unchanged, but, for our activities, having large biomasses of jellyfish (or of bacteria) instead of fish represents a big difference.



What is the efficiency of biogeochemical cycles in the Black Sea when *Mnemiopsis* is thriving, in comparison to when *Mnemiopsis* is absent? The answer to this question might become crucial to show that the efficiency of biogeochemical cycles might not be sufficient to understand ecosystem functioning. And the same might be done by looking at the bearing of jellyfish blooms on ecosystem functioning in the Eastern Basin. In other words, the quantity of the system (in terms of biomass and biogeochemical budgets) might not be related to its quality (in terms of species composition and relative abundances). The study of fisheries long-term series often shows that the total yields remain unchanged, but the species composition changes widely. The example reported in figure refers to 25 years of fisheries in a tuna fishing net in the Ligurian Sea (Boero, 1996). The total yield remains almost constant, but the contribution of each species to the total varies considerably. If the functioning is expressed as total production, then there are no changes, if biodiversity is considered, then the relative abundances of species change considerably. This example shows that total budgets might hide severe changes that, if species are not considered, might pass unnoticed (unless the species are of commercial value).

## Biotic change in the Mediterranean and the Black Seas

As described in the above-mentioned examples, biotic change is very evident in the Eastern basin, due to influx of Erythrean alien species. The appreciation of change, however, is biased by poor previous knowledge of the local biota. It is undeniable, anyway, that the Mediterranean, due to the concomitant occurrence of the opening of the Suez canal and of a rise in temperature, has become prone to biological invasion from the Red Sea and is also offering a proper environment for alien species transported artificially by man, through aquaculture, ballast waters, ship hull fouling, etc.

The rise in water temperature might have impaired the physiology of resident species. A sudden lowering of the summer thermocline from 12 to more than 50 m, for instance, killed gorgonian populations living above 50 m in the Ligurian sea (Cerrano et al. 2000). Temperature anomalies of even short duration, thus, can change dramatically a local fauna. Once a formerly successful population is eradicated, there is ecospace for the establishment of other populations, possibly pre-adapted to the new conditions. In this way, the entrance of alien species might be considered not only an ecological disaster (as is the case of *Mnemiopsis*) but also as a biodiversity resource against impoverishment due to climatic shifts. The Mediterranean, furthermore, can undergo dramatic changes also in the lower tail of its temperature range. In the 2001 winter, for instance, the Adriatic and the Aegean seas went through a period of abnormally low surface temperatures (from 9 °C to freezing) that led to mass mortalities of sardines (*Sardinella aurita*), that stranded in the millions (Guidetti et al. 2002). Such episodes of low temperature might get rid of new invaders of tropical affinity. The tropicalisation of the Mediterranean, thus, might be buffered by episodic events of temperature lowering, preventing extreme success of Erythrean species.

Episodic events, thus, are (or might be) extremely important in conditioning the shape of local biodiversity, even for a long time. The link of episodic, and sometimes undetected, events to subsequent long-lasting changes in species richness, or simply evenness, is often not obvious at all. Obvious cases are the already mentioned lowering of the summer thermocline leading to gorgonian mass mortalities in the Ligurian sea. Without proper monitoring of temperature distribution, however, the causes of the mortality would have been mysterious.

## A research protocol

The monitoring of chemico-physical factors is crucial to understand the driving forces that lead to changes in biota and, sometimes, in ecosystem functioning. This kind of investigation is being carried out since a long time and sophisticated tools (e.g. satellites) and algorithms are being used to acquire data and build up models. This wealth of data and models is not counterbalanced by equal information on the features of the biotic components of the ecosystems. Some measurements of phytoplankton composition can be made almost automatically by considering the relative abundances of photosynthetic pigments, but this is only a tenuous indication of the actual features of the biota. The only data on the biotic component that are object of continuous attention regard the yield of fisheries, and the quest for wise use of natural resources led to great efforts in modelling the dynamics of fish populations, coupled with the effort of fisheries. The outcome of these efforts did not reach the expected targets, since the resource represented by fish populations is rapidly vanishing. It is clear, now, that fish and man are just two components of a very complex system and that marine resources can be managed only while considering marine systems, and not only some of their components (the enforcement of the Ecosystem approach is timely, but it should have been so obvious since the very beginning of research on these systems!). The value of any model can be judged by the number of variables that it considers, compared to the number of variables that can be identified. In non-linear systems, furthermore, apparently irrelevant variables can acquire enormous power (like the episodic events that are mentioned above) and even re-direct the trajectory of a system for reasons that are not immediately obvious. In other words, since we do not know what might become important, in theory we should sample everything and, as a consequence, a useful model should consider everything or, at least, as many variables as possible. The required effort is overwhelming. The sampling of biodiversity requires focused tools according to the investigated domains. Benthic samplings

are different for macro and meiofauna, or for hard vs. soft bottoms. Traditional plankton samples are mainly focused towards crustaceans and are not efficient for gelatinous macrozooplankton. Nekton samples are almost invariably carried out with fishing gears, and only recently the technique of visual census is providing data on non-commercial species.

The impossibility of considering everything led to consider the variables that are more readily acquired from field measurements. Again, we end up with commercial fish, phytoplankton pigments and some components of zooplankton, almost invariably crustaceans. Systematic benthic samplings are rare, and there are very few, if any, long-term series covering the features of the benthos. The expertise and the manpower to carry out all these measurements on a wide geographic scale and in a continuous fashion are not available anywhere (see CIESM, 2003).

The experience deriving from the detected patterns of the past allows identification, however, of two types of information:

Information deriving from stability

Information deriving from instability

Stability is what we can find, sample after sample, in a more or less regular way. If phytoplankton is sampled, chances are good that diatoms will be found. If, instead, zooplankton is sampled, chances are good that copepods and euphausiaceans will be found. Their abundances will change with seasons, but these groups are usually dominating the water column.

Instability occurs when these patterns are disrupted. Dinoflagellates do not become dominant on a regular basis, and the same is true for gelatinous zooplankton. These components are often completely absent, or irrelevant, in plankton samples. But when they become abundant, chances are good that the system will become affected by their presence, and the regularities will become disrupted, leading to novel states of the investigated systems (like it possibly happened in the Adriatic, after the outbreaks of *Pelagia*).

If one builds up models that consider the information deriving from stability, then the model will be reliable as long as things will not diverge much from their usual patterns. But if one wants to cope with the irregularities of the system (the drivers of change), then one has to focus on information deriving from (and leading to) instability.

The history of both the Mediterranean and the Black Seas are showing clearly what are some of the main biological sources of instability: dinoflagellates and gelatinous plankton, and alien species in general, sometimes deriving from human transport. These components of marine systems are not routinely investigated. The reason is simple: they escape routines. A research project on such topics has great chances of failure. On the other hand, if we concentrate on routinary samples, we will not be able to understand why routines (i.e. stability) become interrupted. In the Black Sea and in the Eastern Mediterranean Sea, the occurrence of gelatinous plankton became almost regular, with a precious chance of observing the impact of such organisms on ecosystem functioning. The rate of arrival of alien species, furthermore, is great in the Eastern Mediterranean. The two basins offer a unique opportunity to study instabilities, since what is a source of instability elsewhere became a stable feature of these systems. They might provide the ecological scenarios that will dominate in the future also in other basins.

The conceptual revolution proposed here, then, tends to disregard the stable components of the systems, focusing on the episodic events that might disrupt ecosystem stability. The risk of failure, if this is pursued in the Eastern Mediterranean and in the Black Sea, is low, since these irregularities are becoming the rule.

The protocol, then, is as follows:

Identify driving oceanographic forces within the basins that are presumably affected by dramatic change (i.e. temperature rise, increase in nutrient load) and compare them with the oceanographic features of nearby basins. Why, for instance, the Mediterranean is not prone to the invasion of *Mnemiopsis*? Or, why does *Rhopilema nomadica* not invade the northern and western Mediterranean, remaining confined to the Easternmost part of the basin? What are the impacts of these two species on ecosystem functioning, considering nutrient budgets on the one hand, and communities' species composition on the other hand? What is happening to the species of cold affinity inhabiting the Northern Adriatic?

Genetic studies on the populations of alien species will allow ascertaining if they are the result of single events of colonisation, or if the arrival of propagules from source areas is rather continuous or, at least, occurred several times in the past.

The presence of dinoflagellates should be investigated both as functional stages in the water column and as resting stages in coastal sediments.

## Lessons for the future

The summary of the conditions of both the Mediterranean and the Black Seas represents only the main aspects observed. Historical reconstructions and comparative ecology (based on biogeography and ecosystem functioning) are very strong tools for identification of patterns and processes that should be studied with more refined tools, involving experiments and, eventually, models.

In this framework, the opportunity provided by the Eastern Mediterranean and the Black Seas are unique in the whole world and are conducive to depict scenarios that might represent the future state of much larger systems.

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