A MINIATURE OCEAN THE TOLL OF CLIMATE CHANGE IN THE MED

Dr Alan Deidun discusses the idea that the welfare of the Mediterranean Sea's biota can be seen as a sensitive climate change indicator

The Mediterranean is a regional sea of considerable dimensions. Around 4,000km long and 900km wide, it has a surface area of 2.5 million km^2 and fringes 23 countries and territories, three continents and 200 million inhabitants. The sea is also graced by a large number of islands – around 12,000 in total. The vast majority of these (9,835 – 82%) are Greek, with 10% (1,246) endowing the Dalmatian coast of Croatia and seven other countries (Italy, Spain, France, Turkey, Tunisia, Malta and Cyprus) hosting groups of islands.

However, in a global scenario, its dimensions almost pale into insignificance: the Mediterranean's surface area and volume comprises just 0.82% of the total ocean surface area and 0.32% of the total ocean volume.

Despite these limits, the Mediterranean harbours a disproportionately rich marine biota, with an equally disproportionate degree of endemism. Boudouresque (2004) estimates that the total number of marine macroscopic species to be found in the Mediterranean stands at around 12,000.

The Census of Marine Life scientists, who convened in Valencia, Spain, for the World Conference on Marine Biodiversity in November 2008, estimated the global number of marine species at 230,000 to 250,000. This makes the Mediterranean share an impressive 5%. The fraction of marine endemics is equally as stunning, with around 20% of all marine species ploughing the sea being endemic to it. The animal phylum Porifera (the sponges) boasts the highest fraction of endemic species – 50.1%.

The only region in the world that compares with the Mediterranean in terms of the species diversity of its marine flora is the southern coast of Australia. As a result, the Mediterranean Sea can be considered as a hotspot of marine biodiversity (Bianchi and Morri 2000).

The perception that the Mediterranean Sea behaves like a series of lakes is reinforced by the fact that, like the Baltic Sea, it is almost a tideless sea. Most coastal areas around the Mediterranean are classified as being microtidal (tidal amplitude less than 2m), with a few

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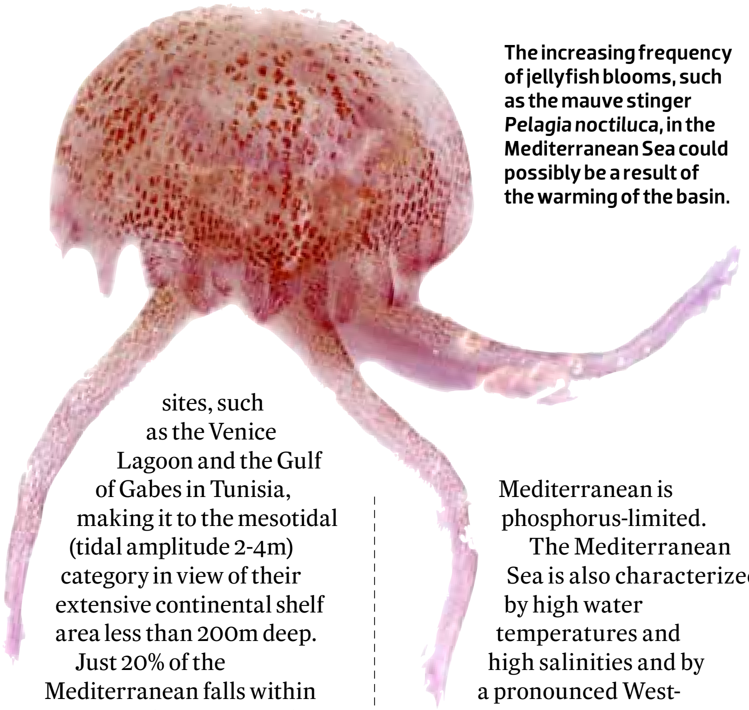

The increasing frequency of jellyfish blooms, such as the mauve stinger *Pelagia noctiluca*, in the Mediterranean Sea could possibly be a result of the warming of the basin.

sites, such as the Venice Lagoon and the Gulf of Gabes in Tunisia, making it to the mesotidal (tidal amplitude 2-4m) category in view of their extensive continental shelf area less than 200m deep.

Just 20% of the Mediterranean falls within the precincts of the continental shelf (Mojetta, 2005), making the Mediterranean a relatively deep sea. The average depth of the Mediterranean is 1,502m, significantly deeper than the North Sea (75m) and the Baltic Sea (55m), yet nowhere near the average ocean depth of 3,800m. The deepest point of the Mediterranean is located at the Hellenic Trough in the Aegean Sea and measures up to 5,092m (corresponding depths for the North Sea and the Baltic Sea stand at 700m and 459m, respectively).

Other defining characteristics of the physico-chemical nature of the Mediterranean include its oligotrophic nature, with low concentrations of dissolved nutrients (nitrates and phosphates mainly) and consequently low levels of primary production and phytoplankton densities.

The oligotrophy of the Mediterranean can be ascribed to two main factors. The first is the fact that surface water from the East Atlantic Ocean, which feeds the Mediterranean Sea, is already poor in nutrients. The second is that relatively few major rivers (generally considered as windfalls of nutrients), such as the Nile, Ebro, Rhone and Po, empty into the Mediterranean Sea. While nitrate content is generally considered as limiting primary productivity in the world's oceans, a number of studies have indicated that the Mediterranean may be an exception. For instance, Berland *et al.* (1984) suggests that primary productivity in the Mediterranean is phosphorus-limited.

The Mediterranean Sea is also characterized by high water temperatures and high salinities and by a pronounced West-East gradient in physico-chemical factors. Water salinity, temperature and oligotrophy increases the further east one goes, with a counter fall in dissolved nutrient concentrations and primary productivity. Although the diffuse terrestrial enrichment of the western basin is apparent from satellite images, enrichment in the eastern basin is restricted to a small area around the Nile Delta (Turley *et al.* 2000). The water salinity reaches a maximum of 39.1 parts per thousand in the extreme eastern part of the Levantine Basin, higher than incoming surface Atlantic water (36.3 parts per thousand) and significantly higher than the average salinity of the Black Sea (18.5 parts per thousand) which is profusely fed by rivers discharging into it.

The high degree of solar radiation received by the Mediterranean, coupled with the low freshwater input, result in a negative water balance, where the loss from evaporation is three times greater than the gain from rivers and precipitation. For this reason, the Mediterranean Sea is sometimes described as an "evaporation basin". Tchernia (1978) estimates that the total riverine freshwater input into

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the Mediterranean corresponds to a water layer thickness of just 1m when spread over the entire basin. In fact, it has been calculated that, if the Straits of Gibraltar were to be sealed off, the Mediterranean would dry up entirely within 3,000 years (Boudouresque 2004), in an uncanny evocation of the Messinian salinity crisis (which occurred ca. 5.6 million years ago and during which large swathes of the Mediterranean Sea dried up due to an interruption of the Atlantic connection).

The oceanography of the Mediterranean Sea is anything but simple. The Mediterranean Sea behaves like a series of interconnected water bodies, each of which has a distinctive seabed topology. Different sectors within the Mediterranean Sea may also be distinguished on the basis of biogeographical characteristics, with biogeography being defined as "The scientific study of the past and present geographical distribution of plants and animals at different taxonomic levels."

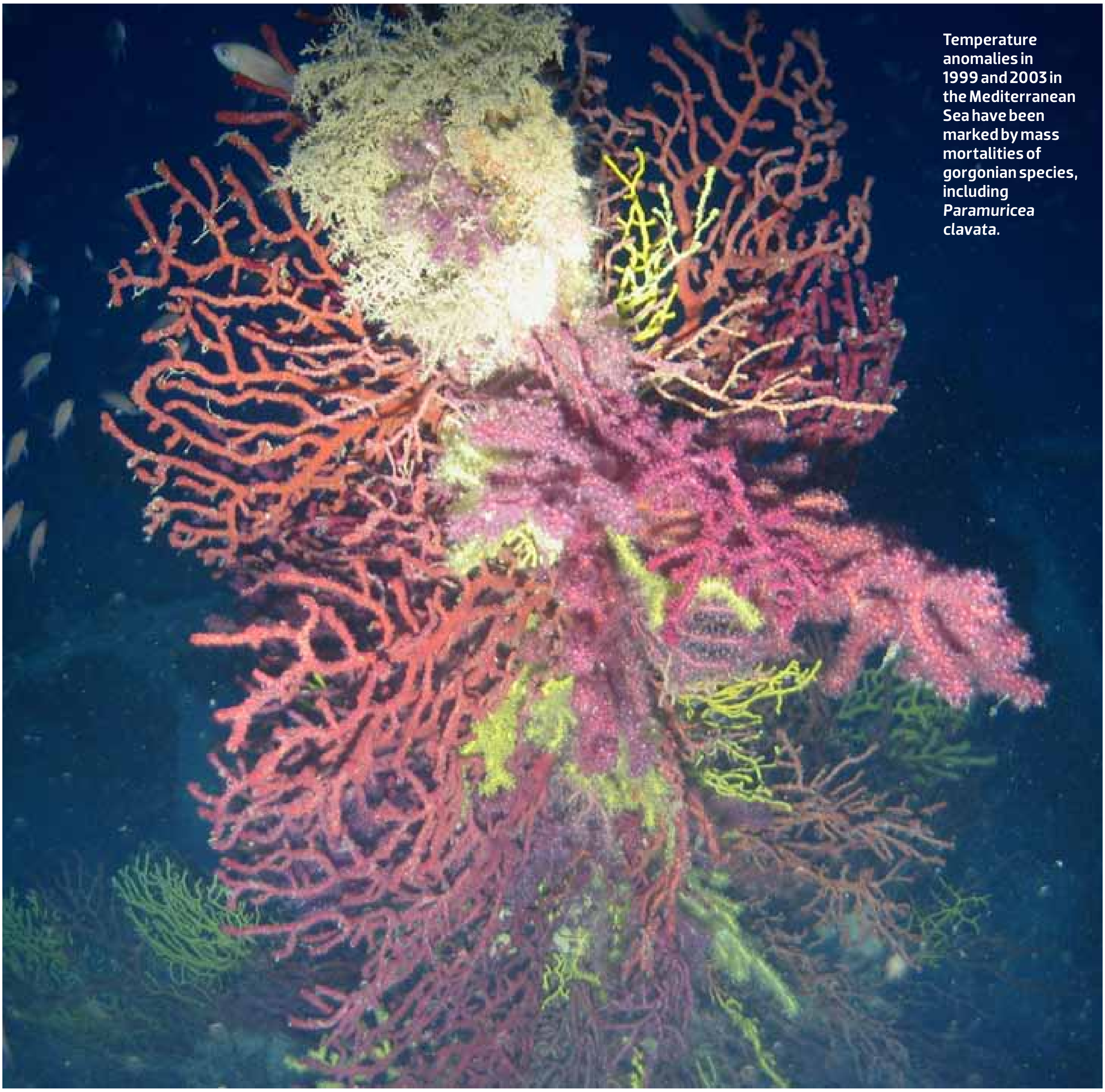
The variety of seabed topologies and features is equally as intriguing. Each of the Mediterranean sub-basins is a silled one. Sills are underwater ridges or rocky ledges (defined depressions) which define the boundary between two adjacent basins. Sills restrict water flow between adjacent basins so that water within a particular sub-basin assumes a unique hydrology which is distinguishable from that of water in other sub-basins. Examples of sills within the Mediterranean include the Otranto Sill, which demarcates the Adriatic Sea from the Ionian Sea and the Siculo-Tunisian Sill, separating the Mediterranean Sea into the West and East Basins. A 'double sill' separates the East Mediterranean from the Sea of Marmara and the Black Sea and is comprised of the Dardanelles Sill and the Bosphorus Sill.

The Central Mediterranean is characterised by frequent past instances of tectonic activity, such as rifting and submarine volcanism, which have chiselled the seabed into a variety of topologies. The Maltese Islands and the island of Lampedusa lie on opposite sides of the main rift system in this part of the basin - the NW-SE-trending Pantelleria Rift System or Sicily Channel Rift Zone (SCRZ). The rift system is in turn characterised by deep water and by a number of submerged valleys, known as grabens – the Pantelleria Graben, the Malta Graben and the Linosa Graben, where the sea depth reaches a maximum of 1,700m (Reuther & Eisbacher 1985).

The Maltese Islands are located on a shallow shelf, known as the Malta-Ragusa Rise, which in turn is part of a submarine ridge known as the Pelagian Block and which extends from the Ragusa peninsula of Sicily (the Hyblean Platform) southwards to the coasts of Tunisia and Libya. As a result, the Ragusa Peninsula of Sicily, the Maltese Islands and the Pelagian Islands (Lampedusa, Linosa and Lampione) are geophysically considered to be part of the African continental plate (Schembri 1993) and share a common carbonate rock composition. The Pelagian Platform forms a shallow shelf separating the deep Ionian Basin from the Western Mediterranean (Galea 2007).

Approximately 100km to the east of the Maltese Islands, the Malta Escarpment marks a drastic increase in sea depth, over a spatial scale of tens of kilometres, from hundreds of metres to the 2-4km of the Ionian Abyssal Plain in the Eastern Mediterranean Basin. The depth of the marine area between the Maltese

The Mediterranean Sea is witnessing an influx of warm-affinity jellyfish species, like the upside-down jellyfish *Cassiopea andromeda* (top and bottom left). Jellyfish blooms, such as the mauve stinger *Pelagia noctiluca* (shown beached, bottom right) are also increasing in frequency in the Mediterranean Sea.



Temperature anomalies in 1999 and 2003 in the Mediterranean Sea have been marked by mass mortalities of gorgonian species, including *Paramuricea clavata*.

Islands and Sicily (the Sicilian Channel) does not surpass 200m and not even 90m in most places, whilst the marine area between the Maltese Islands and the north African coast (the Malta Channel) is much deeper, surpassing 1,000m in some areas (Morelli *et al.* 1975).

Despite the widespread perception that the column of water in our seas is simply a homogenous mass of water, scientific evidence suggests that the same water column is stratified into a number of distinct water layers – the surface layer, the intermediate layer and the deep water layers.

> **"The Mediterranean is anything but simple"**

The Mediterranean Sea thermohaline circulation can be described as a large scale anti-estuarine (the inflow of low-salinity surface water over a deeper outflowing dense, high-salinity water layer) buoyancy-driven circulation, with fresher surface waters (from the Atlantic Ocean) inflowing and subsurface denser saline waters outflowing over the shallow (250m) sill at Gibraltar. The average sea-level of the Atlantic Ocean is slightly higher (3cm in July, 11cm in January) than that of the Mediterranean Sea.

The water which is relatively fresh (compared to Mediterranean water) and thus less dense flows from the Atlantic through the Strait of Gibraltar and becomes Modified Atlantic Water (MAW) due to intense air-sea exchanges with the atmosphere. The MAW, crossing the Strait of Sicily, reaches the eastern basin and ends up in the Levantine. Here, cooling in winter causes convection to intermediate depths (up to 500m) mainly in the Rhodes area, forming Levantine Intermediate Water (LIW, Lascaratos *et al.* 1993).

The Levantine Intermediate Water forms the main component of the Mediterranean outflow to the Atlantic. LIW also provides for the formation of the Eastern Mediterranean Deep Water (EMDW) and the Western Mediterranean Deep Water (WMDW), the two locally formed deep waters of the basin. In addition to the vertical water circulation patterns, the horizontal circulation structure within the Mediterranean Sea is also rather complex.

Modern telemetric techniques conducted by sophisticated satellite sensors have allowed oceanographers to visualise and follow the path taken by water currents. There is no single surface current regime which is uniform throughout the Mediterranean Sea – rather, seabed topography and meteorological factors combine to split the main incoming surface sea current into two branches – one flowing northwards towards the Balearics and other larger (in terms of volume) current flowing along the north African coast, termed the Algerian current, and heading for the Sicilian Channel. Throughout its passage in the Mediterranean, surface waters diverge yet again for an innumerable number of times. According to Drago (1991), the Atlantic flow to the west of Malta results in a southeast surface current to the south of Malta, thus supplying water to the Malta Channel in a southeast direction with a mean speed of 0.2-0.3 m/s.

“According to a 2008 scientific report, global warming is changing the Mediterranean beyond recognition”

The changing sea

According to the new scientific report *Climate Warming and Related Changes in the Mediterranean Biota* by the Mediterranean Science Commission (CIESM 2008), global warming is transforming the Mediterranean beyond recognition. This well-documented, 152-page monograph is the outcome of a recent CIESM Exploratory Workshop where the multidisciplinary expertise of international scientists was drawn together to produce a synthesis on the impacts of climate change on Mediterranean marine species.

Since the 1980s the Mediterranean marine biota has known rapid, dramatic changes, illustrated by alteration of food webs, mass mortalities, or population explosions such as the occurrence of jellyfish blooms. This has prompted some to declare that the Mediterranean Sea is currently undergoing a paradigm shift, mutating from a fish to a jellyfish sea. During the summer of 2010, a 200km-long tide of the alien jellyfish species *Rhopilema nomadica* (the nomad jellyfish) formed off the coast of Israel. Through a simple exercise in ballparking, it is estimated that 100 million jellyfish individuals were incorporated in such a massive swarm, for a total jellyfish biomass of 500,000 tons. If each jellyfish individual is estimated to daily consume 1% of its body weight in terms of plankton, such a swarm would effectively gorge itself on 5000 tons of plankton every day (Menachem Goren, personal communication), literally scraping clean an already impoverished sea. The implications for fisheries are all too resounding.

According to experts, these changes cannot be ascribed solely to the intense anthropogenic activities. As the Mediterranean Sea hosts species with affinity to cold waters (of boreal origin), as well as species with affinity to warm waters (of sub-tropical and tropical origin), these two sets predictably respond to climate warming in different ways. In-situ long-term measurements of temperature and salinity recorded at the Straits of Gibraltar have shown that the deep water outflow through the same straits is warmer (ca. 0.30C) and saltier (ca. 0.06 units) than ten years ago (CIESM 2008).

As described in the CIESM Monograph, native thermophilic species, usually restricted to the southern and eastern, warmer sectors of the Mediterranean Sea are now moving northwards and westwards. This phenomenon (meridionalization) is particularly evident in fish, where over 30 native species have already spread in the northern areas of the Basin. *Lobotes surinamensis* (the Atlantic tripletail) is a case in point. This cosmopolitan fish species was previously only known in the eastern half of the basin, very rarely being recorded in central areas. Until 2005, just one individual of the species had been recorded in Maltese waters.

As documented by Deidun *et al.* (2010), the species was reported on numerous occasions during 2009 and 2010, in shoals and with juveniles, in Maltese nearshore waters suggesting that the species has established populations in this part of the Mediterranean. Meridionalization has been documented for a number of species (Bianchi and Morri 2003; Azzurro 2008), including *Thalassoma pavo*, previously only abundant in the Eastern Mediterranean and now well established in the Western Basin as well. From a literature review, Azzurro (2008) identifies 51 fish species which have expanded their range northwards in the Mediterranean, of which 34 were native and 17 exotic (11 Lessepsian, 6 exotic). Many of these fish species were described as of subtropical or tropical affinity.

Similarly, climate warming facilitates the establishment and spread of tropical, exotic species that are introduced *via* the Suez Canal or maritime transport. This process (tropicalization) is fast advancing and more than 500 exotic species have been recorded of late in the Mediterranean Sea, with most of tropical or subtropical affinity (CIESM, 2008). Recent changes in distribution of indigenous fish species as a putative result of climate change has been well documented (Beare *et al.* 2004; UNEP-MAP-RAC/SPA 2008; CIESM 2008). For example, the Tetraodontidae constitute a striking example of the tropicalization of the Mediterranean fish fauna, with the number of pufferfish species recorded for the Mediterranean waters rising from three (*E. guttiferum*, *L. lagocephalus* and *L. spadiceus*) to 10 species, with seven novel tetraodontids of Lessepsian or tropical-Atlantic origin (Vacchi *et al.* 2007).

The warming of the Mediterranean is also constantly leading to a revision of the inventories of marine species found in this sea as a result of the ushering in of exotic (non-indigenous) species from the Red Sea, mainly of tropical Erythrean (East African) and Indo-Pacific origin. Such migrants are aptly called Lessepsian migrants, as a tribute to the French diplomat Ferdinand de Lesseps who steered the signing of the agreement endorsing the development of the Suez Canal. The opening of the canal (which hosts ca. 6% of the global maritime

traffic, equivalent to almost 20,000 large vessels per year) in 1869 is independent of climate change, but it has certainly provided us with a snapshot of the ramifications of the warming sea, by providing a corridor and paving the way for the tropical migrants to enter the warmer Mediterranean.

German professors visiting the area in the late 19th century commented on the marked dissimilarity between the marine species on both sides of the canal – the warming of the Mediterranean is bridging such a divide, with mostly, as yet, unknown impacts. The first record of a Lessepsian fish migrant dates back to 1902 – nowadays, the count of such species has surpassed the 100 mark, or almost 15% of the total fish species in the Mediterranean. The total number of Lessepsian migrants to date hovers around the 750 mark, with over 50 being recorded so far from Maltese waters. The influx is inexorable indeed.

A small number of Lessepsian migrants are regularly sold in fish markets and restaurants in Eastern Mediterranean countries (for example, the Erythrean conch *Strombus persicus* is offered in restaurants in Israel, while the Erythrean pearl oyster is regularly sold in Beirut). From the earliest stages, the Suez Canal Company sought to exploit the biota in the canal, and hired Gruvel, a fisheries expert who was familiar with the Levantine fisheries, as 'chef de mission' to identify possible commercially advantageous products.

The tropicalisation of the Mediterranean Sea is being documented through the influx of alien marine species of warm affinity, such as *Selene dorsalis* (African moonfish), pictured top. Populations of the *Lobotes surinamensis* (Atlantic tripletail; above) are expanding in the Mediterranean Sea, especially in central and western areas of the basin. The process involving the shifting of the ranges of indigenous species is known as meridionalisation.

Other Lessepsians wreak havoc. The alien nomadic jellyfish species has showed up along Levantine coastlines every summer since the mid 1980's, forming large swarms which depreciate the touristic amenity of the coastal areas and clogging fishing nets. In 2001, the Israel Electric company was forced to remove tons of biomass of the voracious exotic jellyfish from its seawater intake pipes, for an estimated cost of 50,000 US dollars!

A brief delving in the past is eye-opening indeed. The researcher Bodenheimer had expressed way back in 1935 that "It is almost certain that the Indo-Pacific influx is still under way and it will be most interesting to study this process." It seems that our appreciation of changes has waned significantly over the decades, but, at the same time, the same changes have been exacerbated greatly.

According to some studies, the ocean has captured between 28 and 34% of the anthropogenic carbon dioxide emitted to the atmosphere between 1980 and 1994, leading to a reduction of about 0.1 pH units in ocean surface waters compared to pre-industrial times. A further decline by 0.3–0.5 pH units is expected by 2100. Ocean acidification has been proposed to pose a major threat for marine organisms, particularly shell-forming and calcifying organisms, with bivalves being the most vulnerable to changes in ambient pH. Some regions of the Mediterranean present a living laboratory for testing the effects of ocean acidification on marine biota. A case in point are the volcanic Aeolian Islands off the northern coast of Sicily, where underwater volcanic activity is constantly releasing trails of carbon dioxide bubbles from the seabed into the water column, a relentless and similarly fascinating process easily observable through snorkeling. Ongoing research is currently seeking to identify the adaptations possessed by marine biota found in the area.

An indirect effect of a warming sea is the impact on the charismatic sea turtle species. The predicted rise in sea level can potentially spell disaster for the nesting beaches of sea turtles, most of which are nowadays concentrated in the eastern and south-eastern sectors of the Mediterranean. A similar fate could await the monk seal (*Monachus monachus*), which is the only pinniped species known from the Mediterranean and which is critically endangered, with less than 500 individuals left in the wild (IUCN – www.iucnredlist.org/). This species depends on partially submerged sea caves for its breeding, with the same caves menaced by rising sea levels if future climate change scenarios are correct.

Some of the implications of the warming sea on marine species are relatively easy to monitor and quantify – one such example is the mass mortality of gorgonian populations (e.g. *Paramuricea clavata*) along the coasts of Liguria, Italy, and Provence, France, due to temperature anomalies in the summers of 1999 and 2003. The iconic Neptune seagrass, *Posidonia oceanica*, endemic to the Mediterranean, flowers and sheds its olive-shaped fruit on particularly warm years only. The increasing frequency of such an event is considered a harbinger of a warming Mediterranean.

The Mediterranean Sea is the ideal testing chamber to assess the impacts of sea warming on marine biota, by virtue of the high taxonomic diversity of its marine biota, by its sensitivity to current warming trends (mainly as a result of its limited connectivity to the world oceans) and by virtue of the multitude of academic institutions abutting on the same basin, which constantly monitor distribution and phenology of indicator marine species.

Further reading and references can be found at www.societyofbiology.org/biologist