

## The Mediterranean: a synoptic overview

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**Resum.** S'explica de forma breu la formació de la Mediterrània a partir del Tethys així com tota l'estructura geomorfològica amb especial referència a la orogènia alpina. Especial atenció es dedica a la circulació superficial d'origen atlàntic considerada com el factor bàsic de tota la dinàmica mediterrània, amb especial referència al paper dels estrets i al significat de l'efecte estuari. Així mateix l'acció dels vents més importants es té en compte pel fet que afecta la dinàmica complexa oceanogràfica. Com a primer resultat del conjunt de les accions dinàmiques s'estudia i es reflexiona sobre els diferents factors que contribueixen a la productivitat mediterrània considerada superior a l'esperada. En un altre aspecte s'examinen les característiques de l'ecosistema mediterrani considerat com a una gran unitat encara que amb gradients molt característics. Com un dels elements que caracteritzen a l'estructura dinàmica de l'ecosistema mediterrani es revisa la influència de l'home a través de la pesca i la contaminació en tant que factors perturbadors. Finalment com a resum s'exposa una visió global en la que s'assaja d'integrar els factors oceanogràfics, biològics, socioeconòmics amb especial atenció a la dinàmica humana amb l'intent que la integració de tots aquests aspectes permeti una comprensió de la totalitat de la problemàtica mediterrània com a base d'una possible planificació més sostenible.

**Paraules clau:** Mediterrània · productivitat marina · ecosistemes marins · impacte dels humans en la pesca

**Abstract.** The formation of the Mediterranean Sea from the former Tethys, and its geomorphological structure, with special reference to the Alpine orogenesis, are discussed. Special attention is given to the superficial circulation originating from the Atlantic, an essential factor in the Mediterranean's dynamics. Particular reference is made to the role of the sea's straits and to the significance of the estuary effect. Furthermore, the action of the more important winds is considered insofar as they affect the Mediterranean's complex oceanographic dynamics. The dynamic actions of these winds are analyzed, as are the different factors contributing to the Mediterranean's higher than expected levels of productivity. The characteristics of the Mediterranean ecosystem are also analyzed from a different perspective, by considering the Mediterranean ecosystem as a single large unit, although the existence of very characteristic gradients is recognized. The disrupting influence of humans, through fishing and contamination, is acknowledged as one of the elements influencing the dynamic structure of the Mediterranean ecosystem. Finally, as a summary, a global view is put forward that seeks to integrate oceanographic, biologic, and socioeconomic factors with human dynamics. The goal is to integrate these disparate aspects into a unified, broad-ranging comprehension of the Mediterranean that will serve as the grounds for more sustainable planning.

**Keywords:** Mediterranean · sea productivity · marine ecosystems · human impact on fisheries

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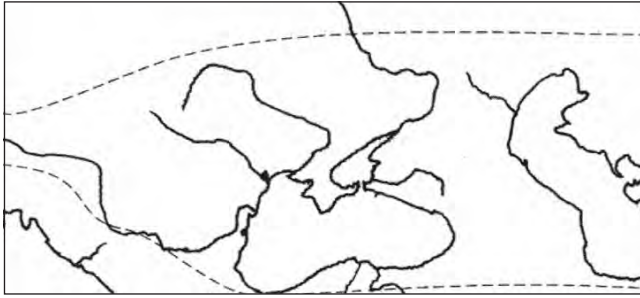
### Presentation

**Origin.** The displacement of the emerged land mass Pangea towards the northern part of the terrestrial globe led to the appearance of a ring-shaped sea, known as the Tethys Sea, that practically surrounded the planet. The contours of this ring blurred during subsequent geological periods, giving way to newly formed land masses and bodies of water, each with its

own distinct characteristics but with a common denominator related to their origin. Today, the best-preserved remnant of the Tethys Sea is the Mediterranean Sea, which except for a narrow strip is completely enclosed by land. In this context, it is necessary to consider another distinct body of water, the Paratethys, whose relationship to the Mediterranean changed over time and is poorly understood (Fig. 1). The difficulty lies in the fact that while the Mediterranean has a very high salinity, the salinity of the Paratethys was almost zero. It consisted of a large continental basin that Central and Southern Europe, all the way to Central Asia. Today, its remains are the Black, Caspian, and Aral Seas. During the Pliocene, 5.5 millions years ago, the straits of Istanbul (Bosporus) and the Dardanelles

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**Fig. 1.** Simplified diagram of the Sarmatic Sea (Paratethys).

opened flow towards the Mediterranean; this, in turn, affected the surrounding areas, especially the northern Aegean Sea. Although the hydrographic and—to a certain extent—biological characteristics of the Black, Marmara, and Azov (Pontic region) Seas are in many ways distinct from those of the Mediterranean, these bodies of water can still be considered in the context of the Mediterranean [1,2].

Alpine orogenic movements were of great importance in the origin of the Mediterranean basin. Not only did they determine its structural morphology but also, when the Strait of Gibraltar opened, some 5 million years ago, were associated with a biotic recolonization of Atlantic origin. These resulted in the current biological structure and reflected extremely important changes that modified the primitive biotic populations. Traces of the successive invasions that took place over several geological periods can still be identified in the current biotic populations.

### Geomorphologic structure

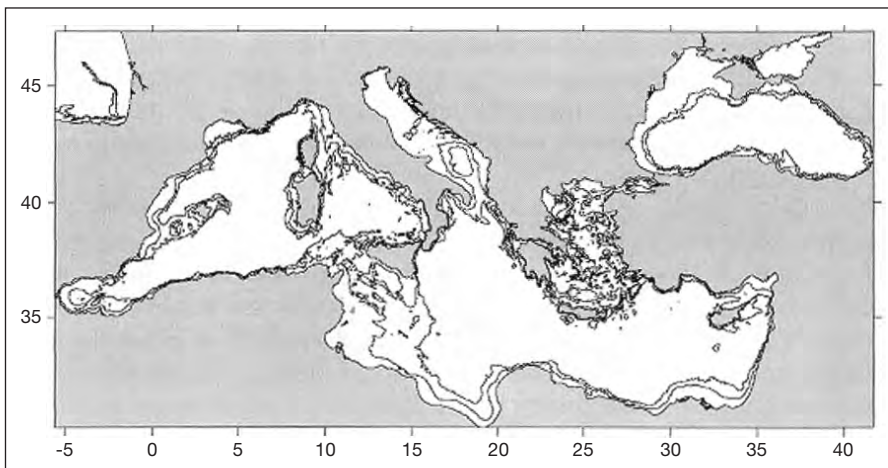
The current, definitive structure of the Mediterranean reflects the most recent orogenic processes, i.e., the Alpine orogeny. Globally, the Mediterranean is a basin that extends latitudinally and is located in the temperate zone of the northern hemisphere. While the northern Mediterranean has a very sinuous structure, with three land formations—the Iberian, Italian and Balkan Peninsulas—that extend southwards, the southern coast is practically rectilinear, broken up only by the gulfs of

Gabes and Sirte. The alpine movements that determined the Mediterranean's structure have had important political consequences for centuries, with particular significance in the western and north-central areas of this region. The Anatolian Peninsula, with its very ancient central nucleus, also has margins of alpine origin. The Mediterranean's alpine orogeny accounts for its narrow continental shelves, its abrupt or poorly developed coastlines, and its continental slopes, with their numerous submarine canyons. In addition, it consists of several vast platforms, some of which correspond to extensive coastal terrestrial zones. These latter structures account for many of the Mediterranean's oceanographic characteristics, in terms of the sea's unique marine biology, and thus to the density of human settlements, which have long benefited and depended on fishing from its waters (Fig. 2) [3].

The most extensive platforms are found in the Castelló-València zone, in the Gulf of Lion and the Rhone River delta, the northern Adriatic, the Gulf of Gabe, and in the Black Sea, in the vast zone between the mouth of the Danube and the Crimean Peninsula. The latter shelf is partly formed by sedimentary contributions from southeastern European rivers, i.e., the Dnieper and Dniester, together with the Don, which flows into the small Sea of Azov.

Along with the Mediterranean's narrow continental shelves, another remarkable feature is the numerous canyons distributed throughout the talus. While some of the canyons are orogenic in origin, the majority represents the continuance of fluvial basins, which have deeply marked particularly the upper part of the continental talus. These basins have been influenced by variations in sea level as well as by the Messinian Salinity Crisis, which reduced the Mediterranean to a few lagoons.

Of equal importance are the three active tectonic plates whose contact zones are located in the Mediterranean: the African plate, the Eurasian plate and the Arabian plate, the latter being responsible for delimiting the sea's most eastern part. The activity of the two former plates not only gives rise the Mediterranean's alpine orogeny, but also to earthquakes and to volcanic areas, both of which occur approximately along a line that crosses the Mediterranean from west to east. This line also marks the location of the Mediterranean Islands, the Bal-



**Fig. 2.** Map of the Mediterranean and Pontic Basins. Isobathymetry of 200 m and 1000 m.

earic Islands, Corsica, Sardinia, Sicily, Malta, Crete and Cyprus. All of these islands are related to orogenic movements that disrupted the Mediterranean basin. Also of note are a group of islands of different origin located in the Aegean Sea. These islands arose through Tertiary and Quaternary collapse/subduction processes that allowed for the appearance of the Aegean Sea and its mountainous remains the islands.

The Mediterranean's straits are another important geomorphologic feature, not only because they join or separate the different Mediterranean sub-basins but also because they are the points of passage of masses of water and thus greatly influence the sea's oceanographic dynamics [4]. Undoubtedly, the most important are the Strait of Gibraltar, which re-establishes the Mediterranean's hydrographic equilibrium, and the Straits of Istanbul (Bosporus) and the Dardanelles, which connect the remains of the ancient Paratethys or Sarmatic Sea with the Aegean and the eastern Mediterranean Sea. Secondly, the Strait of Sicily establishes communication between the western and eastern Mediterranean basins; each of which has retained its own distinct behavior and geological evolution. Obviously, there are other straits, such as the Strait of Otranto, which controls entry to and exit from the Adriatic Sea, and the Strait of Messina, which provides a highly turbulent link between the Tyrrhenian and Ionian seas. In the following section, on Mediterranean hydrography, evidence for the roles of the straits as sites of passage and communication for the sea's currents is discussed [5].

### Sedimentary contributions

The amounts of the different materials in suspension in the Mediterranean vary according to the location and the material itself [6]. In general, the concentration is less in the Mediterranean as a whole—ranging from 0.1 to 4.6 mg/l—than in the Black Sea, where the amount of suspended material may be up to five times higher. The highest concentrations are near the coast and in the proximity of rivers. The many fluvial contributions to the Black Sea explain its higher sediment concentration as well as its lower salinity. Atmospheric contributions must also be considered. These consist of the very fine sands coming from the Sahara desert as well as substances comprising industrial fumes; the latter component may be large enough to contribute to P and N enrichment of the Mediterranean's surface layer. There is a difference in the behavior of the various sediments depending on whether they consist of organic material degraded by bacterial activities or of inorganic material deposited at varying distances from the shore. The first is strongly related to highly productive zones and the second to fluvial contributions, which are responsible for the formation of submarine fans. The presence of slightly fossilized rocks at the boundary between the continental shelf and inferior Pliocene layer is also of interest; stated briefly, it can be said that climate has influenced that in dry climates are represented by less calcium carbonate. The average contribution of amorphous silicic anhydride is around 0.74% and is related to the abundance of plankton, although this sub-

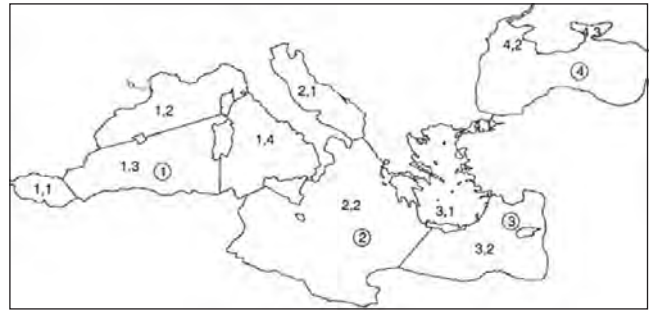


Fig. 3. Proposed Mediterranean subbasins.

Table 1. Current Mediterranean sediments [28]

Area	Sediments
Catalan Sea	Bioclastics, corals, coccoliths, foraminifers
Gulf of Geneva	Bioclastics, turbidites, foraminifers
Algeria	Terrigenous, biogenic, chalks, turbidites
Tyrrhenian	Pyroclastics, hydrothermal, turbidites
Sicily/Tunisia	Bioclastics
Central western basin	Coccoliths, foraminifers
Adriatic	Bioclastics (N and W), muds, clays and detritus (central), terrigenous
Aegean	Bioclastics, pteropods, coccoliths, diagenetics, pyroclastics, turbidites
Ionian	Sands with bioclastics, foraminifers, coccoliths, pteropods, carbonate diagenetics, turbidites
Levantine	Bioclastics, pieces of shell, muds and clays, pteropods, turbidites, foraminifers, coccoliths
Marmara	Terrigenous, turbidites
Black	Muds and clays, especially west of Crimea

stance is occasionally of terrigenous origin. Recent (Holocene) deposits, in the form of fine, 0.2- to 2-cm-thick muddy sheets variable in their color and distribution, are found in the eastern Mediterranean, whereas gray sediments occur in the western Mediterranean. Sapropelic muds that are scarce in the western Mediterranean abound in the eastern part. The deposits in the eastern Mediterranean are the result of changes that took place between 11,000 and 7,000 years ago (Fig. 3, Table 1).

### General circulation of the Mediterranean

The entrance of Atlantic water through the Strait of Gibraltar directly gives rise to a circulatory pattern that affects the entire Mediterranean, and which is highly complex with regards to its dynamics and to the sea's three main layers, i.e., the surface

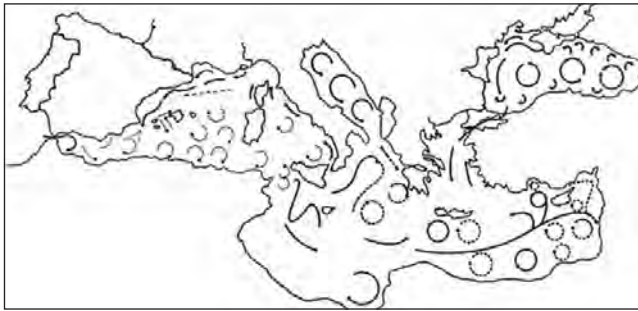


Fig. 4. The Mediterranean's superficial circulation [7].

water, intermediate water, and deep water. The many authors who have dealt with the subject have pointed out quite similar general trends, but there are also important variations in the mesostructure, especially regarding the superficial currents, which are the best studied. These currents penetrate the Strait of Gibraltar from the Atlantic following two very large anticyclonic gyres, one of which is always present while the other is sometimes absent. The most important aspect is the marine front that extends between Almería and Oran. This front, which corresponds to the easternmost part of the second gyre, acts like a large slowly oscillating membrane and probably influences the marine dynamics of the Algerian basin (Figs. 4, 5) [7]. Close to the Algerian coast, the Atlantic current occurs as a succession of gyres running in an eastern direction. Noteworthy is the fact that some of these gyres break away from the aforementioned current and travel freely as large bubbles of Atlantic water, which are distributed throughout the Algerian basin and, as "islets" of Atlantic water, are probably very important for the development of certain species. The fact that these bubbles do not travel past the line that joins the Balearic Islands to the island of Corsica justifies the division of the Algerian basin, distinguishing it from the NW Mediterranean. There are two other currents that separate from the main one: the first greatly diverges at the beginning of the Algerian coast and extends towards the Balearic Islands, mainly between the Pityuses and the Iberian Peninsula, while the second begins at the end of Algeria and penetrates the Tyrrhenian basin. This last branch advances along the Italian coast, continues towards France and the Iberian Peninsula and ends in the Atlantic, passing through the deepest part of the Strait of Gibraltar. Two important processes occur in the vast area comprising the western Mediterranean. The first, in the Tyrrhenian current, south of the Gulf of Liguria, a highly nourishing cyclonic gyre favors the concentration of numerous migratory fish and large cetaceans. The second, in the Catalan sea, consists of a current that arises along the Iberian coast together with waters coming from the Algerian zone; this current passes through the Balearic Islands, moves towards the Catalan sea, and bumps up against the current that closes the great anticyclonic gyre. This process produces a nutrient-rich sinusoid front, as demonstrated by the abundance of lanternfish and *Gonostomatidae* in this zone. On the whole, the large cyclonic current circulates parallel to the shore, at the border of the continental shelf. Moving at average speed, it takes 15–20 days to cover the entire Gulf of Lion, although the flow varies considerably with location (Table 2).

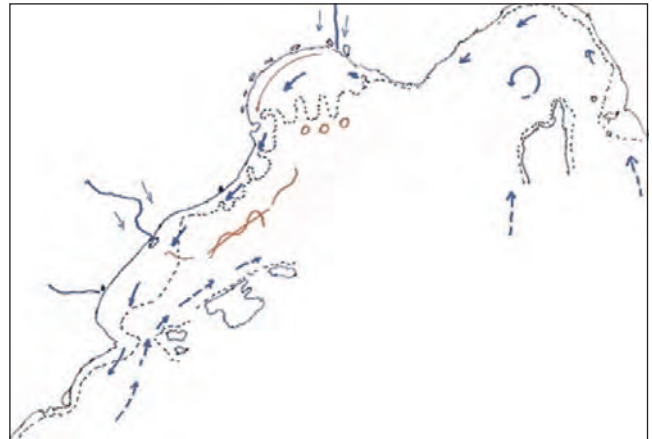


Fig. 5. The NW Mediterranean's circulation.

A significant feature of the great cyclonic gyre of the western Mediterranean is found in the Tyrrhenian Sea. Atlantic waters that penetrate the Sardinia-Sicilian channel, during the summer due to the formation of a front made up of a series of meanders that oppose their entry. Since during the summer there is also no flow of water through the channel of Corsica, the Tyrrhenian circulation stagnates. The Tyrrhenian's dynamics are mainly characterized by a cyclonic gyre, with a current that proceeds parallel to the Italian coast. This current is made up of water that enters through the Sardinian-Sicilian channel and afterwards descends along the eastern part of the islands of Corsica and Sardinia. Maximum activity takes place during the winter, when the entrance and exit passages are open. It is important to point out that the Tyrrhenian plays a very important role in the great cyclonic gyre of the western Mediterranean by regulating the flow that nourishes the Ligurian-Provençal current.

The superficial current does not enter the Tyrrhenian zone but instead moves towards the eastern Mediterranean through the Strait of Sicily. The flow of this current varies between 1 and 3 Svedrups (Sv), with a maximum intensity during the summer. In this zone there is a front that has intense effects on the talus and which marks the transition from the western to the eastern zone. Its structure is similar to that of the current originating in the Strait of Gibraltar with the Almería-Oran front and is of an estuarine structure. The Atlantic current, which at this point has

Table 2. Values of the sea fluxes in different areas ( $Sv = 10^6 \text{ m}^3/\text{s}$ )

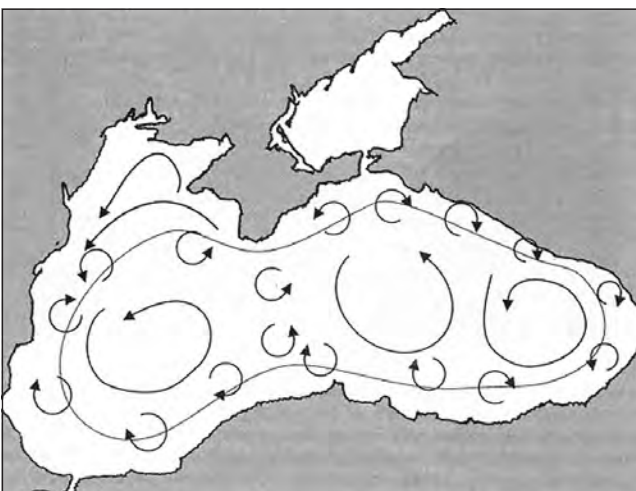
Area	Time, Situation 1	Time, Situation 2
Gibraltar	1.68 (entry)	1.60 (exit)
Catalan Sea	0.1 (February)	0.75–1 (summer)
Alicante-Ibiza	0.2 (south)	0.5 (summer)
Ibiza-Majorca	0.45 (north)	0.15 (south February)
Corsica	1 (winter)	0 (summer)
Sicily	1.15	3 (winter)
Otranto	0.1	
Black-Mediterranean	0.01	
Central Ionian	1.5 (summer)	0.57 (winter)
Marsa Matruk gyre	1.5 (summer)	1.50 (winter)
Shikmona gyre	1.82 (summer)	1.50 (winter)



**Fig. 6.** Circulation in the Eastern Mediterranean (Robinson et al., 1987).

become substantially weaker and somewhat narrower, departs from the coast and continues in an eastern direction. Two secondary gyres occupy the spaces corresponding to the gulfs of Gabes and Sirte. In terms of dynamics, the branch that gives rise to the great cyclonic gyre occupying the central part of the Ionian Sea is the more important one. Its eastern aspect produces the current that nourishes the Adriatic Sea, penetrating across the Otranto Channel. Waters that leave this sea by the eastern part of Italy return to nourish the cyclonic gyre, as do waters that are incorporated from Crete. The dynamic process is very complex, with feedback probably depending on different mechanisms, including the turbulent flow that arrives from the Messina Channel.

Just as in the western Mediterranean a branch of the main current enters the sea from the south, in the eastern basin, a branch of the cyclonic gyre of the Ionian penetrates and controls the circulation in the Adriatic Sea. Note the parallels between the western basin and the Ionian Sea, in that the gyres are very similar. Water advancing in the eastern part produces three gyres in the direction of the Italian coast: the first is located at the level of Dubrovnik, the second along the line between Zadar and Ancona, and the third in the upper Adriatic. These gyres feed the western part, which drains the Italian coast, and then pass through the Otranto channel to become incorporated into the waters of the Ionian Sea. The flow of water entering the Otranto channel is calculated to be 1 Sv [8]. The Adriatic circulation is strongly influenced by the Bora wind that blows

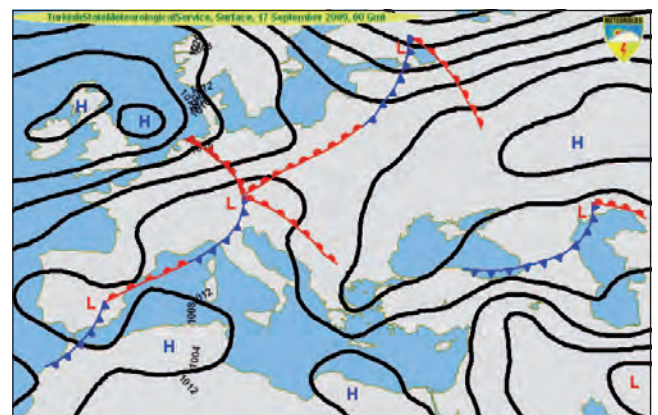


**Fig. 7.** Circulation in the Black Sea.

from the northeast and the fluvial contributions, especially from the Po River, which accounts for approximately half of the total freshwater contribution. These two components explain the thermal differences between the east and west and the north and south. There also are significant differences in salinity. From a dynamic point of view, there is greater stability in the eastern Mediterranean than in the sea's western part. Noteworthy is the fact that in the Italian Mediterranean, waters downstream from the mouth of the Po do not contain the nutrient richness that would be expected based on the river's important contributions. Scaccini attributed this to the very high biomass of the consumers inhabiting the zones surrounding the mouth of the Po [9]. Interestingly, the characteristics of the Adriatic distinguish it from the rest of the Mediterranean, probably for ancient geological reasons—for example, the Sarmatic Sea. The differences are especially evident in the most northern part.

Finally, the Atlantic current, greatly weakened and much narrower, arrives at the easternmost part of the Mediterranean, i.e., the Levantine basin. This current then follows a sinuous path up to the coast of Lebanon. By this time, it circulates at a depth of some 70 m, but most remarkable is the increase in salinity to as high 39‰. There are also a number of quite persistent large gyres of an anticyclonic nature located south of the current, whereas gyres located to the north are smaller and cyclonic [10] (Fig. 6). The current seems to squeeze through these great gyres, separating at the Lebanese coast a branch that travels parallel to the coast of Anatolia. Winds from the south and north determine the nature of the highly dynamic current variations in different parts of the Levantine basin. Finally, the structure of the deep threshold that divides the basin of the Ionian Sea plays an important role in explaining its special characteristics.

Mediterranean waters penetrate the Aegean Sea through the eastern part of the Rhodes-Crete-Kythira arch. After forming a series of gyres and filaments and influenced by the less salty waters coming from the Pontic region, they terminate by flowing into the Mediterranean through the westernmost part of the aforementioned arch. The zone of contact between the waters of Pontic origin passing through the Dardanelles and



**Fig. 8.** Example of the meteorological distribution in the Mediterranean (Turkish Meteorological Service, <http://www.dmi.gov.tr/en-US/actual-maps.aspx?m=surface>)

those of Mediterranean origin remains stable and is thermohaline in nature.

The Pontic zone, especially the Black Sea, which is a remnant of the Paratethys, exhibits two powerful cyclonic gyres located to the east and west of the basin. They are separated by an imaginary line that joins the Crimean Peninsula to the central part of the Anatolian Peninsula. The gyres flow close to the coast, except around the vast shelf that extends between the Crimea and Bulgaria. Very large and abundant rivers flow into this vast shelf as well as into the Azov Sea such that the Pontic zone functions as a dilution basin, in contrast to the Mediterranean, which is a concentration basin (Fig. 7). The exit of water of lower salinity from the Black Sea into the Aegean is especially intense during the summer. In this type of flow, the strong winds coming from the north are especially important, since they can cancel out the compensatory current coming from the Aegean Sea.

Intermediate waters are of interest both dynamically and biologically. The strongest and most persistent winds give rise to the formation of this layer as well as to deep waters. Although most of the Mediterranean's water are of Atlantic origin, they are modified by the action of winds and certain structural characteristics that in some areas finally result in the appearance of intermediate waters, which circulate at depths of 200–400 meters from the easternmost part of the Mediterranean until the Strait of Gibraltar. Thus, intermediate waters originate mainly in distinct areas: south of Anatolia, south of the Adriatic Sea, and the Gulf of Lion, although this does not exclude other, less important places. Intermediate waters circulate between very dynamic surface waters, especially those fed by the Atlantic current, and deep waters, i.e., those below 400 meters, which are more stable but with less well-understood dynamics; these waters are especially important for shrimp fishing. The action of the most persistent winds may cause sudden cooling of the superficial layer through the dispersion of water molecules. This provokes an increase of the salinity/density that favors the sinking of this surface, progressively denser water and contributes to the formation of the deep waters. The latter are characterized by their longevity, as they are estimated to be around a century old.

### Estuarine systems

One aspect of the Mediterranean that needs to be considered is the critical role played by estuarine systems, the passage of water through a series of straits, specifically, those of Gibraltar and the Dardanelles. In these two cases, due to the entry of water of comparatively low salinity into the upper parts of the straits and the compensatory exit of denser water through their lower parts flow is sustained hydrodynamically. In the Almería-Oran front, in the Strait of Gibraltar, and north of the Aegean-Sporades Islands, where the influence of the entrance of Pontic water ends, this results in the formation of a frontal zone ahead of these estuarine structures. In all other passages or straits, this phenomenon is less evident, although the passage of surface water could be viewed as being compensated by

deeper intermediate water circulating in the opposite direction. Nonetheless, there is little difference in the characteristics of the entry and exit waters in the majority of the straits, and thus fronts such as those of the two aforementioned cases are not observed. Generally speaking, the Mediterranean circulation can be considered as a group of estuarine systems of varying complexity that reflect the difference in salinity of the entry and exit waters. The Mediterranean therefore functions as a very large, inverse estuarine system that does not dilute but instead concentrates its components.

### Meteorology of the Mediterranean basin

The Mediterranean is situated between the rather humid climate of the north and the dry desert conditions of its southeastern lands (Fig. 8). Movements of cyclonic areas, in the form of storms, in central Europe and northern Africa are opposed by areas of high pressure around the Azores and in the Middle East. Together this results in the formation of the Mediterranean's characteristic winds, with their tremendous influence on its climate. It must be noted that orographic systems play a very important role in determining the direction of the different atmospheric currents. During the summer, there is progressive warming of the southern and eastern zones while at the same time the Azores' anticyclone spreads progressively over a great part of the western Mediterranean. During the winter, storms coming from the west cross the Iberian Peninsula. Other storms, in the Gulf of Geneva, the upper Adriatic, and Cyprus, produce rains in the western Mediterranean. Storms in northern Africa give rise to intense winds, which blow northwards from the African continent, sometimes with great intensity; they are responsible for the frequent muddy rains in the most northern zones. The combination of the northern and southern winds forms the basis of the characteristic Mediterranean climate. By contrast, the fronts that cross the Iberian Peninsula lose their influence by the time they reach the Mediterranean shores, since they are blocked by the dominating winds—the result of storms and anticyclonic areas blowing in from the north. These winds are the Tramontane (northerly wind) and the Mistral, which is responsible for the variable and complex weather structure throughout the Balearic basin (Fig. 9).

In the Adriatic zone, the Bora wind, from the product of high pressures in central Europe and low pressure in the Mediterranean zone, i.e., the Adriatic, blows from the northeast and has both the climate and the hydrographic dynamics of the basin, influencing especially during the winter. A similar situation occurs in the Aegean basin, where the Stiros winds originate by the conjunction of the high pressures of Eastern Europe with the low pressures of the sea. In addition, the Ethesis winds blow in from the mountains north of the Aegean and have a foehn as well as a seasonal effect both of which considerably alter this region of the Mediterranean. Similarly, the storms in anticyclonic areas of central-eastern Europe are the origin of the Poyraz winds. The cyclonic areas formed in northern Africa cause the Sirocco, which blows from the African deserts towards the Mediterranean and carries a suspension of fine sand



**Fig. 9.** Maps of the most important winds in the Mediterranean.

particles. The winds that accumulate humidity in their long travels over the sea—the easterly winds—if occurring in cold areas can give rise to rains in coastal areas. The Khamsin wind, which to a large extent is under the influence of the Nile valley, affects the most eastern part of the Mediterranean in a manner analogous to that of the Sirocco in the sea's western part.

The aforementioned winds together with other less important ones are not only the determining cause of the Mediterranean climate but are also largely responsible for directing the exact route followed by the sea's currents. Moreover, as discussed above, they are the cause of strong variations in the density of surface waters, which, upon sinking, result in the formation of intermediate and deep waters. These are of fundamental importance in the dynamics of the Mediterranean, from both physicochemical and biological points of view.

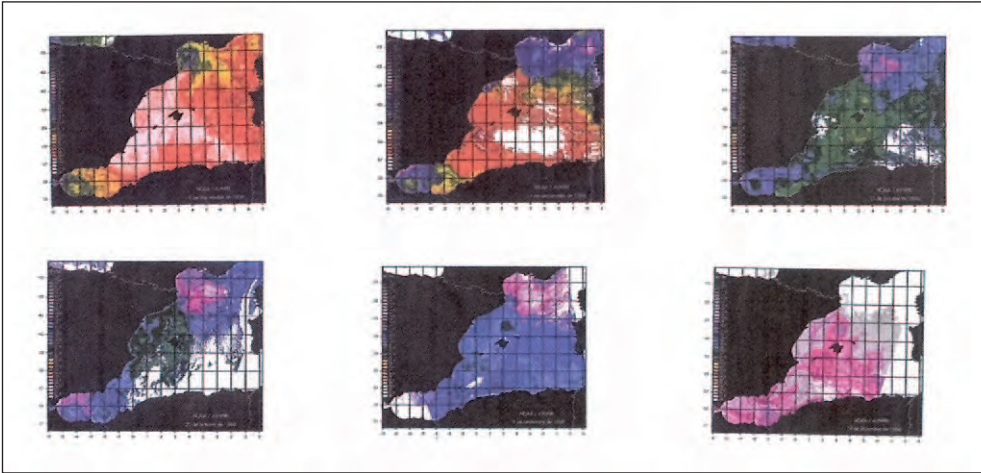
### Sea productivity

The productive capacity of the Mediterranean is much lower than that estimated for most other oceanic zones. This can be explained by several factors; for example, areas with strong upwelling processes are small and scarce in the Mediterranean. Furthermore, waters entering through the strait of Gibraltar are often poor in nutrients, whereas the exiting intermediate waters are relatively nutrient-rich, such that there is a net loss of nutrients. However, a more in-depth analysis offers a more positive interpretation of productivity in the Mediterranean. Not only does it possess several classical upwelling zones but, more importantly, there is a large variety of productive mechanisms. Here, the most interesting ones are briefly analyzed. A significant aspect is the great mass of plankton, which, as it progressively loses its vitality and sinks, constitutes the detritus that plays an important role in the sea's productive dynamics, as will be discussed further on. It is also necessary to take into account the very large amount of organic matter, in the form of fecal pellets that result from the metabolism of zooplankton. This biologically inactive mass is attacked by bacteria, usually in situ, and re-introduced into the Mediterranean's production pathways [11]. This is clearly seen when the verti-

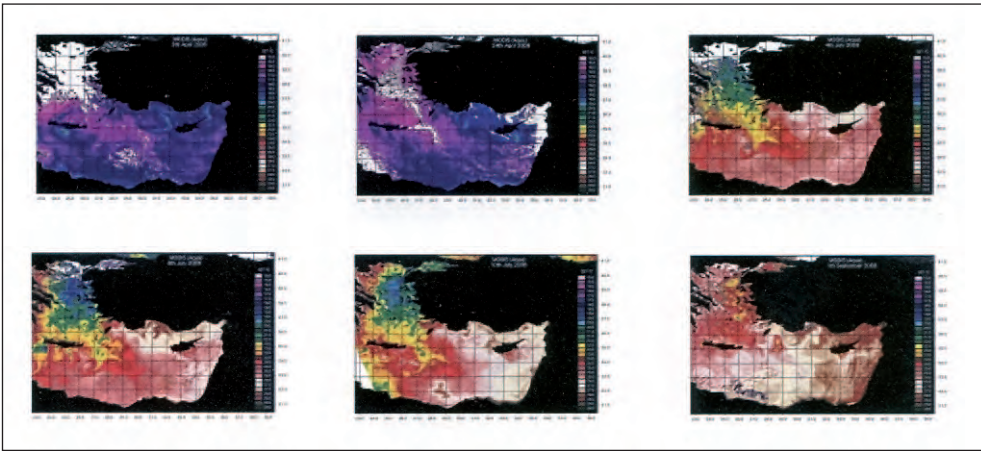
cal distribution of bacterial abundance is studied, with the observed maximum closely related to the concentration of organic matter.

Another productive mechanism is related to what is known as the deep chlorophyll maximum [12], located at the limit of penetration of energetically active light, which, in the presence of a high concentration of nutrients, reactivates the chlorophyll capacity in settling phytoplanktonic organisms. Although the photonic distribution becomes dispersed, picoplankton and nanoplankton readily use this energy. This process is more intense in waters further away from the coast. Another productive mechanism is related to the presence of cyclonic areas, a good example being in the area located south of the Gulf of Geneva. High productivity also occurs in the area of contact between the neritic waters of the continental shelf and the oceanic waters of the slope. These zones contain a high concentration of biomass of different types—a result of their high productive capacity. Other, related factors that contribute to production are, e.g., the energy generated by the friction of waters of different currents, which supports the formation and concentration of biomass, as do headwaters the marine filaments that are so abundant in the Mediterranean [13]. There are also mechanisms related to the numerous underwater canyons that characterize most of the Mediterranean slope. For example, the winds provoke upwellings/water transport along these canyons. Likewise, the chimney effect makes it possible for intermediate waters to reach the surface. These types of production zones, while individually of little importance, together achieve global importance. From a biological perspective, production is enhanced by the great masses of salps, doliolids, and appendicularians that accumulate especially at the end of spring. Rather than being lost, as was originally thought, these organisms are degraded and reused, thus re-entering the productive chain (Fig. 10).

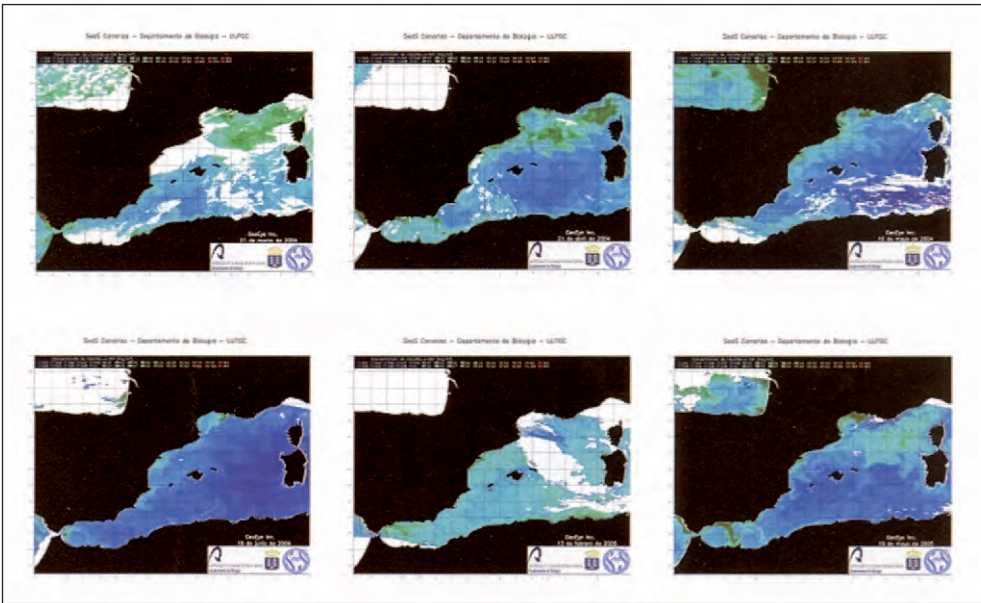
External productivity is favored by fluvial contributions, especially those of the big rivers, which bring terricolous components and organic contributions that enrich the productive process. As discussed for sedimentary processes, the atmosphere also contributes nutrients to the superficial layer, albeit in small amounts. Nonetheless, these nutrients represent a



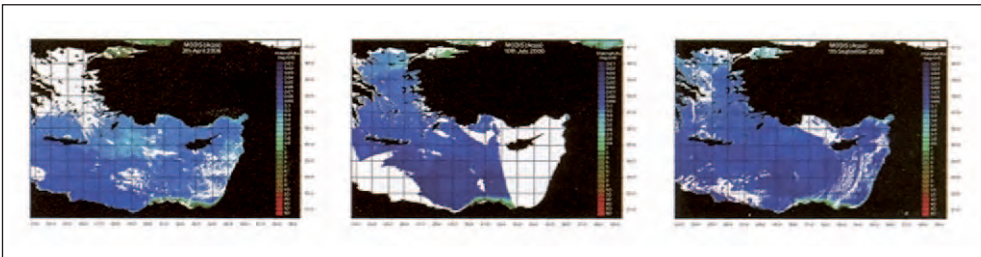
**Fig. 10.1.** Satellite images of the superficial temperature of the western basin (Department of Biology, University of Las Palmas de Gran Canaria, courtesy of AJ Ramos).



**Fig. 10.2.** Satellite images of the superficial temperature of the eastern basin (Department of Biology, University of Las Palmas de Gran Canaria, courtesy of AJ Ramos).



**Fig. 10.3.** Satellite image of the chlorophyll distribution in the western basin (Department of Biology, University of Las Palmas de Gran Canaria, courtesy of AJ Ramos).



**Fig. 10.4.** Satellite image of the chlorophyll distribution in the eastern basin (Department of Biology, University of Las Palmas de Gran Canaria, courtesy of AJ Ramos).



source of enrichment, especially for those areas far from the coast and where classical upwelling processes are limited.

The reality therefore is that the Mediterranean's global productivity is not the result of the classical mechanism in which nutrients are provided by deep-water upwellings, but a complex integration of several different mechanisms—each of little relative importance but in total yielding a higher-than-expected productivity. Estimated values range from 5 to 15 mg Chl/m<sup>3</sup> year, much higher than those determined from classical processes.

An important factor that remains to be considered is the role of bacteria, which are very abundant at the water-seafloor interface and which are responsible for the recycling of deposited organic matter. Furthermore, bacterial attack of microparticles results in an increase in their size, enabling their utilization by filtering microorganisms inhabiting the deep waters. This represents an increase in available food that could not have been taken advantage of otherwise. Finally, there is the particularization of dissolved organic matter, either by microbes or mechanically, which represents another potential mechanism of seawater enrichment (Table 3).

In discussing distribution, it is important to consider the flow of the Atlantic current and the different productivity strategies that are used in the eastern versus the western part, which depend on the dynamic and structural characteristics of the particular region. In the Alboran zone, anticyclonic areas, especially those of the Almería-Oran front, give rise to intense productive activity. In the northwestern Mediterranean, several mechanisms contribute to bring about relatively high productivity: upwellings, fluvial contributions, the surface of the slope, filaments (especially in the Ebro zone), and friction between currents in the central part of the Catalan sea and area of Liguria. Undoubtedly, production in the zone of the Gulf of Lion is very important. In the Algerian zone, there are differences in the gyres originating from the Atlantic current; some are monospecific while others comprise a great variety of species. Zooplankton production varies throughout the annual cycle. Also of interest is the north-south distribution in the occidental basin. In the northern zone we find, for example, krill (euphausiids), whose most abundant species in northern cold waters is *Meganyctiphanes norvegica* whereas in the southern, warmer part *Nyctiphanes couchi*. These diverse origins provide evidence for the colonization or recolonization of the Mediterranean.

In the Tyrrhenian Sea, global production is lower; only in the extremely turbulent Messina Strait are higher values observed. By contrast, the Adriatic is characterized by its high productivity, especially in the northern zone and the Italian shelf. This is explained by the contributions of the Po River, with its high concentrations of nutrients that are distributed midway up the Italian coast. The Bora wind maintains marine dynamics. Nutrient-poor conditions dominate the Dalmatian coast and the entire southern part of the Adriatic Sea. The northern part exhibits eutrophic phenomena and, on occasion, gelatinous masses. Unlike the Tyrrhenian Sea, the Adriatic's global production concentrated along the Italian coast is very high. In the Ionian Sea, productive capacity is confined to the Gulf of Taranto and, probably because of the amplitude of its shelf, the Gulf of

**Table 3.** Primary production

Region	Primary production
Alboran	Cl 0.5–1 mg/m <sup>3</sup> year
NW Mediterranean	±80 g Cl/m <sup>2</sup> year
Liguria	Cl 10 mg/m <sup>3</sup> year (cyclonic area)
Tyrrhenian	Cl 200 mg/m <sup>2</sup> day
Ionian	190 mg Cl (Libya)
Aegean	30–64 g Cl/m <sup>2</sup> year (in the Soronikos proximity) 0.12–0.19 g Cl/m <sup>3</sup> year
Levantine	5–25 g Cl/m <sup>2</sup> year
Algeria	0.25–0.50 mg Cl/m <sup>3</sup>
Adriatic	1.5–6 mg Cl/m <sup>3</sup> year (except east coast) 0.3–1 mg Cl/m <sup>3</sup> year (global Adriatic)
Pontic	4–10 mg Cl/m <sup>3</sup> year (Azov and Odesan platform) 0.2–0.7 mg Cl/m <sup>3</sup> year (rest of the Black Sea)

Gabes. Productivity is reduced along the coast of Libya, being minimal in the central part of this zone. The richest areas of the Aegean Sea are the northern zone and the Saronic Gulf. Although little information is available, the productive capacity likely assures greater fishing possibilities.

The low productive capacity of the easternmost part of the Levantine basin is a consequence of the highly reduced influence of a weakened Atlantic current, the narrowness of the continental shelf, and the high temperature and salinity. The Nile River influences the Pontic zone and accounts for its very high productivity. Likewise, the Azov Sea and its very wide northwestern shelf receive important fluvial contributions. In the central part of the Levantine basin, productivity is lower, resembling that of the northwestern Mediterranean. The very high productive capacities of the Pontic zone and the Adriatic Sea explain the large contribution to the biomass. Similar is the contribution made by the ctenophore *Moneyopsis leydi* and before that by *Aurelia aurita* in the Pontic Sea.

## Mediterranean ecosystems

In many ways, the Mediterranean Sea can be considered as a single ecosystem, based on the following, fundamental considerations: Foremost is the fact that the marine environment is completely influenced by the Atlantic current entering through the Strait of Gibraltar; this current compensates for the hydric deficiency and extends through the different branches to involve the entire Mediterranean, including the regions north of the Adriatic and the easternmost part of the Levantine basin. However, there are also flows that alter the characteristics of the Atlantic water comprising the main current, as is explained below. Otherwise, as noted above, the geomorphologic structure of the Mediterranean basin is largely the result of alpine orogeny and therefore exhibits several basic and highly uniform characteristics, especially in the northern part. Despite the an-

cient geological nucleus of the Anatolian Peninsula, the northern and southern coastal chains are of alpine origin such that the characteristics of these areas and those of most of the peninsula in general are alpine.

The same species, especially those comprising the highest components of the food chain (fish, crustaceans, and mollusks), colonize all of the Mediterranean. Nevertheless there are some differences, which are the result of colonization processes that took place during the different geological periods. This explains the addition of northern and tropical type populations to the ancient colonizers. Their current distribution is in accordance with the environmental characteristics that most closely resemble their original habitats. During the tertiary period, the fauna mainly consisted of tropical and subtropical species, with some temperate components. This was the typical paleo-Mediterranean group. When the Indo-Pacific became isolated, the resulting cooling left endemic remains of the former settlement [14]. This was followed by the entry of new, Atlantic-type populations, which account for most of the present settlement. At the end of the Pliocene and during the Pleistocene, elements of northern origin entered. These took over the earlier temperate ones (from the first ice age), but gradually lost importance as temperate elements once again dominated. This process was repeated several times during the Sicilian and Tyrrhenian ages. Likewise fauna from the Senegalese province replaced the previous faunal species. Finally, during the last ice age—Würm—there was another entry of northern elements, reflecting the thanatocoenosis that occurred at the limits of the continental shelves. At the end of this period, these elements decreased significantly in amount whereas the proto-Mediterranean components together with the remains of ancient colonizers, temperate elements, and other tropical ones remained and together constitute the current settlement. The northern elements remained confined to the most northern zones of the Mediterranean while those of tropical origin became more widespread, mainly along the southern shore. Some of the species are typical of near-Atlantic waters, while others have a very wide distribution. A clear example is *Aristeus antennatus*, typical of the Mediterranean and the Moroccan Atlantic, while *Aristeomorpha foliacea* is more broadly distributed [15].

Endemic species include *Posidonia oceanica*, *Spicara flexuosa*, *S. cryselis*, *S. smaris*, *Raya melitensis*, and *R. polystigma*, as well as several northern migratory species of the genera *Platichthys* and *Sprattus*. Among the Atlantic tropical and subtropical varieties are the serranids, sparids (breams and porgies), wrasses, horse mackerel, and *Balistes* sp. Beyond the opening of the straits of Bosphorus and the Dardanelles, species typical of the Pontic zone are scattered throughout the Mediterranean. Also of interest is the gradual but sustained entry of Lessepsian elements across the Suez Canal.

Most of the species found in the Mediterranean are present throughout, although there are local variations in relative proportions and abundances. For example, in the western Mediterranean, the most abundant species are the picarel *Spicara smaris* and *Spicara chrysalis*, while in the eastern Mediterranean, especially in the Levantine basin, around Cyprus, and in the Aegean Sea, these species are substituted by *S. flexuosa*,

which is also much more abundant in northern than in southern waters. Another species that clearly shows this pattern is the anchovy *Engraulis encrasicolus*, whose abundance is reduced in the eastern direction relative to the southern one such that it has practically disappeared from Tunisia onwards. But it is very abundant in the Black Sea. Pelagic species such as *Sardina pilchardus* are present throughout the Mediterranean, their abundances diminish towards the Gaza Strip; by contrast, *Sardinella aurita*, a species of tropical origin, increases in this same direction, practically replacing the sardine near the coast of Egypt.

The distribution of *Sprattus sprattus* can be traced back to the Paratethys; i.e., northern species that entered the Mediterranean through the Sea of Marmara, when, during the late Quaternary, the Bosphorus and Dardanelles Straits opened. In the northern part of the northwestern Mediterranean, the presence of *S. sprattus* is greatly reduced, whereas in the northern Adriatic, especially along the Dalmatian coast, it is significantly more abundant. Indeed, most of this species' biomass is found in the Black Sea. Together with the anchovy and the sardine, sprats account for most of the pelagic biomass. *Merlangius merlangus*, another important species inhabiting mesopelagic zones of the Black Sea, is also found in the northern Aegean and Adriatic Seas. As a demersal species, the black sea turbot (*Psetta maenotica*) is also very abundant in the Black Sea, especially its western part. Similar species are represented in other corners of the northernmost zones, particularly in the Gulf of Lion.

This distributional pattern of uniformity with regions of drift is not restricted to fish, crustaceans and mollusks, but is also evident for other populations, e.g., some species of algae. In coastal algal populations, to the north of the Cap de Creus, there is an important association between *Padina pavonia* and *Clodostephus verticillatus*, whereas towards the south this species is replaced by *Halopteris scoparia* [16]. A similar situation is found in the distribution of species of the euphausiid group, with Nordic species confined to the northern part, where species that have persisted since the first northern invasions have long been sheltered. The opposite holds true in the south, where *Sardinella aurita* is a clear example of a species that penetrated the Mediterranean during tropical and subtropical invasions. There are also species originally from the subtropical Atlantic but which have now penetrated the western Mediterranean, e.g., *Solea senegalensis*, which has continued to expand along the Iberian peninsular coast and the red pandora bream *Pagellus belloti*.

The most important phenomenon is the well-known, relatively recent Lessepsian migration whereby species of Indo-Pacific origin have gradually penetrated the Suez Canal (Table 4). These migrating species have had a significant impact along the coasts of the Gaza Strip and Israel, where they are very abundant and have overtaken several traditional fishing species. For example, *Mullus barbatus* has been replaced by *Upeneus mollucensis* and *Merluccius merluccius* by *Saurida undosquamis*. *U. mollucensis* is now widely present in the Mediterranean, as far as the Levantine coast of the Iberian Peninsula, but it has also penetrated the Pontic sub-basin, crossing the Aegean Sea. Likewise, many different species have

**Table 4.** Distribution of densities of the most important species (kg/km<sup>2</sup>)

	Alboran	NW Medit.	Algeria	Tyrrhenian	Adriatic	Ionian	Aegean	Levantine	Black
Platform (km <sup>2</sup> )	11,115	54,163	30,276	14,804	94,290	109,950	61,761	56,670	90,288
Sardine	2780	1000	180	340	530	230	400 <sup>a</sup>	220 <sup>a</sup>	50 <sup>d</sup> /50 <sup>e</sup>
Anchovy	990	800	90	40	140	30	270	–	3250
Mackarel	450	60	130	130	30	60	130	20	210
Sparids	450	50	330	520	30	140	310	130	100
Red mullet	60	70	60	180	30	50	100	60	100
Hake	50	130	60	170	50	170	50	30 <sup>b</sup>	–
Slope (km <sup>2</sup> ) <sup>f</sup>	29,467	41,948	42,768	48,609	19,650	138,525	34,973	72,760	24,840
Blue whiting	70	110	50	–	50	6	–	–	–
Lobster	7	10	–	10	50	30	–	20 <sup>c</sup>	–
Red shrimp	20	120	50	20	–	–	–	–	–

<sup>a</sup> Sardine + sardinella.

<sup>b</sup> Hake + *Saurida undoquamis*.

<sup>c</sup> *Natantia* sp.

<sup>d</sup> Alis shad.

<sup>e</sup> Sprat.

<sup>f</sup> The densities corresponding to the slope are minimized since a slope surface of 200–1000 meters is larger than the surface occupied by the species considered.

penetrated the Mediterranean via the Red Sea, progressively spreading in a western direction. By studying the colonization patterns of these species much insight into earlier colonizations can be gained.

## Human impact

**Fishing.** For nearly all of human history, the sea has played an essential role [17]. Indeed, fishing activities have been documented as far back as the arrival of *Homo sapiens* in Europe. Greek settlements in the Pontic zone have also been traced to the importance of fishing.

The linear progression of technological developments in fishing, and thus their impact on the Mediterranean ecosystem, has been closely related to the environment's geomorphology. Where the continental shelf is relatively wide, two types of fishing nets are used: trawls and the purse seine. The first provides access to the sea floor and its initial development paralleled that of primitive communities. Since most of the shelves are relatively narrow, the use of trawl nets has, over time, resulted in overexploitation of the Mediterranean—a situation that has been the focus of recent public and regulatory attention.

The development of the purse seine allowed broader accessibility to Mediterranean fish, as use of the net is not dependent on the structure of the sea floor but can be employed on the shelf, especially for small and medium pelagic fishing, and at high sea, for large migratory fish. This greater access, especially to small and medium pelagic fish, has intensified the pressure exerted by fishing on the Mediterranean's resources, but less so than due to trawling. Nonetheless, tuna have become a highly threatened species in the Mediterranean because of the widespread use of special gears.

The initial forms from which current fishing techniques evolved have not disappeared, and many have largely retained their original characteristics. At the same time, fishing lines,

trammels, nets, traps, etc., have been modified, particularly with regards to their size. For example, fishing lines and nets may reach kilometers in length such that mechanical instruments to guide their maneuvering are required.

The human impact on the marine environment as a result of fishing clearly reflects a gradient of technological development from west to east. Thus, in the western basin, pressures on marine resources are very intense and are an outgrowth of the use of state-of-the-art technological developments whereas in the eastern basin traditional fishing methods are still common. In the west, strong technological pressure and, of course, rapidly growing demand have spurred exploitation of the continental slope, often to depths of up to 1000 meters. By contrast, in the Aegean Sea, which has an average depth of less than 1000 meters, general fishing has been restricted to coastal areas as it involves the use of handmade and relatively undeveloped fishing equipment. What are the causes of these east-west differences? Is it the sea's biological characteristics, the presence of different species, variations in abundance, or a sea floor that is not suitable for fishing? Or are there socioeconomic reasons that have discouraged fishing in the eastern Mediterranean? The second possibility appears to be the more likely one. The socioeconomic impact of the fishing environment decreases from west to east, closely corresponding to the general level of population development. Studies on consumption showed that, up until the 1950s, there was greater interest in meat, which was more expensive than fish; thus, when the average price of fish approached that of meat, consumers shifted to meat products [18]. Later, the situation in the NW Mediterranean evolved, giving greater importance to fish, especially as a local product. It is possible that the situation in eastern countries resembles the earlier one. A similar comparison can be made for the technological aspect of fishing, with a strong technological impulse in the western part and an underdeveloped one in the east. If to these situations we add the political conditions in most of the southern Mediterranean, the reasons why

technological development of fishing in these areas is inferior to that in other Mediterranean areas become readily apparent.

With respect to the species that are fished, target species are present uniformly throughout the Mediterranean, varying only in their relative proportions. However, there are some exceptions, such as the disappearance of the anchovy from the southern coast of Tunisia onwards. If one species of fish is more abundant in a particular region, this impacts the type of fishing, favoring capture of that species over another. For instance, sparids may predominate where traditional fishing nets are more commonly used. In the Alboran Sea, the sardine is the most abundant of the pelagic species, although until the 1980s the anchovy was very important and gave rise to a well defined fishing strategy. Hake, red mullet, and the sparids are the main species that are bottom-fished. On the sea slope, the characteristic species are red shrimp, Norway lobsters, and blue whiting [19], while in the northwestern zone sardines and anchovies dominate along with the large migratory fish. On the platform, hake, red mullet, sparids, flat fish, and gray mullet are found. In the Algerian basin, during the past few years, the sardine and the round sardinella have predominated. Tuna and swordfish are caught in abundance. Also on the platform, together with the aforementioned species, are mostly sparids, red shrimp, and Norway lobsters. In the Tyrrhenian Sea, sardines and anchovies are less abundant than horse mackerel and different species of tuna. The species of fish found on the Tyrrhenian platform are the same as those on the aforementioned one; in addition, picarel are found and their abundance increases towards the east. On the slope, red shrimp and Norway lobster are important.

In the Adriatic Sea the characteristics are similar, although among the pelagic species there are two important differences: the abundance of the anchovy, especially in the Italian area and the presence of the sprat, especially in the northeastern part. In the wide platform of the Italian and central and northern areas, the typical species are the same as those in the rest of the Mediterranean, except that in the southern region the picarel is present in abundance. The large migratory pelagic species include tuna. In the deep zones, which are always in the southern part, Norway lobster is of great importance while towards the bottom of the Italian Peninsula the red shrimp is also present. It should be noted that the Norway lobster is found also in very shallow northern waters and, similarly, on the platform north of the mouth of the Ebro.

In the central Mediterranean—the Ionian Sea—the most abundant pelagic species are sardines and sardinella. The anchovy is restricted to the coasts north of this area and is absent from southern areas. Tuna as well as swordfish are relatively abundant. In the especially large shelves of the south, the customary species are found, albeit in larger quantities where the shelves are wider, such as east of Tunisia; sparids and hakes are abundant species as well. The wide Tunisian shelf also allows for an abundance of king prawn; along the Italian coast, especially the slope between Sicily and northern Tunisia, deep-sea shrimp are abundant and highly fished.

In the Aegean Sea, the sardine, the anchovy and, to a lesser extent, the horse mackerel are under strong fishing pressure.

In the southern part and continuing all the way to Cyprus, which is in the Levantine basin, tuna and swordfish are quite important. Along the continental shelves, the species are those typical of other seas, with a strong presence of sparids. In this region, traditional fishing techniques are more commonly employed. Crustacean decapods are relatively important although species typical of shallow waters are probably more abundant. Finally, in the Levantine basin there is a remarkable increase in sardinella captures, almost completely substituting that of the sardine. Lately, the large migratory species have become important, although it is necessary to distinguish between the tuna trap fisheries on the coast of Libya and the more modern fishing techniques in the northern zones. Sparids dominate the shelf. At the same time, the hake has been partially replaced by *Saurida undosquamis*. Crustaceans and deep-sea shrimp are found near the coast of Israel and possibly in southeast Turkey. Recently, there has been a large increase in the capture of most of the exploited species in the eastern Mediterranean.

The Pontic zone has very particular characteristics regarding exploited species, with the anchovy being the most important one; its catch has in some years surpassed 500,000 annual tons. Among the migratory species, the bonito is important in the southern zone, although its abundance strongly oscillates. On the platform, brill, red mullet, picarel, and sparids are of interest as is the whiting. Also typical for this area are the jellyfish *Aurelia aurita* and the ctenophore *Moneyopsis leydi*.

Cephalopods are important in the western and central Mediterranean, but less so in the eastern basin. The same is true of bivalves. Sponges are typical of the central and eastern areas, with a trend toward a decline. Coral is more typical of the western and central coasts, but its presence is strongly declining [20].

**Pollution.** Another important form of human impact on the Mediterranean environment is direct or indirect pollution. There are three ways in which pollutants reach the sea: directly from the coast, through fluvial contributions, and directly into the sea, including boat spills or the deposition of atmospheric pollutants via inland-generated smoke or fumes. While most pollutants have a common denominator in that they are harmful to the sea environment, some atmospheric fumes are beneficial, by providing nutrients—especially phosphates and nitrates—to areas far away from the coast, thus enriching the surface waters. Global analysis of Mediterranean pollution clearly shows that its maximum is in the western Mediterranean, with a progressive decrease in the eastern direction, i.e., there is a negative west-east gradient. A brief summary of the origin of the polluting contributions reinforces this point of view. Due to the urban agglomerations in the western and central coasts, highly influenced by tourism, enormous amounts of urban coastal residues are deposited into the sea, since water treatment plants are often either inadequate or nonexistent. In the Pontic zone, the large rivers that flow into the northern part of the Black Sea contribute substantial residues from the highly populated cities located on their banks. In this context, the tourist component is particularly important since during the summer it increases the coastal population by five- to ten-fold. These

**Table 5.** Different pesticides/herbicides carried to the sea by the Mediterranean rivers in mg/l [29]

River	Alachlor	Atrazine	Metalachlor	Molinate	Simazine	Total
Po	<0.03–0.106	0.021–0.118	<0.03–0.605	<0.03–1.750	0.06–0.081	0.171–2.660
Rhone	<0.001	0.022–0.386	-	-	0.018–0.372	0.041–0.758
Ebro	<0.001–0.267	<0.001–0.190	<0.001–0.568	<0.001–0.568	0.010–0.138	0.014–1.787
Loudias	nd–0.37	nd–0.63	-	-	nd–0.32	nd–1.32
Axios	<0.05–1.30	<0.05–0.70	<0.001–0.90	<0.001–0.90	<0.06–0.30	0.261–3.70
Aliakmon	nd–1.20	nd–0.74	nd–0.94	nd–0.94	nd–0.06	nd–3.57
Nile	<0.001	<0.001	<0.001	<0.001	<0.001	<0.005

nd: no data.

sources of pollution are poorly controlled and are most intense in the northwestern Mediterranean and the upper Adriatic. In the southern part, urban pollution is less problematic, with the exception of some places along the Tunisian coast.

The fluvial contributions of agricultural and industrial waste derive from the most intense zones of these activities. Thus, the Rhone and the Po, the large Pontic rivers, carry the waste of large industrial sites and mining basins, while the Ebro transports large amounts of toxic products (pesticides, herbicides, and insecticides) employed in the vast agriculture zones found in its basin. The same can be said for other zones (Table 5). In addition to these important sources of Mediterranean pollution, the great amount of crude oil transported through this sea also results in substantial pollution. Finally, heavy metals, of radioactive origin, and other residues originate from navigational activities and to the pollution burden [21].

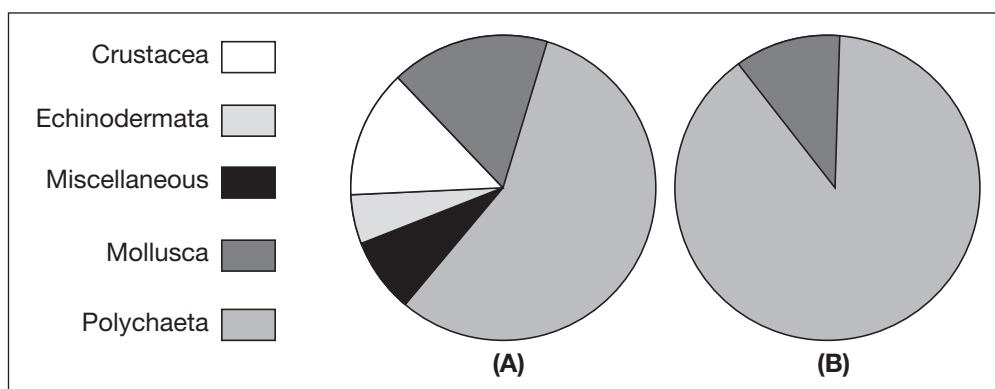
One of the most important effects of pollutants is the changes they cause in the biodiversity of marine ecosystems. Ecosystems that are relatively unaffected consist of 10–20% crustaceans, 15–20% mollusks, 5–8% echinoderms, approximately 58% polychaetes, and the remaining 5–10% of other species, of which the colonial poritids stand out (Fig. 11). When the pollution is intense, there is a very radical change such that the proportion of polychaetes and nematodes becomes as high as 90% of the total, with the remainder comprising a much less diverse group of species. Although the most important impact is clear in demersal populations, pelagic populations are also affected, e.g., by red tides (algal blooms) [22]. Previously, most polluting activities were largely restricted to the coastal zones and to part of the continental shelf, but nowadays they have

become more widespread and their impact on the bionomy of the Mediterranean more important. The massive appearance of jellyfish in most of the Mediterranean is probably caused by multiple circumstances, with pollution playing a significant role.

Obviously, diversity in the Mediterranean is most seriously threatened by fishing, as the targeting of certain species essentially destroys the ecosystem's equilibrium, which can lead to a profound change in its structure if not its total collapse [23].

### Global characteristics

Since the Mediterranean is a structural unit not only from an oceanographic point of view, its dynamism can best be understood by considering the entire range of its strategies. These consist of the oceanographic dynamics and ecosystem components, as discussed so far, but also the impact of humans, whose actions, as a disturbing agent (fishing and pollution), are influenced by socioeconomic and geomorphologic context. This global and integrating perspective corresponds to the approach proposed by Sherman et al. [24] but further expands it by integrating human/social aspects. This extended view is that of the broadened concept of large marine ecosystems (LME). In the following, the dynamics of the Mediterranean are discussed in light of the Iberian, Italian, and Balkan Peninsulas, i.e., three geostrategic formations directed from north to south. This perspective is relevant because the northern part features maximum population density, maximum technological development, and the fact that the countries that comprise it have largely colonized the countries of the southern shore. By con-



**Fig. 11.** Changes in the benthos distribution: (A) former situation; (B) current situation.

trast, in the southern part, the less prosperous conditions frequently give rise to strong north-south tensions, which require very effective and compensatory politics involving sociopolitical and technological transfers. If only the biological component is considered, these considerations seem out of place; but it must be kept in mind that the Mediterranean's marine ecosystem is subject to very strong human pressures, which modify its structure biologically (fishing) as well as with respect to coastal development: ports, destruction of the coast, etc. Thus, the complexity of the Mediterranean demands that any attempt to impose regulations must take all these facets and their mutual influences into account.

Unlike the bioecological structure of the Mediterranean, the socioeconomic pressure exerted on the system is not of uniform impact. The technology affecting the sea environment is very sophisticated and intense in the northwestern part, with a negative gradient in the southeastern direction. However, the size of the human mass able to act on the sea in its different aspects is stronger in southern countries, especially in the most western part. While it is essential that there is an adequate flow of the technological possibilities from the north towards the south-east, it is also necessary to impose regulations on the south regarding its human capital, with the overall goal being to attain an equilibrium between human actions and the bioecological environment, with a mildly uniform pressure that is in accordance with the possibilities of the different zones. This approach recognizes the different needs of social pressure, which are linked to levels of exploitation/market demands, allowing them to be standardized/complemented gradually, while acknowledging the complexity of the sea as a LME and thereby the need to adhere to global norms in terms of sustainability.

This global understanding becomes effective in the context of a bioeconomic model that incorporates each of the relevant factors and their degree of complexity. This model is based on two classical relationships: (1) recruitment + growth = natural mortality + mortality from fishing ( $R+G=M+F$ ) and (2) the equation relating predator with its prey (resource and fisherman), as stated in the Lotka-Volterra expression [25,26]. The inclusion of the recruitment parameter from the model proposed by Solari [27] allows adjustment of the model to take into account current conditions. In considering population growth, it is necessary to include the carrying capacity of the Mediterranean system, together with density-dependent and density-independent processes. These and other parameters are collected—although quite complicatedly—in the ECOPATH and ECOSIM models. The natural mortality parameter is closely related to the actions of predators whereas mortality due to fishing is considered together with bioeconomic aspects and the influence of the markets relative to basic alimentary consumption and luxury consumption. The latter is typical for a large portion of the Mediterranean coast, where the high price of local fish in the respective markets compensates for the small size of the captures and, independently of subsidies, maintains a reasonably successful level of exploitation. While this complex network of bioeconomic relations is generally not in equilibrium, in the best-case scenario it is at the limits of equilibrium conditions.

The concept of elasticity is therefore basic to understanding the ability of the Mediterranean to guarantee subsistence.

The global view provided in this article is an attempt to integrate the Mediterranean's oceanographic, biologic, and socioeconomic factors, especially regarding human population dynamics, with the aim of improving our comprehension of the problems that remain to be addressed. This is an important step in achieving sustainable planning.

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