Regional Climate Change Initiative Republic of Cyprus

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Report of the Task Force on

Marine Environment & Resources

Eastern Mediterranean and Middle East Climate Change Initiative

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Marine Environment & Resources

Eastern Mediterranean and Middle East Climate Change Initiative (EMME-CCI)

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Abbreviations

AMO	Atlantic Multidecadal Oscillation
APP	Autotrophic Picoplankton
BA	Bacterial Abundance
BP	Bacterial Production
BR	Bacterial Respiration
BSW	Black Sea water
C_{ANT}	Anthropogenic Carbon
CC	Climate Change
CCA	Carrying Capacity Assessment
CMEMS	Copernicus Marine Environment Monitoring Service
CRA	Climate Risk Assessment
CV&C	Climate Variability and Change
DHW	Degree Heat Weeks
DIC	Dissolved Inorganic Carbon
DSS	Decision Support System
ECC	Environmental Carrying Capacity
EAP	East Atlantic Pattern
EAWR	East Atlantic-West Russia
EEZ	Exclusive Economic Zone
EMED	Eastern Mediterranean Sea
EMME	Eastern Mediterranean and Middle East
ENSO	El Niño-Southern Oscillation
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIS	Geographic Information Systems
GNP	Gross National Product
GPP	Gross Primary Production
IAS	Invasive Alien Species
ICAM	Integrated Coastal Area Management
IMI	Indian Monsoon Index

IOD	Indian Ocean Dipole
ME	Middle East
MFW	Microbial Food Web
MHW	Marine Heatwave
MS	Mediterranean Sea
NAO	North Atlantic Oscillation
NIG	Northern Ionian Gyre
NIS	Non Indigenous Species
NRS	Northern Red Sea
OA	Ocean Acidification
OECD	Organisation for Economic Co-operation and Development
OHC	Ocean Heat Content
OSC	Ocean Salt Content
OW	Ocean Warming
PAP/RAC	Priority Actions Programme / Regional Activity Centre
PCC	Physical Carrying Capacity
PG	Persian Gulf
PIC	Particulate Inorganic Carbon
POC	Particulate Organic Carbon
PP	Primary Production
RCC	Real Carrying Capacity
RS	Red Sea
SLC	Sea Level Change
SLR	Sea Level Rise
SRS	Southern Red Sea
SST	Sea Surface Temperature
TA	Total Alkalinity
TTD	Transient Time Distribution
UN	United Nations
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
WTO	World Tourism Organization
WTTC	World Travel & Tourism Council

Abstract

Climate change is already impacting the marine environment of the Eastern Mediterranean and Middle East (EMME) region, the effects are expected to be exacerbated in the second half of the century, with implications on ocean circulation, biogeochemical cycling and marine biodiversity. Warmer seawater and ocean acidification will drive the restructuring of ecosystems. Moreover, sea-level rise and the intensification of extreme events is expected to affect human activities as tourism, maritime transport, port activities, offshore energy production and desalination. This report provides an overview of the impact of climate change on the marine environment of the EMME region taking into consideration changes in physical and biogeochemical properties, and the vulnerability of ecosystems.

Executive Summary

The Eastern Mediterranean and Middle East (EMME) marine environment is an ecologically, geopolitically, and economically vital region encompassing a diverse range of semi-enclosed basins including the Mediterranean Sea, Levantine Sea, Red Sea, and the Arabian Gulf. These water bodies support intense maritime activity, critical coastal infrastructure, valuable fisheries, energy operations, and growing tourism sectors. However, they are highly vulnerable to climate variability and change (CV&C), which intensify pre-existing geotectonic hazards and create new ecological and socio-economic pressures.

The EMME region comprises over 83,000 km of coastline, stretching across several key marine environments including the Adriatic, Aegean, Red Sea, and Persian Gulf. Much of this coastline lies adjacent to major active fault zones, making it seismically active and geodynamically complex. These tectonic interactions - driven by the movement of the African, Arabian, and Eurasian plates - create a volatile setting prone to large-magnitude earthquakes, subsidence, and tsunami events.

Coastal zones are also economic and population hubs, containing ports, energy infrastructure, industrial centers, and dense urban settlements. Climate change adds another layer of stress, with sea-level rise, increased storm intensity, and coastal erosion posing major risks to these vulnerable zones. Many of these coasts are low-lying deltas or sandy beaches, highly susceptible to flooding and retreat under future climate conditions. The concentration of critical assets - ports, refineries, desalination plants, and tourism infrastructure - magnifies the potential socio-economic impacts. Finally, the region plays a vital role in global trade through key maritime chokepoints like the Suez Canal and the Strait of Hormuz. Ensuring the resilience of these zones under CV&C scenarios is paramount to both regional and international economic stability.

The EMME's marine systems function as "concentration basins," where evaporation significantly exceeds precipitation and river input. This causes salinity buildup and fuels thermohaline circulation - a driving force in ocean mixing, deep-water formation, and nutrient transport. Each sub-basin has unique circulation patterns and thermal characteristics but shares key physical processes.

In the Eastern Mediterranean, the Adriatic and Aegean seas are sites of strong wintertime surface heat loss, leading to intermittent deep-water formation. These processes are sensitive to climatic conditions such as wind, humidity gradients, and Black Sea water (BSW) outflow. The Aegean's future role in Mediterranean overturning circulation could increase due to decreasing BSW influence and persistent winter cooling. Observed trends show declining surface heat loss over much of the basin, except of the Aegean, where winter losses remain stable. This could shift dense water formation eastwards over time.

In the Red Sea, high evaporation under an arid climate leads to intense surface salinity and thermohaline-driven circulation. Seasonal variability, driven by the Indian Monsoon, alters air-sea fluxes dramatically. Winters bring strong heat loss and convective mixing in the north, while summers sea heat gain. Long-term monitoring has shown warming trends and less frequent extreme heat-loss events, especially in the north, raising concerns over stratification and nutrient cycling.

The Persian Gulf exhibits similar conditions, high evaporation, limited freshwater input, and strong seasonal temperature swings. The Gulf's circulation includes fresh water entering through the Strait of Hormuz and dense, saline water exiting at depth. Changes in heat and freshwater fluxes affect this balance and could increase salinity in the upper water layers.

Across the region, future projections indicate continued warming and decreasing net heat loss, especially under high-emission scenarios. These changes can modulate the formation of dense waters, reduce vertical mixing, and disrupt the supply of oxygen and nutrients to deeper layers, which are key processes for ecosystem functioning. Moreover, increased stratification may amplify the effects of marine heatwaves and atenuate the resilience of regional seas to further warming.

Climate change is already impacting marine ecosystems across the EMME region, and these effects are projected to intensify. The most immediate and visible impact is marine warming, occurring at accelerated rates in the Mediterranean Sea, Red Sea, and Persian Gulf. Satellite data and observational studies reveal that the Eastern Mediterranean is warming up to three times faster than the global average, with rates exceeding 0.4°C per decade in some areas. The Red Sea and Persian Gulf show similar trends, particularly in their northern sectors. This warming is not limited to surface waters but extends into deeper layers, affecting thermal stratification, oxygen levels, and biological processes.

Marine heatwaves (MHWs) - periods of abnormally high sea temperatures - are becoming more frequent and severe. These events lead to coral bleaching, mass fish mortality, and the disruption of spawning and migratory patterns. Coral reef systems in the Red Sea and the Persian Gulf are already showing stress, while the Eastern Mediterranean Sea has seen a decline in native species and a rise in non-indigenous (tropical) species migrating through the Suez Canal, an effect known as “tropicalization.”

Salinification is another critical issue. Due to limited freshwater input and rising evaporation, salinity levels are increasing in the Red Sea and the Eastern Mediterranean Sea, which affects species composition and planktonic food webs. In the Persian Gulf, however, some studies suggest a slight decrease in deeper water salinity, possibly due to increased exchange with the Indian Ocean. Salinity extremes confine biodiversity by creating inhospitable conditions for many marine organisms, especially juveniles and larvae.

Sea-level rise (SLR) is accelerating due to thermal expansion and ice melt. Regional estimates indicate SLR rates of 3–6 mm/year in the Eastern Mediterranean Sea and the Red Sea, slightly above the global average. This rise threatens coastal wetlands, lagoons and low-lying urban infrastructure. Erosion, saltwater intrusion into coastal aquifers and habitat loss for shorebirds and estuarine species are all expected outcomes. Deltaic regions like the Nile Delta face existential threats, as even minor sea-level changes can lead to land loss and salinization of agricultural zones.

Ecosystem productivity and biodiversity are also at risk. The reduction in nutrient mixing due to increased stratification limits primary productivity, particularly in the oligotrophic Eastern Mediterranean. Combined with warming and acidification, this results in a decline in fish stocks and changes in food web dynamics. Fisheries and aquaculture operations face challenges in adapting to these new conditions, with increasing disease outbreaks, invasive species, and habitat degradation.

Cumulative impacts, from warming, deoxygenation, acidification, salinification, and pollution, may trigger ecological regime shifts. Once these systems cross certain thresholds, recovery may be slow or impossible without significant intervention. Protecting biodiversity hotspots, enhancing marine protected areas, and implementing climate-adaptive fisheries management are critical strategies for resilience.

The Eastern Mediterranean region has been a popular travel destination, offering high-quality tourism services. This was amplified by the diverse landscape, extended sandy beaches, scattered archaeological sites, people’s mentality, and adequate infrastructure. In particular, the Eastern Mediterranean attracts more than three hundred million visitors annually. A Carrying Capacity Assessment for the EMME region, based on a selection of fifteen indicators, revealed that Israel, Turkey, and Greece are significantly above the indicator scale limits and are facing issues related to over-tourism. Additionally, the concentration of tourists in the aforementioned countries may accelerate environmental degradation, and as a result, the tourist product may be downgraded. An alternative tourist development and the extension of the tourist season based on local climatic conditions must be applied to ease the over-concentration and, consequently, the degradation of the tourist product.

In conclusion, the EMME marine environment is under escalating threat from a combination of natural geotectonic processes and anthropogenic climate change. The unique geographic and climatic features of the region make it a microcosm for studying the impacts of global environmental shifts. This report emphasizes the importance of region-specific climate modeling, integrated monitoring systems, and adaptive policy frameworks to mitigate the risks posed by warming, salinification, and sea-level rise. Coordinated scientific and policy efforts are imperative for the resilience of these vital marine ecosystems and the sustainability of the societies that depend on them.

1 Geographical Setting

The Eastern Mediterranean and Middle East (EMME) coastal and marine environment is associated with critical resources and significant infrastructure, assets and activities. The EMME coastline (Figures 1 and 2) has a length of more than 83,000 km, consisting of the Adriatic Sea (12,380 km), the Ionian Sea (5,377 km), the Aegean Sea (17,567 km), the Sea of Marmara (1,835 km), the Eastern Mediterranean Sea (13,142 km), the Red Sea (13,144 km), the Gulf of Aden (2,823 km), the Arabian Sea (3,173 km) and the Persian-Arabian Gulf (13,901 km) coasts; the adjoining Black Sea has a coastline length of about 10,472 km (Source: Flanders Mar. Inst., 2018, IHO Sea Areas, v.3, https://www.marineregions.org/, https://doi.org/10.14284/323)

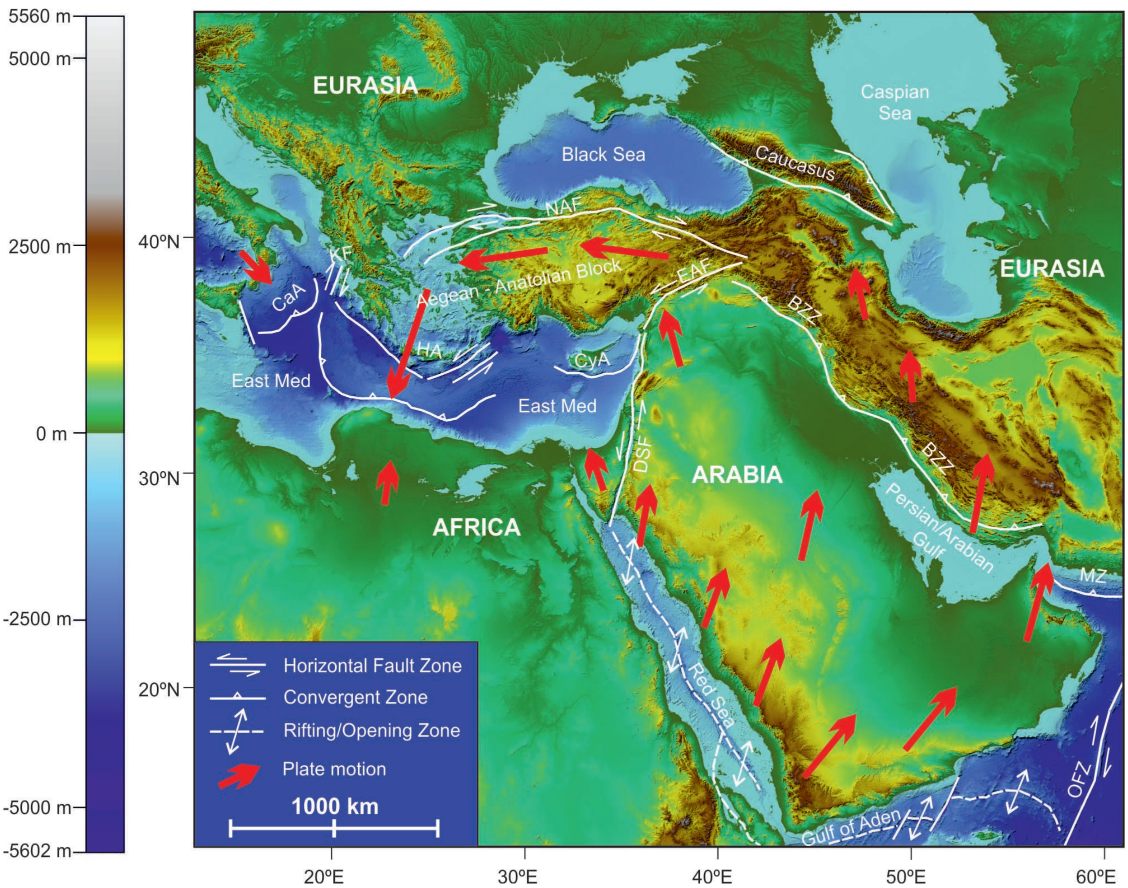
The longest part of EMME's coastline runs parallel to and at relatively short distances from major, active seismogenic fault-zones that have developed in response to the relative motions between the lithospheric plates and blocks of the region (Figure 1).

Rifting and opening of the Red Sea initiated 25-30 million years ago and opening of the Gulf Aden force the Arabian Plate to drift away from Africa, towards N to NNE along the Dead Sea Fault and to collide with the Eurasian Plate along the Bitlis-Zagros Zone. The northward motion of Arabia and its collision with Eurasia force the Anatolian Block to move (escape) westwards along the North and the East Anatolian Faults. This movement initiated some 12 million years ago and adds gradually increasing stress onto the Aegean crust that moves toward SSW already since more than 35 - 40 million years ago. This motion has been recently (5 million years ago) accelerated to 30-35 mm/yr with respect to the Eurasian Plate. The Aegean continental crust overrides the partly oceanic partly continental crust of the Eastern Mediterranean / African Plate that sinks into the mantle below the Hellenic Arc (Ghebreab, 1998; McClusky et al., 2000; Reilinger et al., 2006; Bosworth, 2015; Taymaz et al., 2007 and references therein).

The above geodynamic setting triggers a series of active geotectonic processes localized mainly along the major fault zones that form the boundaries between the individual plates and blocks. Enhanced seismicity with earthquake magnitude exceeding M:6 and reaching magnitudes over M:8, extensive brittle deformation (faulting, uplift, subsidence), terrestrial and submarine landslides as well as disastrous tsunamis are associated with the active geodynamic regime and constitute major hazards for most of EMME's coastline.

Many large urban and industrial conglomerates are located at the coast, as well as critical transport infrastructure and energy plants (e.g. Wolff et al., 2018). The EMME hosts some of the world's busiest shipping lanes, such as the EM shipping corridors, the Suez canal, the Red Sea and the Straits of Hormuz and many of its seaports are vital nodes for international trade, passenger transit and the cruise industry; thus, their resilience under Climate Variability and Change (CV&C) is critical for the sustainable development of the area (UNCTAD, 2020). At the same time, there are important fisheries and aquaculture grounds, coral reef fields as well as increasing offshore hydrocarbon exploitation and a currently small, but increasingly vital marine aggregate industry.

FIGURE 1. Map of active geodynamic features and plate kinematics in the EMME region. Seafloor and land relief

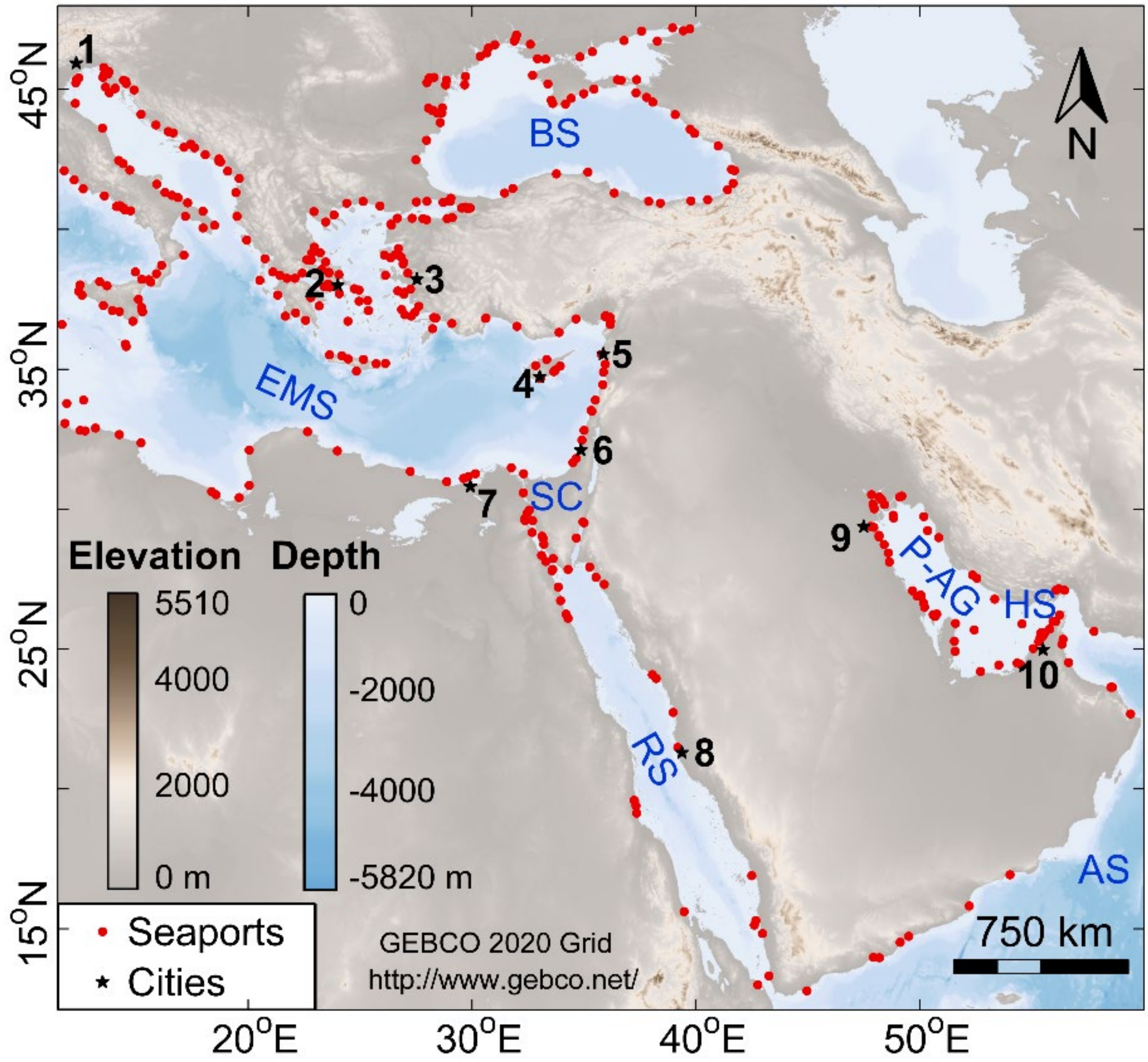


Source: GEBCO Compilation Group (2023) GEBCO 2023 Grid (doi:10.5285/f98b053b-0cbc-6c23-e053-6c86abc0af7b).

Note: Red arrows indicate direction of plate motion in respect to stable Eurasia, while their length represents the rate of motion. Key: BZZ: Bitlis Zagros Zone; CaA: Calabrian Arc; CyA: Cyprus Arc; DSF: Dead Sea Fault; EAF: East Anatolian Fault; HA: Hellenic Arc; KF: Kephallinia Fault; MZ: Makran Zone; OFZ: Owens Fault Zone. See text for explanation and sources.

CV&C will have large impacts on the EMME coastal natural and human environment and the marine resources (e.g. Hinkel et al., 2014). Coastal areas are exposed to many climatic hazards (IPCC, 2014; IPCC SROCC, 2019), such as: a) slow-onset events (e.g. increasing mean sea levels and temperatures and decreasing mean precipitation, and (b) sudden onset events (e.g. storm generated extreme sea levels - *ESLs* and waves, heat waves, winds and heavy precipitation, droughts and cyclones). These hazards will potentially have many negative impacts on coastal populations, assets and activities and the coastal/marine habitats and biological resources.

FIGURE 2. Location map, showing the major EMME subregions and the major seaports



Source:https://hub.arcgis.com/datasets/8be585162b814e1f89afa6a3de4e42cb_0/data?geometry=111.500%2C-27.047%2C113.500%2C31.665

Note: EMS (eastern Mediterranean Sea); RS, Red Sea; AS, Arabian Sea; P-AG, Persian-Arabian Gulf; BS, Black Sea; SC, Suez Canal; HS, Hormuz Strait; 1, Venice; 2, Athens; 3, Izmir; 4, Lemesos; 5, Latakeia; 6, Tel Aviv; 7, Alexandria; 8, Jeddah; 9, Kuwait; 10, Dubai.

Low-lying, developed coasts will bear the brunt of the CV&C impacts, including retreat and/or drowning of beaches, permanent and/or temporary flooding of deltaic coasts and damages to coastal infrastructure/assets. Many EMME coasts are major tourism destinations. Tourism, which is increasingly associated with beach recreational activities ('*Sun-Sea-Sand*-3S' model) and accounts for a large fraction of the *GDP* of many EMME coastal and island States (UNWTO, 2017, 2019), will be severely affected by the increasing erosion and/or more frequent flooding of beaches and their backshore assets (e.g. Monioudi et al., 2017; Bitan and Zviely, 2018) as well as the increased intensity and /or frequency of extreme temperatures (Mazarakis et al., 2014). Coastal transport infrastructure, such as seaports and their inland transport connections will be also affected (e.g. Bowyer et al., 2020; UNCTAD, 2020), whereas coastal installations for the offshore hydrocarbon industry (e.g. pipelines, LG and oil terminals) will also face increasing climatic hazards. Very important biological resources, such as the coral reefs, fisheries and aquaculture and as well as the coastal agriculture will be also impacted to varying degrees, due to permanent and/or temporary coastal flooding/erosion, aquifer salinisation, seawater acidification, precipitation changes, droughts and wildfires. In the following sections, some of the major climatic hazards and impacts are considered, with a particular focus on the coastal areas.

2 Physical and biochemical functioning

2.1 Atmosphere-Ocean Interaction - Atmospheric deposition / Marine heatwaves / Medicanes

2.1.1 Introduction

Measuring, estimating, monitoring and projecting air-sea heat fluxes in marginal semi-enclosed seas is essential for understanding and predicting regional climate dynamics, maintaining marine ecosystem health, supporting oceanographic and weather research, managing human activities, and monitoring significant environmental changes.

The Eastern Mediterranean and the Middle East Seas (the Red Sea and the Arabian Gulf) are areas of particular importance since they host a large population under a rapidly changing climate. All three areas are semi-enclosed basins, surrounded by large continental areas, providing humidity/water to the surrounding populations, under rapidly varying climate conditions (intensifying the hydrological cycle).

All basins behave as concentration basins, producing dense/salty waters, mainly due to high evaporation compared to smaller (or close to zero) precipitation and river influx. The circulation of each sub-basin is largely determined by the air-sea exchanges of heat, mass and momentum. The fact that all sub-basins are connected to the open ocean (or with other sub-basins) through Straits, provides a standard constraint at the Strait (e.g. Garrett et al., 1993) on the estimates of the basin mean values through the atmosphere.

2.1.2 Eastern Mediterranean

2.1.2.1 Heat Fluxes

The net surface heat fluxes (Q_{net}) are the sum of radiative (net shortwave Q_{SW} and net longwave Q_{LW}) and turbulent fluxes (latent heat Q_l and sensible heat Q_s). Positive values represent heat gain by the ocean.

$$Q_{net} = Q_{SW} + Q_{LW} + Q_l + Q_s$$

The net shortwave radiation term (Figure 3) represents the absorbed solar radiation (Figure 4a) whereas the net longwave represents the sum of the incoming radiation from the atmosphere minus the outgoing radiation from the ocean surface (Figure 4b). The turbulent fluxes depend on the near-surface temperature and humidity gradients, as well as on the wind speed. The latent heat flux is responsible for the highest heat loss in all basins (Figure 4d), though significantly higher in the Aegean (by more than 20 W m^{-2}) compared to the Adriatic.

a. Historical: Observed changes in the historical period

Typical climatological conditions for the present climate indicate that the Eastern Mediterranean Sea is overall losing heat from its surface over a long period of time (e.g. Garrett et al., 1993), mainly due to the strong evaporative fluxes of its two northern smaller sub-basins, the Adriatic and the Aegean Seas. From a recent estimate using a 30-year numerical simulation output forced with ERA-Interim (Petalas et al., 2022), the larger southern Eastern Mediterranean sub-basins show surface heat budgets close to zero, with a weak heat gain for the Levantine (+2 W/m^2) and a weak heat loss for the Ionian (– 1.7 W/m^2). The strong heat losses appear in the north for the Adriatic (– 19.6 W/m^2) and even more for the Aegean Seas (– 28.0 W/m^2), indicating that these could be regions favorable for deep water formation (Figure 3). However, the thin surface layer of less haline, modified Black Sea outflow into the north Aegean Sean, stratifies the water column preventing the Aegean from being a steady source of Eastern Mediterranean deep-water, sporadically allowing this to happen under a combination of conditions. The Black Sea water (BSW) also absorbs the air–sea fluxes acting as an effective insulator regarding dense-water formation processes, therefore the role of BSW to the Aegean is twofold: (a) moderates the buoyancy fluxes over its path and (b) provides significant lateral buoyancy to the Aegean, thus making it very sensitive to meteorological forcing (Tragou et al., 2022). However, according to Mamoutos et al. (2024), the role of BSW in hindering deep water formation is gradually diminishing, based on evidence for a recent drastic reduction of BSW presence in the surface layer of the North Aegean Sea.

FIGURE 3. Mean heat flux over the East Mediterranean and the Black Seas over the 1985–2015 period from ERA-Interim. The black rectangle marks the region under examination. The negative sign signifies heat loss, positive signifies heat gain by the sea (from Tragou et al., 2022)

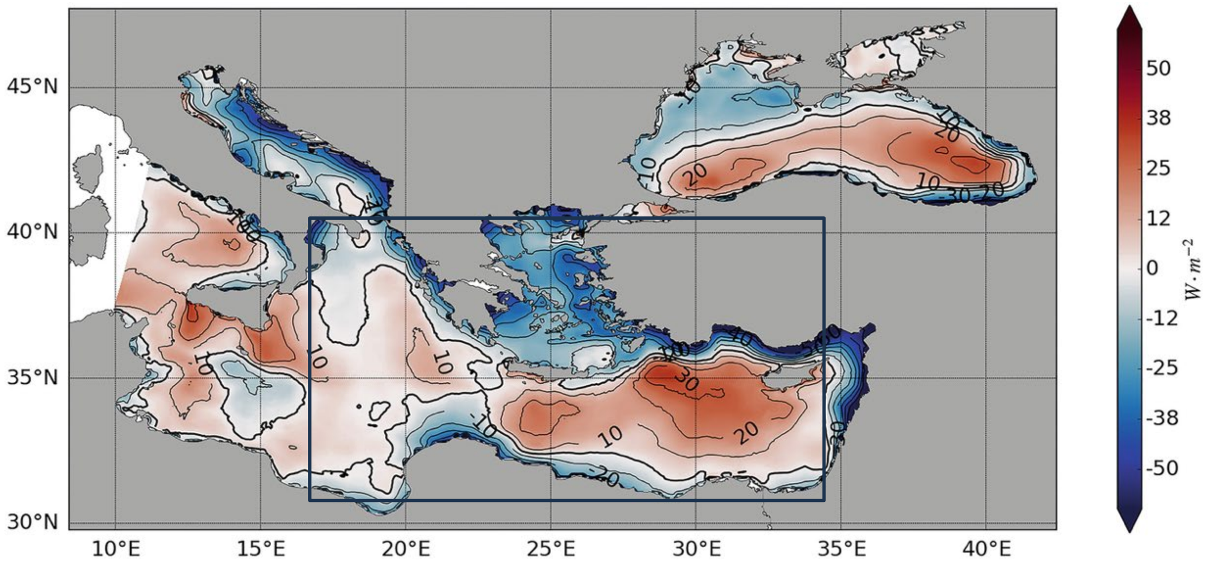
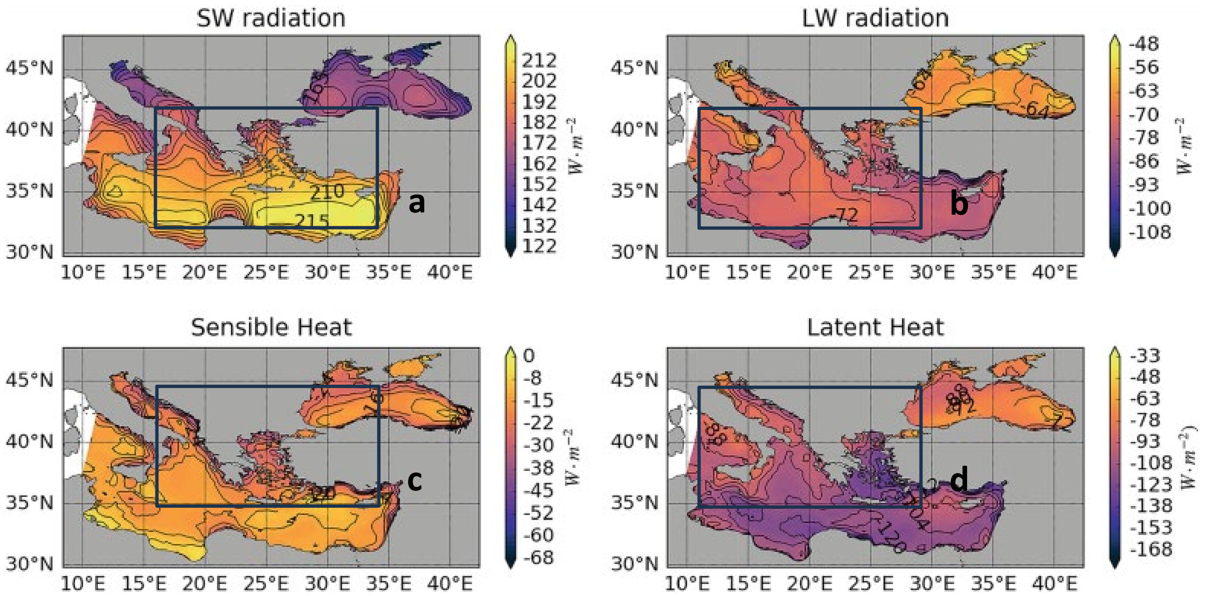


FIGURE 4. Mean heat-flux components over the Eastern Mediterranean and Black Seas over the 1985–2015 period (a) Shortwave solar radiation, (b) Longwave radiation, (c) Sensible and (d) Latent heat flux. Note the different color bar limits (from Tragou et al., 2022)



The net heat flux variability reflects the combination of the individual components and is dominated by the turbulent heat flux contribution with extremes of daily heat loss exceeding -900W m^{-2} in winter. In a recent analysis, Josey and Schroeder (2023) highlighted the weakening of winter surface heat losses in the deep-water formation site of Nothwestern

Med since 1950 (mainly because of reduced latent heat flux), threatening dense water formation (reduced by 40% in the period 1969-2018). They provide evidence for an ongoing shift of the main Mediterranean convection site from the west towards the Aegean Sea (where winter surface heat loss has not changed, remaining -172 Wm^{-2}), due to different variability of air-sea humidity and temperature gradients. Focusing on the heat fluxes, the mean sea-level air-temperature has risen faster than the sea-surface temperature throughout the Mediterranean; however, this difference in much higher in the western Med and the Adriatic than the Aegean, causing much higher reduction of the heat losses in the former areas than the latter (Josey and Schroeder, 2023). If this tendency of steady winter surface heat fluxes in the Aegean continues in the future and is combined with the tendency for reduced outflow of BSW, the Aegean is very likely to become a more permanent deep-water formation site of the Mediterranean.

The heat loss patterns of the Mediterranean basin are largely determined by large-scale atmospheric variability modes, such as the North Atlantic Oscillation (NAO) and the East Atlantic Pattern (EAP), especially during winter, and to a lesser degree in summer (Schroeder et al., 2023). According to Josey et al. (2011), the sign of EAP (positive or negative) affects the basin-average heat flux, either increasing or reducing surface heat losses over the Mediterranean Sea. When these atmospheric modes are exceptionally strong, they can create airflows that lead to significant heat loss, as observed in the winter of 2004/2005 in the northwestern Mediterranean (Schroeder et al., 2010). However, the Aegean Sea winter heat losses (such as the anomalously highs of the EMT years 1991-1993) are not directly related to these modes (e.g. Josey, 2003), but rather to the East-Atlantic / West Russian or the similar North Caspian Pattern (Gunduz et al., 2013).

Harzallah et al. (2018) estimated the trends of the net heat flux at the sea surface (using Med-CORDEX results) and found sign and magnitude of the trends to differ among models. Most models showed positive trends of the heat content rate (in agreement with observations), compatible with an average heat flux trend from the simulations of $+58 \times 10^{-3}$ Wm^{-2} $year^{-1}$.

b. Future

A series of studies have demonstrated that in the future, the net heat loss by the sea surface is anticipated to continue to decline, mainly because of the expected increase in shortwave radiation due to reduction of cloud cover, which is not compensated by the expected rise in latent heat loss (e.g. Dubois et al., 2012; Gualdi et al., 2013; Adloff et al., 2015; Soto-Navarro et al., 2020).

Projections of coupled regional climate models indicate that the decrease in the net heat loss could be in the range of -1.8 to -5.5 W m^{-2} by 2050, according to the medium-range A1B scenario (Dubois et al., 2012). The potential range for this decrease is between -2.1 and -6. 4 W m^{-2} (resp. -1.0 and -3.7 W m^{-2}) at the end of the 21st century following high-range RCP8.5 (resp. medium-range RCP4.5) scenarios (Soto-Navarro et al., 2020).

This suggests that, in some models, the atmosphere may begin to warm the Mediterranean Sea from the mid-21st century, in contrast to the current climate conditions. The changes in the Mediterranean Sea surface heat budget are dependent on the socio-economic scenario selected. It has been demonstrated that the greater the greenhouse gas emissions, the more pronounced the response of the budget (MedECC, 2020). However, it is important to note that the aforementioned ensembles do not concur on the future of the Aegean overturning cell, largely due to different simulation approaches of the exchange with the Black Sea, or even the omission of the exchange.

Parras-Berrocal et al. (2022) recently found using a high-resolution regional climate model that dense water formation in the Northwestern Med collapses by 2040– 2050 primarily due to stronger vertical stratification. Parras-Berrocal et al. (2023) also suggested that the source of the dense waters of the Eastern Mediterranean will move from the Adriatic to the Aegean Sea. Mamoutos et al. (2024) demonstrated that since the 1990s there is a long-term trend of the sea level difference which forces the exchange of the two basins, leading to the currently observed minimal presence of the Black Sea water in the North Aegean Sea. The variability of this exchange and its impact on the buoyancy balance of the Aegean may become a significant factor to the production of dense water in this basin. Overall, in this critical area for the overturning circulation of the Eastern Mediterranean, the future evolution of the Aegean overturning cell will depend on whether this trend will continue, in addition to the variability of local atmospheric forcing.

2.1.2.2 Freshwater Fluxes

Surface freshwater fluxes in the Eastern Mediterranean Sea are influenced by a variety of factors including evaporation, precipitation, riverine inputs, and groundwater flows. The net evaporation (E-P) is positive over virtually the entire Mediterranean (as a typical concentration basin), with higher values in the Eastern basin. This shows that the evaporation exceeds precipitation over the whole basin.

a. Historical

The observational records demonstrate that the Mediterranean has exhibited decadal variability and a general tendency for annual-mean conditions to be warmer and drier during the period between 1860 and 2005 (Mariotti et al., 2015). The freshwater deficit increases, and the increase becomes higher in the eastern part of the basin (Romanou et al., 2010). The observed water deficit can be attributed to an increase in evaporation driven by rising sea surface temperatures. In contrast, precipitation shows no discernible trend over the period in question.

b. Future

An increase in the net surface water loss by the sea is expected in the future due to a decrease in precipitation and in river runoff and an increase in evaporation (Giorgi, 2006; Somot et al., 2008; Lionello et al., 2012; Mariotti et al., 2015).

2.1.3 Red Sea

2.1.3.1 Heat Fluxes

The Red Sea, a critical marine environment located between Africa and Asia, is characterized by its unique climatic and oceanographic features. The study of air-sea fluxes is essential to understand the heat, moisture, and momentum exchanges that regulate the regional climate, weather patterns, and marine ecosystem.

a. Historical: Observed changes in the historical period

Despite its location in the tropics, surrounded by two of the world's largest deserts, the Red Sea exhibits a weak annual net heat loss (-8 ± 2 W/m^2, e.g. Tragou et al., 1999). The Red Sea is in a highly arid environment, which results in one of the highest evaporation rates of the world ocean, with an annual average of approximately 2 m/year, while precipitation is negligible (e.g. Tragou et al., 1999; Sofianos et al., 2002; Albarakati and Ahmad, 2013; Ahmad and Albarakati, 2015). The annual-mean thermohaline circulation of the Red Sea is forced mainly by the high net evaporation; the relatively weak thermal forcing is of secondary importance on longer timescales. The surface heat flux is low and well constrained in value by heat fluxes through the strait of Bab el Mandab (Tragou et al., 1999). The strongest air–sea buoyancy exchange occurs in the northern Red Sea during the winter months, resulting in convective mixing and the formation of the deepest mixed layers. These mixed layers are responsible for the formation of very saline water masses (Krokos et al., 2024).

Over the last 50 years, significant research has been conducted to explore heat fluxes. One of the critical findings is the pronounced seasonal and spatial variability of air-sea fluxes in the Red Sea (e.g. Tragou et al., 1999; Sofianos et al., 2002; Matsoukas et al., 2007; Nagy et al., 2021). According to Sofianos and Johns (2001) the seasonal variability of air-sea fluxes in the Red Sea is primarily influenced by wind patterns associated with the Indian Monsoon. During winter, the region experiences high evaporation rates driven by the northeast monsoon winds, leading to significant heat loss and salinity increases. In contrast, the summer months are characterized by lower wind speeds and reduced evaporation, resulting in a net heat gain. According to Sofianos and Johns (2001) the seasonal variability of air-sea fluxes in the Red Sea is primarily influenced by wind patterns associated with the Indian Monsoon. Interannual variability, influenced by ENSO and IOD, further modulates these seasonal patterns, affecting the overall heat and moisture budget of the Red Sea. Research by Abualnaja et al. (2015) examined the impact of various climate modes on air-sea heat exchange, with significant influences during boreal winter from the North Atlantic Oscillation (NAO), east Atlantic-west Russia (EAWR) pattern, and Indian monsoon index (IMI). However, the impact of the modes on the Red Sea is observed to be comparatively less pronounced than in the neighbouring Mediterranean basin.

Recent studies on air-sea fluxes in the Red Sea have focused on various aspects of heat and moisture exchange, extreme weather events, and their implications for regional climate dynamics. The variability of winter air-sea heat fluxes over the Northern Red Sea appears to be strongly influenced by atmospheric forcing, particularly the turbulent components of surface fluxes such as latent and sensible heat (Papadopoulos et al., 2013). More recently Nagy et al. (2021) showed that the Northern Red Sea is overall losing heat from its surface and the Southern Red Sea is gaining heat, while they found a significant linear trend in the surface net heat flux of +0.21 ± 0.020 (W/m^2)/yr for the entire Red Sea, during the period 1981-2020.

Recent research has identified extreme heat loss events in the Northern Red Sea, primarily occurring between November and March, and more often during December and January. These events are associated with specific regional atmospheric circulation patterns, often showing daily-averaged values lower than -1000 W/m^2 (Papadopoulos et al., 2022). Dry-air outbreaks over the Northern Red Sea significantly influence heat loss, dominated by latent heat fluxes due to low relative humidity. These events affect surface water mass transformation and have potential implications for the oceanic thermohaline-driven overturning circulation. This emphasizes the critical role of atmospheric humidity and temperature in modulating air-sea interactions (Menezes et al., 2019).

Finally, a recent evaluation of surface heat fluxes over the Northern Red Sea and Arabian Gulf using reanalysis datasets (ECMWF-ERA5 and NASA-MERRA2) suggests that while ERA5 might be preferable for the Arabian Gulf, MERRA2 appears to be more suitable for the Red Sea. This underscores the importance of selecting appropriate datasets for accurate modeling and prediction of air-sea fluxes (Al Senafi et al., 2019).

These studies provide valuable insights into the complex dynamics of air-sea fluxes in the Red Sea, emphasizing the interplay between atmospheric conditions, regional weather patterns, and oceanic processes. They also highlight the importance of accurate modeling and continuous monitoring to understand and predict the region's climate dynamics. The Red Sea's unique characteristics and its interaction with adjacent basins make it a critical area for ongoing research to predict, mitigate and adapt to the impacts of climate variability and to provide management tools of the environmental impacts in the region.

b. Future

A limited number of scientific studies has been conducted on the climate change in the Red Sea region, and most of them analyze global climate model results with coarse resolution (e.g. Shaltout, 2019; Agulles et al., 2021; Bawadekji et al., 2022), examining standard atmospheric and oceanic variables, without any discussion on air-sea heat fluxes. GCMs results project an averaged warming at the end of the century (2080–2100) of 3.3 ± 0.6°C at the surface under the scenarios RCP8.5, with the projected warming expected to largely overcome the natural multidecadal variability, which could induce temporary and moderate decrease of the temperatures but not enough to fully counteract it (Agulles et al., 2021).

Future research should focus on improving climate change projections for the Red Sea region. Enhanced modeling efforts, incorporating high-resolution climate models and downscaling techniques, are needed to predict the impacts of global warming on regional air-sea fluxes. Understanding the potential changes in extreme events and their implications for the marine environment is also a priority for this sensitive region of the global ocean.

2.1.3.2 Freshwater Fluxes

a. <u>Historical</u>

The Red Sea is one of the most saline bodies of water due to high evaporation rates and minimal freshwater inputs (e.g. Morcos, 1970). The basin experiences high evaporation rates due to its warm and dry climate, contributing significantly to its high salinity. Evaporation rates can exceed 2 meters per year, particularly in the northern parts of the sea (e.g. Sofianos and Johns, 2002). Studies indicate that the region loses more water to evaporation than it gains from precipitation and runoff combined. Precipitation over the Red Sea is relatively low, averaging about 0.1 to 0.2 meters per year (e.g. Tragou et al., 1999). Seasonal variability in precipitation is observed, with most rainfall occurring during the winter months, while this minimal rainfall contributes to the net loss of freshwater. The Red Sea lacks significant riverine inputs. Small seasonal wadis may occasionally contribute freshwater, but their impact is minimal. There is limited information on groundwater discharge, but it is generally considered negligible compared to evaporation and precipitation (Alaa El-Din and Jacobs, 2006). The exchange of water with the Gulf of Aden through the Strait of Bab el Mandab plays a crucial role in the Red Sea's water balance, compensating for the overall water mass loss from its surface (e.g. Sofianos and Johns, 2003). Several studies and datasets have been used to analyze the freshwater fluxes over the Red Sea, including satellite observations, climate models, and reanalysis datasets like ECMWF-ERA5 and NASA-MERRA2. In a recent analysis Nagy et al. (2021), (analyzing results from the ERA-5 dataset) gave an annual mean surface net water flux loss to the atmosphere over the entire Red Sea of about +1.46 ± 0.23 m/yr. The seasonal surface net water flux peak occurs in winter because of the northeast monsoon wind, which increases evaporation rate over the whole length of the Red Sea. The highest surface net water flux (+2.1 m/yr) occurred during 2020, while the lowest value (+1.3 m/yr) occurred during 1985 (Nagy et al., 2021).

b. Future

Future climate projections suggest potential changes in precipitation patterns, which could impact the freshwater balance in the region. According to Majdi et al. (2022), precipitation is expected to decrease in the region, although the uncertainties are large. This development, combined with increased evaporation due to rising temperatures could also further exacerbate salinity levels.

2.1.4 Comparative Analysis

The Red Sea and the Persian Gulf, both being semi-enclosed seas in the Middle East, exhibit some notable similarities in their air-sea exchanges due to their geographic proximity, climatic conditions, and regional atmospheric circulations. Here are some key similarities in their air-sea exchanges:

1. High Evaporation Rates

Both the Red Sea and the Persian Gulf experience extremely high evaporation rates due to their hot and arid climates. This high evaporation is driven by the intense solar radiation and low humidity, particularly during the summer months.

- Red Sea: Evaporation rates can reach up to 2 meters per year.

- Persian Gulf: Evaporation rates are even higher, reaching up to 3 meters per year.

2. Heat Fluxes

The heat fluxes in both seas are characterized by significant seasonal variability, influenced by the regional monsoon systems and extreme temperatures.

- Sensible Heat Flux: During the winter, both seas experience high sensible heat loss to the atmosphere due to cooler air temperatures over the warmer water bodies.

- Latent Heat Flux: High latent heat fluxes are observed due to the high evaporation rates, which contribute significantly to the heat budget of these seas.

3. Seasonal Variability

Both regions exhibit pronounced seasonal variations in their air-sea exchanges, largely driven by the surrounding atmospheric conditions.

- Winter: The seas lose heat to the atmosphere, which leads to cooling of the surface waters. Wind patterns during this time also enhance mixing and vertical heat exchange.

- Summer: The regions gain heat due to high solar radiation, and the surface waters warm significantly. Evaporation rates peak during this season, further affecting the heat and moisture fluxes.

4. Influence of Monsoon Systems

The atmospheric circulations in both seas are influenced by the monsoon systems, which affect wind patterns, temperature, and humidity levels.

- Red Sea: The Indian Ocean monsoon system plays a significant role, with northeasterly winds prevailing in winter and southwesterly winds in summer.

- Persian Gulf: The monsoon impacts are similar, with Shamal winds (northwesterly winds) prevalent in winter and more variable winds in summer.

5. Limited Freshwater Input

Both seas receive limited freshwater input from riverine sources, which accentuates the effects of high evaporation rates and leads to higher salinities.

- Red Sea: Very few perennial rivers, with freshwater input being minimal.

- Persian Gulf: Limited input from the Shatt al-Arab river, but still dominated by evaporation over precipitation.

6. High Salinity

Due to high evaporation and limited freshwater input, both the Red Sea and the Persian Gulf exhibit high salinity levels, which affect their thermohaline circulation and stratification.

- Red Sea: Surface salinity ranges from 36 to 41 PSU.

- Persian Gulf: Surface salinity can exceed 40 PSU, particularly in the shallow northern parts.

7. Strong Thermohaline Circulation

The high evaporation rates and resultant high salinities drive strong thermohaline circulation in both seas, which is crucial for their water mass exchange with adjacent open seas.

- Red Sea: Dense, high-salinity water sinks and flows out through the Bab el Mandeb Strait.

- Persian Gulf: Similar outflow of dense, saline water through the Strait of Hormuz.

The Red Sea and the Persian Gulf share several similarities in their air-sea exchanges, primarily driven by their geographic and climatic conditions. High evaporation rates, significant seasonal variability, and strong thermohaline circulation are common features that define the air-sea interaction in these two seas. Understanding these similarities helps in predicting their responses to climatic changes and managing their marine resources effectively.

2.1.5 Conclusion

Subregional scale variability plays a key role on the overall evolution of the climatic conditions (temperature, precipitation and pressure – altering the sea-surface heat, freshwater and momentum fluxes) of the sub-basins examined in this report. Still, there are largely common physical processes that appear to all the sub-basins due to global scale anthropogenic climate change:

Heat fluxes:

Global warming is not equally evident over the planet, and temperature increase becomes higher with latitude (e.g. Lionello and Scarascia, 2018, Lionello et al., 2023). This effect is also evident in the basins of the EMed, Red Sea and the Arabian Gulf, with the Mediterranean warming at a rate about 20% faster than the global mean (Cherif et al., 2020; Lionello et al., 2023). Anthropogenic aerosols are more abundant over industrial areas of the northern Mediterranean, reducing the absorbed solar radiation (global dimming). However, a recent decreasing trend in aerosols has been partly considered responsible for the recent warming acceleration (Urdiales-Flores et al., 2023).

The higher (than the surrounding land) ocean heat capacity of all three sub-basins brings non uniform warming among all areas, regarding the warming rate, the season and the longer-term variability.

Atmospheric circulation changes at a regional scale, and their interaction with the surrounding land, seems to be responsible for enhanced warming during the summer season. For the Mediterranean, summer warming is 50% stronger than the global mean (Lionello et al. (2023). A possible explanation comes from the lack of near surface moisture of the surrounding land that could provide some surface cooling during the dry summer period, further increasing the warming.

Stress the importance of BSW both in setting the precondition for DWF in the Aegean, as well as affecting the air-sea heat exchanges, therefore, regional climate models must appropriately include this outflow for future models. In fact, the greatest spread of model intercomparison efforts (Med-Cordex) appears in the North Aegean region (Soto-Navaro et al., 2020).

Freshwater fluxes:

The atmospheric warming is expected to accelerate the water cycle, increasing water vapor content of the atmosphere. This is related to increased atmospheric transport of water vapor and stronger contrasts among E-P regions, which also applies to the Mediterranean - dry conditions will become drier (Held and Soden, 2006).

At regional scales, historically observed/simulated changes of precipitation are basically driven by atmospheric advection of humidity. Different causes are responsible for the lack of humidity and the decrease of precipitation over the Mediterranean. In the summer, low-pressure systems develop over continental areas and their circulation tends to isolate these areas from the oceanic source of humidity, and in the winter, cyclones attenuate, and their path shifts northward (Lionello et al., 2023).

Model projections of the Mediterranean region reveal future differences between the northern and the southern parts, where extreme precipitation increases, and no significant change, respectively (Lionello and Scarascia, 2020).

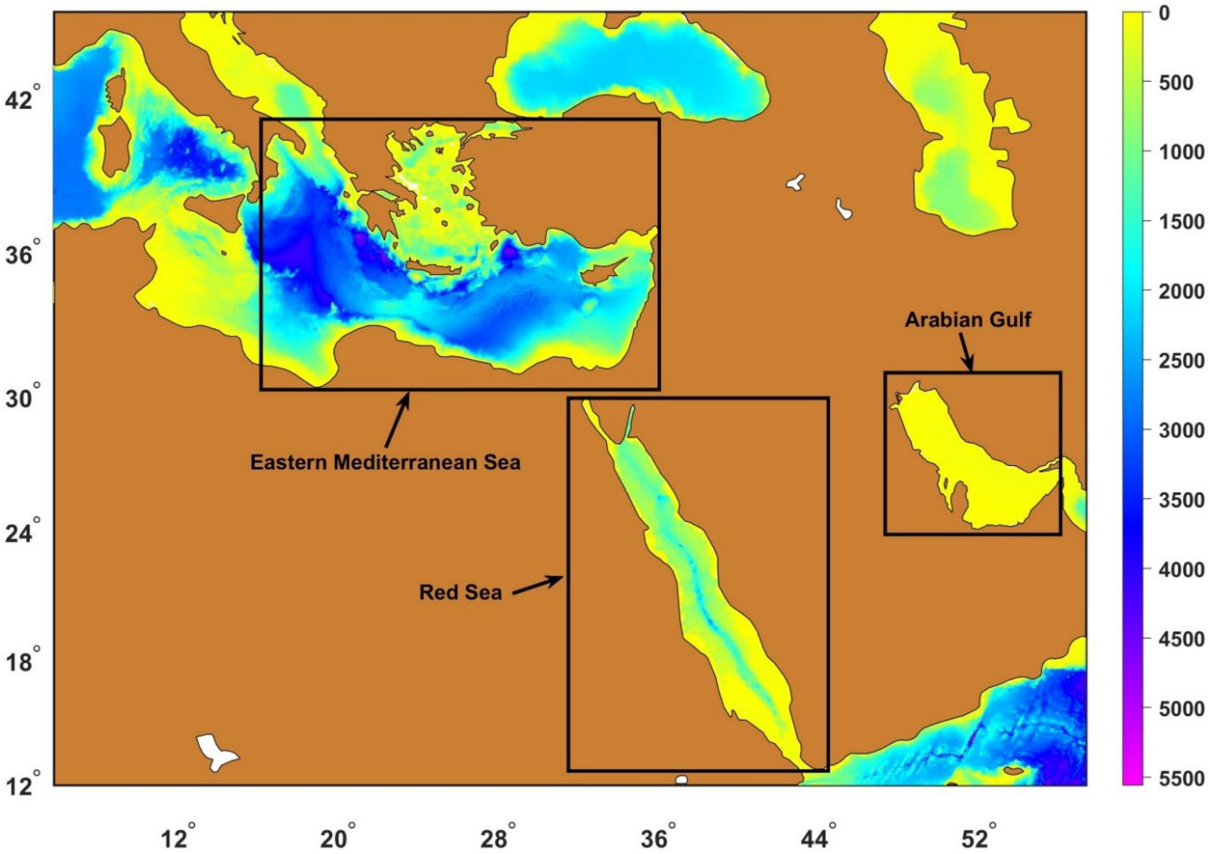
Overall, observations show uncertain changes of total precipitation and precipitation extremes, comparing the evolution of those variables from the preindustrial time until the beginning of the 21st century.

2.2 Warming and Salinification

2.2.1 Introduction

This section examines the physical changes that have occurred in the marine environment in the three neighboring regions (Eastern Mediterranean Sea, Red Sea, Arabian/Persian Gulf, Figure 5). In particular, the focus will be on the observed and predicted progressive warming and salinification of the water masses, changes in circulation, changes in sea level, as well as changes in the occurrence and intensity of extreme events (e.g. marine heat waves, "medicanes"). The three basins function as "concentration" basins and show many similarities in their overturning circulation patterns, though the Arabian Gulf is very shallow compared to Eastern Mediterranean and Red Sea.

FIGURE 5. Map of the three adjacent oceanic basins (bathymetry from GEBCO-2023)



The Mediterranean Sea is considered as a downscaled laboratory of the global ocean (Béthoux et al., 1998; 1999; Malanotte-Rizzoli et al., 2014). The basin is characterized by key oceanic physical processes, such as open-sea convection and shelf dense water cascading occurring in the Gulf of Lion, the Adriatic, Aegean, and Levantine Seas, where surface cooling leads to formation of deep and intermediate water masses (e.g. Durrieu de Madron et al., 2005, 2013; Schroeder et al., 2012; Houpert et al., 2016; Theocharis et al., 2018). The excess of evaporation over precipitation and river runoff in the Mediterranean basin is responsible for the so-called “inverse-estuarine” thermohaline circulation. This circulation pattern is characterized by a surface eastward flow of the relatively fresh Atlantic Water, from the Strait of Gibraltar towards the Levantine Sea through the Sicily Strait. A westward subsurface backflow of the very salty and warm Levantine Intermediate Water and Cretan Intermediate Water formed in the Eastern Mediterranean Sea (Figure 5), crosses the Sicily Channel, and eventually outflows from the Mediterranean through the Gibraltar Strait.

The Red Sea is an elongated young oceanic basin, spanning 19 degrees in the meridional direction (Figure 5), surrounded by arid and semi-arid areas. The basin exhibits a variety of climatic conditions as its southern part is affected by the Arabian Sea monsoon, whereas a seasonal cycle with a warm and a cold period, typical for subtropics worldwide, prevails over its northern half (Abualnaja et al., 2015; Viswanadhapalli et al., 2017). The Red Sea displays a similar to Mediterranean inverse-estuarine circulation pattern. As a “concentration” basin, it is characterized by one of the world’s highest evaporation that reaches or exceeds 2m per year (Tragou et al., 1998; Sofianos et al., 2002) and its water deficit is counterbalanced by inflow of relatively fresh water from the Indian Ocean through the Bab-El-Mandeb Strait at its southernmost edge. The low-salinity surface water flows northward and becomes gradually hypersaline reaching values > 40 over the northernmost parts of the basin. In the northern Red Sea under winter cooling intermediate and deep-water masses are formed and flow back to the south to renew the subsurface water and ventilate the deep water layers (Cember 1988; Sofianos and Johns, 2003; Yao et al., 2014; Sofianos and Johns, 2015; Papadopoulos et al., 2015; Yao and Hoteit, 2018; Papadopoulos et al., 2022). Especially, the intermediate water travels to the far south and exits the basin as the Red Sea Outflow Water (Sofianos and Johns 2003; Yao et al., 2014; Sofianos and Johns, 2015) to the Indian Ocean through the Gulf of Aden.

The Persian/Arabian Gulf is a subtropic, shallow semi-enclosed oceanic plateau lying between the Arabian Peninsula and the Iranian coastline with a length reaching 1.000 km in the NW-

SE direction. It exchanges water with the Gulf of Oman and the Indian Ocean through the Strait of Hormuz at its southeastern edge (Figure 5). The Gulf is characterized by large seasonal temperature variations exceeding 20°C (Vaughan and Burt, 2016; Vasou et al., 2024) and a mean annual sea surface temperature (SST) that exceeds 27°C (Al-Shabi, 2019). Some of the highest SST in the global ocean have been recorded in the Gulf, exceeding 36°C (Burt et al., 2009; Alawad et al., 2020; Alosairi et al., 2020). The arid climate with high evaporation and very limited precipitation and river runoff renders the Gulf a “concentration” basin showing an inverse-estuarine circulation, in analogy to the Mediterranean and Red Seas. Relatively fresh water with salinity <37 enters the Gulf through the Strait of Hormuz and flows in a general cyclonic circulation along the Iranian coastline towards the northern and western parts of the plateau where salinities values exceed 40 (John et al., 1990; Chao et al., 1992; Swift and Bower, 2003; Al Azahr et al., 2016; Vaughan et al., 2019). High salinity and seasonal surface cooling lead to dense water formation and fuel a steady deep outflow from the Gulf to Indian Ocean throughout the year (Reynolds, 1993; Swift and Bower, 2003; Pous et al., 2004; Vasou et al., 2020; Vasou et al., 2024).

One more remarkable similarity between the Mediterranean and Red Sea is their long-term SST variability, which is characterized by a natural oscillation with a periodicity of approximately 70-year that is coherent with Atlantic Multidecadal Oscillation (AMO, Schlesinger and Ramankutty, 1994; Felis et al., 2000; Marullo et al., 2011; Macias et al., 2013, Krokos et al., 2019). Therefore, we need to deal more skeptically with the high warming rates reported using recent satellite-era datasets of a shorter period (25-30 years), as they are masked by a combined effect of the global warming and a positive phase of the background natural SST oscillation (Krokos et al., 2019).

Here, we present an overview along with an up-to-date status regarding the temporal evolution of warming and salinification in the three basins using the long-term Met Office Hadley Centre observational SST dataset (Rayner et al., 2003) and the high-resolution (0.083° × 0.083°) Copernicus Global Ocean Physics Reanalysis (Lellouche et al., 2021). To facilitate the comparison between the three basins, a common scale for the spatial distribution of the surface temperature and salinity trends is used.

2.2.2 Eastern Mediterranean

During the 20th century, most of the global ocean displays positive SST trend and this warming has been intensified over the last years of the previous century and at the beginning of the 21st century (Ting et al., 2009; Large and Yeager, 2012; Reid and Beaugrand, 2012; IPCC, 2019). However, SST trend varies considerably over the oceans and the marginal seas with even spots of cooling to be scattered over the globe (Casey and Cornillon, 2001; Belkin 2009). In accordance with the global ocean, SST trend in the Mediterranean Sea is positive, though it exhibits spatial and temporal variations and seasonal rate fluctuation (Bethoux et al., 1998; Zveryaev and Arkhipkin, 2008; Nykjaer, 2009; Skliris et al., 2011; Juza and Tintoré, 2021).

Mediterranean water masses are becoming warmer and saltier, as suggested by an increasing number of observations and model simulations (Béthoux and Gentili 1999; Rixen et al., 2005; Beuvier et al., 2010; Vargas-Yáñez et al., 2010; Borghini et al., 2014; Schroeder et al., 2017; Harzallah et al., 2018; Soto-Navarro et al., 2020). The temperature increase involves the whole water column, and the whole basin (Marullo et al. 2011; Macias et al., 2013; Rivetti et al., 2017; Vargas-Yáñez et al., 2017; Pastor et al., 2018; Iona et al., 2018), but the eastern Mediterranean (EMED) is more affected than the western Mediterranean (MedECC, 2020). For instance, the temperature and the salinity of the LIW/CIW during the period 1993-2016 have increased at rates of 0.24°C/decade and 0.06 /decade, respectively (Schroeder et al. 2017). However, the thermohaline properties of intermediate and deep water masses show a marked decadal variability (Roether et al., 2007; Gačić et al., 2010; Schroeder et al., 2016). The number, intensity, and duration of marine heatwaves have also increased considerably in the past decade (Darmaraki et al., 2019, Pastor and Khodayar, 2023; Marullo et al., 2023; Hamdeno and Alvera-Azcaráte, 2023).

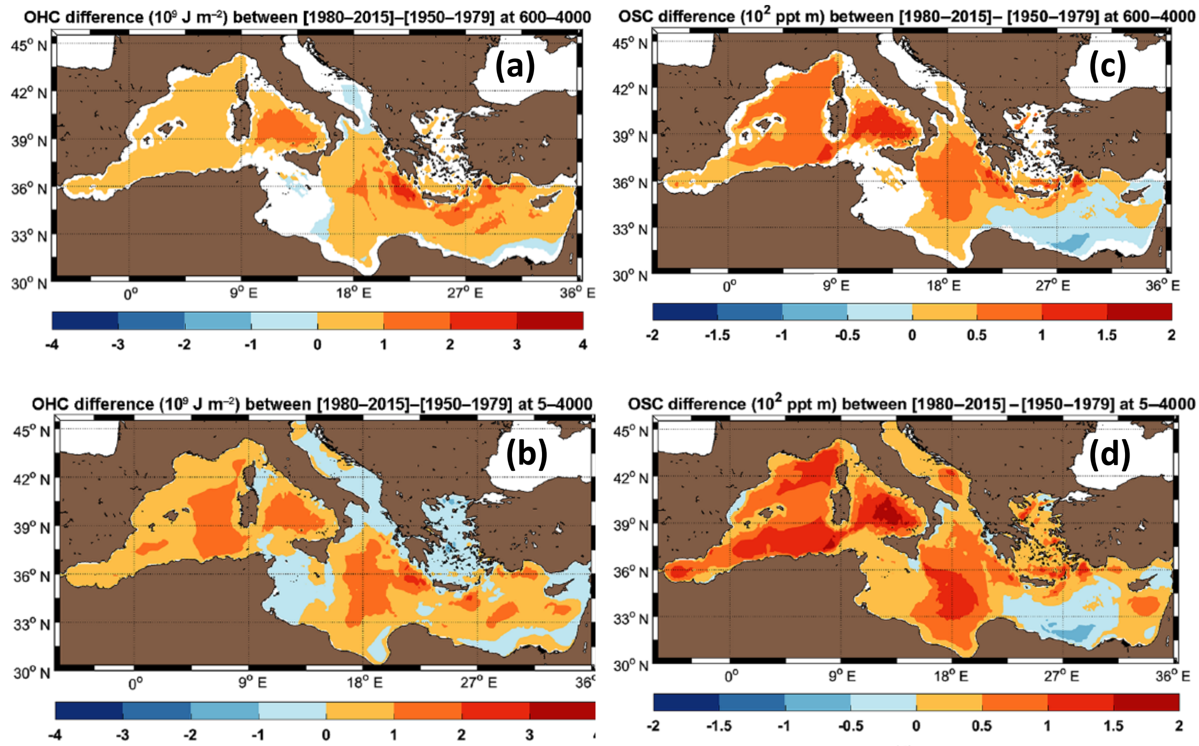
Similar rates of increase of the average SST in the Mediterranean Sea have been lately reported for the period spanning the last 30-40 years. Increase rate of 0.41 ± 0.06°C/decade for the period 1982-2018 is reported by Pisano et al. (2020), 0.38 ± 0.02°C/decade between 1982 and 2020 by Juza and Tintore (2021), and 0.34 ± 0.032°C/decade between 1993 and 2023 by Von Schuckmann et al. (2023). It is noteworthy that an increase rate of 0.4°C/decade is about threefold the rate of the global ocean warming reported for the four last decades

(IPCC, 2021). Still, within the Mediterranean Sea the spatial variability of the reported trend is conspicuously high (Ibrahim et al., 2021; Juza and Tintoré, 2021).

Climatic indices for temperature, salinity, Ocean Heat Content (OHC) and Ocean Salt Content (OSC) anomalies derived from a high-resolution climatology of temperature and salinity based on historical *in situ* observations also reveal that over the period 1950 to 2015, the Mediterranean Sea have become warmer and saltier (Iona et al., 2018). However, due to the regional climate variability and the circulation patterns of water masses, temperature and salinity changes are not uniform. The comparison of the thermohaline content between two successive periods 1950-1979 and 1980-2015 demonstrates significant variation in climate shift across the Mediterranean Sea. Deep waters (600-4000m) throughout the basin are experiencing warming the last 36 years except in the southern Adriatic, southern Levantine, and south-western Ionian basins (Figure 6a), while for the whole water column (5-4000m) the OHC shows a decrease at several parts of the basin for the last 36 years compared to the previous 30 years climatic period (Figure 6b). The change in the OSC is unambiguous in the western Mediterranean while in the eastern Mediterranean a notable salt content increase is observed in the areas of deep water formation and a decrease in the most of the Levantine basin (Figures 6c, 6d). Skliris et al. (2014) have also reported a significant salinity increase in the Mediterranean over the past few decades, particularly in the deep waters (> 1000 m), with rates surpassing other regions in the global ocean.

The linear trend of 57 running decades from 1950-1959 to 2006-2015 based on the decadal T/S anomalies averaged over four representative depth layers shows some additional remarkable findings (Iona et al., 2018). Specifically, throughout the entire water column, there is a statistically significant increase in salinity from 1950 to 2015, more intense in areas such as the Adriatic Sea and the Aegean Sea (Figure 7b). Regarding the temperature, it appears that there is an increasing trend everywhere except the north-central Aegean and southern Adriatic seas, areas where deep water formation occurs in the eastern Mediterranean (Figure 7a).

FIGURE 6. Climate shift between two successive periods 1980–2015 and 1950–1979 of areal density of ocean heat content in 10^9 J m^{-2} for: (a) 600-4000m, (b) 5-4000m and ocean salt content in 10^2 ppt m for: (c) 600-4000m, (d) 5- 4000 m depth



Time series of the decadal Ocean Heat Content (OHC) and Ocean Salt Content (OSC) anomalies integrated over the whole column depth and area of the Mediterranean Sea are shown in Figure 8. There is intense decadal variability, slow-downs and accelerations especially the last 25 years from 1990 to 2015. Similar results for salinity are also found at Skliris et al. (2018). For the whole period (1950 to 2015) there is an overall increase (at 95% confidence level) of OHC and OSC by (3.8 ± 0.5) x 10^{20} J/decade and (4.7 ± 0.4) x 10^{13} ppt m^3, respectively, corresponding to an approximate increase of 0.024°C/decade for temperature and 0.012/decade for salinity. The similar analysis for the EMED shows an approximate increase for temperature and salinity of 0.017°C/decade and 0.011/decade, respectively.

The decadal variation of the Mediterranean OHC exhibits a statistically significant correlation (R=0.87) with the Atlantic Multidecadal Oscillation (AMO) index, suggesting a potential influence of the AMO on Mediterranean climate.

FIGURE 7. 57 running decades liner trend of temperature (a) and salinity (b) anomalies averaged over 5–4000 m, in and °C per decade and ppt per decade, respectively. Regions where the linear trend is not significant at the 95% confidence level are not plotted

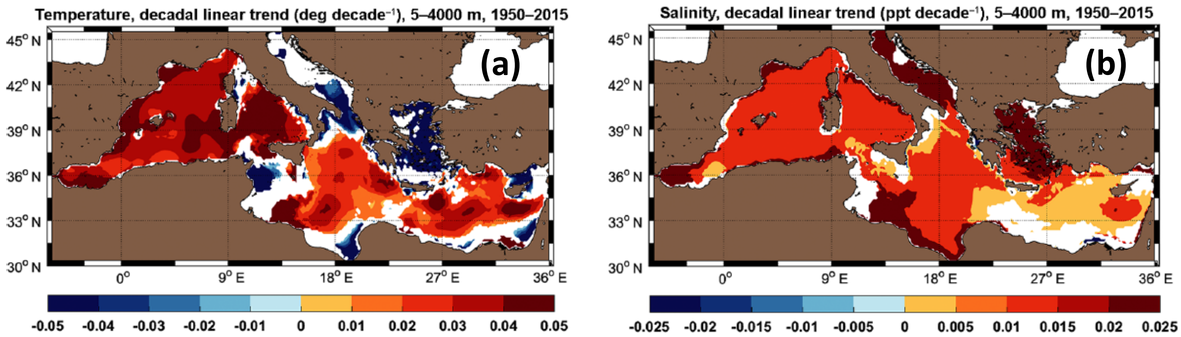
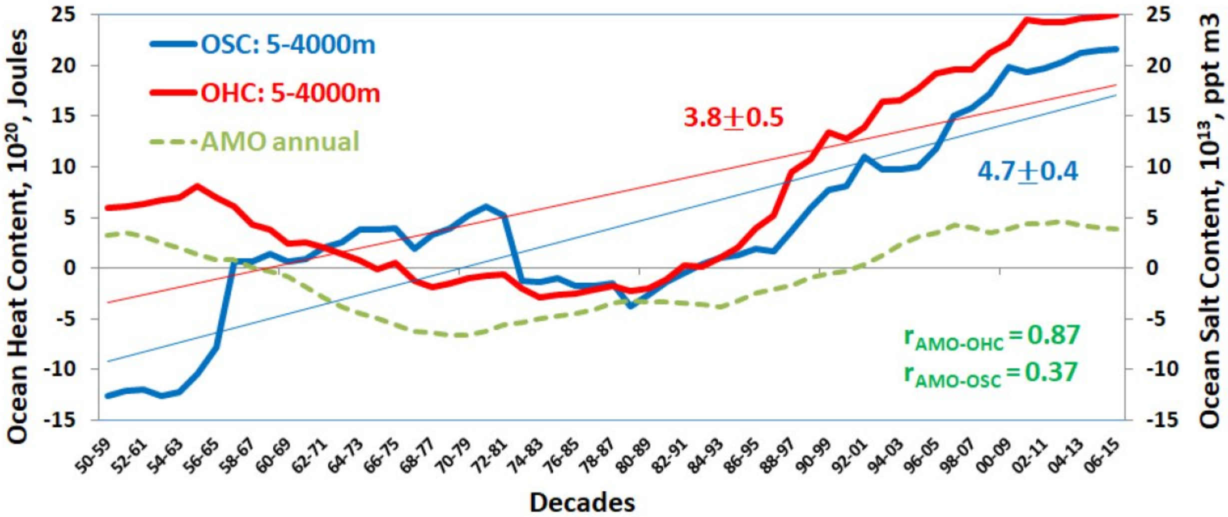


FIGURE 8. Volume integrals of OHC (10^{20} J) and OSC (10^{13} ppt m^3) anomalies at 5–4000 m over the entire Mediterranean Sea. Trend values (per decade) are given in red for OHC and in blue for OSC. AMO annual values (multiplied by 25 to resemble the OHC shape) are shown with green dots. The correlation between annual AMO and decadal OHC significant at the 95% confidence level is shown in green



The analysis of mean annual SSTmax data acquired from the AVHRR satellite sensor (GHRSST L4 AVHRR v2.0) for the period 1982-2019 provides some additional valuable insights into the SST distribution and its potential impact on the reproduction of marine organisms in the Aegean Sea and respectively in the Eastern Mediterranean Sea. As depicted in Figure 9a, there is an obvious decrease in SSTmax from North to South and from West to East.

For the same period the analysis of the decadal trends of the SSTmax anomalies, shows a noticeable increase in the Northern Aegean (Figure 9b). Also, the SSTmax was 1°C higher from the mean SSTmax for the period 1982-2019 only for 8 years (Figure 10a) while the SSTmin was less than 1°C from the mean SSTmin for 28 years (Figure 10b).

FIGURE 9. Mean annual SST maxima (a) and decadal trend of SST maxima anomalies (b) for the period 1982-2019 based on the GHRSST L4 AVHRR satellite data

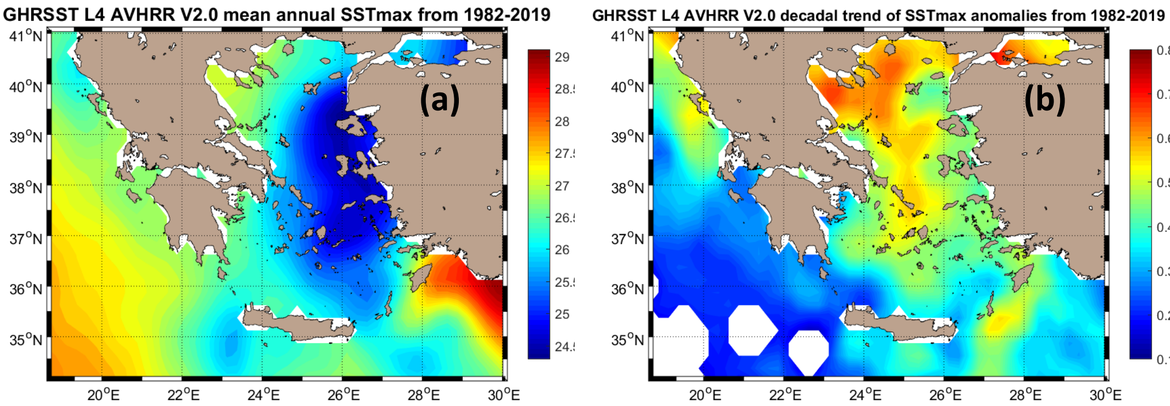


FIGURE 10. Years with annual SSTmax > 1°C than the mean SSTmax (a) and years with annual SSTmin < 1°C than the mean SSTmin (b) for the period 1982-2019 based on the GHRSST L4 AVHRR satellite data

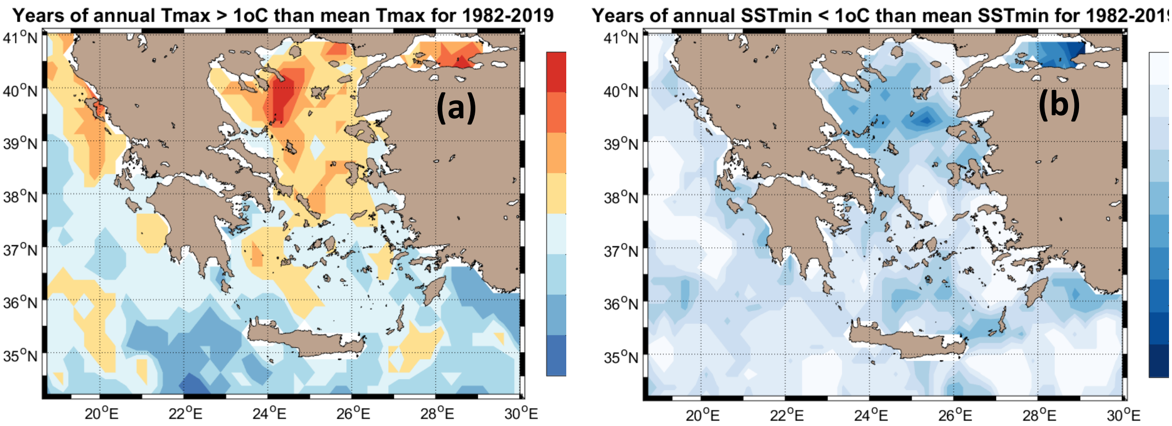
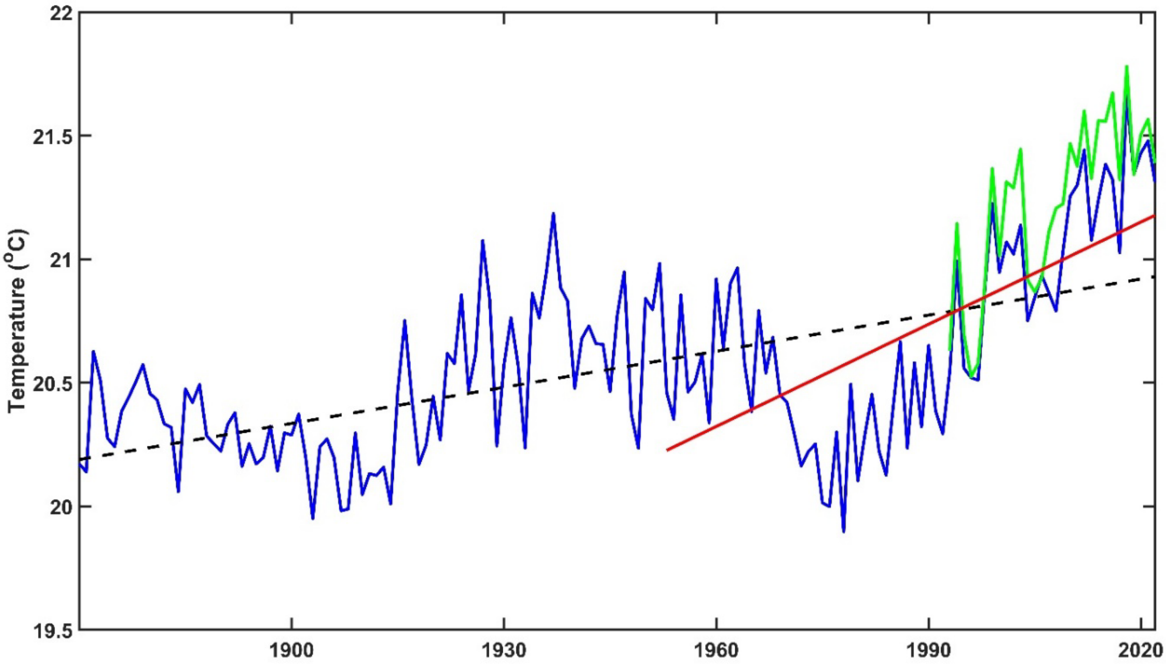


Figure 11 presents the temporal evolution of the spatially averaged SST for the EMED based on Hadley dataset for the period 1870-2022. The Copernicus average for the relatively short period of the last 30 years (1993-2022) is also shown. The warming trend of the EMED for the period 1870-2022 (153 years) is 0.05°C/decade. Taking into account the natural periodicity of approximately 70 years, we calculate the linear trend of the last natural cycle (red line in Figure 11) which is 0.14°C/decade, a value well above the long term one. Both trend values are significant at >95% confidence level following the Mann-Kendall trend test (Mann, 1945; Kendall, 1975). This is a clear indication of the ongoing increase in the SST warming rate of the EMED, though in rates apparently lower than the ones referred to the satellite-era observations.

FIGURE 11. Evolution of spatially averaged annual SST for the Eastern Mediterranean Sea spanning the period 1870-2022 based on the Hadley Center dataset (blue) with the long-term linear trend (black dashed line). The red line represents the linear trend for the last 70 years based on the same dataset. The green line displays the near surface (depth of 5m) sea temperature evolution for the period 1993-2022 based on the Copernicus dataset



The spatial distribution of the warming rates in the EMED for the last 30 years is given in Figure 12. The more intense warming is found in the eastern part of the Ionian Sea, South of Crete, and the Levantine Sea. As mentioned above, the warming of the EMED has affected the whole water column. Based on the Copernicus dataset for the period 1993-2022 the warming rate of the water volume of the deeper layers (>2500m) is 0.02°C/decade (statistically significant at 95% according to the Mann-Kendall trend test).

Regarding the change in salinity, the Copernicus reanalysis suggests an increase of 0.16 /decade at 5m and 0.02 /decade for the deeper layer (>2500m) for the period 1993-2020. Figure 13 presents the spatial salinity trend in the EMED for the same period. The highest increase is found in the eastern Aegean Sea just south of the typical outflow of the Black Sea Water from the Dardanelles Strait. Spots of salinity decrease are found in the northern Aegean Sea.

FIGURE 12. Warming rates in the EMED for the period 1993-2022 based on the Copernicus reanalysis at 5m. Only the statistically significant rates are shown

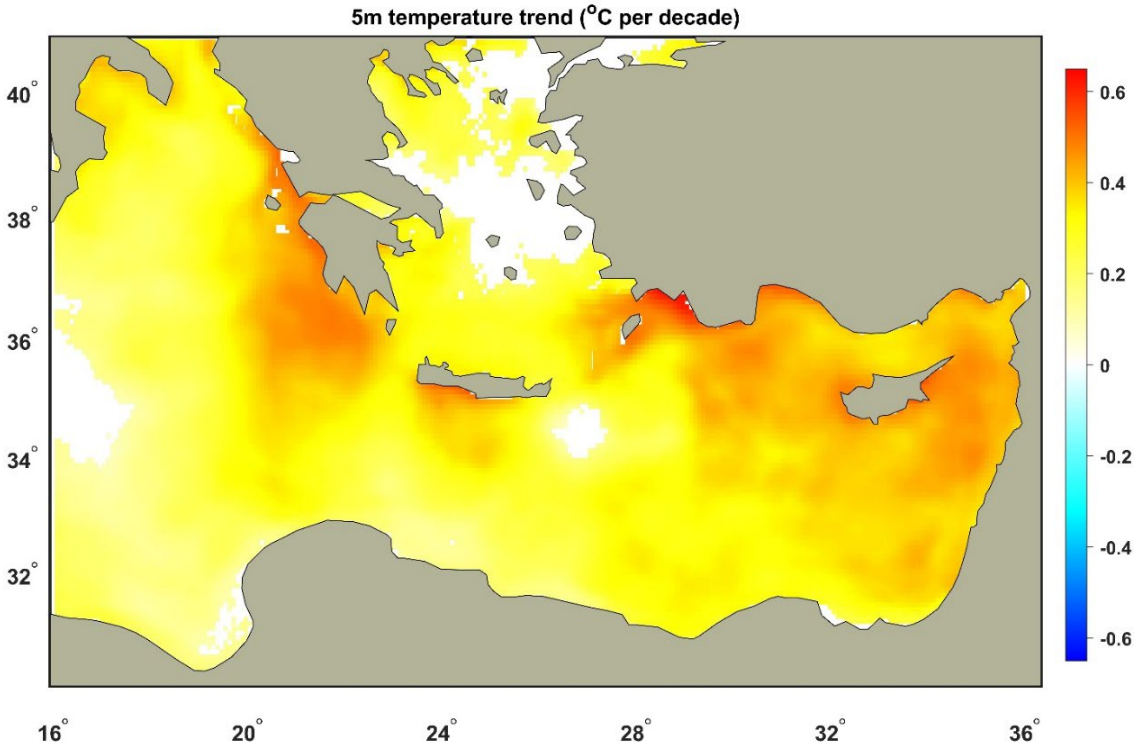
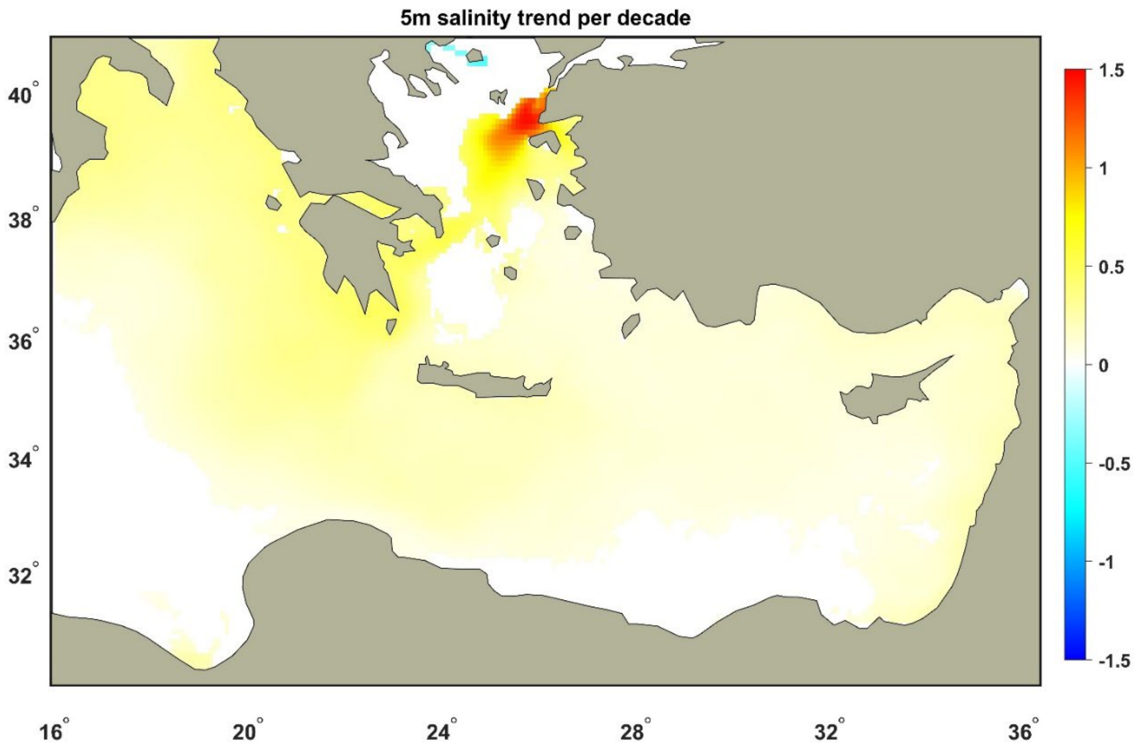


FIGURE 13. Salinity change rates in the EMED for the period 1993-2022 based on the Copernicus reanalysis at 5m. Only the statistically significant rates are shown



2.2.3 Red Sea

Several studies suggested an ongoing warming in the Red Sea with rates higher than those documented for the global ocean and higher over its north part compared to south. Candin et al. (2010) reported an increase in the SST over the entire basin between 0.4 and 1°C since the mid-1970s. Raitsos et al. (2011) showed that the Red Sea after the mid of 1990s experienced an intense warming with an abrupt increase of 0.7°C after 1994. Chaidez et al. (2017) for the period 1982–2015 estimated an overall rate of warming for the Red Sea of 0.17°C/decade noting that the northern part of the basin shows a considerably higher rate between 0.40 and 0.45°C/decade. Shaltout (2019) found a significant warming trend of around 0.3°C/decade between 1982 and 2016. Genevier et al. (2019) estimated a warming of 0.37°C/decade during 1985–2015 in the Northern Red Sea which decreases to 0.14°C/decade in the southern part of the basin. Likewise, Alawad et al. (2020) identified a non-uniform warming trend beginning around the mid-1990s over the whole basin, amplified over the northern half with a rate of 0.4°C/decade, which falls to 0.1°C/decade at the southern part of the basin. Bayoumy et al. (2021) for the period 1982–2019 estimated an average warming rate of 0.342°C/decade over the entire Red Sea. In addition, similar to the neighboring EMED, the frequency and the duration of the marine heat waves shows a positive trend (Chaidez et al., 2017; Genin et al., 2019, Genevier et al., 2019; Bayoumy et al., 2021).

As the Red Sea displays a north-south differentiation in its climatic and hydrographic regime, and the studies so far suggest a different warming behavior of the northern (NRS) and southern (SRS) basin, we present the temporal SST evolution for each basin adopting a separation line at the latitude of 21°. Figures 14 and 15 show the spatially averaged SST based on Hadley dataset for the period 1870-2022 along with the satellite-era Copernicus reanalysis for the period of the last 30 years (1993-2022) for the NRS and SRS. The warming trend of the NRS for the 153 years 1870-2022 is 0.06°C/decade. Again, due to the natural periodicity of approximately 70 years, we calculate the linear trend of the last natural cycle (red line in Figure 14) which is 0.14°C /decade, a value well above the long term one, but obviously lower than the values estimated by the satellite-era observations. Both trend values are significant at >95% confidence level following the Mann-Kendall trend test (Mann, 1945; Kendall, 1975). Correspondingly, the long-term rate for the SRS is 0.04°C/decade and the rate for the last 70 years is 0.06°C/decade, both lower compared to counterparts for the northern half of the Red Sea (Figure 15).

FIGURE 14. Evolution of spatially averaged annual SST for the Northern Red Sea spanning the period 1870-2022 based on the Hadley Center dataset (blue) with the long-term linear trend (black dashed line). The red line represents the linear trend for the last 70 years based on the same dataset. The green line displays the near surface (depth of 5m) sea temperature evolution for the period 1993-2022 based on the Copernicus dataset

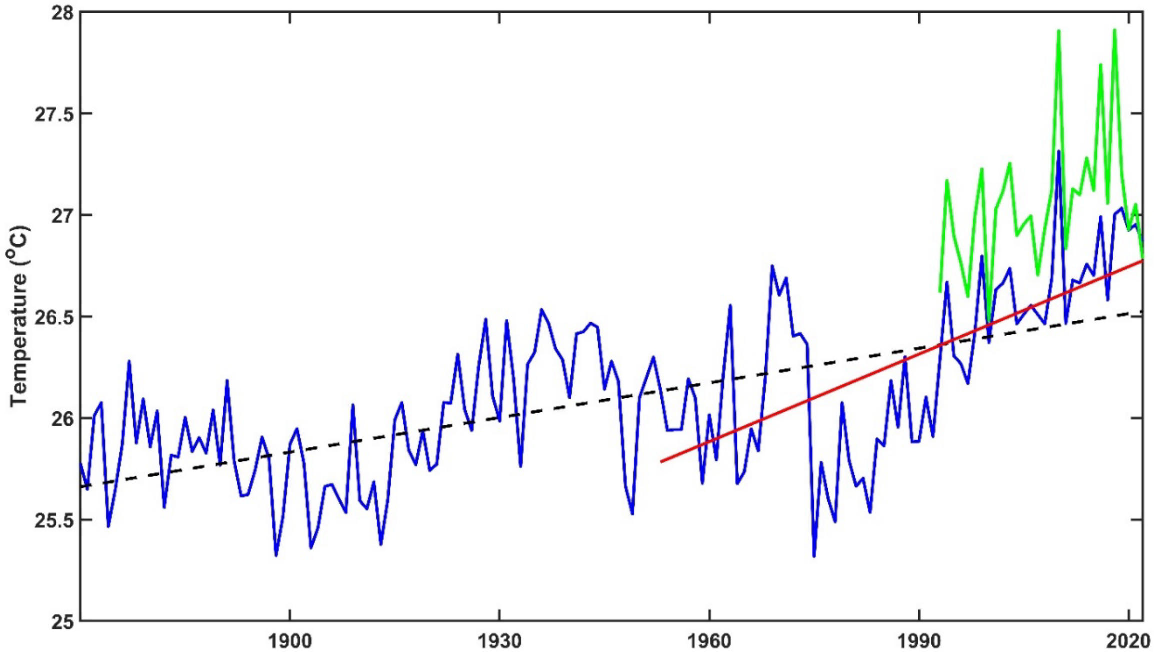
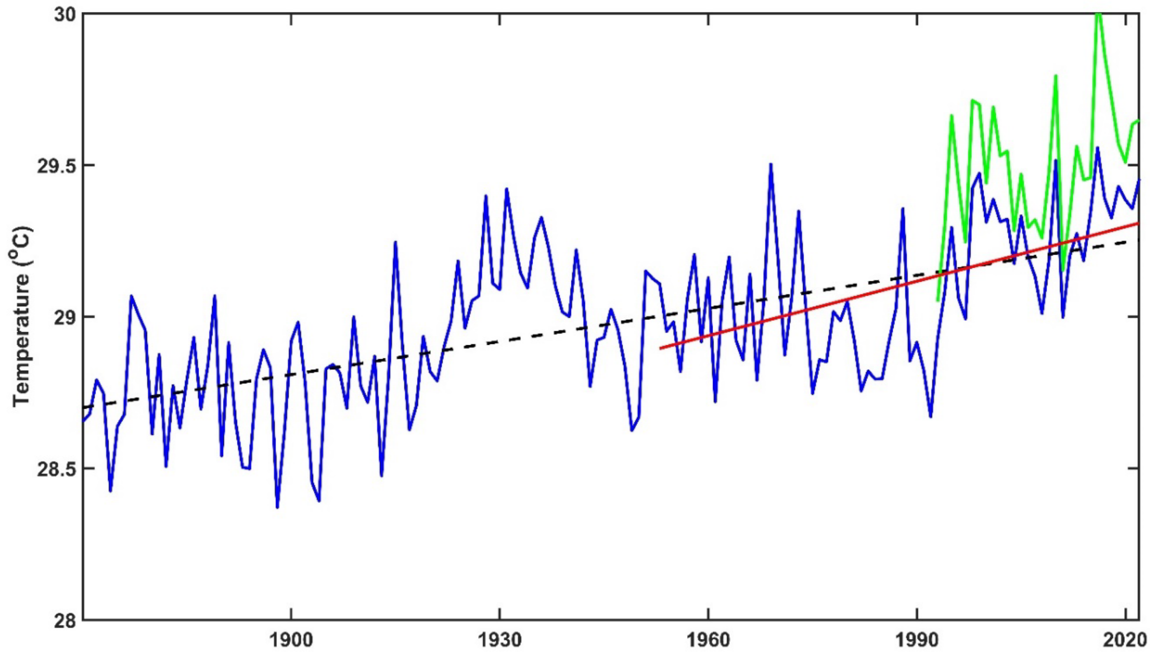
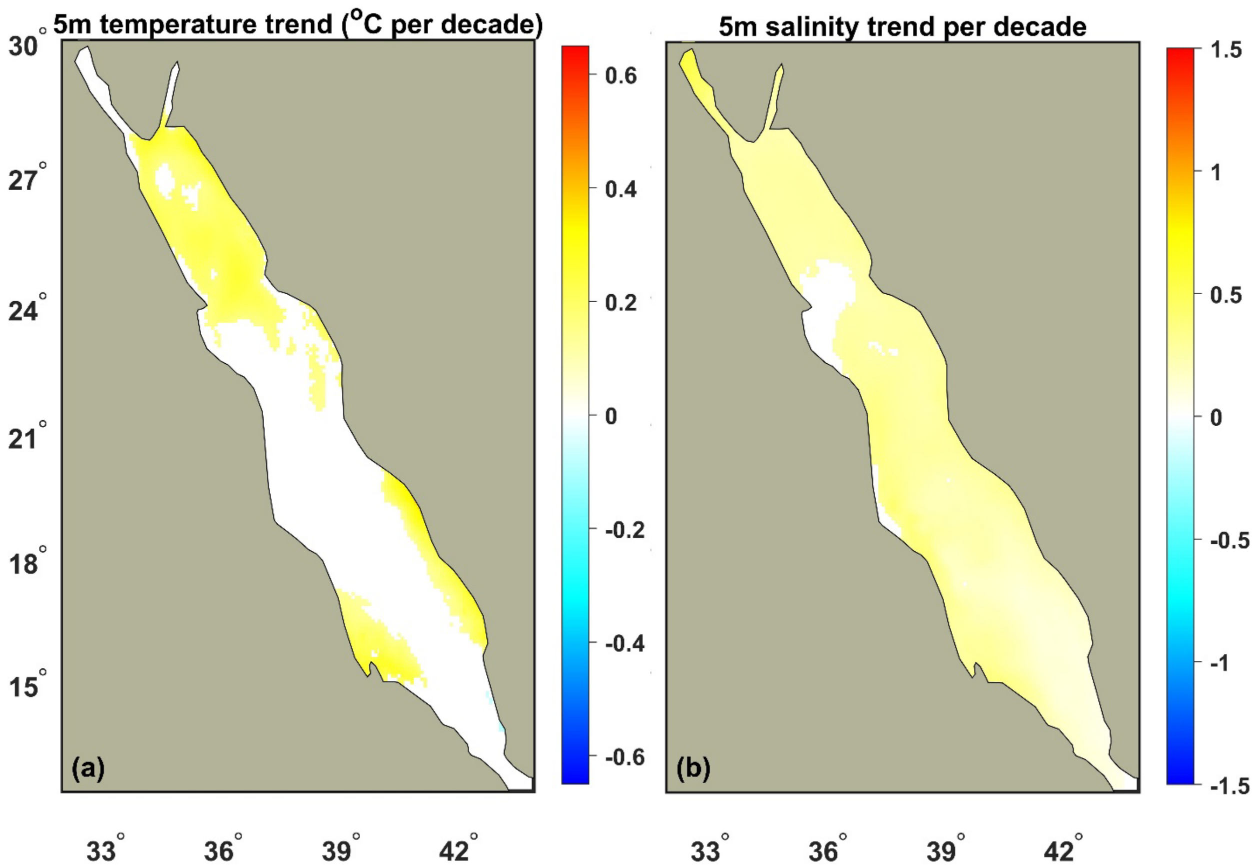


FIGURE 15. As in Figure 14, but for the Southern Red Sea



The spatial distribution of the warming rates in the Red Sea for the last 30 years is shown in Figure 16a. The more intense warming is found in the northern part of the basin and along the coastline in the southern part. Interestingly, a large area in the basin shows no significant trend, as well as a small narrow lane along the Arabian coastline in the southern Red Sea appears cooling rates. Based on the Copernicus dataset for the period 1993-2022 the warming rate of the water volume occupying the deeper layers (>800m) is 0.36°C/decade in the northern part and 0.61°C/decade in the southern part. Both rates are statistically significant at 95% according to the Mann-Kendall trend test, though the values seem to be apparently high and decline from the available observations. However, the available hydrographic datasets for the Red Sea are scarce and unevenly distributed in time, thus insufficient to provide accurate rates of warming and salinification.

FIGURE 16. Temperature (a) and salinity (b) change rates in the Red Sea for the period 1993-2022 based on the Copernicus reanalysis at 5m. Only the statistically significant rates are shown



Salinity trend at 5m is positive in both northern and southern parts of the basin as the Copernicus reanalysis suggests an increase of 0.27 and 0.21 /decade, respectively. The deeper layer (>800m) shows also positive salinity trends with values 0.12 /decade for the northern Red Sea and 0.21 /decade for the southern for the period 1993-2020. Figure 16b presents the spatial salinity trend in the Red Sea for the same period. The Gulf of Suez over the northern edge of the basin along with the nearshore areas of western part of the central and southern Red Sea exhibit the highest salination trend.

2.2.4 Arabian/Persian Gulf

A warming trend has also been reported for the Gulf by several studies. Al-Rashidi et al. (2009) using satellite and *in situ* observations estimated that its northern part exhibits a significant SST trend of 0.6°C /decade from 1982 to 2002. A similar rate of 0.57°C/decade has been observed for the period of 1950–2010 (Shirvani et al., 2015). Hereher (2020), from remotely sensed SST (MODIS) data for the period 2003–2018 reported a positive trend between 0.08°C to 0.7°C/decade from east to west, while Hamdeno et al. (2022) estimated an average SST warming trend of about 0.44°C/decade from 1982 to 2020. Vasou et al. (2024) showed that the Arabian Gulf exhibits an increasing trend of 0.2°C/decade based on their model results and 0.27°C/decade based on satellite derived SST for the period 1993-2021.

The temporal evolution of spatially averaged Hadley SST for the Gulf is presented in Figure 17. The overall trend for the period 1870-2022 is positive with a rate of 0.05°C/decade, whereas the trend for the last 70 years is 0.13°C/decade (red line in Figure 17), indicating an apparent rate increase with the time.

The spatial distribution of the warming rates in the Gulf for the last 30 years based on the Copernicus reanalysis is illustrated in Figure 18a. The more intense warming is found along the central line of the basin with the highest values over the northwestern edge. Based on the Copernicus dataset for the period 1993-2022 the warming rate of the water volume occupying the deeper layers (>30m) is 0.15°C/decade.

According to the Copernicus reanalysis, spatially averaged salinity trend at 5m is slightly negative, yet statistically insignificant (-0.02 /decade). Salinity trend in the deeper layers (>30m) is also negative with a statistically significant rate of -0.11 /decade. This negative trend of the salinity could be attributed to an increase in the volume of waters being exchanged with the Indian Ocean (Vasou et al., 2024). Figure 18b presents the spatial salinity trend in the Gulf for the 30 years 1993-2022. A large part of the Gulf shows no significant trend with the highest values in the north, negative in the northeastern and positive in the northwestern side.

FIGURE 17. Evolution of spatially averaged annual SST for the Arabian Gulf spanning the period 1870-2022 based on the Hadley Center dataset (blue) with the long-term linear trend (black dashed line). The red line represents the linear trend for the last 70 years based on the same dataset. The green line displays the near surface (depth of 5m) sea temperature evolution for the period 1993-2022 based on the Copernicus dataset

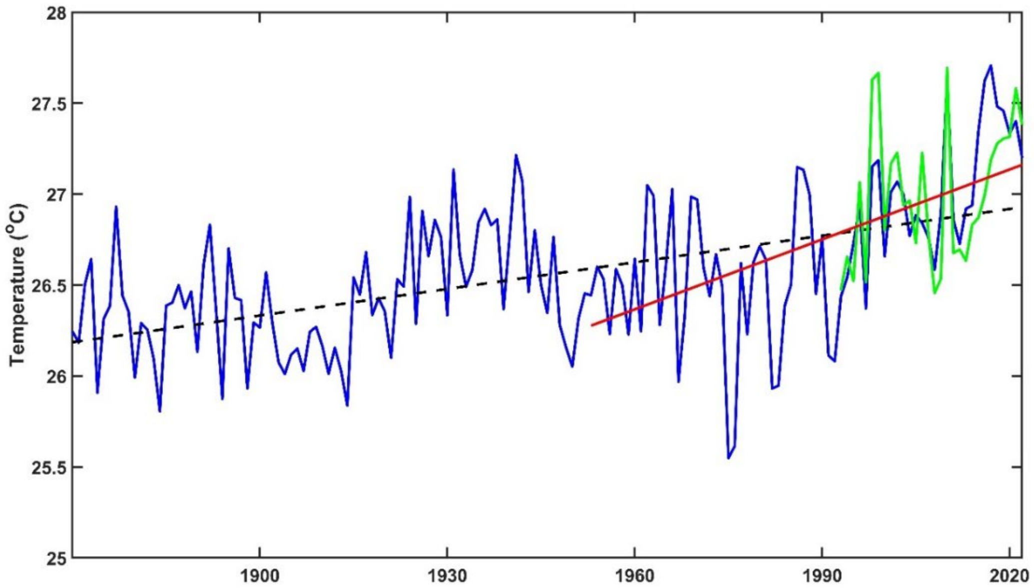
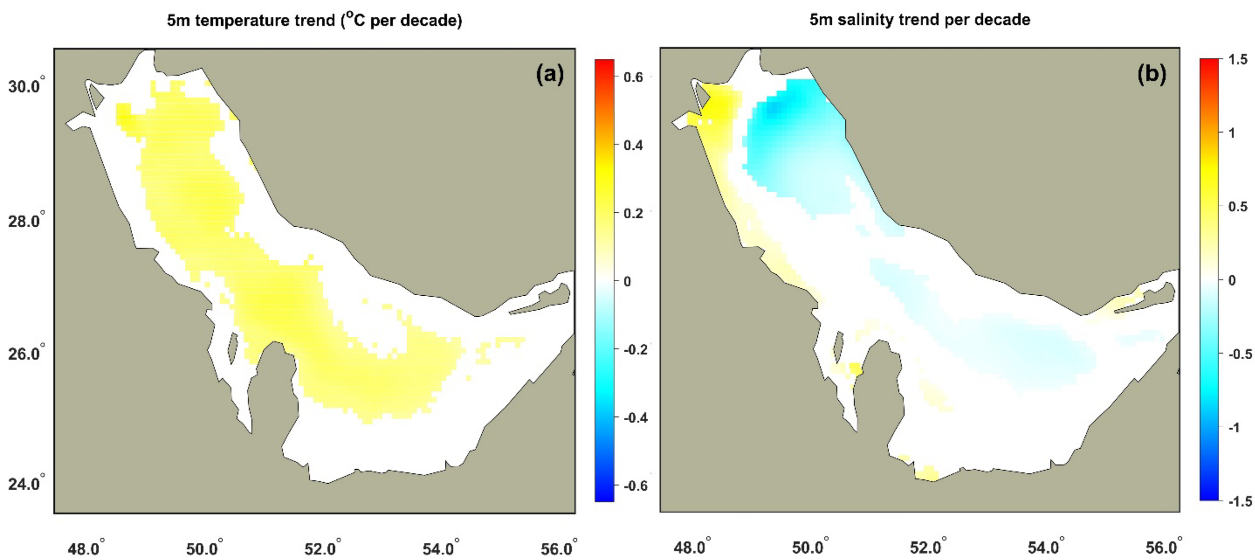


FIGURE 18. Temperature (a) and salinity (b) change rates in the Arabian Gulf for the period 1993-2022 based on the Copernicus reanalysis at 5m. Only the statistically significant rates are shown



2.2.5 Comparison of the three basins

Table 1 provides a synoptic picture for the trends of temperature and salinity in the three basins to facilitate a comparison of their behavior. The key points deduced by the comparison of their behavior are as follows:

- The long-term temporal evolution SST in the Eastern Mediterranean Sea, the Red Sea, and the Arabian Gulf is affected by the Atlantic Multidecadal Oscillation, a natural climate oscillation with a periodicity of approximate 70 years
- All three basins experience a long-term positive (warming) SST trend remarkably higher in the last 70 years of the AMO cycle, indicative of a recent warming acceleration
- Numerous studies analyzing satellite-era observations provide an exaggerated picture of warming as they ignore the AMO cycle effect on the three basins
- The warming trend seems to affect the whole water column in the three basins
- The Eastern Mediterranean and the Red Sea show a positive salinity trend while the Gulf appears a slight negative trend

TABLE 1. A synoptic comparison of the temperature and salinity trends estimated for the Eastern Mediterranean (EMED), the northern Red Sea (NRS), the southern Red Sea (SRS), and the Arabian Gulf. Deep layer represents depth >2500m for the EMED, >800m for the NRS and SRS, and >30m for the Gulf. White cells indicate statistically insignificant (at 95%) trend

Parameter / Basin	Long term 1870-2022 SST (°C/decade)	Last 70-year cycle SST 1953-2022	Deep layer Temperature 1993-2022	Salinity at 5m 1993-2022 (units/decade)	Deep layer salinity 1993-2022
EMED	0.05	0.14	0.02	0.16	0.02
NRS	0.06	0.14	0.36	0.27	0.12
SRS	0.04	0.06	0.61	0.21	0.21
GULF	0.05	0.13	0.15	-0.02	-0.11

2.3 Sea level changes in the EMME region

2.3.1 Background

Sea level is defined by the position of the sea surface relative to the coast, whilst sea level change is a measure of the relative shift in position of these two surfaces, which coincides with the vertical and horizontal displacement of the associated coastline. Sea-level change (SLC) is the integrated outcome of eustatic[1] (E), isostatic[2] (I), and tectonic[3] (T) components.

Medium-term (10^3–10^6 years) sea level changes are mainly caused by climate changes associated with the occurrence of glacial/interglacial periods. During these periods, the capture or release of water on the continents causes sea levels to fall or rise on the one hand and the continental crust to be charged or discharged on the other. This resulted in the isostatic adjustment of the continents, glacial-isostacy, and of the oceanic crust, hydro-isostacy (Clark et al., 1978).

For the Quaternary period, using a model of ice cover, ocean temperatures and the LR04 curve (Lisiecki and Raymo, 2005), sea level was calculated for the last 1 Ma (Bintanja et al., 2005) and despite a high degree of uncertainty, the gradual transition from 100 Ka cycles to 41 Ka cycles, in the interval 0.6 – 1.4 Ma before present, is adequately depicted.

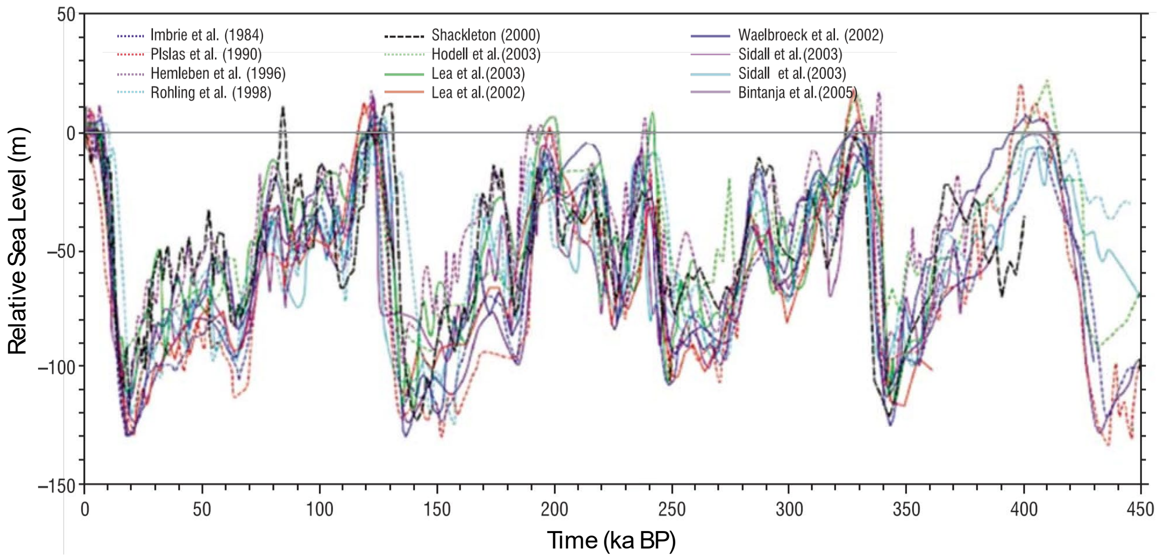
Figure 19 presents graphically the evolution of global sea level over the last 450 ka BP, where it is typically shown that during the glacial periods, sea level was between 80 m and >130 m lower than present-day levels, while during the interglacial periods, it had reached or exceeded present-day levels, but not by more than 20 m. During the previous interglacial period (120–125 ka BP), the sea level reached 4-9 m above the present level. At the end of the last glacial period (21 ka BP), the global mean sea level was about 130 m lower than today.

[1] The term eustacy includes all those processes that lead to a uniformly global change of sea level, which reflects a change in the quantity of water in the ocean (mostly to climate variability), or a change in the shape and capacity of the ocean basins (usually related to movements of lithospheric plates).

[2] The term isostasy refers in geology to the gravitational balance between the lithosphere and the underlying asthenosphere, with a typical example being the flotation of lithospheric plates at an altitude that depends on their thickness and dens.

[3] The term tectonism includes the action of the forces that cause the earth's crust to be deformed, producing continents, mountains, uplift or downlift etc.

FIGURE 19. Sea level change curves for the last 450 thousand years (from Caputo, 2007)



For short duration (10^{-1}–10^{3} years), the changes are due to briefer duration and lower intensity of climatic changes, which usually include anthropogenic interference, meteorological changes combined with changes in the wave regime, sea circulation, while tides contribute to the periodic change in sea level. Two are the main mechanisms of temporary sea level change: the astronomical tide and the meteorological tide. Tides are caused by the changing gravitational effects of the Moon and Sun as they change position relative to the rotating Earth. Meteorological tides are caused by short-duration meteorological phenomena, such as the sea or land breeze of coastal areas, differences in barometric pressure, mass accumulation due to wind drift, storm surges, and seiches.

Current and future sea level rise

Based on tide gauge measurements up to 1993 and satellite altimetry measurements, the recorded rate of rise in mean sea level for the period 1961–1993 is of the order of 1.8±0.5 mm/year, and for the decade 1993–2003, it is almost twice as high at 3.1±0.7 mm/year. These values are slightly higher than the rates of rise attributed to climate change (Table 2). These differences are partly attributed to the accuracy of instrumental measurements and homogenization of the records especially for the period before 1993, while there is considerable uncertainty in the measurements of thermal expansion, as measurements of thermal expansion are not available for the entire global ocean, just as there are different estimates in the measurement of ice cover shrinking. The dynamic relationships between the individual components and the role of river inputs and precipitation are also investigated, as the hydrological cycle is also expected to be affected by climate change.

TABLE 2. The climate components (in mm/year) of the rate of sea level change and the corresponding values from observations for the periods 1961-2003 and 1993-2003 based on the 2007 IPCC report (Bindoff et al., 2007)

	1961-2003	**1993-2003**
Thermal expansion	0.42±0.12	1.60±0.50
Glaciers and ice caps	0.50±0.18	0.77±0.22
Greenland ice sheet	0.05±0.12	0.21±0.07
Arctic ice sheet	0.14±0.41	0.21±0.35
Total climate components	***1.10±0.55***	***2.80±0.70***
Observed (instrumental)	***1.80±0.50***	***3.10±0.70***

The ongoing increase of atmospheric temperature since the middle of the 20th century is the consequence of human intervention in the physicochemical conditions of the atmosphere (mainly the increase of greenhouse gases such as water vapor, methane, carbon dioxide, etc.). According to the latest report AR6 of the Intergovernmental Panel on Climate Change (IPCC AR6; Legg, 2021), the rate of sea level rise has increased to more than 3 mm/year on a global scale, which is threefold higher than the mean (natural) rise of no more than 1 mm/year during the past 5-6,000 years. It is also worth mentioning that sea level rise (SLR) due to climate change (rise in atmospheric temperature) has caused both the melting of the permanent Arctic glaciers and the glacial Greenland covers, as well as the thermal expansion of the upper (up to 200 m deep) layer of the ocean.

According to the high-priority scenarios proposed in the most recent Intergovernmental Panel on Climate Change (Legg, 2021) report, the sea level rise (SLR) is expected to be between 0.17 m and 0.31 m for 2050, between 0.28 m and 1.01 m for 2100 and between 0.37 m and 1.88 m for 2150 (Table 3).

TABLE 3. Long-term projections of sea level rise (in m) for baseline gas emission scenarios (from Legg, 2021)

Scenario	2100 Best estimate (Possible range)	2150 Best estimate (Possible range)
SSP1a-1.9	0.42 (0.28–0.55)	0.62 (0.37–0.86)
SSP1b-2.6	0.47 (0.32–0.62)	0.73 (0.46–0.99)
SSP2- 4.5	0.60 (0.44–0.76)	1.00 (0.66–1.33)
SSP3- 7.0	0.73 (0.55–0.84)	1.10 (0.84–1.72)
SSP4- 8.5	0.82 (0.63–1.01)	1.43 (0.98–1.88)

2.3.2 Sea level rise during late Quaternary (21.000 year BP)

During the last interglacial period, which began at the end of the Pleistocene and continues to the present day, sea levels begin to rise in line with the temperature rise. This period of rise is characterized by three main phases (Figure 20): (i) phase 1, which coincides with the beginning of the (slow) rise of sea level from about 21 ka to 14.6 ka; (ii) phase 2, the rapid rise of sea level at a rate of about 1 cm/year, which ends before about 7 ka; and (iii) phase 3, the slow rise of sea level, with a rate of rise of about 1 mm/year. Phase 3, which has been continuing, due to global warming, since the mid-20th century, has a rate of >3 mm/year.

During the second phase of the rapid sea level rise, three episodes of increased meltwater pulse can be distinguished (Blanchon, 2017). The first at 14.3 ka BP, during which (lasting about 290 years) the sea level rose by 13.5 m (i.e., at a rate of ~4.7 cm/year). The second episode took place between 11.4 and 11.1 ka BP, during which (lasting about 160 years) the level rose by 7.5 m (i.e., at a rate of ~4.7 cm/year). Finally, in the third episode, which lasted about 140 years (8.2-7.6 ka), the level rose by 13.5 m (i.e., at a rate of ~9.5 cm/year).

The third phase (i.e., past 7±1 ka BP), climate variations are characterized by warmer and wetter periods and others relatively cooler and drier (Figure 21a), which were probably accompanied by sea-level changes, albeit of limited magnitude (<1 m). Research effort in this area is ongoing; one of the few available sea-level change curves over the last 8 ka is given in Figure 21b.

FIGURE 20. Sea level rise after the last glacial maximum (from https://commons.wikimedia.org/wiki/File:Post-Glacial_Sea_Level.png)

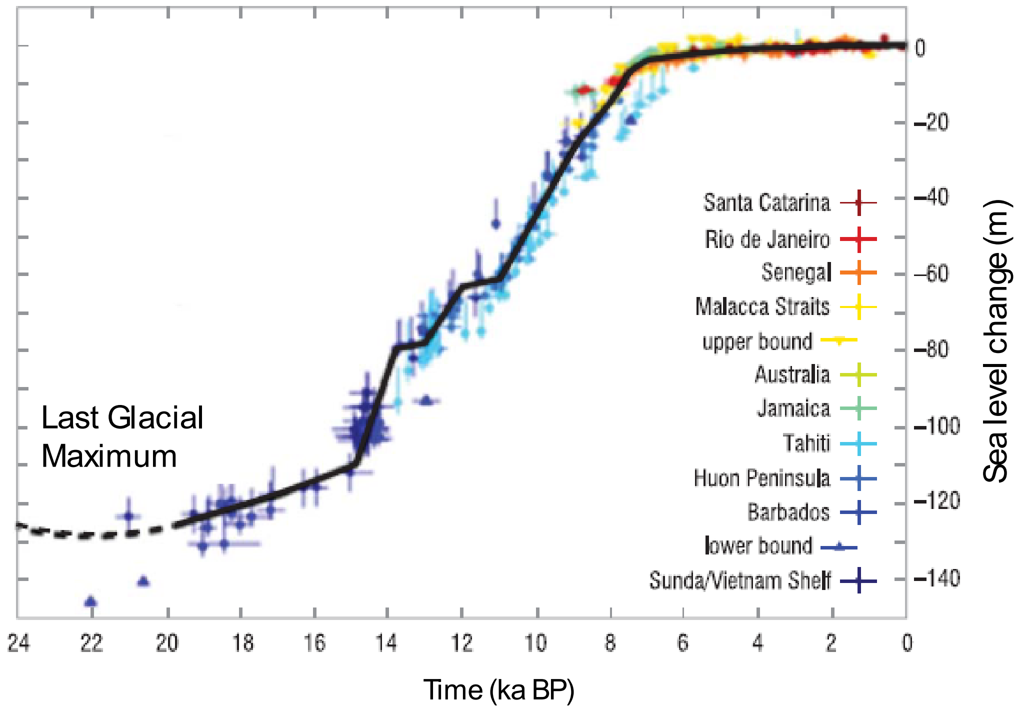
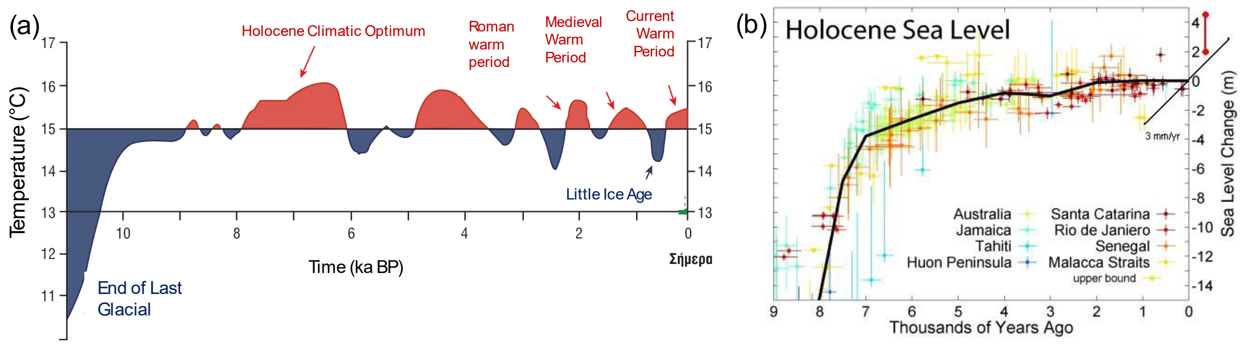


FIGURE 21. Climate changes (alternation of warm and cold periods) during the Holocene (from Daansgaard et al., 1985) and (b) Sea level change after the peak of the last glacial period (from Wright et al., 2020)

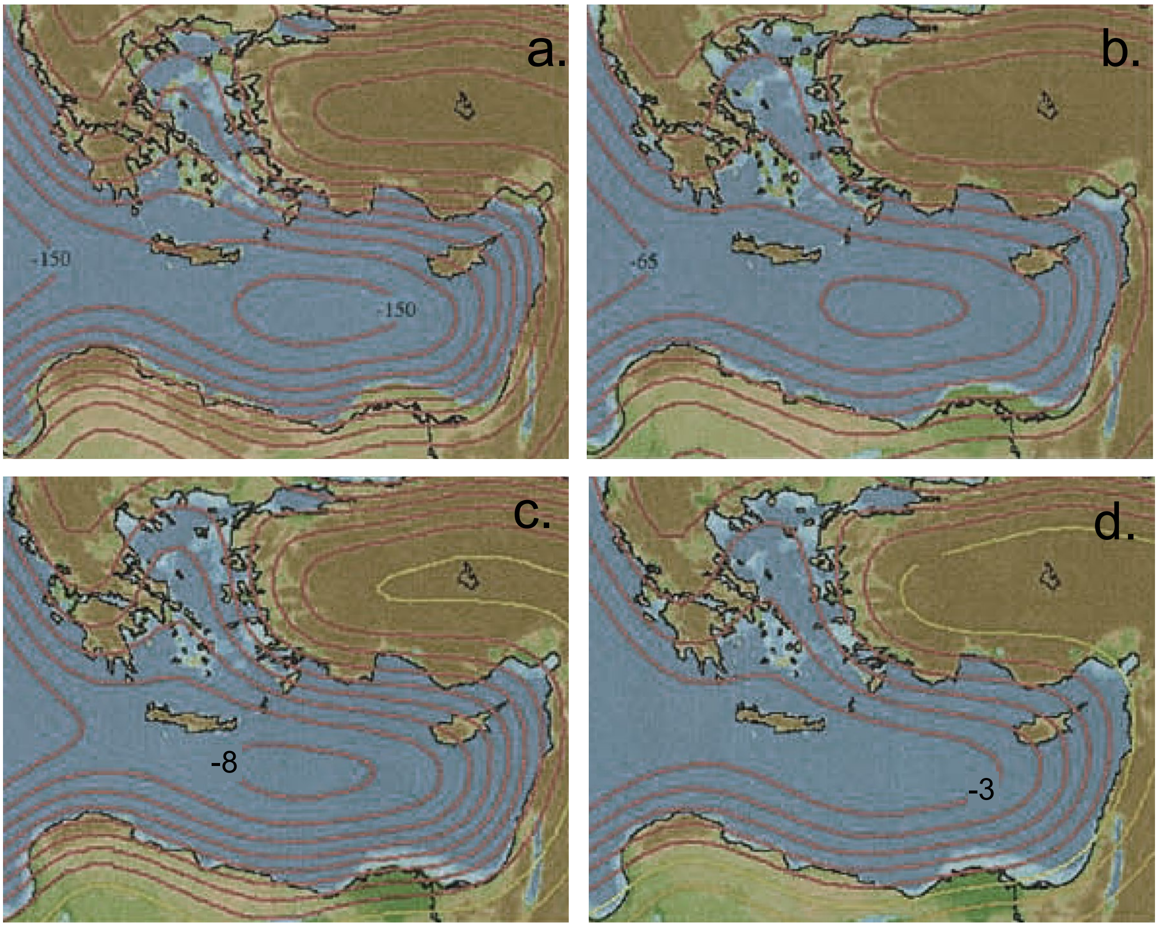


2.3.2.1 Eastern Mediterranean Sea (Levantine Basin)

The predicted sea water levels of the eastern Mediterranean from the glacio-hydro-isostatic model of Lambeck and Johnston (1998), Lambeck et al. (2003), Lambeck and Purcell (2005) are shown graphically in Figure 22. It must be noted that throughout the analysis, the tectonic contributions have been assumed to be either absent or corrected for; the latter refers to small uncertainties in Holocene sea-level inferences, of the order of 0.3–0.4 m at 12 ka BP or about 0.5–0.6 m at the Last Glacial Maximum (LGM; ca. 20 ka BP).

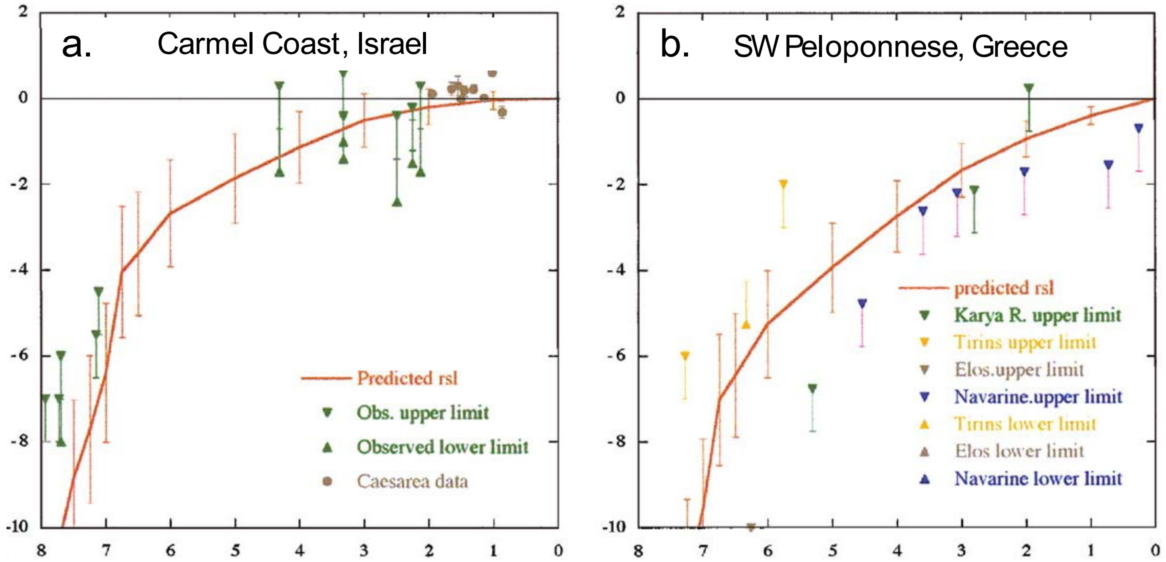
As shown in Figure 22, the central part of the Levantine basin was about 135 m below present sea level (bpsl) being reduced towards its periphery to about 110 m. In the early Holocene (10ka BP), sea level was 65 m bpsl at its central part reduced to about 50 m along its coastal margin. At the mid-Holocene (6 ka BP), sea level was offshore 8 m bpsl and 4 m along its coast. Finally, 2 ka BP sea level was as much as 3 m bpsl offshore and less than 1 m along its coast.

FIGURE 22. Estimated sea levels for the eastern Mediterranean basin for the periods (a) 20 ka, (b) 12 ka, (c) 6 ka and (d) 2 ka. The contour interval for the 20 ka, 10 ka years is 5 m, for the 6 ka period is 1 m and for the 2 ka period is 0.25 m (modified from Lambeck and Purcell, 2005)



It should be also mentioned that according to the same authors, there is a difference between the sea level curve of the SW Peloponnese coast and the Carmel Coast in Israel (Figure 23). For example, at 6, 4 and 2 ka BP sea-level was 2.75 m, 1 m, 0.5 m bpsl in Carmel coast when in SW Peloponnese was 5 m, 3 m, 1 m bpsl, correspondingly. This difference may be associated to different tectonism and isostatic contribution.

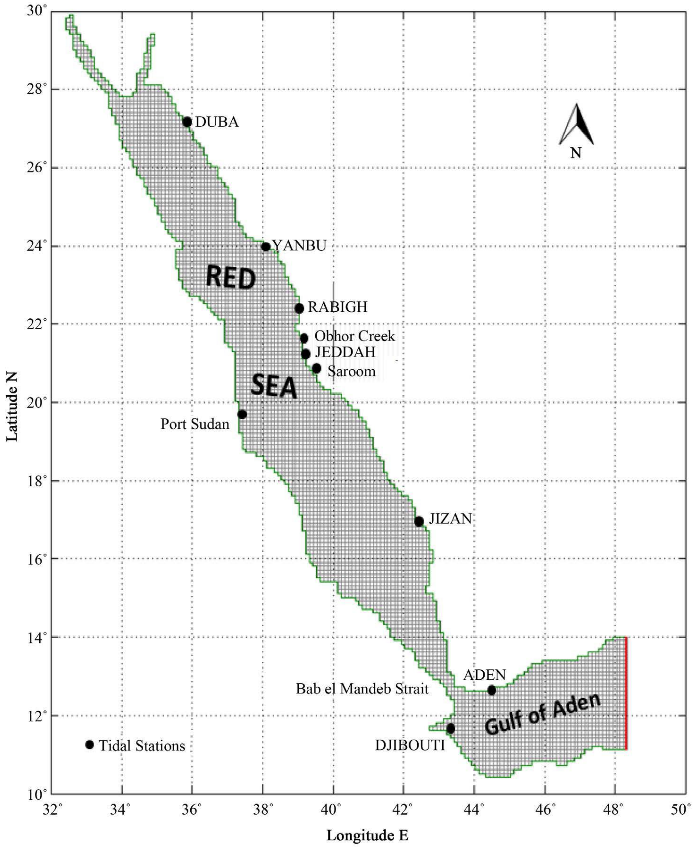
FIGURE 23. Sea level curve in Carmel Coast in Israel and the SW Peloponnese in Greece (from Lambeck and Purcell, 2005)



2.3.2.2 Red Sea

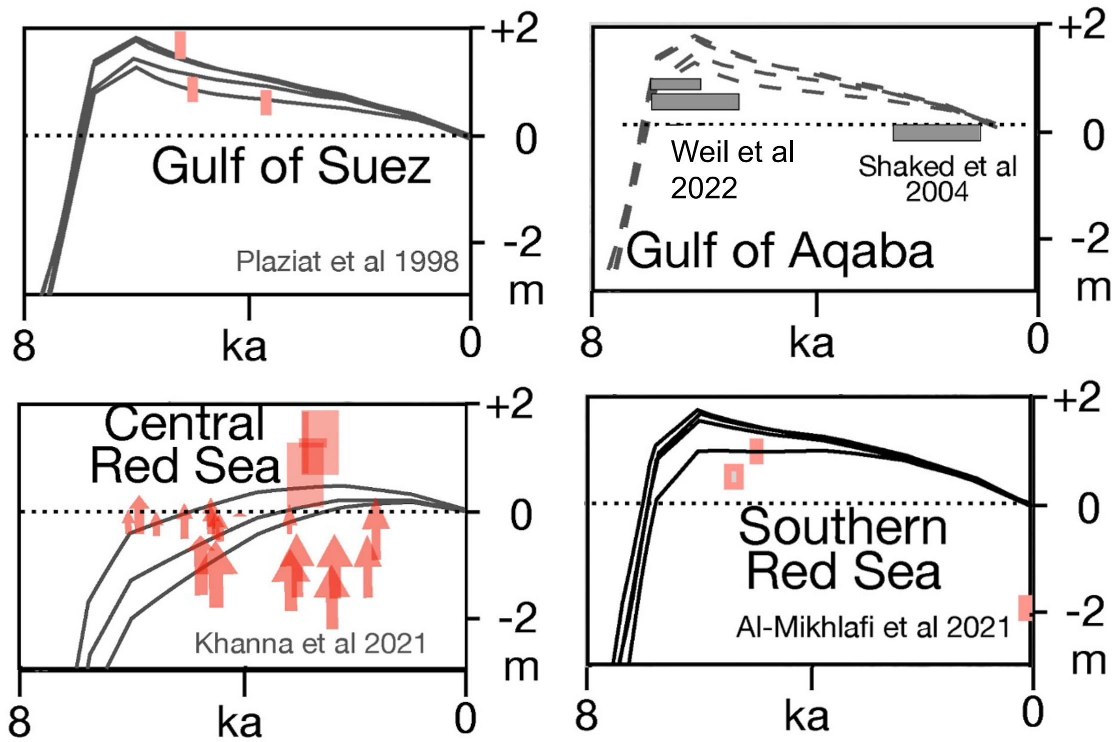
Sea level change in the Red Sea (Figure 24) presents different trends from north to south, due to tectonic uplift of the Arabian Peninsula.

FIGURE 24. Red Sea map (from Madah et al., 2015)



The northern part (i.e. the Gulf of Acaba) eustatic sea level signatures are overprinted by tectonic uplift due to its proximity to the Dead Sea Transform Fault. The central part of the Red Sea sea-level rise counterparts tectonic uplift (Khanna et al., 2021). Finally, at its southern part, eustatic signals overprinted by glacio-isostatic-adjacent (however, no influence of plate tectonics) (Al Mikhlafi et al., 2021). Therefore, the sea-level curve at the northern part of the Red Sea (i.e. the Gulf of Acaba) is that about 6.8 ka BP its level was 1-2 m above psl (Weil et al., 2022; Figure 25a). In the late Holocene (possibly after ca. 3.5 ka), sea level declined to its modern levels. The southern part exhibits the same trends (Figure 25c), while in its central part, sea-level rise did not exceed 0.5 m (Figure 25b). Furthermore, the glacio-hydro-isostatic model applied by Lambeck et al. (2021) presents an analogous picture of sea level rise along the western (Egyptian) coast, as shown in Figure 25d.

FIGURE 25. Holocene Red Sea Level curves for Gulf of Suez (after Piazat et al. 1998), Gulf of Aqaba (after Shaked et al. 2004; Weil et al. 2022), Central Red Sea (Khanna et al. 2021), and Southern Red Sea (after Al-Mihlafi et al., 2021)

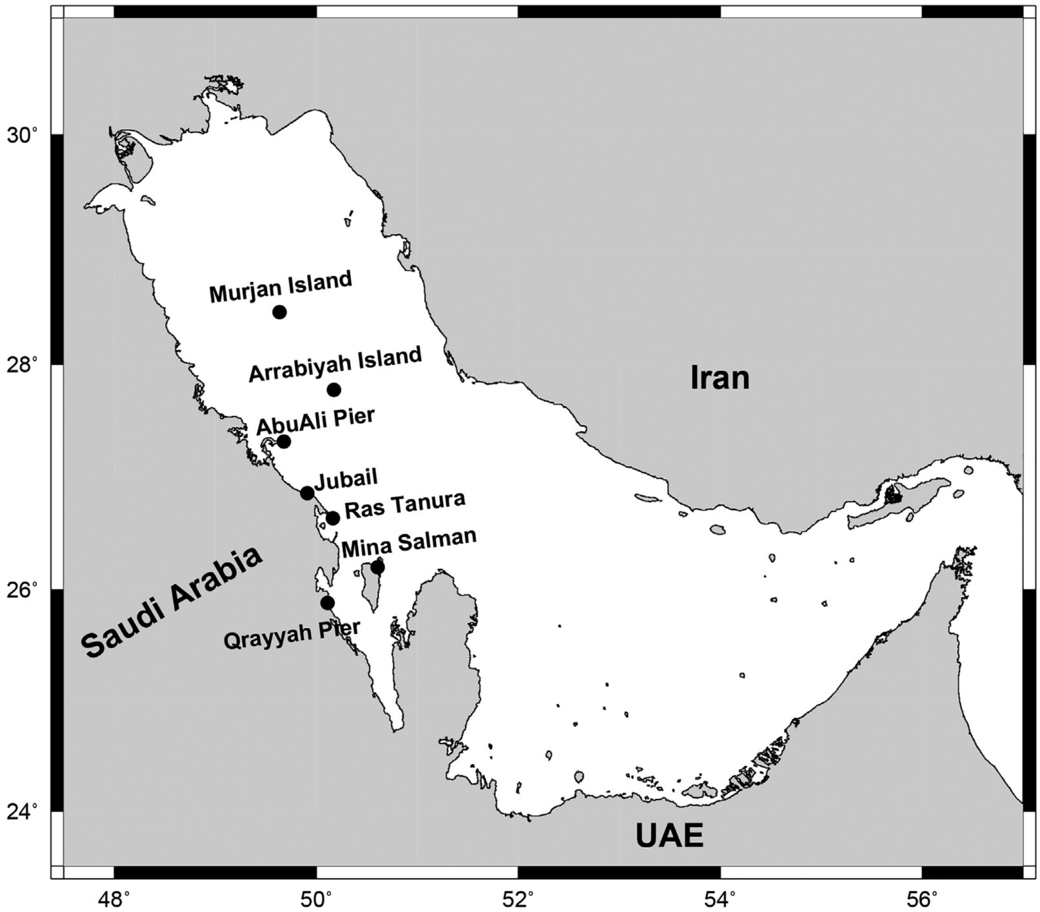


2.3.2.3 Arabian Gulf

Based on glacio-hydro-isostatic models (i.e. Lambeck, 1996) along with observations from radiocarbon dating of sea-level change of palaeo-shoreline, the Arabian (Persian) Gulf (Figure

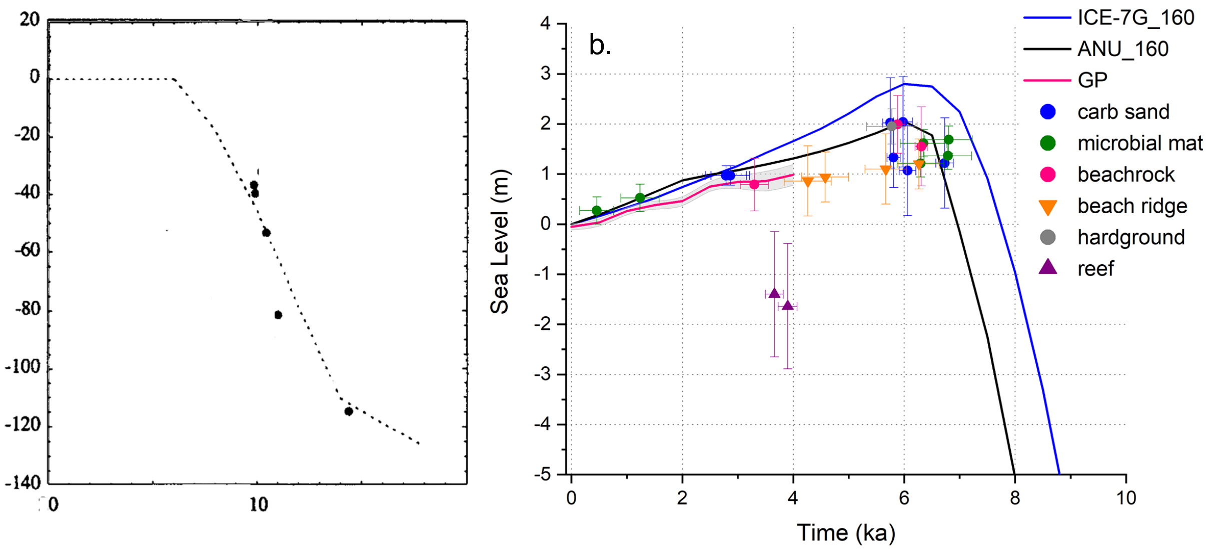
26) represents a terrestrial environment from the peak of the last glaciation (18-20 ka BP) up to 14 ka BP, when the Strait of Hormuz had opened. Marine influence at the central part of the Gulf commenced by ca. 12.5 ka BP, with the Gulf flooding phase taking place at about 11.3 ka and 10.5 Ka BP (Bailey et al., 2007).

FIGURE 26. A map of the Arabian Gulf (from Alsharhan and Kendall, 2003)



In Figure 27, sea-level curve in the Arab/Persian Gulf is shown, being the output of Lambeck's glacio-hydro-isostatic model. According to this model, from 14 ka up to 6 Ka BP a contestant and rather steady increase in sea level took place, with a rate of ca. 1.4 cm/y. Moreover, at 6 ka BP sea level rose 1-2 m above its present level. A recent work by Mauz et al. (2022) at the SW coast of the Gulf found a sea-level high-stand at 1.6 ± 0.4 m which lasted from ca. 6.7 ka to 6.0 ka BP. Note also that dating's of in-situ samples (i.e. Carb sand, Microbial mat, beach rock, beach ridge, hardground, and reef) between 6-6.5 ka show lower high-stand values, with most of them being in the order of 1 m ± 0,5 m. The trend of sea level rise during the past 6 ka is analogous to that referred to the Red Sea, reaching progressively (if not steadily) its present level.

FIGURE 27. Sea-level curves (a) sea level curve by Lambeck (1996) and (b) predicted by ICE-7 G (blue) and ANU (Black) glacio-hydro-isostatic models and by the Gaussian Process (GP) model (purple) compared to all proxy data (for details see Mauz et al., 2022)



2.3.3 Current trend of sea level change

2.3.3.1 Eastern Mediterranean

The Eastern Mediterranean coasts are dominated by mixed but mainly semi-diurnal tides. M2 is predominant in all locations compared to the other main harmonics (S2, K1, O1). The range of spring tides was calculated at around 30 cm in the west of the Levantine Sea, ca. 23 cm in Cyprus, and ca. 15 cm in Alexandria (Egypt) (Tsimplis et al., 1995). The largest tides occur on the Mediterranean (Levantine) coast of Turkey which is around 50-70 cm (Ozturk et al., 2023).

Meli et al. (2023) investigating trend variability in the Mediterranean Sea for the period 1993–2019, identified trends for the Levantine (2.6 ± 0.9 mm/yr) similar to those for the Aegean (3.1 ± 1.0 mm/yr) being consistent with Mohamed and Skliris (2022), who found an average rate of 3.23 ± 0.61 mm/yr for the eastern Mediterranean over the same period. In contrast, trends for Southern Crete (0.3 ± 1.3 mm/yr) are regarded in-significant (Fig. 28).

2.3.3.2 Red Sea

In general, tide ranges between 0.65 m in the north, near the mouth of the Gulf of Suez and 1 m in the south near the Gulf of Aden, but it fluctuates between 0.20 m and 0.30 m away from the nodal point. The central Red Sea (Jeddah area) is therefore almost tideless and as such, the annual water level changes are more significant.

The Red Sea experiences significant spatial and temporal differences in oceanographic and meteorological conditions. The southern Red Sea is experiencing seasonally reversing wind patterns, while the northern Red Sea is experiencing approximately unidirectional wind throughout the year, even though the intensity differs seasonally.

The trend of sea-level rise from 1993 to 2019 has a clear positive signal, in the order of 3.6-4.3 mm/year, which is consistent with the global rate of 3.3 ± 0.5 mm/year (Abdulla et al., 2021). This value increases by 5.8-6.9 mm/year for the post 2000 period (see Table 4). In Figure 29, the trend of sea level rise is presented graphically showing an overall trend of 3.88 mm/year that increases to 6.4 mm/year (for the period 2000–2019).

FIGURE 28. Annual sea level time series from altimetry (black solid line), steric (dashed yellow), thermosteric (dotted red), and halosteric (dash-dotted blue) components over different spatial scales for Southern Crete (left) and Levantine (right) (see top map). Vertical lines denote significant changepoint in the related component (same color and line style) at a specific time (from Meli et al., 2023)

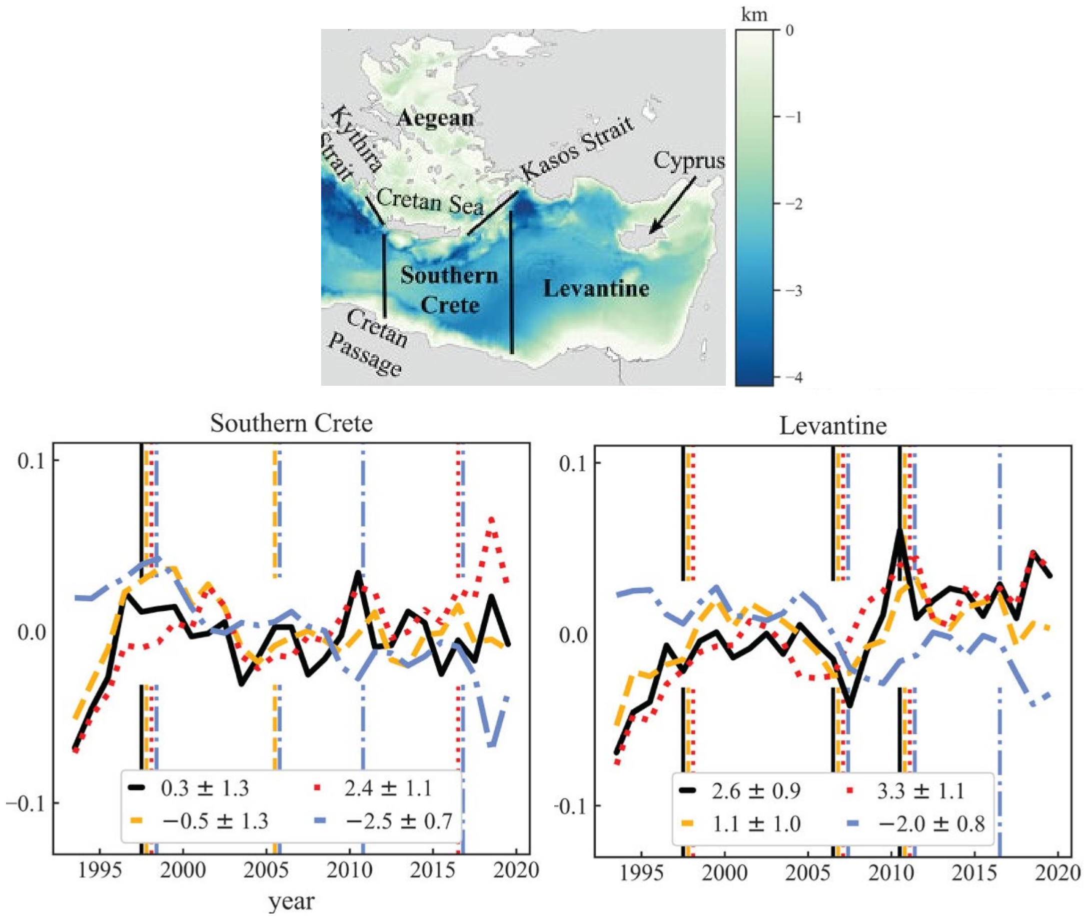
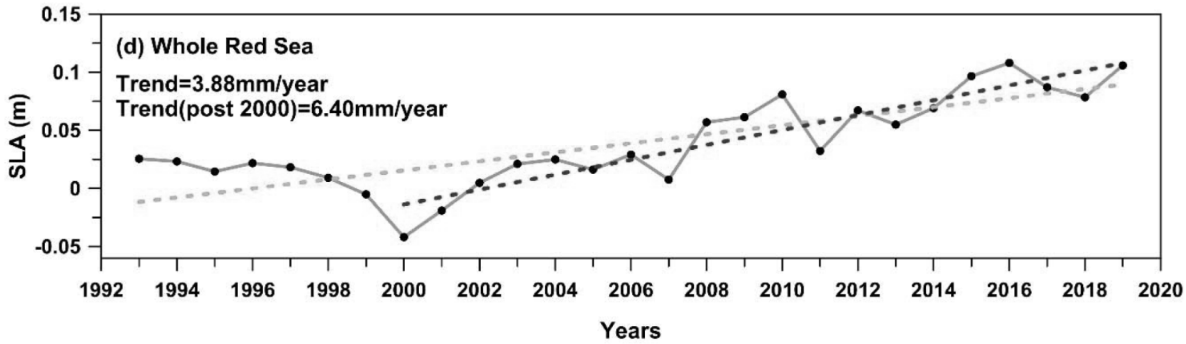


TABLE 4. Average trends of sea level rise in the Red Sea (from Abdulla et al., 2021)

	Northern	Central	Southern
Average trend (mm/year) for 1993–2019	4.22	3.81	3.68
Average Trend (mm/year) for 2000–2019	6.82	6.59	5.87

FIGURE 29. Graphical trend of sea level rise for the whole Red Sea and for the period 1993–2019 (from Abdulla et al., 2021)



The interannual fluctuations of sea level is related to the variability in the global climate modes, e.g., El Niño-Southern Oscillation (ENSO) events, the East Atlantic-West Russia (EAWR) oscillation, and the Indian Ocean Dipole (IOD) (Abdulla and Al-Subhi, 2021); the impact of the El Niño-Southern Oscillation mode on sea level is higher than other climate modes. The mean sea level in the Red Sea has a general trend of higher sea level towards the eastern side, which is consistent with previous studies (e.g. Abdulla and Subbi, 2020). The amplitude of average sea level oscillation in the Red Sea was found to be around 40 cm.

The annual mean sea level was shown to have a falling trend until 2000. Afterward, a continuous increase in sea level followed by some non-linearity. The observed interannual variability was consistent throughout the seasons, even though the amplitude of variability was less during summer. Apart from the seasonal and interannual variability, a multi-year (roughly 3–7 years) oscillation was observed in the sea level and SST, in connection with ENSO, EAWR, and IOD events.

2.3.3.3 Arabian Gulf

On the SW coast of the Arabian Gulf (Figure 26), diurnal and mixed tidal regimes dominate with tidal ranges of 1.0–1.5 m in protected zones (e.g., lagoons) and ~2.5 m on open coasts (Alsharhan and Kendall, 2003). The mean spring tide is 1.1 m and the mean neap tide is 0.75

m, modified by diurnal inequality and occasional strong winds. The same authors found that the harmonic constituents of tide show pure diurnal tide at Murjan Island, semidiurnal type at Mina Salman, and mixed type with semidiurnal dominance at the remaining five stations.

Moreover, Siddig et al. (2019) utilizing altimetry data spanning the period 1993–2018 estimated that the mean sea level trend for the Arabian Gulf was about 3.6 ± 0.4 mm/year, while for the global ocean was 2.8 ± 0.4 mm/year. They also showed that among the seven tide gauge stations (Table 5), the highest sea-level trend is found at Mina Salman (3.4 ± 0.98 mm/year), which agrees with the local estimate from the Multi-Missions Satellite Altimetry data. The minimum trend is found at Jubail (1.6 ± 0.71 mm/year) and Ras Tanura (0.7 ± 0.31 mm/year). At Arrabiyah Island station, the sea-level trend is about 2.4 ± 0.66 mm/year, which is obtained after removing the interruptions from a relatively longer duration (15 years) data. This agrees with other stations and the estimates from the altimetry. Table 5 lists all the trends estimated in this study as well as in the previous studies for an inter-comparison of values, however, the data duration may vary among the studies (for locations, see Figure 26).

TABLE 5. Sea-level trends of the Arabian Gulf

Stations	**Period**	**Estimated trend (mm/year**
Murjan Island	1986–2008	2.4 ± 0.94
Arrabiyah Island	1990–2000	2.4 ± 0.66
AbuAli Pier	2000–2008	3.1 ± 0.70
Jubail	1980–2008	1.6± 0.71
Ras Tanura	1980–2008	0.7 ± 0.31
Qurrayyah Pier	1980–2000	2.2± 0.84
Mina Salman	1979–2007	3.4± 0.98

2.3.4 Future estimates of sea level change

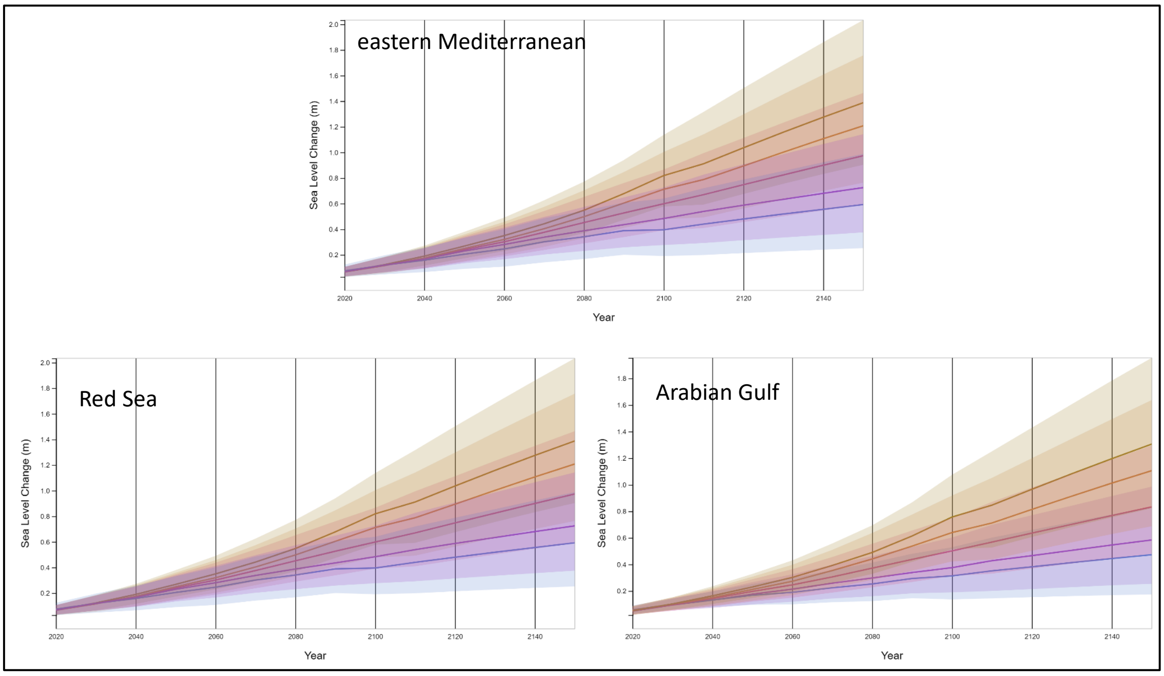
According to IPCC 6th Assessment Report Sea Level Projections (REF) and using the Sea level projection tool provided by NASA (https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool), the median projections of sea level rise for the eastern Mediterranean, the Red Sea, and the Arabian Gulf, relative to the 1995–2014 baseline, are presented for the year 2100 in Table 6 and presented graphically in Figure 30. Note that in the sea level projections, likely ranges are based on the combination of the uncertainty in the temperature changes associated with the emissions scenarios and the uncertainty in the relationships between temperature and drivers of projected sea level change, such as thermal expansion, ocean dynamics, and glacier and ice sheet mass loss. In general, 17th-83rd percentile results are interpreted as likely ranges, reflecting the use of the term likely to refer to a probability of at least 66%.

TABLE 6. Average estimates of sea level rise (in m) for the year 2100 from the 1995–2014 baseline

	Eastern MED	Red Sea	Arabian Gulf
SSP1-1.9	0.40	0.36	0.31
SSP2-2.6	0.47	0.42	0.37
SSP3-4.5	0.60	0.54	0.50
SSP4-7.0	0.74	0.67	0.64
SSP5-8.5	0.82	0.77	0.76

The three marine regions under investigation present similar trends of SLR between 2020 and 2150 (Figure 30), having differences of no more than 5 cm for each SSP scenario. In general, and for the year 2100, sea level change is expected to increase from a mean value of ca. 0.4 m for SSP1-1.9, up to 0.8 m for SSP5-8.5.

FIGURE 30. Sea level change for the five SSP scenarios according to IPCC AR6 until 2015. Projections are relative to a 1995–2014 baseline. Plots derived from NASA Sea Level Projection Tool (https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool)



2.4 Ocean carbon cycle and ocean acidification in the Middle East

2.4.1 Ocean carbon cycle: biological and solubility aspects

The ocean carbon cycle is one of the critical natural cycles. Its interaction with the atmospheric carbon dioxide (CO_2) makes it of fundamental importance to the Earth's climate. The atmospheric and oceanic carbon reservoirs are naturally and regularly connected through air-sea exchanges of CO_2. The transfer of carbon between the atmosphere, the ocean surface mixed layer, the ocean interior and ocean sediments involves several transport processes termed collectively as the "ocean carbon pumps" (DeVries, 2022). These latter comprise the "solubility" and "biological"pumps (e.g. Bates, 2018).

The exchange of CO_2 between the atmosphere and the ocean is defined as the "solubility pump" that is controlled through physical processes such as heat flux, advection and diffusion, and ocean circulation. This transfer of atmospheric CO_2 to the deep ocean is controlled by circulation patterns of the surface ocean (wind-driven circulation) and the deep ocean (thermohaline circulation; e.g. Sarmiento and Gruber, 2006).

The biological carbon pump is a combination of the soft-tissue pump also known as "organic carbon pump" and the carbonate pump known as "carbonate counter-pump" (Neukermans et al., 2023). As explained in Salter et al. (2014), the organic carbon pump is the downward flux of particulate organic carbon (POC) from the surface to the deep ocean (Volk and Hoffert, 1985). The fraction of settling POC, that is not remineralized in the winter mixed layer, sinks to depth driving a reduction in surface ocean partial pressure of carbon dioxide (pCO_2) that is compensated by oceanic uptake of atmospheric CO_2 (Sigman and Boyle, 2000). Counteracting the organic carbon pump in terms of its influence on air–sea CO_2 exchange is the carbonate counter pump (Heinze et al., 1991). The precipitation of calcium carbonate ($CaCO_3$) shells by mainly coccolithophores, foraminifera (both calcite) and pteropods (aragonite), and the resulting particulate inorganic carbon (PIC) flux from the surface ocean, causes an increase in surface ocean pCO_2 (Frankingnoulle et al., 1994). Moreover, these pumps have opposing effects on the surface carbon cycle by modifying dissolved inorganic carbon (DIC) and total alkalinity (TA) differently (e.g. Zeebe and Wolf-Gladrow, 2001; Sarmiento and Gruber, 2006; Hain et al., 2014). Organic matter production results in CO_2 uptake and a basification of the surface ocean. In contrast, the production of $CaCO_3$ causes a release of CO_2 and an acidification of the surface ocean (Planchat et al., 2024). Finally, the behavior of the sea surface as a CO_2 source or sink to the atmosphere is the consequence of the interplay of the two pumps (solubility and biological) affecting the air–sea exchange of CO_2 (Gruber et al., 2009).

The chemistry of carbon dioxide in seawater gives rise to a rather complex chemical system, often referred to as the seawater CO_2-carbonate system, having as chemical basis the hydration reaction of CO_2 to form carbonic acid (H_2CO_3) and subsequent dissociation chemical reactions (Eq. 1):

$$CO_{2\,gas} \leftrightarrow CO_{2\,aq} + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ + CO_3^{2-} \qquad (1)$$

Although carbon is exchanged between the atmosphere and ocean in the form of CO_2, most carbon dioxide is transferred into bicarbonate (HCO_3^-), and carbonate (CO_3^{2-}) ions within the ocean. In the narrow pH range of seawater (approximately 7.8 to 8.2), most inorganic carbon is found in the form of HCO_3^- (90%) and CO_3^{2-} (~9%), and only a small remainder, up to 1%, as dissolved CO_2/H_2CO_3. The transfer of carbon dioxide into bicarbonate and carbonate ions then leads to the ocean holding 50 times as much carbon as the overlying atmosphere (e.g. Williams and Follows, 2011). These reactions (Eq. 1) provide a chemical buffer, maintain the pH variation of the ocean within a small range, and constrain the amount of atmospheric CO_2 that can be taken up by the ocean (e.g. Zeebe and Wolf-Gladrow, 2001; Dickson et al., 2007; Bates, 2018). Starting from an equilibrium state, any increase of atmospheric CO_2 leads to the invasion of CO_2 into the ocean. As atmospheric CO_2 is steadily increased by the anthropogenic emissions, the equilibration of the air and sea increases the amount of CO_2 in the ocean, thereby mitigating climate change, but causing fundamental shifts in the seawater CO_2-carbonate system commonly referred to as "ocean acidification" (OA). OA is attributed to the series of chemical reactions of Eq. 1, that ultimately result in a reduction of seawater pH and CO_3^{2-} concentrations and an increase in dissolved CO_2 and bicarbonate ions (Gattuso and Hansson, 2011; Wolf-Gladrow and Rost, 2014).

The chemical characterization of the seawater CO_2-carbonate system is achieved through the knowledge of acid-base equilibrium and kinetics, and of two of its four commonly measurable parameters: **(1)** dissolved inorganic carbon (DIC); **(2)** total alkalinity (TA); **(3)** pH (i.e., the negative logarithm of the H^+ concentration, pH = $-\log_{10}[H^+]$) and, **(4)** partial pressure or fugacity of CO_2 (i.e. pCO_2 or fCO_2), in addition to other essential parameters such as temperature, salinity, pressure and nutrient concentrations (e.g. Lewis and Wallace, 1998). The concept of pH is commonly known; however it complicates in seawater (e.g. Dickson, 1984) due to the existence of different pH scales to define it in the marine environment. At present, the most recommended is the so-called total hydrogen ion concentration scale (e.g. Dickson et al., 2007; Riebesell et al., 2011), (Eq. 2):

$$pH_T = log\ ([H^+]_F + [HSO_4{}^-] = -log\ [H^+]_T \qquad (2)$$

DIC is equivalent to the sum of concentrations of all the CO_2 species in seawater (Eq. 3):

$$DIC = [HCO_3^-] + [CO_3^{2-}] + [CO_2] \qquad (3)$$

The TA is defined as the capacity of seawater to accept protons and is a measure of the bases that are present, consisting mainly of HCO_3^- and CO_3^{2-} plus several minor constituents. According to Dickson (1981), the equation of TA (Eq. 4) is:

$$TA = [HCO_3^-] + 2[CO_3^{2-}] + [B(OH)_4^-] + [OH^-] + [HPO_4^{2-}] + 2[PO_4^{3-}] + \\ + [SiO(OH)_3^-] + [HS^-] + 2[S_2^-] + [NH_3] - [H^+] - [HSO_4^-] - [HF^-] \qquad (4)$$

For simplicity, Eq. 4 is written as follows (Eq. 5):

$$TA = [HCO_3^-] + 2[CO_3^{2-}] + [B(OH)_4^-] + [OH^-] - [H^+] \\ \pm\ minor\ constituents \qquad (5)$$

The pCO_2 or fCO_2 of seawater measures the contribution of CO_2 to the total gas pressure. Of the four measurable parameters, pCO_2 or fCO_2 and pH are highly influenced by temperature and pressure changes in the ocean, while DIC and TA are independent of such environmental changes (e.g. Zeebe and Wolf-Gladrow, 2001; Dickson et al., 2007).

The formation and dissolution of calcite and aragonite (Eq. 6), the polymorphic mineral forms of $CaCO_3$, also affect the ocean CO_2 system.

$$Ca^{2+} + CO_3^{2-} \leftrightarrow CaCO_3 \qquad (6)$$

The solubility product, K_{sp}, of aragonite is lower than that of calcite, i.e., aragonite shells and skeletons (pteropods, corals) are more soluble than those containing calcite (coccolithophorids, foraminifera). The carbonate saturation state, Ω (Eq. 7), indicates the seawater saturation of calcite or aragonite.

$$\Omega = \frac{[Ca^{2+}]_{sw}\,[{CO_3}^{2-}]_{sw}}{K_{sp}} \qquad (7)$$

If the product of the concentrations of calcium and carbonate ions in seawater is higher than the solubility product, the Ω value is higher than 1 indicating a supersaturation state, i.e. favourable conditions for the calcification process. In contrast, values of Ω lower than 1 denote an undersaturation state and thus, corrosive conditions for calcifiers (e.g. Doney et al., 2020). However, the amount of CO_2 the ocean is able to absorb and accumulate is limited (Revelle and Suess, 1957). The fractional change in [CO_2] over the fractional change in DIC has since been referred to as the Revelle factor, or R (Broecker et al., 1979):

$$R = \frac{\partial ln[CO_2]}{\partial lnDIC} \qquad (8)$$

where the partial differentials indicate that other state variables such as total alkalinity are kept constant as DIC changes (pCO_2 and [CO_2] being proportional to each other, the Revelle factor can be defined equivalently as $R = \partial \ln pCO_2 / \partial \ln DIC$). As formulated, the Revelle factor quantifies the ocean's sensitivity to an increase in atmospheric CO and its formula has been revisited by Egleston et al. (2010) to improve the quantification of ocean chemistry’s response to changes in DIC and TA.

2.4.2 The carbonate system in the Eastern Mediterranean and the Middle East seas

2.4.2.1 Eastern Mediterranean Sea

The Ionian, Aegean and Levantine sub-basins of the Eastern Mediterranean Sea have particular characteristics concerning the CO_2-carbonate system variables, reflecting the existing differences in geographical position, basin morphology, bottom topography, riverine discharges, the interplay between the “solubility” and “biological” pumps and, especially, the prevailing hydrographic conditions and water masses presence.

In the Mediterranean Sea, the surface TA increases in the eastward direction (Schneider et al., 2007; Rivaro et al., 2010; Touratier and Goyet, 2011; Álvarez et al., 2014; Hassoun et al., 2015; Gemayel et al., 2015), following the salinity gradual increase due to evaporation processes. Freshwater inputs from rivers' draining catchments with carbonate minerals in rocks and recent sediments, as well as the brackish waters of Black Sea origin inflowing through the Dardanelles Strait, also contribute to increasing TA (Copin-Montégut, 1993), especially in the Aegean sub-basin where TA and salinity are negatively correlated (Cossarini et al., 2015; Krasakopoulou et al., 2017). The strong evaporation due to high temperatures occurring in summer induces an increase in TA concentrations with the summer–wintertime difference of TA presenting high values in both the Ionian and Levantine sub-basins (Schneider et al., 2007; Gemayel et al., 2015).

Characterized by extremely oligotrophic conditions and poor vertical mixing, the Eastern Mediterranean Sea has a DIC range that is quite narrow (~20 μmol kg^{-1}) compared to the Western Mediterranean Sea where winter mixing, primary production, and remineralization processes are more intense, causing greater fluctuations (Gemayel et al., 2015).

The variability of both TA and DIC in the Eastern Mediterranean Sea is triggered by seasonal cycles of summer concentrations due to evaporation and winter vertical mixing. The locations of the Eastern Mediterranean Sea where intermediate and deep-water masses are formed during winter, i.e. the NW Levantine and the Aegean Sea (e.g. Fach et al., 2023 and references therein; Durrieu de Madron et al., 2005) consist of areas where large influxes of CO_2 occur (Krasakopoulou et al., 2009; 2017).

In the intermediate layer of the Levantine sub-basin, both DIC and TA have lower concentrations than in the Aegean and Ionian sub-basins (Table 1), while in general, the TA in the three sub-basins follows the salinity pattern (Álvarez et al., 2014). Deviations from this pattern appear in upper water column at the northern part of the Aegean sub-basin where enhanced concentrations of both DIC and TA occur, reaching 2428 and 2827 μmol kg^{-1} respectively, revealing the major influence of riverine and Black Sea Waters on the carbonate system of the area (Krasakopoulou et al., 2017).

The saturation degree for both calcite and aragonite is well above 1, with the mean values of ΩCa and ΩAr in the different depth layers (0-150, 150-500, 500-2500, >2500 dbars; Table 7) varying between 2.9 and 5.6 and 2.0 and 3.7, respectively. The highest ΩCa and ΩAr values were observed in the surface layer coinciding with high pH_T values.

TABLE 7. Mean values and standard deviation for temperature, salinity and CO2 species at various depth layers in the different Eastern Mediterranean sub-basins as sampled in May 2013. Surface: 0-150 dbars,, intermediate: 150-500 dbars), deep: 500-2500 dbars and bottom: > 2500 dbars. Ar stands for aragonite and Ca for calcite. (Hassoun et al., 2015)

	T (ºC)	S	TA µmol kg^{-1}	DIC µmol kg^{-1}	pH	ΩCa	ΩAr
Surface (0-150m)							
Ionian Sub-basin (n = 23)	16±2	38.6±0.4	2591±46	2275±42	8.090±0.023	5.26±0.25	3.4±0.17
Aegean Sub-basin (n = 8)	17±1	39.07±0.02	2614±6	2273±10	8.112±0.017	5.65±0.16	3.66±0.11
Levantine Sub-basin (n = 32)	18±2	38.9±0.2	2613±11	2278±18	8.091±0.018	5.58±0.27	3.62±0.19
Intermediate (150-500m)							
Ionian Sub-basin (n = 14)	15±0.6	38.9±0.06	2626±15	2311±19	8.099±0.010	5±0.2	3.23±0.14
Aegean Sub-basin (n = 8)	15±0.3	39.03±0.02	2598±41	2278±32	8.103±0.014	5.04±0.29	3.26±0.19
Levantine Sub-basin (n = 27)	15±0.7	38.9±0.1	2626±17	2317±15	8.088±0.010	4.92±0.25	3.18±0.16
Deep (500-2500m)							
Ionian Sub-basin (n = 16)	13.8±0.1	38.74±0.04	2612±13	2306±12	8.066±0.027	3.96±0.49	2.59±0.3
Aegean Sub-basin (n = 2)	14.7±0.03	39.015±0.004	2594±1	2261±1	8.124±0.000	4.97±0.02	3.23±0.01
Levantine Sub-basin (n = 32)	13.8±0.1	38.75±0.02	2611±7	2305±12	8.077±0.020	4.17±0.37	2.72±0.23
Bottom (>2500m)							
Ionian Sub-basin (n = 4)	14±0.06	38.719±0.002	2607±4	2295±2	8.003±0.017	2.84±0.18	1.89±0.11
Aegean Sub-basin	-	-	-	-	-	-	-
Levantine Sub-basin (n = 1)	14.00±0.04	38.76±0.00	2601±0.0	2288±0.0	8.027	3.13	2.08

2.4.2.2 Red Sea

Data on the carbonate system parameters were firstly collected in the Red Sea during a GEOSECS expedition in December 1977 (Weiss et al., 1983) and then during the French Merou A and B expeditions in June and October 1982 (Poisson et al., 1983) and the MINERVE cruises in 1991, 1992, and 1999 (Metzl et al., 1995). These surveys have typically been conducted along the north–south central axis of the Red Sea.

The total alkalinity of the Red Sea surface water is higher than the mean surface ocean total alkalinity (~2300 μmol kg^{-1}, Millero et al., 1998), resulting from the enhanced concentration of dissolved ions caused by the intense evaporation. The south-north increasing salinity gradient along the Red Sea is also reflected in TA that however deviates from the conservative behavior. The surface salinity in the Red Sea increases from ~36 near the Straits of Bab el-Mandeb, to approximately 40.7 at the northern part of the Red Sea (Tomczak and Godfrey, 2003). The TA deficiency is attributed to the precipitation of biogenic $CaCO_3$ formed by either pelagic calcareous plankton or coral reefs on the margins (e.g. Steiner et al., 2014) and heterogeneous $CaCO_3$ precipitation from supersaturated water onto suspended solids (Wurgaft et al., 2016). Anderson and Dyrssen (1994) had estimated that the Red Sea is a sink for TA of 1.65×10^{12} mol yr^{-1}.

The DIC concentration in the deep-water of the Red Sea is relatively low, being ~2150 μmol kg^{-1} (Papaud and Poisson, 1986; Krumgalz et al., 1990). The combination of high bottom water temperature, high alkalinity and low DIC results in high saturation degree of $CaCO_3$ minerals, Ω, along the entire water column of both the Red Sea and the Gulf of Aqaba (Wurgaft et al., 2016). In the Gulf of Aqaba, Ω values range between 4.6 and 6.7 and from 3.1 to 4.4 with respect to calcite and aragonite, respectively (Wurgaft et al., 2016). The saturation state of aragonite in surface waters of the Red Sea equals 4.08 ± 0.26 (n = 22; Jiang et al., 2014), while in the deep waters of the Red Sea, Ω values are lower being 3.2 and 2.2 for calcite and aragonite, respectively (Wurgaft et al., 2016).

The carbonate system in the Red Sea is under the intricate influence of natural processes and anthropogenic impacts, with studies indicating significant anthropogenic CO_2 saturation in the northern Red Sea due to winter overturning circulation (Krumgalz et al., 1990). This CO_2 penetration reflects the broader concern of ocean acidification within the basin, where despite high seawater temperatures and natural TA that generally support reef accretion, increasing temperatures are now shown to detrimentally affect coral calcification rates (Roik et al., 2018). A marked decline in coral calcification rates has been observed in the southern Red Sea, evidencing a drastic reduction in the contribution of hermatypic corals to the $CaCO_3$ budget by about 100% from 1998 to 2015, signaling severe ecosystem stress (Steiner et al., 2018). The CO_2 system characterization across various coastal habitats by Saderne et al. (2019) and the noted anomalies in the carbonate system (Baldry et al., 2020) suggest that ecosystem metabolic processes significantly influence the coastal waters' chemistry. The notable seasonal shifts from calcification and photosynthesis to dissolution and heterotrophy further complicate the system's dynamics. These changes, in tandem with the documented decline in net calcification, underline the urgent need to monitor the Red Sea's carbonate system continuously. The few available papers point to a Red Sea carbonate system experiencing profound shifts due to anthropogenic CO_2, with consequent effects on ocean acidification patterns, coral reef calcification rates, and overall ecosystem health.

Ranges in the Red Sea:

- Total Alkalinity (TA): TA in surface waters along the north–south axis of the Red Sea varied between 2373 and 2488 µmol kg^{-1} (mean concentration 2438 ± 40, n = 22) (Jiang et al., 2014). Ali (2017) reports that in the Sudanese coastal Red Sea for the 2009-2013 period, the average surface (4 m) TA ranges between 2420 µmol kg^{-1} in spring/summer and 2460 µmol kg^{-1} in autumn/winter and the sub-surface (>10 m) TA between 2452 and 2471 µmol kg^{-1}. Steiner et al. (2018) refer that TA of surface water along the Red Sea varied between 2371 and 2508 µmol kg^{-1}. Along the Red Sea coast of Yemen, Rushdi et al. (2019) found TA to range from 2327 to 3616 µmol kg^{-1} at surface layers and from 2408 to 2966 µmol kg^{-1} in seawater layers deeper than 100 m. Roik et al. (2018) provide TA values for coral reef areas along a cross-shelf gradient in the Saudi Arabian central Red Sea ranging between 2391 ± 15 µmol kg^{-1} and 2494 ± 16 µmol kg^{-1}. Saderne et al. (2019) also mention TA measurements in various habitats, including a coral reef with TA values of 2415 ± 34 µmol kg^{-1}. Baldry et al. (2020) report TA values for different habitat types (coral reefs, seagrass meadows, mangrove forests) and offshore and transition surface waters of the eastern (Saudi-EEZ) part of the Red Sea:

the minimum mean value (2393 ± 54 µmol kg^{-1}) was recorded at the seagrass meadows and the maximum mean value (2797 ± 767 µmol kg^{-1}) was observed at the mangrove forests.

- Dissolved Inorganic Carbon (DIC): Ali (2017) reports that in the Sudanese coastal Red Sea for the 2009-2013 period, the average DIC concentration at the surface decreases from 2080 µmol kg^{-1} in winter to 2048 µmol kg^{-1} in summer, while in the sub-surface water, the change from winter to summer is much smaller (from 2091 to 2088 µmol kg^{-1}). Steiner et al. (2018) refer that DIC of surface water along the Red Sea varied between 2047 and 2145 µmol kg^{-1}. Saderne et al. (2019) report DIC concentrations in the central Red Sea coral reef with a mean value of 2061 ± 58 µmol kg^{-1}. Similar to AT, Baldry et al. (2020) report that the minimum DIC mean value (2043 ± 116 µmol kg^{-1}) was recorded at the seagrass meadows and the maximum mean value (2595 ± 860 µmol kg^{-1}) was observed at the mangrove forests.
- pH: Along the Red Sea coast of Yemen pH ranged from 7.983 to 8.198 at surface seawater and from 7.960 to 8.052 at deeper layers (Rushdi et al., 2019). Saderne et al. (2019) mention pH measurements along a cross-shelf gradient with values ranging from 7.95 ± 0.26 in the mangrove forest to 8.016 ± 0.077 in the coral reef. Baldry et al. (2020) also mention that the minimum pH_T mean value (7.724±0.254) was observed at the mangrove forests and the maximum one (8.055 ± 0.032) at the offshore Red Sea surface waters.

2.4.2.3 Persian Gulf

The carbonate system in the Persian (Arabian) Gulf is a dynamic interplay of natural processes and human influence, with recent studies providing a detailed quantitative analysis of its current state. The surface seawater pCO_2 in the Exclusive Economic Zone (EEZ) of Qatar is notably higher than the atmospheric levels, averaging 458 ± 62 µatm, which suggests that the Gulf acts as a source of CO_2 to the atmosphere (Izumi et al., 2022). The elevated pCO_2 is attributed to the combined effect of high salinity and temperature, and a net calcification process that raises pCO_2 to levels such as 577 µatm as estimated by model calculations (Izumi et al., 2022). Anthropogenic modifications are evident near Abu Dhabi (United Arab Emirates, UAE), where coastal engineering projects have altered the carbonate sedimentary environments, yet some sedimentary facies have shown resilience to these changes (Lokier and Fiorini, 2016). The northern Arabian Gulf waters have exhibited increasing acidity over a four-year study period, with biweekly pH measurements indicating a trend that could have severe implications for marine life (Uddin et al., 2012). Whiting events, crucial for ecosystem balance, may be threatened by global warming, as evidenced by high $CaCO_3$ saturation levels along the southern coastlines of the UAE, Qatar, and Bahrain (Shanableh et al., 2017). The Northwestern Arabian Gulf, in particular, has seen changes due to climatic conditions and anthropogenic stress that threaten the ecosystem's functioning (Al-Said et al., 2021). Hydrography data from the central Arabian Gulf indicate temperature and salinity decreases from nearshore to offshore, with no immediate threat of acidification based on pH observations (Elobaid et al., 2022). The impact of coral bleaching on carbonate budgets is significant, as seen in Bahrain's reefs, where a decrease in hard coral cover and net carbonate budget following a severe bleaching event has shifted the reef from a positive budgetary state towards net neutral (AlMealla et al., 2024). Chemical oceanography studies from the 1980s still provide valuable insights into the region's hydrographic properties and carbonate system perturbations (Brewer and Dyrssen, 1985). Recent occurrences of hypoxia have affected extensive areas of the Persian Gulf, with severe implications for marine ecosystems (Saleh et al., 2021). Collectively, these studies illustrate a carbonate system in the Persian Gulf that is under stress from environmental change, with a critical need for continued research and monitoring to manage and mitigate the impacts on this vital marine region.

Ranges in the Persian Gulf:

- Total Alkalinity (TA): In nearshore coral reefs of the northern Persian Gulf, the average TA was between 2411 ± 3 µmol kg^{-1} and 2481 ± 8 µmol kg^{-1} (Saleh et al., 2020). Izumi et al. (2022) based on data from 2 cruises at the Qatari EEZ provide a mean TA value of 2532 ± 30 µmol kg^{-1}. The average TA based on the results of a cruise conducted within the Iranian EEZ in September 2021 was 2507.2 ± 41.5 µmol kg^{-1}, ranging from 2416.0 to 2635.8 µmol kg^{-1} (Saleh et al., 2025).
- Dissolved Inorganic Carbon (DIC): Saleh et al. (2020) reported that in coral reefs of northern Persian Gulf, the average DIC was in the range of 2031 ± 22 µmol kg^{-1} to 2122 ± 17 µmol kg^{-1}. The average DIC concentration at the Qatari EEZ according to Izumi et al. (2022) is 2180 ± 40 µmol kg^{-1}. The average DIC calculated from TA and pH_T within

the Iranian EEZ in September 2021 was 2123.9 ± 106.8 µmol kg^{-1}, with values ranging from 1953.7 to 2305.6 µmol kg^{-1} (Saleh et al., 2025).

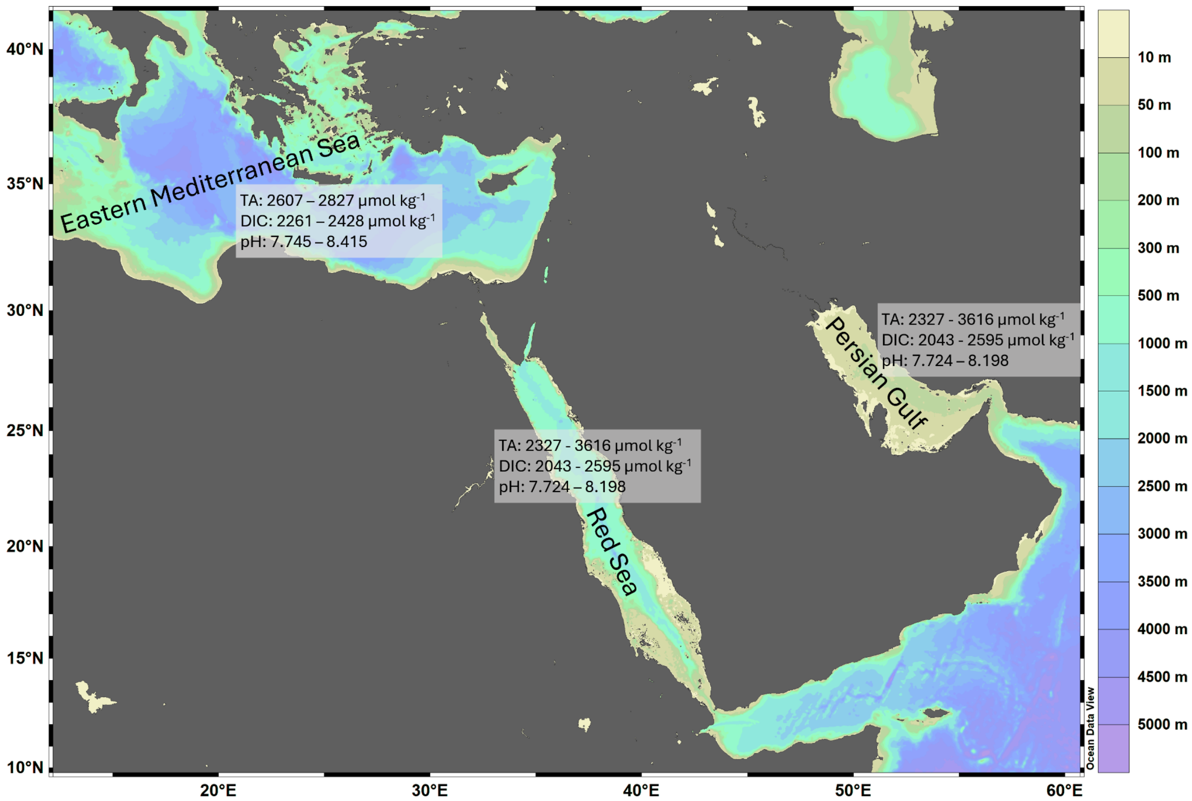
- pH: In nearshore coral reefs of the northern Persian Gulf, the average pH(NBS scale) ranged between 8.15 ± 0.02 and 8.23 ± 0.03 (Saleh et al., 2020). Izumi et al. (2022) provided an average pH value (calculated from TA and DIC) of 8.02 ± 0.05, while Elobaid et al. (2022) reported that pH at the Qatari EEZ varied between 8.01 and 8.21. Saleh et al. (2025) reported that the average pH_T within the Iranian EEZ in September 2021 was 8.001 ±0.073, with a relatively wide range of about 0.3, from 7.832 to 8.126.

Based on the available literature retrieved and assessed in this report, the ranges of the carbonate system variables (DIC, TA, pH) in the Eastern Mediterranean Sea, Red Sea, and the Persian Gulf are summarized in Figure 31. It was revealed that in the Eastern Mediterranean Sea field observations of CO_2-carbonate system parameters were performed mostly in open-sea waters during oceanographic cruises. Part of the observations were obtained along stations' transects crossing different sub-basins in the frame of trans-mediterranean cruises (e.g. Álvarez et al., 2014; Hassoun et al., 2015). In addition, other research efforts covered particular regions of the Eastern Mediterranean Sea (e.g. Krasakopoulou et al., 2009; 2017 – Aegean sub-basin; Sisma-Ventura et al., 2016; 2017 - South-eastern Levantine sub-basin; Wimart-Rousseau et al., 2021 - North Western Levantine sub-basin, etc.) providing various spatio-temporal information. The availability of resources (European and national) seems to be a major determinant of the spatio-temporal distribution of observations of the marine carbonate system in the Eastern Mediterranean Sea (Hassoun et al., 2022).

In the Red Sea, sampling efforts of the CO_2-carbonate system parameters were quite intense till the end of '90s with internationally coordinated surveys that were typically conducted along the north–south central axis of the Red Sea (Ali et al., 2021 and references therein). Afterwards, the international scientific interest remarkably declined, probably due to the limitation of funding opportunities. However, regional researchers have conducted studies in coastal ecosystems, particularly in seagrass meadows, mangrove forests and coral reefs, confined to the territorial waters of each country surrounding the Red Sea.

Till quite recently, only one study of the CO_2-carbonate system parameters that provided a wide coverage of the Persian (Arabian) Gulf was conducted several decades ago (in 1977; Brewer and Dyrssen, 1985). The few internationally coordinated basin-wide surveys carried out in the region to study the effects of the 1991 Gulf War provided useful oceanographic information, but none of them focused on studying the CO_2-carbonate system, which remained one of the least studied topics in the Persian Gulf (Al-Yamani and Naqvi, 2019). This changed in September 2021 when a cruise was conducted within the Iranian EEZ covering the area from the Arvand River (also known as the Shatt al-Arab) to the Strait of Hormuz, aiming to assess the status of the seawater carbonate system in the Gulf. In addition, in recent years, few studies have also been carried out by marine scientists in the shallow territorial waters of their own countries (Al-Yamani and Naqvi, 2019).

FIGURE 31. An overview of the ranges of the carbonate system variables in the Eastern Mediterranean Sea, Red Sea, and the Persian Gulf



In the Eastern Mediterranean and the Middle East Seas, the most used combination of the four widely-measured carbonate system parameters to characterize and quantify the marine CO2-carbonate system was the pair of TA-DIC. It has to be mentioned that in some studies, the pair of TA-pH was measured (e.g. Rushdi et al., 2019; Saleh et al., 2025), in others only TA was determined (e.g. Roik et al., 2018) and in fewer the CO_2-carbonate system was over-determined as three parameters were measured (e.g. TA, DIC and pH in Wimart-Rousseau et al., 2021).

2.4.3 CO_2 air-sea exchanges: sink or source?

2.4.3.1 Eastern Mediterranean Sea

There is a lack of in-situ studies on pCO_2 and air-sea CO_2 fluxes with adequate spatial and/or temporal coverage in the Eastern Mediterranean Sea (Hassoun et al., 2022; Alvarez et al., 2023). In the ultra-oligotrophic and warm South-Eastern Levantine sub-basin, the air-sea CO_2 exchange varies seasonally with the area acting as a CO_2 source to the atmosphere during most of the year (May to December) with outfluxes ranging between 0.9±0.3 and 6.2±1.4 mmol m^{-2} d^{-1}, whereas it acts as a sink of atmospheric CO_2 in winter (January to April) with influxes varying between -0.3±0.04 and -0.9±0.15 mmol m^{-2} d^{-1} (Sisma-Ventura et al., 2017). The disproportionality in flux direction and magnitude leads to an annual air-sea CO_2 outgassing of 845±270 mmol C m^{-2} y^{-1}, indicating that the South-Eastern Levantine is a significant net source of CO_2 to the atmosphere (Sisma-Ventura et al., 2017). The temporal succession of the "sink" or "source" of CO_2 to the atmosphere was also observed in the adjacent North-Western Levantine sub-basin and was ascribed to TA variations that regulate the seawater pCO_2 and the air-sea CO_2 exchanges, in addition to the thermodynamic and biological drivers (Wimart-Rousseau et al., 2021). In the Aegean sub-basin, only two field studies providing pCO_2 calculated from TA-DIC or continuous pCO_2 shipboard measurements were performed in May 1997 and February 2006. Both studies have shown that the Aegean sub-basin acted as a weak sink of atmospheric CO_2 at a rate of -0.60/-1.43 mmol m^{-2} d^{-1}, depending on the formula used for the gas transfer velocity, in May 1997 (Krasakopoulou et al., 2006) and as a stronger sink of -6.2/-11.8 mmol m^{-2} d^{-1} in February 2006 (Krasakopoulou et al., 2009). In contrast to these two snapshots, one next study that was based on high-frequency time-series measurements provided estimates of pCO_2 by TA-pH during an annual cycle and showed that the area of Saronikos Gulf in the Aegean sub-basin acts as a weak CO_2 source to the atmosphere at a rate of 0.20 mol CO_2 m^{-2} y^{-1} (Gonzalez-Davila et al., 2016). More recently, Frangoulis et al. (2024) estimated in the South Aegean sub-basin a weak annual flux of -0.16±0.02 mol CO_2 m^{-2} y^{-1}, using nineteen months of high-frequency sensor recordings of CO_2 with completion of any data gaps by pCO_2 calculated from TA-pH. Similarly, the simulated mean monthly (2010-2022) air-sea CO_2 flux in the Levantine sub-basin was found to fluctuate between ~5 mmol m^{-2} d^{-1} and ~-5 m^{-2} d^{-1} but the negative air-sea flux extends over a longer period and finally the sub-basin acts as weak CO_2 sink (-0.25 mol CO_2 m^{-2} y^{-1} for 2010-2022; Tsiaras et al., 2024). The scarceness of field studies with direct *p*CO_2 measurements which are temporally limited to one time-series station and spatially to few cruises with most *p*CO_2 data being estimates from other carbonate system parameters, do not allow at this time to conclusively characterize the Eastern Mediterranean Sea's role as a CO_2 source or sink. It is quite possible that different areas in the oligotrophic Eastern Mediterranean Sea currently act as either weak source or sink of CO_2. Further, ongoing changes in temperature, atmospheric CO_2, biological productivity, wind regime, and even the possibility that the Aegean may soon become the main source of Eastern Mediterranean deep water, underline that a transition period is underway (Frangoulis et al., 2024). A study that compared the fluxes from the 1980s and 2000s showed a tendency for the Eastern Mediterranean to become a weaker CO_2 source (Taillandier et al., 2012) and the same trend was predicted by a study covering the period 1999-2019 (Cossarini et al., 2021).

2.4.3.2 Red Sea

The Red Sea exhibits complex CO_2 air-sea exchange dynamics that are seasonally and regionally variable. In the northern Red Sea, anthropogenic CO_2 saturation is evident, where studies have documented an excess CO_2 signal close to zero (0 ± 7 μmol kg^{-1}) in the upper 200 m, implying that this region may not act as a significant sink for atmospheric CO_2 (Krumgalz et al., 1990). Published studies that were based on data collected in the Red Sea during the period 1977-1999, consistently, have shown that the Red Sea is a source of CO_2 to the atmosphere. Souvermezoglou et al. (1989) used two methods (direct and indirect) to determine the summer and winter carbon budget in the Strait of Bab-El-Mandeb and concluded that the Red Sea is a source of CO_2 during both seasons. Similarly, Metzl et al. (1989) using an inverse model for transport and carbon exchange showed that the air–sea CO_2 flux was towards the atmosphere during both summer and winter. In addition, in a study that primarily covered the Indian Ocean, the Red Sea appeared to be a source of CO_2 for the atmosphere, in accordance with previous studies, however, the size of the CO_2 source decreased from south to north, and the northernmost part of this enclosed sea was a sink during the summer of 1991 (Metzl et al., 1995). A study of CO_2 flux in the western part of the Red Sea (Sudanese coastal Red Sea) showed that this area is a net annual source for the atmosphere (October 2014–October 2015), while acting as a sink for CO_2 during winter (Ali et al., 2021). The same researchers using both coastal and open sea data for the period 1977-2015 assessed the long-term trends of surface seawater pCO_2 and concluded that the rate of pCO_2 change was 1.75 ± 0.72 µatm y^{-1} for winter-spring and 1.80 ± 0.41 µatm y^{-1} for summer-fall, both slightly lower than that of the atmosphere (1.96 ± 0.02 µatm y^{-1}), and they assumed that the Red Sea has shifted from being a source area of CO_2 to the atmosphere throughout the year to become a sink area for CO_2 during parts of the year. The anthropogenic CO_2 pattern suggests that the northern Red Sea could be a localized source of CO_2 to the atmosphere during periods of winter overturning, influenced by the overflow of younger waters from adjacent gulfs. The Red Sea's role in CO_2 air-sea exchanges is multifaceted, with certain areas acting as localized CO_2 sources while others retain some sink capacity. The documented decline in coral calcification rates further underscores the need to reassess the Red Sea's overall contribution to oceanic carbon sequestration processes in light of ongoing climate change and ocean acidification.

2.4.3.3 Persian Gulf

The Persian (Arabian) Gulf exhibits a complex behavior in terms of CO_2 air-sea exchanges, functioning variably as both a sink and a source under different conditions. Recent observations within the EEZ of Qatar have reported surface seawater pCO_2 levels averaging 458 ± 62 µatm, which are higher than the atmospheric pCO_2, indicating that in these areas, the Gulf is acting as a source of CO_2 to the atmosphere (Izumi et al., 2022). This is in stark opposition to the prevailing assumption of the ocean's role as a CO_2 sink and suggests a significant influence of temperature and salinity on the carbonate system within the Gulf. In contrast, the average surface pCO_2, calculated from pH_T and TA, within the EEZ of Iran in September 2021 was 403.9 ± 69 µatm. Based on the surface pCO_2 values, approximately 15% of the Gulf's surface within the western and eastern edges of the Iranian EEZ, acted as a potential source of CO_2 to the atmosphere, while the remaining 85% functioned as a potential sink (Saleh et al., 2025). In the same study that was performed under stratified water column conditions, the deep Arabian Gulf water exhibited elevated DIC and low average pH (7.924 ± 0.030) as a result of organic matter decomposition and low oxygen levels. Additionally, the detection of increased acidity levels in the northern Arabian Gulf surface waters over a four-year period implies an increased uptake of CO_2, which can exacerbate ocean acidification (Uddin et al., 2012). Furthermore, Brewer and Dyrssen (1985) provided an early assessment of the chemical oceanography of the Persian Gulf, revealing that the Gulf's seawater carbonate system is heavily perturbed by the precipitation of calcium carbonate, influencing the total alkalinity and total carbon dioxide balance and hence the CO_2 exchange dynamics. Similarly, Saleh et al. (2025) estimated that calcium carbonate precipitation contributed to significant alkalinity losses (~66.2 μmol kg^{-1}) that correspond to an annual $CaCO_3$ deposition of 31 million tons; however, this loss is slightly more than half of the value reported by Brewer and Dyrssen (1985) for the entire Gulf. The diverse findings from these studies highlight the intricate and potentially shifting roles of the Persian (Arabian) Gulf in global carbon cycling, necessitating a nuanced understanding of its function as both a CO_2 sink and source. Overall, the Persian (Arabian) Gulf's status as a CO_2 source is a result of an interplay of environmental conditions and anthropogenic impacts, underlining the importance of regional studies in understanding the global carbon cycle.

2.4.4 Anthropogenic CO_2 and ocean acidification patterns

2.4.4.1 Eastern Mediterranean Sea

The Mediterranean Sea, especially its Eastern basin, has been identified as an important anthropogenic carbon storage area because the water column inventory is proportionately higher than that of the Atlantic Ocean, Pacific Ocean and Indian Ocean (Schneider et al., 2010). The warm, highly alkaline surface waters of the Eastern Mediterranean Sea, with a low Revelle factor (close to 10; Álvarez et al., 2023 and references therein), corresponding to a high buffering capacity, are prone to absorbing CO_2 from the atmosphere and transporting it to the deep and abyssal layers through the active overturning circulation (Álvarez et al., 2023 and references therein). The NW Levantine and the Aegean Sub-basins are among the locations of the Eastern Mediterranean Sea where intermediate and deep-water masses are formed (e.g. Fach et al., 2023 and references therein; Durrieu de Madron et al., 2005), having an increased potential to transfer anthropogenic CO_2 from surface to depth (Krasakopoulou et al., 2017).

Anthropogenic carbon (C_{ANT}) is a variable that cannot be measured directly and is estimated through three main approaches and under several assumptions: (i) the back-calculation techniques (e.g. TrOCA, Touratier and Goyet, 2004; Touratier et al., 2007); (ii) the Transient

Time Distribution (TTD) methods (e.g. Waugh et al., 2006); and (iii) using coupled circulation/ biogeochemical models. The TrOCA approach was widely applied to estimate C_{ANT} in the Eastern Mediterranean: basin scale (Touratier and Goyet 2011; Hassoun et al., 2015), Aegean Sub-basin (Krasakopoulou et al., 2017), Ionian Sub-basin and Cretan Passage (Rivaro et al., 2010) and the Levantine Sub-basin (Rivaro et al., 2010; Sisma-Ventura et al., 2016). Furthermore, the TTD approach was applied by Schneider et al. (2010) and a high resolution regional model for the Mediterranean developed by Palmiéri et al. (2015) to simulate anthropogenic carbon storage.

More specifically, all different approaches showed that C_{ANT} has already penetrated all water masses of the Eastern Mediterranean Sea (Schneider et al., 2010; Touratier and Goyet 2011; Hassoun et al., 2015, 2022) and is detected in the intermediate and deep layers of its various sub-basins. The absorbed C_{ANT} is estimated to range between 34 ± 5 and 73.2 ± 4.9 µmol kg^{-1}, depending on the depth and the type of water mass, as well as the year of sampling (Table 8).

Since the pre-industrial era, the pH decline has varied between -0.055 and -0.156 pH units (in the year 2013; Hassoun et al., 2015) with slight differences between intermediate and deep water masses (Table 8). High quality estimates of pH changes can only be assessed by repeated observations over time and space. Unfortunately, this kind of data is generally lacking in the Eastern Mediterranean Sea compared to the Western Mediterranean Sea (Hassoun et al., 2022). In the Eastern basin, the intensity of OA has been estimated by a few observational studies conducted on multi-annual and decadal scales (Hassoun et al., 2019; Wimart-Rousseau et al., 2021). The annual OA rate in the upper 50-80 m of the Eastern Mediterranean presented homogenous trends varying from -0.0021 ± 0.0010 (offshore of the Lebanese coast, Hassoun et al., 2019) to -0.0024 ± 0.0004 pH unit y^{-1} (North Western Levantine Sub-basin, Wimart-Rousseau et al., 2021), while high annual acidification rate was reported in shallow waters (< 5m) of the South-Eastern coastal area (-0.009 ± 0.004 pH unit y^{-1}; Hassoun et al., 2019; Table 2). Compared to OA levels estimated for the surface global ocean (-0.0149 ± 0.0010 to -0.0210 ± 0.0070 pH units $decade^{-1}$; Ma et al., 2023), the Eastern Mediterranean Sea displays a higher acidification rate. The relatively higher estimates have been associated with the specific inherent characteristics enabling the Eastern Mediterranean Sea to absorb larger amounts of anthropogenic CO_2 from the atmosphere (Schneider et al., 2010; Hassoun et al., 2015).

Along the water column, the pH decrease varies differently, with maximum and minimum decreasing trends in the surface and the intermediate layers, respectively (Table 8). Contrary to what is reported for the global ocean (e.g. Lauvset et al., 2019), the abyssal and deep layers of the Mediterranean Sea also display a noticeable pH decrease, slightly lower than the surface waters' values. This vertical pattern is attributed to the processes and dynamics happening in water masses, as well as their relative ages (ventilation process). Surface waters, being in direct contact with the atmosphere are more affected by the increase of CO_2 in the air, which uptake determines the pH decrease. Deep waters also display an evident pH decreasing trend due to dense water formation processes that transfer surface water, enriched in anthropogenic CO_2 to intermediate and deep layers. In the global ocean, as the intermediate and deep waters are much older than the surface waters, the anthropogenic carbon signal is not particularly evident. However, in the Mediterranean Sea, the intermediate and deep waters are much younger (Stöven and Tanhua, 2014; Li and Tanhua, 2020), therefore showing anthropogenic CO_2 invasion and consequently clearer acidification signals.

Acidification trends have also been assessed through biogeochemical modeling. Cossarini et al. (2021) provided aspects of the carbonate system variability and interannual trends, based on the Mediterranean re-analysis over the last two decades (1999-2019), as part of the Copernicus Marine Environment Monitoring Service (CMEMS) model product. The reanalysis suggests that, in the 1999-2019 time period, there were significant trends in all carbonate variables in the Eastern Mediterranean basin, with an increase of A_T by 2.0 µmol kg^{-1} y^{-1} and DIC by 1.5 µmol kg^{-1} y^{-1}, and a related decrease in pH of approximately -0.0012 units y^{-1}. Since those trends are computed over the 1999-2019 period, they cannot be linearly extrapolated over the last 2 centuries, which have been characterized by a constant increase in atmospheric CO_2.

2.4.4.2 Red Sea

Studies paint a picture of a Red Sea that is experiencing shifts in ocean acidification patterns due to increasing levels of anthropogenic CO_2, with important implications for the region's marine ecosystems and global carbon cycling. Krumgalz et al. (1990) found that the northern Red Sea's water column has been saturated with excess anthropogenic CO_2, with a near-zero excess CO_2 signal (0 ± 7 µmol kg^{-1}) in the upper 200 meters. This suggests minimal CO_2 uptake in these layers, while deeper waters exhibit a pronounced anthropogenic CO_2 signal, reaching -28 ± 5 µmol kg^{-1} at around 600 ± 100 m depth, and then slightly increasing to -15 ± 6 µmol kg^{-1} between 800 to 1500 m. These patterns below 600 m are attributed to the influx of younger waters from the Gulf of Elat and the Gulf of Suez over the sill in the Strait of Tiran. Furthermore, at depths of 600 ± 100 m, the anthropogenic CO_2 signal reaches its maximum negative values of approximately -28 ± 5 µmol kg^{-1}, increasing to around -15 ± 6µmol kg^{-1} from 800 to 1500 m. Complicating the typical sink/source narrative, coral reefs in the central Red Sea, despite the naturally high total alkalinity conducive to calcification, have shown a decline in net carbonate budget states, with an average cross-shelf carbonate budget of 0.66 kg $CaCO_3$ m^{-2} yr^{-1}. Notably, the highest carbonate budget measured offshore was 2.44 kg $CaCO_3$ m^{-2} yr^{-1}, indicating some capacity for CO_2 uptake in these regions (Roik et al., 2018). This latter study revealed a pattern of net-erosive, neutral, and net-accretion states across a cross-shelf gradient. These patterns are comparable to other oceanic regions but are below optimal reef production rates, suggesting that these reefs may not fully compensate for the acidifying effects of increased CO_2. However, this rate is below the "optimal reef production" of 5-10 kg $CaCO_3$ m^{-2} yr^{-1} and is indicative of a system under stress. Further stressing the Red Sea carbonate system, Steiner et al. (2018) reported a significant decline in total $CaCO_3$ deposition rates along the basin, with a reduction of 26 ± 16% in total alkalinity-driven calcification rates between 1998 and 2015. These numbers signify a substantial decline in the Red Sea's traditional role as a CO_2 sink, potentially altering its contribution to global carbon cycling. Thus, the corals' capacity to act as a CO_2 sink is diminishing. Saderne et al. (2019) characterized the CO_2 system in different coastal habitats in the central Red Sea, observing mean values of pH_T, DIC, and TA in a coral reef at 8.016 ± 0.077, 2061 ± 58 µmol kg^{-1}, and 2415 ± 34 µmol kg^{-1}, respectively, with pCO_2 at 461 ± 39 µatm. The study revealed the significant impact of calcification and photosynthesis in summer-autumn and dissolution and heterotrophy in winter-spring on the CO_2 system. These findings underscore the complexity of ocean acidification patterns in the Red Sea, shaped by both natural seasonal processes and the impact of anthropogenic CO_2.

TABLE 8. Anthropogenic CO_2 and pH trends in the Mediterranean Sea. pH25 trends since the pre-industrial period marked with an asterisk (*) have been calculated by multiplying the annual rates by 171 (years from 1850 to 2021). Anthropogenic CO_2 (C_{ANT}) is reported as the average and standard deviation of C_{ANT} (Mean±SE) or as a range (min-max) (Hassoun et al., 2022)

Area (coastal or offshore)	Water mass/Depth	Sampling Frequency	Period (duration)	Annual pH25 average variation (Mean±SE)	pH25 variation since pre-industrial (Mean±SE; min-max)	C_{ANT} (µmol/kg)	Reference
SE Levantine: B1 (coastal), B2 (offshore)	Surface water	53 cruises (monthly)	2012-2017 (6 yrs)	-0.009 (±0.004)	-1.54 *[@2021]	-	Hassoun et al. (2019)
SE Levantine: B2 (offshore)	Upper 80 m	54 cruises (monthly)	2012-2017 (6 yrs)	-0.0021 (±0.001)	-0.36 *[@2021]	-	Hassoun et al. (2019)
NW Levantine	Upper 75 m	10 cruises	2001-2019 (19 yrs)	-0.0024 (±0.0004)	-0.41 *[@2021]	-	Wimart-Rousseau et al. (2021)
Thyrrenian, Ionian & Levantine	0-500 m	Single cruise	October-November 2001	-	-	70 ±3	Schneider et al. (2010)
Ionian & Levantine	Eastern Mediterranean Deep Water	Single cruise	October-November 2001	-	-	34 ±5	Schneider et al. (2010)
Ionian & Levantine	Levantine Intermediate Water	Single cruise	May-June 2013	-	0.106 ±0.019 (-0.076 to -0.136) [@2013]	69.7 ±13.5 (49.6-92.8) [@2013]	Hassoun et al. (2015)
Cretan passage	Cretan Intermediate Water	Single cruise	May-June 2013	-	0.093 ±0.016 (-0.074 to -0.119) [@2013]	61.5 ± 10.1 (49.9-78.3) [@2013]	Hassoun et al. (2015)
Ionian & Levantine	Eastern Mediterranean Deep Water (Aegean)	Single cruise	May-June 2013	-	0.074 ±0.014 (-0.055 to -0.126) [@2013]	47.5 ±8.9 (35.3-80.4) [@2013]	Hassoun et al. (2015)
North Aegean	All water column	Single cruise	October 2013	-	-0.07 to -0.12 [@2017]	67.5 ±8.9 (50.3-79.2)	Krasakopoulou et al. (2017)
North Aegean	Modified Levantine Intermediate Water	Single cruise	October 2013	-	-0.103 ± 0.007 [@2017]	73.2 ±4.9	Krasakopoulou et al. (2017)
North Aegean	North Aegean Deep Water	Single cruise	October 2013	-	-0.094 ± 0.015 [@2017]	66.3 ±9.2	Krasakopoulou et al. (2017)
Eastern Mediterranean (offshore)	Surface water	-	1800-2001 (201 yrs)	0.0004	-0.084 ±0.001 [@2001 from 1800]	-	Palmiéri et al. (2015)

2.4.4.3 Persian Gulf

The Persian/Arabian Gulf is experiencing significant anthropogenic impacts on its CO_2 levels and ocean acidification patterns. Izumi et al. (2022) highlight that the Gulf's surface waters show an average pCO_2 significantly higher than atmospheric levels, indicating a considerable release of CO_2 into the atmosphere, while more recently Saleh et al. (2025) showed that about 85% of surface waters of the Gulf acted as CO_2 sinks, driven by photosynthetic carbon uptake. Uddin et al. (2012) report a trend of increasing acidification based on pH and temperature data, hinting at a shift in the acid-base balance of the Gulf's waters and raising concerns about the potential impacts on marine ecosystems, including coral reefs and shell-forming organisms. Further compounding the issue, the research by Shanableh et al. (2017) models the effects of rising atmospheric CO_2 on the carbonate saturation state of the Gulf, revealing that areas such as the southern Gulf are experiencing the highest levels of $CaCO_3$ saturation, making them particularly sensitive to acidification. This sensitivity is critical as the Gulf houses diverse ecosystems, which are integral to its ecological and economic value. Anthropogenic stressors, including industrial effluents, oil spills, and coastal development, are also contributing to the region's ocean acidification, as evidenced by Alharbi and El-Sorogy (2019), who documented the presence of heavy metals in the coastal waters of the Arabian Gulf, indicating pollution from various anthropogenic sources. Lachkar et al. (2024) using model simulations studied the Persian (Arabian) Gulf's evolution from 1980 to 2018 and discovered that changes in surface winds have warmed the Gulf and weakened the water exchange between the Gulf and the Sea of Oman during summer. This reduction of the water outflowing the Gulf has led to increased accumulation of nutrients and biomass in the Gulf over the recent decades, intensifying respiration, causing oxygen depletion and heightening acidification, particularly in the deeper parts of the Gulf. The culmination of the abovementioned factors underscores the necessity for concerted efforts to monitor, assess and mitigate the effects of anthropogenic CO_2 and ocean acidification in the Persian (Arabian) Gulf to protect its marine life and maintain its critical role in regional/global carbon cycling.

2.4.5 Concluding remarks

The current work has shown that large areas of the EMED are under-studied or not studied at all, such as its southern part surrounded by North African countries. Similarly, the Red Sea and the Arabian Gulf, except for one cruise performed by Iranian institutes in 2021 in the latter, are both severely under-sampled, with some international surveys dating back decades. The lack of observations of the carbonate system at high spatio-temporal resolution makes it difficult to quantify trends, and variability and to estimate the annual CO_2 flux with a high degree of confidence. Given the importance of the marine CO_2 system, more oceanographic cruises and regular monitoring efforts should be undertaken to better understand the ongoing biogeochemical changes due to warming and ocean acidification. Concerted activities of this kind will help to separate the natural variability from anthropogenic changes, to estimate better the annual sequestration rate of anthropogenic CO_2 and the role of these marine regions as a sink or source of CO_2. Sampling efforts in the straits and channels (e.g. Dardanelles, Cretan Arc, Ormuz) should also be addressed, as the lack of this information hinders the understanding of the connectivity between the sub-basins on the one hand and the adjacent seas on the other. The exchange of waters with different physical and biogeochemical properties through each strait influences the inventory of CO_2-carbonate system variables of both neighbouring regions.

It is important to promote and encourage collaborations between research groups from the countries surrounding the EMME. This would enable capacity building in the region by creating an international collaborative network of researchers and a critical mass of scientists to efficiently study the CO_2 cycle and dynamics. The active cooperation of the members of this network will contribute to the integration and sharing of knowledge, research infrastructures, data and modelling tools, training and capacity building, as well as improved communication/networking between the scientific community and policy makers. Investing in shared research infrastructure (e.g., joint research cruises, shared labs, facilities, secondary standards, etc.) would facilitate the in-situ data collection and enlarge the spatio-temporal coverage of these seas. Fortifying the scientific exchanges, interactions and cooperations of scientists with different levels of expertise (i.e., researchers, PhD students, etc.) and possibly of different scientific disciplines will improve the ability of local researchers in sampling, analyzing and producing high quality data that will be consistently shared on open data portals. A FAIR data policy should be a priority for all datasets produced and should be adopted by the scientists involved (Tanhua et al., 2019), as it is beneficial for both data owners and users and essential for the development of new services (e.g., big data technologies).

3 Ecological impacts

3.1 Introduction

Climate change causes several impacts on the abiotic marine environment. From the ecology viewpoint, the major physical alterations include ocean warming (Levitus et al., 2000; Barnett et al., 2001; Hollowed and Sundby, 2014), increased climatic variability leading to more frequent extreme events (Rahmstorf and Coumou 2011; Frölicher et al., 2018), and changes in sea level, sea ice, thermal stratification, ocean circulation, and upwelling (Schmittner, 2005; Harley et al., 2006; Wang et al., 2015). Furthermore, both warming and altered ocean circulations interact to reduce subsurface oxygen concentrations (Shepherd et al., 2017) and carbon dioxide emissions, responsible for the ocean acidification. All these processes can act on ecology both directly (e.g. when sea temperature exceeds species physiological tolerances) and indirectly (e.g. by changing habitat availability, species interactions and productivity) (Worm and Lotze, 2021). In addition, other impacts include eutrophication, habitat destruction, invasions and impact on fisheries (Lotze and Worm, 2002; Hoegh-Guldberg et al., 2007; Murray et al., 2015).

Overall, detected shapes of biodiversity alteration are gradually being understood in respect to temperature variation in, both over time (Mannion et al., 2014) and space (Tittensor et al., 2010; Worm and Tittensor, 2018). Most efforts to investigate the ecological impacts of climate change, whether on land or in the sea, have concentrated on single species (e.g Parmesan and Yohe, 2003; Parmesan, 2006). More recently, community metrics such as species composition and diversity have been explored in direct relation to climate variability and change (Worm et al., 2005; Menéndez et al., 2006; Hiddink and Ter Hofstede, 2008; Cheung et al., 2009; Pinsky et al., 2013; Jones and Cheung, 2015). Recent changes in climate produce impacts that are superimposed on other stressing effects that have already acted on biodiversity (Harnik et al., 2012) thus making more difficult to clearly attribute recorded alterations into a single factor. Finally, it has been also proposed that biodiversity loss may reduce adaptive capability and diversity of biotic responses to climate change (Elmqvist et al., 2003; Schindler et al., 2010).

The Mediterranean Sea (MS) has a complicated geological history that has rendered it a crossroad of biogeographical influences between the large oceanic masses of temperate and tropical regimes; its complex topography, including a highly intricate coastline, sub-basins and straits, a multitude of islands, and an equally elaborate circulation pattern of its water masses, has facilitated speciation and local adaptation, forming seascapes and biogenic assemblages that are at the same time unique at a global scale and diverse at the local regime (Coll et al., 2010). Although it occupies only 0.8% of the global ocean area and 0.3% of its volume, it hosts remarkable biodiversity, representing 4-18% of the world's marine species, depending on the phylum taken into consideration (Bianchi et al., 2012). In the above context, the MS has been acknowledged as a 'miniature ocean' (Lejeusne et al., 2010), condensing the interface of interaction between the spectrum of pressures and their receptors (habitats and species), and thus a pertinent testbed to assess the ecological effects of climate change on marine biodiversity and test potential adaptation and mitigation strategies (Cramer et al., 2018; Aurelle et al., 2022).

The total alkalinity of the MS, controlled by water exchange with the Atlantic and the Black Sea, as well as by riverine inputs and sedimentation of calcium carbonate, is greater compared to that of the open ocean (Schneider et al., 2007). Its higher total alkalinity along with its active overturning circulation and the relatively high temperatures, gives it greater capacity to take up anthropogenic CO_2, indicating that its potential pH decrease is greater than that of the adjacent Atlantic Ocean (Hassoun et al., 2022), thus posing a higher acidification risk. However, the quantity of anthropogenic CO_2 that has been absorbed by the MS remains uncertain (Palmiéri et al., 2015). Touratier and Goyet (2011) demonstrated that for the year 2001, even the deepest waters of the MS have been acidified by values decreasing from 0.14 to 0.05 pH units since the beginning of the industrial era. Additionally, the water masses exchanged through the Otranto Strait during 1995 had already experienced a significant pH drop in relation to the 'natural' pH levels (Krasakopoulou et al., 2011). However, related time series are limited in the Mediterranean (Hassoun et al., 2022) and especially in the Eastern Mediterranean (EM) (Frangoulis et al., 2024).

Although ocean acidification (OA) trends and the resulting biological impacts are likely exacerbated in the semi-enclosed and highly populated MS, some fundamental knowledge gaps still exist (Hassoun et al., 2022). However, Pallacks et al. (2023), studying the biogenic calcification in the MS, found that increased OA led to basin wide reductions in size normalized weights by modulating foraminiferal calcification; they suggested that further increases in OA will drive ongoing reductions in marine biogenic calcification in the MS.

The Eastern Mediterranean and Middle East (EMME) region has been identified as a major climate change hotspot (Zittis et al., 2022). Carbon dioxide and other anthropogenic emissions are growing rapidly, exceeding those of the European Union, whereas, during the few last decades, the EMME is warming almost two times faster than the global average and significantly faster than other regions (Zittis et al., 2022). For the rest of the century, the same authors expect an overall warming of >5°C, as well as, a strong increase in the intensity and duration of heatwaves. Wedler et al. (2023) proposed that heat waves in the EM are projected to occur seven times more often and last three times longer by the end of the 21st century.

Ibrahim et al. (2021) examined the descriptive spatial variability and trends of the marine heatwave (MHW) events and their main characteristics in the EM from 1982 to 2020. They found that over the last two decades, the mean MHW frequency and duration increased by 40% and 15%, respectively. In the last decade, the shortest significant MHW mean duration is 10 days, found in the southern Aegean Sea, while it exceeds 27 days off the Israeli coast.

The warming trend is particularly striking also in the Red Sea (RS). A warming trend was observed that began in 1994 and has intensified significantly since 2016. This rise in temperature is accompanied by an increase in the frequency and total number of MHW days in the basin. In the last four decades (1982-2021), there have been 78 MHW events with a total of 1016 heat days (Hamdeno et al., 2024). It is noteworthy that 46% of the events and 58% of the heat days occurred in the last decade. The link between 35 climate indices, atmospheric conditions and the occurrence of MHWs in the RS was highlighted (Hamdeno et al., 2024).

Kashkooli et al. (2022) examined, for the first time, MHWs in the Persian Gulf (PG) and Oman Sea during 1982 - 2020. The spatial extent of MHWs has nearly doubled in the last 24 years. Since 1997, the average number of MHW days in the central parts of the PG has increased about 19 times compared to the period 1982–1997. The average number of the detected MHW events has increased by about three times. Simultaneously with the increase in MHWs frequency trend, the trend in the average number of MHW days has also increased. Since 1997, the average number of MHW days in the study area has almost increased by 10 times.

The mean duration of the detected MHWs ranged from 5 to10 days. Finally, about 1 - 2 MHW events occur annually in the PG.

Regarding marine bioinvasions, EMME includes the Suez Canal; worldwide there is no other vector of invasive alien species that provides such high numbers for so long at a certain location (Galil, 2023).

Here, we provide a review of all available existing information, on the ecological impacts from climate change concerning, directly or indirectly, the EMME. There are sections including impacts on benthic communities, plankton communities, life traits and marine fisheries, a section on invasive species, a section on marine birds and a section concerning the metal exposure of organisms under climate change. We attempt to emerge the most vulnerable issues in this system and finally to propose, where possible, mitigation actions.

3.2 Impact on marine ecosystems, biodiversity and community structure

3.2.1 Benthic communities

3.2.1.1 Habitat alteration and biodiversity shifts

Climate change, acting as a broad-scale pressure, has evolved into a major driver of change in global marine ecosystems, strongly shaping biodiversity trends and altering ecosystem functioning. While ocean warming is anthropogenic in its source, through the increased emission of greenhouse gasses to the atmosphere induced by human activities, it acts cumulatively with other human pressures exerted at the local scale, such as pollution, habitat modification, and extraction of resources, altering marine ecosystems at an unprecedented rate and extent (Gissi et al., 2021). The combined effect of these stressors can drive abrupt changes (phase shifts) to the ecosystems, leading to alternative and, often, unpredicted alternative stable states (Montefalcone et al., 2011).

Subtidal canopy-forming macroalgal communities, mainly formed by species of the genus *Cystoseira sensu lato*, including the genera *Cystoseira*, *Ericaria* and *Gongolaria* (Orellana et al., 2019), as well as the genus *Sargassum,* constitute a dominant feature of the Mediterranean euphotic rocky habitats. These habitat-forming perennial macroalgae create structurally complex communities, representing the highest level of Mediterranean rocky reef complexity and exhibiting similar functional properties to kelp forests, thus providing shelter and nursery habitats for a remarkable diversity of organisms (Pinna et al., 2020). However, exert of a diverse array of anthropogenic pressures in the Mediterranean coastline throughout the late 20th century led to the degradation of macroalgal assemblages, mainly through decrease of water quality, habitat destruction and trophic cascades resulting from overfishing natural predators, already by the early 2000's (Sala et al., 1998; Soltan et al., 2001; Thibaut et al., 2005). The advent of ocean warming combined with increased frequency and intensity of marine heatwaves in the past two decades, further increased pressure to the already degraded canopy-formers through local depletion by mortality events (Verdura et al., 2021), as well as intensification of grazing by the non-indigenous (i.e. the rabbitfish *Siganus luridus* and *S. rivulatus*) on top of the native (i.e. sea urchins *Arbacia lixula* and *Paracentrotus lividus*) herbivores (Tsiamis et al., 2013; Salomidi et al., 2016; Nikolaou et al., 2023).

Ongoing degradation has resulted in complete removal of canopy-forming macroalgae along broad extents of the coastline in the EM and the Levantine, creating extensive areas devoid of erect or bushy algae, where the formerly dominant marine forest has been replaced by algal turf or reef barren (Sala et al., 2011; Tsiamis et al., 2013; Salomidi et al., 2016). Since hosted biodiversity in barren fields is consistently reported to be remarkably lower than in adjacent locations dominated by canopy-forming algae (Pinna et al., 2020), the shift from macroalgal forests to encrusting algal crusts or turf barrens can lead to significant impoverishment of coastal habitats in terms of primary productivity, biomass, and biodiversity, implying a cascade effect to ecosystem services through the reduction of functional diversity and resilience to human impacts.

These consequences are currently more pronounced in the EM basin, which suffers increasingly dramatic effects from climate-driven alterations. For example, it has been reported that the ecological status of the shallow sublittoral reef communities over 89 locations at 0-15 m depth in the Aegean Sea are at risk (Savin et al., 2023). This is expected to escalate in the future years, by sea warming and extreme events, as well as by the progression of newly introduced herbivorous species, such as the long-spined large echinoid *Diadema setosum* which shows alarming proliferation and expansion from 2018 onwards (Zirler et al.,

2023) and is expected to have significant ecological footprint by regulating macroalgal growth and severely limiting early stages of colonisation.

A significant impediment towards the assessment of the ecological state and, consequently, any sound and effective managerial or restorative action in the Mediterranean marine habitats, is the lack of baseline reference studies. While change is often perceived by field scientists, this is not systematically documented and quantified, therefore leading to a 'sliding baseline syndrome' (Gatti et al., 2015), where an already degraded environmental status might be accepted as reference, thus lowering the ecological standards of evaluation. In the absence of long-term biodiversity data-series, several studies have been revisiting locations where quantitative assessments have been performed in the past, in an attempt to document stability or habitats alteration at the local scale.

Notably, Bianchi et al. (2014) revisited previously studied sites at the island of Kos (Dodecanese, South-East Aegean Sea) and assessed biodiversity of shallow (down to 10 m) marine habitats over a 30-year timespan between 1981 and 2013. Striking differences were documented, where out of a total 120 taxa found in both surveys, only 51 were common in both; 30 species were found in 1981 but not again in 2013 ('losses'), 38 were found exclusively in 2013 ('gains'), 16 increased their abundance ('winners'), 8 got scarcer ('losers'), and only 28 underwent little or no change. Remarkably, percent proportion of native thermophilic species almost doubled (19 to 10) in the examined timespan, while establishment of non-indigenous species (NIS) and loss of natives implied a dramatic species turnover of more than 60%. Combining the assessment of change to biological assemblages with change in the stressor regime between the two time points, the authors were able to identify a synergistic effect of environmental shift due to the exponential rise of tourism within 30 years with climate change-induced pressures such as the seawater temperature rise and the advent of biological invasions. Similar habitat and biodiversity shifts are documented in later studies, combining historical data and current observations on Mediterranean hard substrate assemblages over greater depth zones (down to 50 m) and time spans, reaching 70 years (Gatti et al., 2015, 2017; Bianchi et al., 2019), consistently identifying the tipping point of change during the abrupt climate shift of the 1990s, when species turnover, reduced structural complexity, biological invasions, and biotic homogenisation led to new and completely different ecosystem status thereafter.

The European purple sea urchin (*Paracentrotus lividus*) is considered to be a key herbivore throughout its distribution range North-East Atlantic and MS. It was also abundant in its eastern distributional edge, on rocky habitats of the coastline of Israel, but its populations have recently collapsed, and today it is an extremely rare species in the region. Yeruham et al. (2015) found massive urchin mortality when temperatures crossed 30.5 °C before reaching peak summer values. They suggested that elevated seawater temperatures in recent years may be the main cause for the disappearance of *P. lividus* from the southeast MS, which may indicate distributional range contraction in this region.

Albano et al. (2021) assessed the diversity loss on the Israeli shelf, maybe the warmest area in the MS, by comparing current native molluscan richness with the historical one obtained from surficial death assemblages. They recorded only 12% and 5% of historically present native species on shallow subtidal soft and hard substrates, respectively. This was the largest climate-driven regional scale diversity loss in the oceans documented to date. By contrast, assemblages in the intertidal, more tolerant to climatic extremes and in the cooler mesophotic zone showed about 50% of the historical native richness. Notably, about 60% of the recorded shallow subtidal native species did not reach reproductive size, making the shallow shelf a demographic sink. Finally they predicted that, as climate warms, this native biodiversity collapse will intensify and expand geographically, counteracted only by Indo-Pacific species entering from the Suez Canal; these assemblages, shaped by climate warming and biological invasions, give rise to a ‘novel ecosystem’ whose restoration to historical baselines is not achievable.

Wabnitz et al. (2018) attempted to assess the potential impacts on, and the vulnerability of marine biodiversity in the Persian/Arabian Gulf (PG) under climate change. Using three separate niche modelling approaches under a `business-as-usual' climate change scenario, they projected the future habitat suitability of the PG for 55 expert-identified priority species. They suggested a high rate of local extinction (up to 35% of initial species richness) by 2090 when compared to 2010. While the projected patterns provided useful indicators of potential climate change impacts on the region's diversity, the magnitude of changes in habitat suitability are more uncertain.

One of the most vulnerable marine habitats to climate change are coastal lagoons (Newton et al., 2014), as they are directly affected by increasing average and maximum temperatures;

declining total precipitation and associated droughts/desertification, increasing frequency and intensity of storms, and sea level rise (Taylor et al., 2021). Rising temperatures and alterations in precipitation patterns will disrupt the delicate balance of these ecosystems, leading to regime shifts and anoxic episodes (Derolez et al., 2020). Increased frequency and intensity of extreme weather events, such as storms and floods, further exacerbate habitat degradation through increased surface run-off and associated pollution inputs (Fabbrocini et al., 2017). Numerical models that simulate hydrodynamics and water transport time scales of coastal lagoons in response to climate change indicate that there will be a general loss of intralagoon and interlagoon variability of their physical properties and that a homogenization of the physical characteristics with a tendency toward marinization (Ferrarin et al., 2014). Loss of habitat complexity and heterogeneity due to climate change will also decrease overall biodiversity and disrupt ecological processes essential for ecosystem functioning (Brigolin et al., 2014).

3.2.1.2 Coral reefs

Climate change impact was evident in the coral bleaching and extreme low tides during 2007, exposing reef flats and causing extensive coral mortality in the southern Egyptian Red Sea (RS) (Tesfamichael and Pauly, 2016). Similar patterns occurred in the Saudi Arabian coral reefs as rising water temperatures (Baker et al., 2004) resulted in decreased coral reef growth (Cantin et al., 2010), decline of large corals in the last two decades (Riegl et al., 2012) and bleaching (Kotb et al., 2008; Furby et al., 2013). Sudden starfish upsurges have caused extended damage on coral reefs along the RS (Wilkinson, 2008).

Corals in the northern RS exhibit high thermal tolerance despite the increasing heat stress. It is assumed that corals throughout the RS have similar bleaching thresholds (32°C or higher), and hence greater bleaching tolerance of corals in the northern RS region is likely due to lower ambient water temperatures (25–28°C) that remain well below the corals' physiological maxima (Osman et al., 2018). Eladawy et al. (2022) used remotely sensed SST data spanning 1982–2020 to model spatial distributions of Degree Heat Weeks (DHW) across the RS in relation to assumed coral thermal threshold values of 30, 31 and 32°C. They showed that applying 32°C thresholds dramatically reduces effective DHW in the north, but not in central or southern RS regions, a finding that is consistent with historical bleaching observations

(1998–2020) all over RS. Further, model predictions under a most extreme scenario exhibited ~3°C warming by the end of the 21st century throughout RS with less pronounced warming for the northern RS (2–2.5°C) compared to the central and southern regions (2.7–3.1°C). This warming rate will remain below the assumed thermal threshold for the northern RS which should help this region to serve as refugia for corals to persist for decades ahead. They finally proposed that the northern RS will not reach assumed bleaching thresholds (32°C) before the end of the 21st century; hence coral reefs in the northern region may be among the last standing against climate change.

Coral disease is a growing problem for coral reefs globally and diseases have been linked to thermal stress, excess nutrients, overfishing and other human impacts (Harvell et al., 2007). The RS is a unique environment for corals with a strong environmental gradient characterized by temperature extremes and high salinities, but minimal terrestrial runoff or riverine input and their associated pollution. Yet, relatively little is known about coral diseases in this region. Aeby et al. (2021) conducted disease surveys at 22 reefs within three regions, Yanbu, Thuwal and Al Lith. Coral reefs of the central RS had a widespread but a surprisingly low prevalence of disease (<0.5%), based on the examination of >75,750 colonies. They recorded 20 diseases affecting 16 coral taxa, whereas 16 out of 30 coral genera were the most commonly affected. Differences in disease prevalence, coral cover, amount of heat stress as measured by degree heating weeks (DHW) and extent of bleaching was evident among sites. Disease prevalence was not explained by coral cover or DHW, and a negative relationship between coral bleaching and disease prevalence was found. The northern-most sites had the highest average disease prevalence and highest average DHW values but no bleaching. This information provides a foundation and baseline data for coral disease prevalence in the central RS, which is projected to increase as a consequence of increased frequency and severity of ocean warming.

The RS has been recognized as a coral reef refugia, but it is vulnerable to warming and pollution. Cai et al. (2024) investigated the spatial and temporal trends of 15 element concentrations in 9 coral reef sediment cores to study the influence of global warming and industrialization on the Eastern RS coral reefs. They observed increased trace metal concentrations in coral reefs with severe bleaching histories, consistent with previous reports that trace metals might result in decreased resistance of corals to thermal stress under warming scenarios; they pointed to the urgent need for reducing the local discharge of trace metal pollutants to protect this biodiversity hotspot.

Coral reefs are facing global challenges, with climate change causing recurrent coral bleaching events at a faster rate than corals may be able to recover from, and leading to an overall decline of coral cover and shifts in communities across the tropics. Scleractinian corals are ecosystem builders that provide a habitat for numerous marine species, and their loss is disrupting a range of ecosystem functions and services that reefs normally provide (Riegl and Purkis, 2012; Vaughan et al., 2019). Climate change will continue to warm the world's oceans, leading to thermal conditions similar to those already existing in the Persian/Arabian Gulf (PG). Indeed, the PG is in the summer the world's hottest sea (SST > 36 ^{o}C) and thus represents a "natural laboratory" in which to understand how reefs in other regions might respond under increasing temperatures (Bouwmeester et al., 2020). It has been shown that physiological thresholds of PG corals are higher than elsewhere, allowing them to survive in the PG's extreme temperatures (Riegl et al., 2012). However, these marginal conditions result in coral communities that are low in diversity and comprised mainly of stress-tolerant species that provide limited three-dimensional structure (Bouwmeester et al., 2020). This low complexity habitat and the environmental extremes are associated with reef fish communities that have lower diversity, abundance, biomass, and size at maturity compared with conspecifics outside of the PG, and these fish communities have been shown to function quite differently (Bouwmeester et al., 2020). As climate change continues, coral reef ecosystems around the world are expected to gradually shift to thermal conditions similar to the present-day PG, and as such today's PG can provide insights into ecological patterns and processes we can expect in the tropics in the future. However, while the PG fauna are adapted to extreme temperatures, they live very close to their upper thermal threshold each summer; recent climate change has resulted in recurrent mass bleaching events that have caused widespread loss of coral and knock-on effects on reef-dependent fishes; thus, paradoxically, on the world's most robust reefs, we may be witnessing the world's first region-wide extirpation of reef fauna as a result of climate change (Bouwmeester et al., 2020).

3.2.1.3 Marine heatwaves driving mass mortality events

Mass mortality events (MMEs) are incidents where large numbers of organisms are eradicated along a specific area and within limited time duration. In the marine realm, where empirical observation and remote sensing over broad territorial scales is challenging, mass mortalities of inconspicuous, short-lived, or economically unimportant organisms, often go unnoticed. On the other hand, reports of MMEs of economically relevant, habitat forming, or emblematic organisms, often emerge and are perceived as catastrophic events, e.g. the massive die-off of commercial sponges in the Caribbean Sea in the 1940s (Smith, 1941), or the recurrent bleaching of coral reefs over broad geographical scales in temperate regimes (Hughes et al., 2017).

Marine MMEs were early-on associated with unusually warm seawater temperatures along the affected areas, usually prolonged over several consecutive days. These events, now broadly acknowledged as marine heatwaves (MHWs), are globally increasing their frequency over the past 20 years, along with their duration, intensity, and geographical extent (IPCC, 2022) and this increase is expected to become significantly more pronounced in the MS (Darmaraki et al., 2019). The association of seawater temperature anomalies with MMEs has been well documented for tropical coral reefs (Hughes et al., 2017). In the Mediterranean, Rivetti et al. (2014) were able to provide a concrete link between temperature anomalies and mass mortality incidents, while Garrabou et al. (2022) documented an acceleration of the ecological impact of MHWs in the last half of the 2010s along hundreds of kilometres of coastline and down to a depth of 45 m, using a combined approach of environmental monitoring and empirical observations at the basin level.

In the MS, the first mass mortality incident reported in the scientific literature was the so-called sponge disease in 1986, actually a pronounced MME with devastating impact to commercial bath sponge stocks (mainly *Spongia officinalis* and *Hippospongia communis*) over an extensive area including the Aegean Sea and the Tunisian plateau (Pronzato, 1999). Despite its severity, no empirical data exist on the actual mortality rates and possible other taxa affected, due to the lack of an established monitoring scheme; however, the pronounced extent of the population reduction can be clearly manifested in landings reports following the year of the event (Gerovasileiou et al., 2018). Regional sponge populations showed signs of recovery only after 1988 in the Aegean Sea (Voultsiadou et al., 2011), while in the Western

Mediterranean, the impact of the event was less pronounced and acting at a more local scale (Gaino et al., 1992). Although occasional epidemic mortalities had previously been reported along the coastline of the commercially exploited EM basin (Pronzato, 1999), those were of reduced extent and severity.

Several small- to moderate-scale episodes of mass mortality were reported from various locations along the north-western Mediterranean basin during the 1990s, affecting different groups of sessile benthic invertebrates, such as anthozoans, sponges, bivalves and ascidians (Cerrano et al., 2000). Then, two MMEs of unprecedented scale followed in 1999 and 2003 (Pérez et al., 2000; Garrabou et al., 2009), with both incidents affecting a multitude of sessile marine taxa and extending over thousands of kilometres of coastline, from the central Ligurian Sea to the Catalan coast and the Balearic Islands. Both events occurred in late summer to late autumn and were the first MMEs in the Mediterranean to be positively associated with MHWs, owing to existing timeseries of seawater temperature data in the vicinity of the affected habitats, combined with satellite data. The extent of the affected bathymetric zone was overall down to 50 m but showing local variations and regional gradients.

As a rule, the taxa most affected by these events were gorgonian anthozoans, mainly *Eunicella singularis*, *E. cavolini*, *Paramuricea clavata,* as well as the Mediterranean precious red coral *Corallium rubrum*. Apart from gorgonians, the reef-building scleractinian *Cladocora caespitosa* was impacted. In several instances, the whole colony of the affected cnidarians was necrosed, and whole populations were decimated. Keratose sponges (*S. officinalis, H. communis, Scalarispongia scalaris*, *Ircinia* spp.) were also broadly affected, with partial or total necrosis, along less pronounced impact on bryozoans, tunicates, and bivalves. In the EM, reports of affected marine taxa populations were reported during the same periods (Cerrano et al., 2000; Garrabou et al., 2009), but in those cases the major impact was reported on sponge taxa, presumably due to the deeper distribution of gorgonians in the eastern basin. Also, no quantitative data exist for EM incidents in this period, due to the lack of regular biodiversity monitoring schemes and scientific coordination.

Combining datasets from regularly monitored locations and singular census campaigns in the extent of the Mediterranean basin, Garrabou et al. (2022) were able to document five consecutive years of MMEs in the 2015-2019 period, affecting 50 marine taxa across 8 phyla and directly linked with exceptional thermal conditions. The persistence of these events can only be compared with a similar succession of recurrent broad-scale coral bleaching incidents during 2014 to 2020, yet not repeating over five consecutive years (Cheung et al., 2021; Hughes et al., 2021). The above findings (Garrabou et al., 2022) suggest the establishment of the MHW/MME synergy as a persistent feature within the Mediterranean ecoregion.

While temperature anomalies are undoubtedly driving mass mortalities of benthic invertebrates in the MS, the precise mechanisms causing the death of the organisms remain largely unknown. The prolongation of summer conditions through enhanced stratification of the Mediterranean upper layers, induced by ocean warming, have been shown to impose energy constraints to benthic organisms through limitations to food availability, thus extending the 'summer dormancy' state and resulting in considerable biomass loss and partial necroses (Coma et al., 2009). The resulting physiological stress can render the affected organisms more susceptible to opportunistic thermotolerant or thermo-dependent microorganisms. For example, *Vibrio coralliilyticus* was indicated experimentally as the major factor responsible for the mortality of the cnidarian *Paramuricea clavata* during the 2003 mass mortality incident, among other pathogens isolated from diseased gorgonians (Bally and Garrabou, 2007). The thermo-dependent pathogen *V. coralliilyticus* was previously known only from the Indo-Pacific region, infecting tropical corals, whereas its discovery in the MS implies a recent introduction and expansion (Bianchi et al., 2012).

Other notable MMEs in the MS can be indirectly coupled with temperature anomalies. For example, the native fan mussel *Pinna nobilis* has suffered a recent devastating epidemic effect from 2016 on, which brought it in the brink of extinction (Kersting et al., 2019). Mortality started at the Spanish coast and the Balearic Islands and spread eastwards to the full extent of the Mediterranean basin in the next three years, causing mortality rates higher than 90%, with only few and geographically limited refugia supporting healthy populations (Katsanevakis et al., 2021). The swift and expansive spread of this event has been shown to be facilitated by water circulation patterns (Cabanellas-Reboredo et al., 2019), implying a pathogenic causative agent. The newly described haplosporidian parasite *Haplosporidium pinnae* appeared to be responsible (Tiscar et al., 2022), but additional experimental studies have indicated synergies with other opportunistic microorganisms such as *Vibrio mediterranei* and showed activation of pathogenicity in elevated temperatures above 25^{o}C (Prado et al., 2020). Enhanced spreading of microbial procaryotes, including viruses, using marine mucilage as a vector, has been shown to be associated with sea surface warming, (Danovaro et al., 2009), thus indicating an increasing trend to the frequency and extension of marine diseases in the forthcoming decades.

The ecological consequences of MMEs are not confined to strict biodiversity loss defined as the reduction in abundance (or extinction) of particular taxa. Since most of the affected organisms are key species and habitat-formers through the provision of three-dimensional complexity, their removal induces major consequences to the structure and functioning of benthic habitats, such as the highly productive Mediterranean coralligenous assemblages (Gómez-Gras et al., 2021) and other Marine Animal Forests (Rossi et al., 2022). Loss of ecological functions and habitat degradation can consequently pose significant impact to ecosystem services to local and global societies and economies (Smith et al., 2021). Contrastingly to a rather limited perception by society and restricted media coverage compared to terrestrial biodiversity losses, marine mass mortality events emerge as a foremost and acute consequence of climate change in the MS, with direct implications to human well-being.

3.2.2 Plankton communities

Marine plankton form the basis of the ocean's food-web indicative of the state of the wider pelagic habitat. The impacts of climate change on plankton communities are poorly understood, although information coming from the integration of short mesocosm experiments, field observations and ecosystem modeling, have indicated that the rapid warming and acidification of the sea during the last few decades has affected distributional patterns of marine planktonic communities.

As a genetal trend microbial communities in oligotrophic waters, such as phototrophic pico- and nanoeukaryotes are considerably enhanced by ocean acidification, when compared with the non-significant or even negative response of larger groups and autotrophic prokaryotes, under nutrient-rich conditions (Sala et al., 2016). Microbial ecosystems at higher temperatures are characterized by increased productivity but probably decreased biomass stocks as a result of high export events that reduce nutrient availability in the surface ocean.

Trophic dynamics mediate community structure shifts resulting in increased heterotroph to autotroph ratios at higher temperatures (Archibald et al., 2022).

There is experimental evidence that, in the upper layer of a stratified and oligotrophic ocean temperature increases will probably result in an increase bacterial respiration (BR) of organic carbon and of bacterial losses to grazers, increasing the biomass flux within the microbial food web. If enough resources are available (such as labile organic matter) bacterial production (BP) and bacterial abundance (BA) would also increase, and a higher proportion of inorganic nutrients would accumulate as bacterial biomass, thus strengthening the role of heterotrophy. Planktonic communities would tend to decrease their average size and a reinforcement of the already dominant role of microbes in the carbon cycle in a warmer ocean is highly probable (Sarmento et al., 2010).

Decreasing body size has been suggested as a universal biological response to global warming together with shifts in phenology. Phytoplankton average cell sizes tend to become smaller in warmer waters, although temperature is not always necessarily the environmental factor driving size shifts, which can be attributed to metabolic explanations but also top-down effects, i.e. intensified size-selective consumption at higher temperatures. In natural phytoplankton experiments with a factorial combination of warming and consumer type, size shifts of individual phytoplankton species and community mean size were analyzed. Both, mean cell size of most of the individual species and mean community cell size decreased with temperature under all grazing regimes. Only grazing by copepods caused an additional reduction in cell size. (Peter and Sommer, 2013). In another study Sommer et al. (2017) discussed the implications of nutrient supply and grazing in temperature-related size trends based on known functional traits associated with phytoplankton size. For a phytoplankton community dominated by smaller algae they predicted that a higher proportion of primary production (PP) will be respired within the microbial food web; a smaller share of PP will be channeled to the classic phytoplankton –zooplankton - fish food chain, thus leading to decreased ecological efficiency and finally a smaller share of PP will be exported through sedimentation, thus leading to decreased efficiency of the biological carbon pump.

The oligotrophic eastern Mediterranean (EM), is characterized by the important role played by the microbial food web in the production and transfer of biomass and energy towards higher trophic levels. In the central Adriatic Sea, the Self-Organizing Map (SOM) was used to analyse the time series of a number of microbial parameters at two stations with different trophic status. The results showed that responses of the microbial food web (MFW) structure to temperature changes are reproducible in time, regardless of the trophic status. The rise in temperature was associated with an increasing importance of microbial heterotrophic activities (increase bacterial growth and bacterial predator abundance, particularly heterotrophic nanoflagellates) and an increasing importance of autotrophic picoplankton (APP) in the MFW (Solic et al., 2018).

Mesocosm experiments have been fundamental to investigate the effects of elevated CO_2, ocean acidification (OA) and ocean warming (OW) on plankton communities. During a 10 - day mesocosm experiment in the EM where the pH decreased by ~0.3 units and temperature increased by ~3 °C the abundance of *Synechococcus* increased in response to warming, while the SAR11 bacteria clade immediately benefited from the combined acidification and warming (Tsiola et al., 2023). Similarly, in Thau Lagoon several microorganisms, including virio-, bacterio-, and phytoplankton < 10 µm in size, were monitored for 19 consecutive days in six mesocosms. Three mesocosms (control) had the same natural water temperature as the lagoon, and the other three were warmed by + 3 °C in relation to the control temperature. Important was the dominance of picophytoplanktonic cells, including *Prochlorococcus*-like and *Picochlorum*-like cells, which had not previously been found in Thau Lagoon. The experimental warming treatment increased the abundances of nanophytoplankton, cyanobacteria, bacteria and viruses during the experiment and triggered earlier blooms of cyanobacteria and picoeukaryotes (Courboules et al., 2022)

Assemblages of living coccolithophores were investigated off Methana, Eastern Peloponnese Peninsula (Greece), along a pH gradient formed by natural CO_2 seeps. High numbers of holococcolithophore species were dominating the assemblages in the surface water. Assemblages were unaffected by low pH environment and holococcolithophores and in particular *Algirosphaera robusta* displayed an increasing trend with lower pH. No malformed and very few corroded coccoliths were observed. Changes in the community structure were rather related to increased temperatures and nutrient content, while the overall trend associated low pH values with high cell densities. Diversity showed a weak decreasing trend, apparently linked with the dominance of *A. robusta* (Triantafyllou et al., 2018)

Coccolithophores are a group of calcifying phytoplankton that can reach high densities in the MS, and whose responses to OA are modulated by temperature and nutrients. D'Amario et al. (2020) investigated the impacts of the combined OA and OW on an oligotrophic EM coccolithophore community using a land-based mesocosm. Coccolithophore density drastically decreased under both OW and combined OA and OW (greenhouse, GH) conditions. *Emiliania huxleyi* calcite mass decreased consistently only in the GH treatment; moreover, anomalous calcifications (i.e. coccolith malformations) were particularly common in the perturbed treatments, especially under OA. Finally, it was suggested that the projected increase in sea surface temperatures, including MHWs, will cause rapid changes in EM coccolithophore communities, and that these effects will be exacerbated by OA.

The frequency of MHWs is projected to increase in the MS (more intensely in the eastern part), over the next decades. Soulié et al. (2023) performed an *in situ* mesocosm experiment in a Mediterranean lagoon for 33 days. Three mesocosms were used as controls following the natural temperature of the lagoon. In three others, two MHWs of + 5 °C compared to the controls were applied from experimental day (d) 1 to d5 (MHW1) and from d11 to d15 (MHW2). Gross primary production (GPP), respiration (R), phytoplankton growth (μ) and loss (L) rates were calculated. MHW1 significantly increased GPP, R, chl-a, μ and L by 7 to 38%. MHW2 shifted the system toward heterotrophy by only enhancing R. In addition, natural phytoplankton succession from diatoms to haptophytes was altered by both MHWs as cyanobacteria and chlorophytes were favoured at the expense of haptophytes. It was evident that MHWs have pronounced effects on Mediterranean plankton communities.

The effect of heatwaves (HWs) on phytoplankton is of particular concern because they are a key source of C, N, P and essential fatty acids to aquatic ecosystems. Laboratory studies have verified that phytoplankton grown at warmer temperatures are a lower quality food source, but how HWs affect phytoplankton quality at the community scale is currently unclear. Kim et al. (2024) demonstrated that zooplankton that consumed "HW" phytoplankton attained lower community biomass than those fed "constant warming" or "ambient" phytoplankton. In addition, despite receiving similar total heat input, phytoplankton exposed to "HW" conditions contained lower C, N, P and fatty acid concentrations compared to phytoplankton grown in "constant warming" conditions. Correlations between zooplankton biomass and all measured phytoplankton traits revealed that decreases in zooplankton biomass were best explained by low quantities of C, N and monounsaturated fatty acids in "HW" phytoplankton. Finally, it has been proposed that the effects of HWs on phytoplankton quality are clearly distinct from those caused by constant warming temperatures and that HW-mediated decreases in resource quality have immediate effects on consumer productivity.

EM is expected to be affected mainly due to changes in water circulation and surface water productivity is expected to increase (Macias et al., 2015). Modeling projections in the Aegean Sea propose an increase in primary productivity, which is anticipated to become mesotrophic from currently oligotrophic (Sgardeli et al., 2022).

On the contrary in the Middle East (ME) region, where temperature in 2090 to 2099 (compared to 1990–1999) will exceed the global threshold of 3.64 °C, a side effect of acidification will be a decrease in primary productivity (Cooley et al., 2009; Bopp et al., 2013), as well as, the increased acidity is expected to trigger dramatic changes to phytoplankton (Dutkiewicz et al., 2015). Roxy et al. (2016) confirmed such a change, as they found a negative trend in surface chlorophyll (between 20-30%), over a period of six decades.

Time-series are crucial to understand the status of plankton communities and to anticipate changes that might affect the entire food web. Semmouri et al. (2023) using time series data (2009-2022) found a significant abundance decrease (up to two orders of magnitude) in 4 dominant copepods (*Temora longicornis, Acartia clausi, Centropages* spp., *Calanus helgolandicus*). Generalized additive models pointed out that temperature, turbidity and chlorophyll-a were the variables consistently showing a relative high contribution in all models predicting the abundances of the selected species. The observed MHWs which occurred during the summer periods of the investigated years coincided with population collapses (versus population densities in non MHW- years) and are considered the most likely cause for the observed copepod abundance decreases. Moreover, the recorded water temperatures during these MHWs corresponded to the physiological thermal limit of some of the studied species. This was the first study to observe ocean warming and MHWs having such a dramatic impact (population collapse) on the dominant zooplankton species in shallow coastal areas.

Ensemble niche modelling has become a common framework to predict changes in communities' composition under climate change scenarios; in the sea forecasts have usually focused on taxa representing the top of the marine food-web, thus overlooking plankton.

Benedetti et al. (2018) modelled the habitat suitability of 106 copepod species and estimated the dissimilarity between present and future zooplankton assemblages in the surface MS. Their results proposed that nestedness with decline in species richness is the pattern driving dissimilarity between present and future copepod assemblages; the projections contrast with those reported for higher trophic levels, suggesting that different components of the pelagic food-web may respond discordantly to future climatic changes. Notably, the choice of modeling methodology emerges as a primary source of uncertainty, emphasizing the complexity of predicting zooplankton responses to climate change accurately. Despite these challenges, such modeling efforts provide crucial groundwork for anticipating potential shifts in zooplankton communities and their ecological ramifications.

Benedetti et al. (2019) used the functional traits and geographic distributions of 106 copepod species to estimate the zooplankton functional diversity of Mediterranean surface assemblages for the 1965 - 1994 and 2069 - 2098 periods, based on multiple environmental niche models. All but three of the 106 species presented range contractions of varying intensity. A relatively low decrease of species richness (- 7.42 on average) was predicted for 97% of the basin, with higher losses in the eastern regions. They proposed that climate change is not expected to alter copepod functional traits distribution in the MS, as the most and the least sensitive species are functionally redundant, which should buffer the loss of ecosystem functions. As the most negatively impacted species are affiliated to temperate regimes and share Atlantic biogeographic origins, these results are in agreement with the hypothesis of increasingly more tropical Mediterranean communities.

Benedetti et al. (2021) using a group of species distribution models for a total of 336 phytoplankton and 524 zooplankton species attempted to determine their present and future habitat suitability patterns. For the end of this century, under a high emission scenario, they found an overall increase in plankton species richness driven by ocean warming, and a poleward shift of the species' distributions at a median speed of 35 km/decade. Phytoplankton species richness is projected to increase by more than 16% over most regions except for the Arctic Ocean. In contrast, zooplankton richness is projected to slightly decline in the tropics, but to increase strongly in temperate to subpolar latitudes. In these latitudes, nearly 40% of the phytoplankton and zooplankton assemblages are expected to be replaced by poleward shifting species. This implies that climate change threatens the contribution of plankton communities to plankton-mediated ecosystem services such as biological carbon sequestration.

Key responses of zooplankton to ocean warming include shifts in phenology, geographical range, and body size, as well as, implications on both the biological carbon pump and the interactions with higher trophic levels. Phenology is highly responsive to a species' temperature sensitivity, thermal optima and adaptation rates. Under a warming environment, species have generally shifted polewards and/or to deeper layers to maintain their core within their optimum water temperature ranges; these range shifts, however, are not consistently observed and vary greatly in strength and direction and are often species-specific (Ratnarajah et al., 2023). Alongside shifts in phenology and range, declines in body size have been described as the third universal response to climate warming. Global studies on marine copepods, the most abundant multicellular aquatic animal on Earth, revealed that temperature was a better predictor of body size than either latitude or oxygen, with body size decreasing by 43.9% across a temperature range of 1.7 - 30 °C (Ratnarajah et al., 2023).

Berline et al. (2012) examined Mediterranean mesozooplankton time series from six coastal stations in the Balearic, Ligurian, Tyrrhenian, North and Middle Adriatic and the Aegean Sea, focusing on fluctuations of major zooplankton taxonomic groups and their relation with environmental and climatic variability. Concerning the Aegean Sea (Saronikos Gulf), they observed an increase of zooplankton abundance and decrease in chlorophyll possibly caused by reduction of anthropogenic nutrient input, increase of microbial components, and a more efficient grazing control on phytoplankton. The rapid warming of the world's oceans during the last few decades has affected distributional patterns of marine planktonic communities.

Villarino et al. (2020) investigated links between sea warming and changes in copepod community composition over the last 3 decades (1980 - 2012), using zooplankton time-series data collected at 3 sites; eastern North Atlantic (Bay of Biscay, Kattegat Sea) and the EM (Saronikos Gulf). Their results showed that in the Kattegat and the Saronikos Gulf, where the increase in temperature was greatest among the regions, the copepod community alteration was directly linked to temperature, indicating that species follow their thermal ecological niche over the years.

Kalloniati et al. (2023) explored the long-term changes of plankton biomass and timing of growth (phenology) in relation to warming, in the Saronikos Gulf, during 26 years (1988–

2015); interplay between warming and alterations in ecological status was evident. During higher nutrient input (1989–2004), a temporal mismatch between zooplankton and phytoplankton and a positive zooplankton growth - SST association, were observed; in the warmer, less mesotrophic period (2005–2015), an earlier timing of zooplankton growth was matching with phytoplankton growth. Finally, an abrupt negative interannual relationship between SST and mesozooplankton, and a summer biomass decrease (linked with cladoceran abundance) was detected. These results indicated that current warming could alter plankton abundance and phenology in the coastal EM, suggesting shifts in plankton community composition, causing potential cascading effects on higher trophic levels.

Ouba et al. (2016), exploring the potential impact of environmental changes on zooplankton abundance in the Levantine basin, found pronounced increase in zooplankton abundance concurrent with shifts in water mass dynamics; the activation of the Aegean Sea as a source of dense water formation as part of the "Eastern Mediterranean Transient-like" event, underscored the critical influence of thermohaline circulation on zooplankton populations. They also observed changes in the phenology of some taxa accordingly with a predominantly advanced peak of zooplankton abundance. These findings highlight the intricate relationship between climate-driven hydrological changes and zooplankton dynamics, emphasizing the need for sustained monitoring efforts to discern long-term trends accurately.

Batistić et al. (2014) investigated potential connections over the past 2 decades between mesoscale circulation regimes in the Ionian Sea and newly-observed species and the concurrent rise in sea temperature in the Adriatic Sea. Analyses of plankton samples from 1993 to 2011 in the southern Adriatic revealed marked changes in the non-crustacean zooplankton community. Eleven species were recorded for the first time in the Adriatic, while 3 species reappeared after years of absence. They found that the changes in the zooplankton community were related to the circulation regimes in the Northern Ionian Gyre (NIG). The occurrence of Atlantic/Western Mediterranean species coincided with anti-cyclonic circulation in the NIG, probably due to the advection of Modified Atlantic Water into the Adriatic, while the presence of Lessepsian species coincided with the cyclonic pattern, controlling the entry of EM waters. The impact has been that new species now make a significant contribution to the zooplankton community in the southern Adriatic and, in certain cases, have replaced native species. All the above, underscore the role of oceanic circulation in mediating species introductions and highlight the potential for future colonization events driven by climate-induced disruptions in circulation barriers.

Anthropogenic carbon dioxide emissions directly or indirectly drive ocean acidification, warming and enhanced stratification; the combined effects of these processes on marine plankton calcifiers at decadal to centennial timescales are poorly understood. Pallacks et al. (2023) investigated the response of surface-dwelling pelagic foraminifera to increases in atmospheric carbon dioxide; they found that increased anthropogenic carbon dioxide levels led to basin wide reductions in size normalized weights by modulating foraminiferal calcification. Finally they suggested that further increases in atmospheric carbon dioxide will drive ongoing reductions in marine biogenic calcification in the MS.

Large blooms of *Rhopilema nomadica*, a highly venomous rhizostamatid scyphozoan species, introduced to the Mediterranean through the Suez Canal, have become ubiquitous in the summer and winter months along the Israeli coasts since the mid-1980s. Though lacking data from the source population in the RS, the high within-population diversity and the high diversity of COI haplotypes support the hypothesis of multiple introductions events, or an open corridor with a continuous influx of propagules (Giallongo et al., 2021). It has been finally verified that the Israeli population is characterized by a rapid expanding trend. Since first reported in the EM during 1970s, this swarm-forming scyphomedusa, has been continuously expanding. Dror and Angel (2024) examined the effect of temperature on the benthic stages (polyps, podocysts, and strobilae) of this species. High temperatures proved beneficial to polyp survival and asexual reproduction, yet in some cases, polyps were able to survive at temperatures as low as 12°C. They proposed that the role of podocysts in *R. nomadica* is mainly to increase the current season’s polyp population, contributing to swarm formation and expected that future climate change conditions will increase the performance and expansion range of this scyphozoan.

In conclusion, climate change poses multifaceted challenges to plankton communities in the EM, with far-reaching implications for marine ecosystems. Sustained monitoring efforts, coupled with interdisciplinary research endeavors, are essential for elucidating the complex responses of plankton to climate change and informing adaptive management strategies aimed at preserving marine biodiversity and ecosystem resilience in the face of ongoing environmental changes.

3.3 Impact on life traits of marine organisms

Changes in the ocean chemistry due to climate change can cause severe sublethal effects which may affect future populations and communities composition. More specifically, disruption of the organisms' acid-base balance and alteration of their physiological functions has been observed, while organisms with calcium carbonate structures (e.g. shells, skeletons) may experience dissolution of their forms (Cummings et al., 2019). Conditions of lower pH and/or higher temperature can affect directly or indirectly growth, development, reproduction, metabolism, and behavior of marine species, thus impacting their population balance and overall health.

3.3.1 Reproduction

Ocean acidification (OA) impacts reproductive processes in marine invertebrates, but this research is very limited; the lack of such information has significant consequences for commercial aquaculture, wild fisheries, as well as for conservation and restoration of wild populations (Padilla-Gamiño et al., 2022). Implications of climate change on the sex ratio of a species will affect the proportions of females or males capable of breeding in a population, thereby reducing the effective population size (Padilla-Gamiño et al., 2022). For example, asynchronous or delayed gametogenesis might result in decreased fertilization success and larval fitness, which can alter recruitment dynamics and limit the expansion of oyster reefs thus eliminating all the valuable ecosystem services derived from those habitats (Boulais et al., 2017). The gametogenesis, fertilization success and early offspring development of the eastern oyster *Crassostrea virginica* were not affected by moderate near-future OA scenarios (pH 7.5), while more severe acidification (pH 7.1) inhibited gametogenesis and fertilization success (Boulais et al., 2017). In addition, acidification had an impact on the sex ratio of the eastern oyster, as it has been found that the less energetically costly spermatogenesis was favoured in relation to oogenesis thus resulting to an increased number of male oysters (Boulais et al., 2017). Low pH conditions resulted in higher survival of oyster larvae, reduced shell height and increased deformities (Clements et al., 2020).

Low pH experimental treatments had no significant effect on the fertilization success and the early development of the mussel *Mytilus edulis* larvae, including shell formation and feeding;

however, these larvae were 28% smaller than the control ones after 2 months (Bechmann et al., 2011). On the contrary, exposure of the mussel *Musculista senhousia* under low pH conditions resulted in eggs of bigger size indicating increased maternal care and more resilient larvae (Zhao et al., 2019). Indeed, larvae with a history of transgenerational exposure to elevated pCO_2 developed faster, survived better and completed metamorphosis in higher percentages, thus indicating a metabolic plasticity that generated more energy for fitness-related functions (Zhao et al., 2019). Acidification did not affect survival and growth of the abalone *Haliotis iris*, while warming increased their growth rates (Cummings et al., 2019). However, low pH conditions affected the quality of the abalone juveniles' shell and cased dissolution and thinning, with potential implications for resilience to physical stresses such as predation and wave action (Cummings et al., 2019).

Experiments on the coral *Primnoa pacifica* indicated a negative effect of OA on its oogenesis; oocyte diameter was reduced, fecundity was decreased and the proportion of the reabsorbed vitellogenic oocytes was higher, resulting to a subsequent limited amount of lipids necessary for successful larval development (Rossin et al., 2019). Even if the reproductive parameters of oocytes and spermacies (abundance and size) in the Mediterranean coral *Astroides calycularis* seemed unaffected after 3 months under low pH experimental conditions, a delay in spermacy development in the pre-fertilization period and a persistence of mature oocytes in the fertilization period were observed; a delay or interruption of the fertilization process leading to a lack of embryos, appears to have been caused by the acidified conditions (Marchini et al., 2021).

Similarly, acidified conditions reduced the naupliar production and growth of the benthic copepod *Tisbe battagliai*, which may drive shifts in life history strategies favouring smaller brood sizes, which might destabilize marine trophodynamics (Fitzer et al., 2012). The effect of low pH on shrimp larvae *Pandalus borealis* larvae caused a significant delay in zoeal development time, although overall survival was not reduced (Bechmann et al., 2011).

The combined impact of low pH and increased temperature on vital rates of the dominant pelagic copepod *Acartia clausi* were investigated in the Saronikos Gulf (Zervoudaki et al., 2014). Four different conditions were examined: 2 pH levels (present: 8.09 and future: 7.83) at 2 temperatures (present: 16°C and present+4 °C = 20°C). The reproductive output was decreased significantly at future pH for both temperatures. It was finally proposed, that the combination of acidification, warming and ambient oligotrophic conditions, can decrease species capability to allocate resources for coping with multiple stressors.

The gonadosomatic index of the female sea urchin *Paracentrotus lividus* was lower under low pH, suggesting a decreased energy investment in reproduction (Marčeta et al., 2020). Kurihara and Shirayama (2004) indicated that fertilization rate, cleavage rate, developmental speed, and pluteus larval size of the sea urchins *Hemicentrotus pulcherrimus* and *Echinometra mathaei* showed a decreasing trend when pH was getting lower, hence negatively affecting their early development and life history. Similarly, acidification and warming affected the reproductive potential of the sea urchin *Tripneustes gratilla*, where warming increased the gonad index, while acidification decreased it (Dworjanyn and Byrne, 2018). Mos et al. (2020) indicated that larvae of the sea urchin *Centrostephanus rodgersii* during metamorphosis had higher percentage of abnormalities and less number and smaller length of spines and pedicellaria at low pH conditions, although settlement rate or size were not affected.

In general, fish are considered more resilient to climate change since they are able to migrate and to maintain their internal pH through active ion transport (Melzner et al., 2009), which is of course highly costly in energetic requirements and can therefore affect physiology and overall development (Ishimatsu et al., 2008). Nagelkerken et al. (2021) indicated that OA indirectly increased energy budget for reproduction and parental care on fish species that were habitat generalists and competitively dominant; female fish reduced foraging and aggression activity to increase reproduction, while male fish increased energy intake by intensified foraging in order to increase reproductive investment. Miller et al. (2015) indicated that the interaction between low pH and high temperature on the reproduction of the reef fish *Amphiprion melanopus* was rather complex, while temperature appeared to have the major impact on reproduction; embryos developed under low pH had a 50% reduction in survival and the respective larvae were shorter and had less yolk compared to the control ones, leading to both reduced somatic growth at early stages and inferior juvenile performance.

Ocean warming is expected to affect fish reproduction either by shifting the spawning phases or by complete inhibition of reproduction, and this will be more pronounced in species that have a restricted capacity to shift geographic ranges (Pankhurst and Munday, 2011); impacts on reproduction are caused through the endocrine system, and more specifically due to the impairment of ovarian oestrogen production. Warming can also disturb the aromatase synthesis and activity, thus affecting the reproductive cycle, the sexual differentiation and the sexual inversion process in several fish species (Brulé et al., 2022).

Rising temperatures and prolonged MHWs are also increasingly reported to negatively affect the reproductive cycle and early developmental stages of the Mediterranean canopy brown algae (Falace et al., 2021), and *Posidonia oceanica* meadows (Rinaldo et al., 2023), posing further threats to the conservation and numerous key ecosystem services provided by these valuable habitat-formers (e.g. Gattuso et al., 2018; Krause-Jensen et al., 2018; Pergent-Martini et al., 2021).

3.3.2 Metabolism and behavior

The disruption of normal behavior processes in marine organisms, which is often the result of an altered metabolic path, has the potential to influence individual fitness and overall population success (Briffa et al., 2012). Behavioral responses guide the ability to perform essential tasks such as avoiding predators, feeding, competition and obtaining mating opportunities (Briffa et al., 2012).

Low pH increased oxidative stress and basal metabolic costs of the eastern oyster *Crassostrea virginica* (Beniash et al., 2010), which cannot be compensated by the reduced feeding activity observed under such conditions (Bamber, 1990). Wright et al. (2018) indicated that acidified conditions may alter the shell morphology and the metabolic reaction of the oyster *Crassostrea gigas* under the presence of a predator and thus increase its “visibility” as prey. The bivalve *Abra alba* almost completely ceased suspension feeding under reduced pH in comparison to ambient seawater pH in order to reduce the intake of low pH water during feeding and respiration (Vlaminck et al., 2022). On the contrary, the polychaete *Lanice conchilega* increased its pumping frequency after exposure to low pH conditions, thus suggesting higher metabolic demands (Vlaminck et al., 2022).

Low pH levels deteriorated the escape behavior of the conch gastropod *Gibberulus gibberulus gibbosus*, as result of a decision-making impairment, caused by a neurotransmitter receptor dysfunction due to the increased CO_2 (Watson et al., 2014). In addition, when the intertidal gastropod *Littorina littorea* was maintained under low pH conditions, not being able to induce defense against predators by thickening its shell, it showed an increased avoidance response and crawled out of the water sooner than control individuals (Bibby et al., 2007). Of course this behavior alteration is energetically costly due to increased locomotion and may have been coupled with the reduction of other activities such as grazing (Briffa et al., 2012). Herbivore gastropods might be characterized by increased consumption rates but, at the same time, decreased movement and less effective escape behaviors could result to increased predation pressure under future scenarios (Bass and Falkenberg, 2023).

Hermit crab *Pagurus bernhardus,* exposed to acidified conditions, reduced their ability for receiving information and decision making, thus indicating impaired selection behavior (de la Haye et al., 2011). In another study, hermit crabs under low pH treatment were less effective at locating their food source and showed lower rates of antennular flicking used for chemoreception than those exposed to normal seawater (de la Haye et al., 2012). The respiration rate of the sea urchin *Paracentrotus lividus* increased under low pH for both males and females, while ammonia excretion and lysozyme activity exhibited an increasing trend in males and decreasing in females (Marčeta et al., 2020).

The impacts of acidification on metabolism of teleost fish are contradicted, as this is probably related to the habitat type, where benthic and stenohaline fish species are more sensitive to acidification effects (Cattano et al., 2018). According to Cattano et al. (2018) fish larvae formed bigger otoliths under low pH conditions, however, it is not known if this could reduce their ability of sound detection and cause similar problems such as the ones that have been observed with otolith asymmetry (Gagliano et al., 2008). Nevertheless, Simpson et al. (2011) indicated that CO_2 enriched conditions indeed affected the auditory response of juvenile fish with potentially detrimental effects on their early survival due to their failure to avoid predators. Cattano et al. (2018) indicated that olfaction was the most sensitive sensory function affecting fish behavior at low pH levels. Under acidified conditions, fish larvae have been observed to even get attracted to the smell of their predators or to completely lose their ability to sense and detect them (Dixson et al., 2010; Munday et al., 2010). Fish predators are also adversely affected by low pH and instead of being attracted by their prey they might present avoidance behavior on the presence of injured prey (Cripps et al., 2011).

Fish reared under acidified conditions were characterized by a higher activity rate and they spent less time in their shelter, therefore becoming more susceptible in predation risks

(Munday et al., 2010). Despite higher activity patterns fish might present a lower feeding activity under acidified conditions, therefore reducing their ability to respond to fluctuating food availability (Cripps et al., 2011). According to Domenici et al. (2012) individual lateralization (decision of fish to turn either left or right) was disrupted under acidified conditions, thus providing evidence that brain function in larval fishes is affected together with a series of relevant cognitive tasks. The cause of such behavioral alterations can be the result of implications of the low pH on the correct functioning of the GABAA receptors, which are the main inhibitory neuroreceptors in the brain of vertebrates (Nilsson et al., 2012). Behavioral implications could result in a greater predation risk and a reduced foraging activity, which might cause increased mortality and lower growth from the individual at the community level (Cattano et al., 2018). The behavioral effects of reduced pH seem to be more dramatic for prey species, especially their larvae, than predators; even the impairment of predation capabilities cannot compensate for the effects of ocean acidification on prey mortality (Cripps et al., 2011).

3.4 Invasive species and altered pathways of species introductions

According to the EU and globally accepted definition, an alien or non-indigenous (NIS) species is "*any live specimen of a species, subspecies or lower taxon of animals, plants, fungi or micro-organisms introduced outside its natural range; it includes any part, gametes, seeds, eggs or propagules of such species, as well as any hybrids, varieties or breeds that might survive and subsequently reproduce*" (EU, 2014). In addition, NIS "*whose introduction or spread has been found to threaten or adversely impact upon biodiversity and related ecosystem services*" are called invasive alien species (IAS).

Invasive species (IAS, NIS), being among the major direct drivers of biodiversity change, have become a concern in virtually all marine coastal ecosystems around the world, but nowhere more than in the Mediterranean Sea (Galil et al., 2021). Off the Israeli coast 445 invasive species were recorded so far, more than anywhere in the Mediterranean (Galil, 2023), thus serving as a hotspot, beachhead, and dispersal hub for their spreading throughout the basin. The Suez Canal is the main pathway of IAS introduction into the Mediterranean Sea; its successive enlargements have raised concern over increasing propagule pressure resulting in continuous introductions of new Erythraean species and associated degradation and loss of native populations, habitats, and ecosystem services (Galil et al., 2017). It is now widely believed that "If we do not understand and mitigate the ecological risks associated with the expansion of the Suez Canal, the integrity of a large part of the Mediterranean ecosystem could be in jeopardy" (Samaha et al., 2016). Erythraean algae, invertebrates, and fish have profoundly marked the composition of the biota of the southeastern Mediterranean Sea, their impacts are determined, in part, by their demographic success (abundance and spread) (Galil et al., 2021). With few exceptions, the ecological impact of NIS on the native Mediterranean biota have not been scientifically studied (Galil, 2023). Meanwhile, many Erythraean species have become the most conspicuous denizens in Marine Protected Areas across the Levant, having displaced and replaced native species, thereby reversing marine conservation efforts and hampering stock recovery of key economically and ecologically important species (D'Amen and Azzurro 2020).

In the Mediterranean, research associated with invasive species has been constantly increasing during the last decades. Towards the needs of monitoring NIS and IAS, several databases have been established, such as the EASIN, AquaNIS, NOBANIS, MEDMIS, DAISIE that cover wider geographic areas and, in cases, include IAS taxa that are not aquatic. In addition, several countries have established their own databases, as in Italy (SIBM), Greece (ELNAIS) and Cyprus (CyDAS). On the other hand, marine invasion has not received such a great attention in the ME marine areas, presumably since the phenomenon is not of the same magnitude. Indeed, Lessepsian migration (i.e. the influx of Red Sea-Indian Ocean origin species into the Mediterranean) has and is still being thoroughly studied, whereas the opposite phenomenon (anti-Lessepsian migration) does not appear in the scientific literature to the same extent with only a few recent works being conducted. According to a recent account by Galanidi et al. (2023) half of NIS recorded in the Mediterranean are of Indo-Pacific origin having entered the basin through the Suez Canal. Morover, 59% of NIS in the eastern part is Lessepsian migrants, with this percentage becoming lower as we move westwards, indicating the strong effect of the Canal. The introduction of NIS in new biota has been strongly induced by climate change, as rising sea temperatures favor the likelihood of introduction, establishment and expansion of thermophilic species (e.g. Karachle et al., 2022).

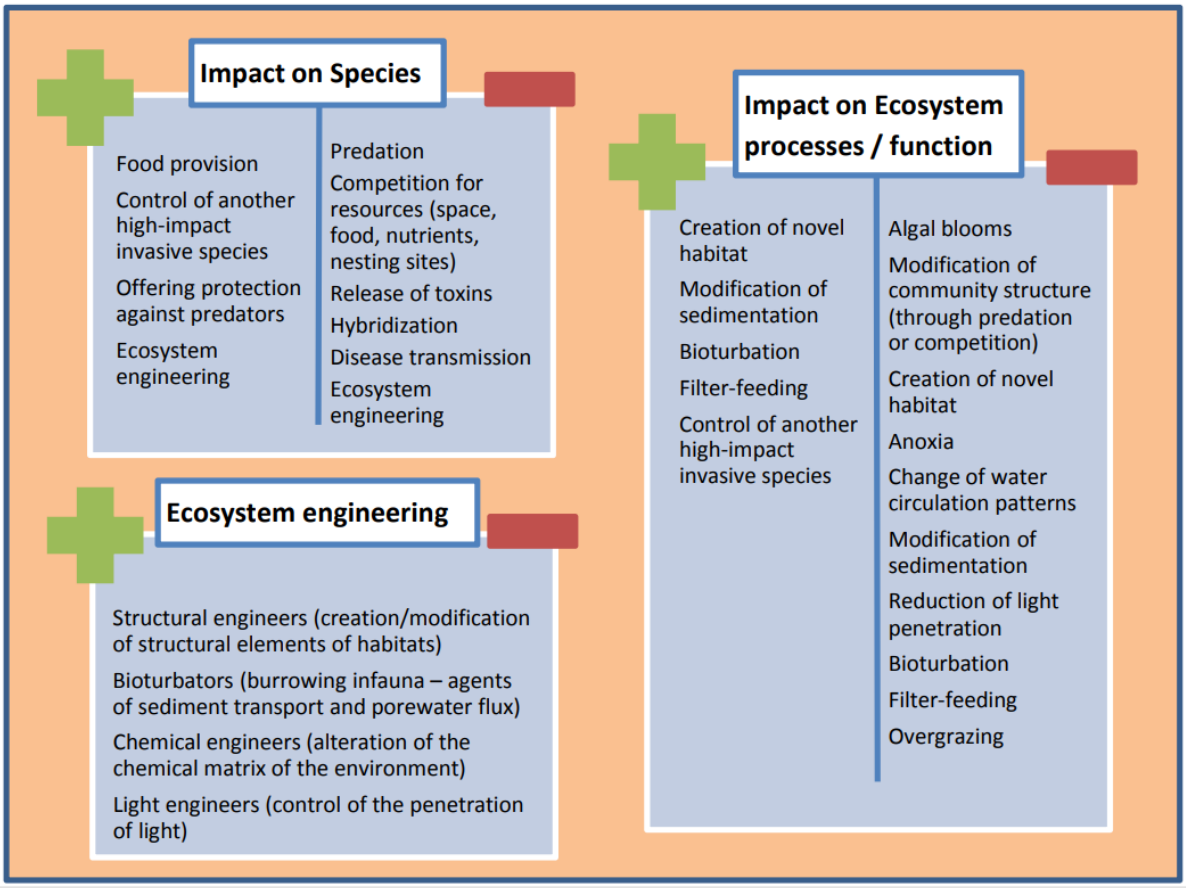
The Convention of Biological Diversity (CBD, 2014) has identified and described the potential pathways of NIS introductions across all environments. This classification comprises of six (6) major pathways, the following:

1. release in nature: organisms that are being intentionally introduced in any given ecosystem (e.g. for biological control, aquaria releases, fishery in the wild (including game fishing), introduction for conservation purposes or wildlife management),
2. escape from confinement: includes species that are used in an area for example for aquaculture / mariculture purposes, research and *ex-situ* breeding (in facilities), live food and live bait, etc,
3. transport – contaminant: species that are being transferred as contaminants and/or parasites,
4. transport – stowaway: here are included organisms that are being transferred as hitchhikers, e.g at ship/boat ballast water and hull fouling,
5. corridor: via interconnected waterways/basins/seas, such as through the Suez Canal,
6. unaided: natural dispersal across borders of invasive alien species that have been introduced through pathways 1 to 5.

All of the above pathways have been identified as vectors of introductions in the marine environment. With respect to the MS, the prevailing one is corridors, with more than half of the approximately 1000 NIS species having entered through the Suez Canal, followed by transport – stowaway (Galanidi et al., 2023).

The impacts of marine IAS have been documented, and are mainly being identified on biodiversity, ecosystem services (e.g. fisheries, tourism, industry) and human health. Impacts of IAS are not only negative, but in cases have a positive effect. In a thorough account, Katsanevakis et al. (2014) have mapped the mechanisms with which marine IAS impact biodiversity (Figuge 32) and ecosystem services (Figure 33). This work was further elaborated by Tsirintanis et al. (2022), including also impacts on human health.

FIGURE 32. Review of the key mechanisms that alien species impact biodiversity. Green cross: positive impacts; Red minus sign: negative impacts (from Katsanevakis et al., 2014)

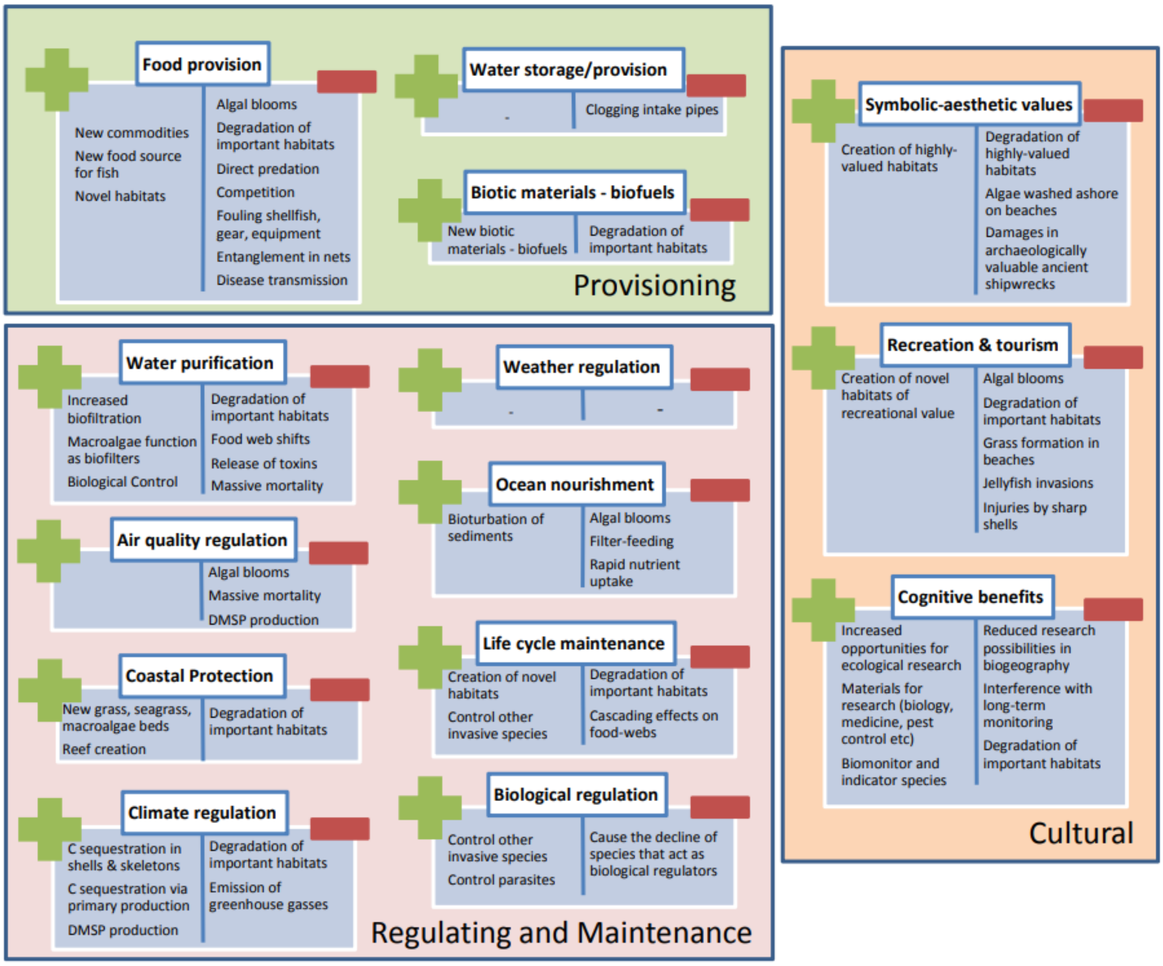


With respect to impacts on biodiversity, these are mainly perceived, as to date there are only reports and no actual proof. Indeed, evidence as well as the implementation of ecological indices reveals that IAS, and especially those of Indo-Pacific origin, could either displace (e.g. Bariche et al., 2004; Giakoumi, 2014), narrow the trophic niche (e.g. Stergiou, 1988), and/or decrease the biomass of local species (e.g. Bariche et al., 2004; Arndt et al., 2018) through competition for space and resources, and result in ecosystem and habitat degradation (e.g. Tsirintanis et al., 2023). Nevertheless, CC, combined with anthropogenic impacts, may induce extinction and/or extirpation of native species (e.g. Cheung et al., 2010; Robinson et al., 2019).

Food provisioning, recreation and tourism, as well as symbolic - aesthetic values are the most negatively impacted ecosystem services. Aquaculture and fisheries are affected from IAS in a wide variety of ways (e.g. Katsanevakis et al., 2014; Huseyinoglu et al., 2022; Tsirintanis et al., 2022; and references therein): (a) algal blooms, (b) macroalgal and ‘sessile species’ fouling;

(c) damage on fishing gear or catch, for example due to *Lagocephalus sceleratus* and *Callinectes sapidus*; (d) net clogging by *Rhopilema nomadica* swarms; (e) reduced fisheries yields; and (f) collapse of pelagic fisheries, as in the case of the Black Sea, due to the presence of *Mnemiopsis leidyi*. In certain areas of the EM, reduced biomasses of native commercial fishes and, in contrast, increased numbers and biomass of low-value IAS are being recorded with strong effects on fisheries (e.g. Bariche et al., 2004; Arndt et al., 2018; Kondylatos et al., 2023). On the other hand, IAS could be proven as a new fisheries resource increasing the income of fishers (e.g. van Rijn et al., 2020).

FIGURE 33. Review of the key mechanisms that alien species impact ecosystem services. Green cross: positive impacts; Red minus sign: negative impacts (Katsanevakis et al.,2014)



Finally, when we take into consideration the impact of NIS - IAS on human health they are only negative (e.g. Galil, 2018; Tsirintanis et al., 2022). The species that impacting human health belong to Osteichthyes, Cnidaria, and Echinodermata (Tsirintanis et al., 2022). To date, there are ten species that have been documented to cause injuries and poisoning: the fishes

Lagocephalus sceleratus, *Plotosus lineatus*, *Pterois miles*, *Siganus luridus*, *Siganus rivulatus*, *Synanceia verrucosa*, and *Torquigener hypselogeneion*,; the hydroid *Macrorhynchia philippina*; the jellyfish *Rhopilema nomadica*, and the sea-urchin *Diadema setosum*. Of those, it was worth making special reference to *L. sceleratus*, a fish that entered the Mediterranean through the Suez in 2003 (Akyol et al., 2005) and has spread across the basin (Coro et al., 2018; Ulman et al., 2021). The species is highly toxic as it contains a strong neurotoxin, Tetrodotoxin, that if ingested in high concentrations can lead to death. Moreover, recently, the species has been displaying an aggressive behaviour, attacking bathers. By 2023, more than 28 records of physical attacks, at least 144 non-lethal poisoning episodes, and 27 human fatalities resulting from consumption of the species have been recorded in the MS alone (Ulman et al., 2024).

Thus, the phenomenon of species invasions is strongly related to CC and increasing sea temperatures are expected to lead to further introductions, establishments and spreads. It is necessary for management actions to be taken in order to avoid the arrival of additional species, and definitely measures to be implemented in order to mitigate the impacts of NIS-IAS on biodiversity, ecosystem services and health. Such actions should include (Huseyinoglu et al., 2022; Figure 34): (a) prevention of new arrivals, through constant monitoring, information of relevant stakeholders and the public, and the enforcement of regulations; (b) early detection of new arrivals, in order for proper monitor and surveillance; (c) management, by means of removal, control and, if possible, eradication; and (d) adaptation, based on long-term monitoring and exploitation of those species that can be used, e.g. a food recourse, in the aquaculture industry (as fish-feeds), for pharmaceutical uses, and cosmetics.

FIGURE 34. Management strategies for IAS (from Huseyinoglu et al. 2022; copyright: IUCN)

3.5 Impacts on marine fisheries

In most marine regions worldwide, climate models predict intensity of extreme phenomena, changes in seasonality, changes in water circulation, stronger stratification and a significant reduction in primary productivity, especially in lower latitudes (Barange et al., 2018). Globally about 9% of animal food comes from marine fisheries; 39 million people are directly employed in it and about four times that number in dependent industries (FAO 2020). However, the effect of climate change (CC) on fishery resources is already present and predisposes to the degradation of the above numbers. CC can affect fisheries in a multitude of ways:

(i) **Rising sea temperatures** may trigger distributional shifts, forcing marine organisms to seek water masses within their temperature tolerance limits; poleward migration or occupation of deeper water strata have been documented (Cheung et al., 2009; Nye et al., 2009; Perry et al., 2005). In response to decreasing abundance and limited availability of commercial species in traditional fishing grounds, certain fisheries may have to re-allocate their activities towards distant marine regions, jeopardizing their economic viability (Pinsky &Fogarty, 2012).

(ii) **Ocean Acidification (OA)**, is the result of the absorption of excess atmospheric CO_2 produced from human activities leading to a decrease in pH (Gattuso and Hansson, 2011). It affects organisms that have calcium carbonate parts (e.g. gastropods, bivalves, corals) and ecosystems such as the coral reefs by weakening their ability to produce healthy hard parts (e.g. skeletons and shells). Although shellfish fisheries are the most commonly affected (Gazeau et al., 2007; Narita and Rehdanz, 2017), its impact on phytoplankton (Berge et al., 2010) can disrupt the whole marine food web, leading to declining primary productivity (Chust et al., 2014) and in turn lower fisheries yields (Cooley and Doney, 2009).

(iii) **Storminess**, is a climate stressor affecting marine life and habitats, with a potential negative consequence on fisheries yield and the well-being of coastal communities. Unprecedented extreme weather events are directly linked to global warming (Diffenbaugh et al., 2017) and are manifested, among others, through hurricanes, typhoons, storms and flooding. Storms affect fishing activities, compromise security at sea for fishers, and threat their vessels and gears, as well as land-based infrastructure. Although ocean warming may alter the potential fish catch in the near or distant future, changing storminess has the potential to cause more immediate and catastrophic impacts (Sainsbury et al., 2018).

(iv) **Sea Level Rise**, is a side-effect of global warming as ice sheets and glaciers melting will add excessive freshwater in the worlds' oceans (IPCC, 2022). Although dependent on future greenhouse gas emissions, even under optimistic projections a substantial rise is expected by the end of this century (Pörtner et al., 2019). Elevated sea level will result in loss of key coastal habitats (e.g. estuaries) serving as nurseries for several commercial species and a decline to fisheries production (Perry et al., 2005).

(v) **Altered Fish Physiology**, expected changes in ambient temperature and seawater chemical composition due to CC (IPCC, 2022) can trigger diverse physiological responses in marine organisms such as: disruption of reproductive cycle (timing and success of spawning) and reproductive fitness (Pankhurst and Munday, 2011), development rate of eggs and larvae (Petitgas et al., 2013), sex determination (Geffroy and Wedekind, 2020) and even evolutionary changes to adapt in a changing environment (Nagelkerken et al., 2023). As fishers plan their activities based on long established ecological knowledge of fish behaviour and availability, any variation in fish physiology and behaviour can affect the viability of fishing communities.

Other consequences of CC on marine habitats include expansion of the Oxygen Minimum Zones, disruption of ocean circulation and physicochemical properties affecting ecosystem functioning, alteration of species composition, limiting vertical and horizontal movements of migratory and other species, with consequences for connectivity between populations and more frequent growth of toxic phytoplankton and spreading of parasites and pathogens to commercially targeted species.

All the above are projected to reduce potential fisheries production by 2.8-5.3% by 2050 under the strict greenhouse gas mitigation scenario (RCP2.6) and by 7-12.1% under the very high emissions scenario (RCP8.5) (Barange et al., 2018). These alarming projections foresee significant impacts on local communities (e.g. poverty and food security).

3.5.1 Impact on EM fisheries

Mediterranean fisheries have certain distinct features: (i) high diversity of catches, (ii) high number of captured species (as many as 115 species), (iii) absence of large single stocks, (iv) a relatively small body size of specimens (known as Mediterranean nanism ("dwarfism", Tortonese, 1951) and (v) small scale vessels (>80% of the vessels, are smaller than 12 m in length). Moreover, fishing activity in the Mediterranean is mostly exerted along coastal areas, where biodiversity is high, targeting small sized species, or juveniles prior to maturity. Caddy (2009) has aptly defined Mediterranean fisheries as "fisheries for juveniles". Mediterranean fisheries have experienced a rapid expansion during the 20th century. Motor powered vessels have gradually set aside the traditional sailing vessels in the beginning of 1900s; after WWII, almost all trawlers were equipped with motor engines (Osio, 2012). Noticeable escalation of fishing capacity (engine power and fishing depth range), became evident after the 1960s. Progressively, this resulted in declining catches, which is quite notable considering the abrupt steep intensification of fishing efficiency during the past century (FAO, 2022a). The exploitation rate of Mediterranean stocks over the past 20 years has been steadily increasing, selectivity (proportional exploitation of juveniles) has been deteriorating, and stocks have been shrinking (Vasilakopoulos et al., 2014). This perennial exploitation of marine resources must have shaped the currently poor status of most commercially exploited stocks; 9 out of 13 currently assessed stocks in the EM region have fishing mortalities more than twice the target for achieving sustainable exploitation (FAO, 2022a).

However, in recent years the plausible contribution of CC in this alarming stock status has been investigated. MS is storing a disproportionally large stock of anthropogenic carbon and at the same time, it is characterised by a faster warming, compared to other ocean regions (Khatiwala et al., 2013; Adloff et al., 2015). It is suggested that Mediterranean fisheries vulnerability to CC is higher, given overfishing, higher exposure to warming, arrival of non-indigenous species, and an overall lower adaptive capacity (Hidalgo et al., 2018). A recent Climate Risk Assessment (CRA) methodology employed on Mediterranean fisheries, combining catch-based vulnerability with a suite of socio-economic parameters, suggested that the southeastern Mediterranean countries stand out as the most vulnerable to climate change impacts; Egypt and Tunisia scoring the highest risk (Pita et al., 2021).

Global warming causing an expansion of the tropical jellyfish range triggering 'regime shifts' such as from fish to jellyfish. In the last decade an increasingly high number of gelatinous plankton blooms are occurring and it is now questioned whether '*a Mediterranean Sea full of jellyfish is a probable future*'. Jellyfish jeopardize, among others, the economic viability of fisheries as they consume larvae of commercial fish species (Gravili, 2020).

Gkanasos et al. (2021) found that sardine and anchovy in the north Aegean Sea reacted negatively to a temperature increase, with anchovy being more affected, as its spawning and larval growth periods largely overlap with the period of maximum annual temperature and low prey concentration. Simulation based on future climate scenarios predicted that temperature increase and zooplankton abundance decrease, will negatively affect anchovy, resulting in sardine prevalence. Comparably, environment suitability for valuable commercial cephalopods such as squids, cuttlefish and octopus, is decreasing in the MS with their favorable areas rapidly shifting to the North European waters (Schickele et al., 2021). In contrast, the population of round sardinella in the north Aegean Sea exhibited a 30-fold increase since the early 1990s and revealed a positive correlation to sea surface temperature (Tsikliras, 2008). Such distributional shifts and population outbursts will most likely affect community and ecosystem functioning which in turn may threaten local fisheries economy by altering the composition and amounts of catches.

Similar models predict "winners" and "losers" species on a long-term scale (Moullec et al., 2019; Tsagarakis et al., 2022; Papantoniou et al., 2023). At basin scale, projected climate change would have large consequences for marine biodiversity by the end of the 21st century under a business-as-usual scenario (RCP8.5 with current fishing mortality) (Moullec et al., 2019). The total biomass of high trophic level species (fish and macroinvertebrates) is projected to increase by 5 and 22% while total catch is projected to increase by 0.3 and 7% by 2021-2050 and 2071-2100, respectively. The bulk of increase in catch and biomass would be located in the southeastern Mediterranean. Winner species would mainly belong to the pelagic group, are thermophilic and/or exotic, of smaller size and of low trophic level while loser species are generally large-sized, some of them of great commercial interest, and could suffer from a spatial mismatch with potential prey subsequent to a contraction or shift of their geographic range. Nevertheless, simulations of more sustainable exploitation of resources result in increased resilience to climate change in the EM as well (Bastardie et al., 2022; Moullec et al., 2023), as in other parts of the world.

Re-organization of communities and changes in the composition of fishery catches (Tzanatos et al., 2014) have been attributed to regime shifts, for the most part triggered by a warming climate (Damalas et al., 2021). Projections in the Aegean Sea foresee an increase in primary productivity, which is expected to become mesotrophic from currently oligotrophic; mullet stocks might be favoured, while the European hake stock is more likely to be in decline (Sgardeli et al., 2022). In the Mediterranean Egyptian waters climate change has apparently influenced the overall productivity as well as the species composition of the catch; mean temperature of catch (MTC) has increased by an annual average of 0.07 °C per year since 1987 (Khalfallah et al., 2023). A similar increase was found in the Mediterranean Turkish waters, reaching 0.48°C per decade (Keskin and Pauly, 2018). A pan-Mediterranean study (Peristeraki, et al., 2019), concluded that elevated MTC values were observed in the central and eastern areas with bottom temperature increases occurring after 2010, in a west to east and north to south direction. However, this recently observed increase in bottom sea temperature has not resulted in an immediate response by demersal marine communities.

Observed changes in the distribution of species consist of the movement of species from the South to the North, from the Mediterranean to the Black Sea and, above all, the invasion of thermophilic species from the Indo -Pacific through the Suez Canal (Hidalgo et al., 2018). EM is expected to be affected mainly due to changes in water circulation and surface water productivity is expected to increase (Macias et al., 2015). The impact on the southeastern Mediterranean is manifested through the invasion of alien species competing with native ones for the same resources. Alien invasions, as a result of CC, have transformed Levant reefs, and even well managed marine reserves had little effect on alien species presence (Rilov et al., 2018). There is growing evidence for increasing contribution of alien species in the Aegean Sea catches (Zenetos et al., 2011), with partial replacement of mullets *Mullus* spp. with goatfish *Upeneus* spp. (Bianchi et al., 2014), and of salema *Sarpa salpa* with spinefoot *Siganus* spp. (Giakoumi, 2014), already occurring. For instance, Siganids represent about 80% of the abundance of herbivorous fish in the EM coastal waters already since more than a decade ago (Bariche et al., 2004). These changes are expected to result in a reduction of the catch and income of fishermen, changes in their activity and a redistribution of fishing effort towards new fishing grounds. As most alien species are mainly found in shallow waters, the most affected will be the small coastal fisheries which make up an 83% in number of vessels and a 57% in workforce.

The anthropogenic CO_2 concentration in the MS is higher than in the Atlantic Ocean and the Pacific Ocean at the same latitude, and higher than other marginal seas in the northern hemisphere (Lacoue-Labarthe et al., 2016). Although adult fish seem to withstand amplification of OA, early life stages of fish and shellfish in general may be severely impacted through growth impairment and reduced calcification respectively. However, indirect impacts of OA may have far more widespread consequences, such as changes to biodiversity, habitat loss and trophic web alteration (Lacoue-Labarthe et al., 2016). In this context, the cumulative effects of warming and acidification pose a significant threat to Mediterranean fisheries (Rodrigues et al., 2013), especially the ones targeting small pelagic populations, which seem to be the more seriously affected (Martin et al., 2012).

As several fish species tend to reach maturity at a smaller size in warmer waters, recent studies investigated the plausible impacts, considering that CC will continue to warm the seas. Shapiro Goldberg et al. (2019), studying a set of 16 fish species, found that this trend is more pronounced in the southeastern MS, while Legaki et al. (2023) suggested that a large-scale climate driven environmental regime shift in the eastern Ionian Sea led to a decline in the size-at-maturity of European hake. It is put forward that this size reduction is dramatically larger in active fish species than more sedentary species, as the temperature dependence of oxygen consumption depends on activity levels (van Rijn et al., 2017). As size at maturation shapes population dynamics and the stocks resilience/vulnerability to fishing, the impact on the fishing industry is yet to be investigated.

3.5.2 Impact on ME fisheries

The Red Sea (subarea 51.1) and Persian/Arabian Gulf (subarea 51.2) comprise part of the Western Indian Ocean (FAO major fishing area 51).

The Red Sea (RS), oceanographic and biological features are quite unique, as it hosts extended regions of coral reefs. It holds the earliest record of human consumption of seafood (~125,000 years ago; Walter et al., 2000) and is currently an important fishing ground for the seven countries along its shores. RS fisheries are multi-gear and multi-species in nature. At large, fishing is exerted by wooden boats ranging from 5 to 18 meters. RS total catch increased from 50,000 t annually in the 50s-60s, to a peak of 177,000 t in 1993, due to massive boat motorization and industrial fishing initiation, and remained stable until the mid-2000s when it started to decline (Tesfamichael and Pauly, 2016); apparently due to resource depletion. Artisanal fisheries are the main players contributing half of the catch; interestingly, catch composition is highly variable, with no single species dominating. Fisheries are practically open-access as most countries lack fisheries regulatory schemes and monitoring, control and enforcement is ineffective. In terms of production, Yemen (36%), Egypt (28%), Saudi Arabia (23%) and Eritrea (11%) have sizeable and long-established small-scale fisheries, while Saudi Arabia has a recently established industrial fishery. More important in social than economic terms, the sizeable small-scale fisheries (~50% of the fleet) provide opportunities for employment and sustain local communities "well-being" (Tesfamichael and Pauly, 2016).

The Persian/Arabian Gulf (PG) is a partially enclosed body of water, surrounded by the arid region of the ME. It is characterized of highly productive coastal habitats, including intertidal mudflats, seagrass, algal beds, mangroves, and coral reefs, supporting important commercial fisheries (Sheppard et al., 2010). The utilization of the fishing industry in the PG region is second in importance only to oil and gas in stimulating the economic development of the coastal States (Sale et al., 2011). Fisheries have been supporting local livelihoods in the region since the 6th millennium BC (Beech, 2002). Currently, fisheries are multi-specific and multi-gear, dominated by small scale coastal fisheries vessels, with the exception of industrial shrimp trawlers in Kuwait, Saudi Arabia, and Iran. Most common fishing boats operate with hook-and-lines, gillnets, traps (gargoor), and weirs (hadrah). Total marine fisheries catches suggest a gradual increase from around 200,000 t in 1950 to a peak of 600,000+ t in 1997, followed by a sharp decline to 380,000 t in 2004 and a relative stability in total catches thereafter. Artisanal fisheries account for 75% of total catches. Iran accounts for the largest catches, with 56%, followed by the UAE (12%), Kuwait, Saudi Arabia, and Bahrain (9% each). Catch composition is quite diverse consisting of herring-like fishes (Clupeiformes, 10%), sharks and rays (8%), shrimps and prawns (7%), crabs and lobsters (6%), ponyfishes (6%), and catfishes (6%) (Al-Abdulrazzak et. al., 2015).

In the western Indian Ocean increasing warming has been observed for more than a century, at a rate faster than any other region of tropical oceans (Hoegh-Guldberg et al., 2014; Roxy et al., 2014). The sea surface temperatures increased by 0.60 °C between 1950 and 2009.

A long-standing OA trend is apparent during the past decades; this trend being consistent with the increase in atmospheric CO_2 (Dore et al., 2009). A decrease of sea surface pH by 0.1 is expected while dissolved oxygen (between 200 m and 600 m depth) is projected to increase by the end of the century under the optimistic RCP2.6 scenario (Bopp et al., 2013). The aforementioned stressors are projected to hit extremes under the pessimistic RCP8.5 scenario; especially water temperature in RS and PG region in 2090 to 2099 will exceed the global threshold of 3.64 °C. A side-effect of acidification will be the primary productivity reduction (Cooley et al., 2009).

In particular, the RS is undergoing an intense and rapid increase in temperature; mean temperature during 1994–2007 was 0.7 °C higher than during 1985–1993; this being the greatest shift over the past 160 years (Raitsos et al., 2011). Climate change caused coral bleaching, decreased coral reef growth and decline of large corals in the last two decades (Baker et al., 2004; Kotb et al., 2008; Cantin et al., 2010; Riegl et al., 2012; Furby et al., 2013; Tesfamichael and Pauly, 2016)

Comparably, the PG surrounded by hot deserts, is obviously exposed to SST warming. Although a positive trend in SST time series is evident, the increase varies among the east and west coasts. In the eastern side, SST change ranges between 0.08 and 0.11 °C/decade while on the western side, between 0.56 and 0.7 °C/decade (Hereher, 2020). Increasing SST is linked to significant coral reef bleaching (Hereher, 2020). Climate change impact on the PG ecosystem is projected to be intensified, due to its quasi-enclosed nature limiting species reallocation, overfishing, and pollution (Ben-Hasan and Christensen, 2019).

The coral reef ecosystems (including mangroves and seagrass beds) which provide important fish habitat and support coastal fisheries in the region are facing unprecedented stress from warming and rising seas, acidification and storms (Obura et al., 2017b). Furthermore, changes to primary productivity will likely put additional stress on fisheries resources in this region where oxygen depletion, acidification and overfishing have already impacted the resources (Obura et al., 2017a).

Catches of coral reef fisheries will be the most severely affected, threatening the livelihoods of coastal communities as these fisheries represent a significant part of their subsistence. By contrast, locally-operated artisanal or semi-industrial fishing fleets could be severely affected unless they can innovate and adapt their gears to the changing habitat conditions (e.g. fishing deeper; Barange et al., 2018). Small-scale reef fisheries across the region are highly vulnerable to CC (IPCC, 2014).

Studies on the RS fisheries of Saudi Arabia identified a continuous decrease in the total annual catches of iconic commercial species such as groupers and emperors. This alarming fisheries scenario is assumed to be a combined effect of CC, natural fluctuation, and overexploitation (Al-Rashada et al., 2021).

In the PG area, the predicted increase in the average temperature and the sharp decrease in precipitation (Al-Maamary et al., 2017) may lead to a decline in many priority species, with the decline predicted to reach 35% in 2090 compared to the status quo level in 2010 (varying in different regions of the PG). Simulations suggest that local extinctions might be experienced throughout the PG region; the greatest impact occurring along the coast of its western side (number of species and catch), including Bahrain, Qatar, Saudi Arabia, and UAE (Wabnitz et al., 2018). A jellyfish bloom during 2022 in the Gulf of Oman and PG resulted in a reduced fisheries catch, owed to damaged fishing gear and interrupted fishing operations (Daryanabard and Dawson, 2008). Lachkar et al. (2022) observed a decline in oxygen concentrations in the PG over the past few decades accompanied by an expansion of seasonal near-bottom hypoxia and a lengthening of the hypoxic season. It is suggested that this alteration of the PG physical environment will have profound potential implications for the ecosystems and the fisheries of the region.

3.6 Impacts on aquaculture

Aquaculture is an important economic sector in the whole EMME. Following the global trend for increased demand of aquaculture products, the region has shown increasing rates in production over the last 30 years, with its growth being retained even amid the worldwide COVID-19 pandemic (FAO, 2022b). Such rates have been exceptionally high in densely populated developing countries such as Egypt, where aquaculture contributes more than 60% of the total fisheries and aquaculture production, thus setting successful examples for other countries with similar conditions. The main producing countries are Egypt, Turkey, and Greece with an annual marine and coastal finfish production of 350, 289, and 110 thousand tonnes respectively for the year 2020 (FAO, 2022b). A small but growing number of finfish farms operate across the rest of the EMME countries while Saudi Arabia also maintains a sizable production of crustaceans in the coastal zone (Salama et al., 2016). Due to the oligotrophic nature of the EM and the RS, farming of molluscs and algae is very limited and the majority of mariculture products comes from finfish. In particular the main farmed species are the gilthead seabream (*Sparus aurata*) and the European seabass (*Dicentrarchus labrax*) in Turkey and Greece and the flathead grey mullet (*Mugil cephalus*) in Egypt, the three of which comprising over 95% of the production (Eldeep and Abozied, 2013; FEAP, 2019). Emerging species like the meagre (*Argyrosomus regius*), the greater amberjack (*Seriola dumerili*), the red porgy (*Pagrus pagrus*), and the barramoundi (*Lactes calcarifer*) are also farmed to a lesser extent.

Unlike wild fish which can alter their behaviour to avoid unfavorable conditions by moving to deeper waters or migrating on the latitudinal axis, farmed fish are physically constrained by the production system they are reared into and therefore cannot escape from such conditions. As has long been recognized, this renders aquaculture a vulnerable sector to Climate Variability and Change (CV&C) (De Silva and Soto, 2009; Rosa et al., 2012). This is especially the case for the EM due to the higher than global warming rates and thus, a large number of potential climate change impacts have been identified which will affect not only the aquaculture industry but also the dependent communities (Brugère, 2015; Collins et al., 2020). These impacts can typically be attributed to individual physical-chemical climate factors (climate stressors) such as temperature increase, ocean acidification, marine heatwaves, sea level rise, changes in salinity, circulation patterns and combinations of the above while their severity will depend on the intensity of the stressors coupled with the vulnerability of the farmed species. That being said, due to the intensively managed nature of the aquaculture activity, the actual impact of the identified threats will largely depend on the ability and flexibility of the industry for mitigation and adaptation.

Undoubtedly, the increase of temperature is the CV&C factor with the most prominent effects on fish biology, which is why it has been extensively studied for most farmed species (Reid et al., 2019) and there is relative confidence in assessments of its potential impacts. Traits such as growth, survival, maturation, fecundity, and timing of reproduction have been associated with temperature (Crozier and Hutchings, 2014). Moreover, for established species such as g. seabream, E. seabass, and flathead grey mullet the thermal tolerance and thermal preferences have been studied sufficiently (Claireaux et al., 2006; Ozolina et al., 2016; Islam et al., 2020; Stavrakidis-Zachou et al., 2022) while they remain elusive for the emerging species. Considering that growth performance is optimal within a species specific temperature range and deteriorates bilaterally outside it (Pörtner et al., 2017), one should critically evaluate the potential effects on the farmed species in combination with the projected increase in temperature. Indicatively, a positive relation between temperature and high production is supported by both laboratory research and historical data on wild populations (Bento et al., 2016; Bouaziz et al., 2017). Consequently it has been suggested that aquaculture in the Mediterranean should exploit the warmer temperature to increase production, although other considerations such disease outbreaks and oxygen limitations due to high production volumes should also be taken into account (Rosa et al., 2012). Moreover, the effect on growth seems to be stage-specific, and therefore it is critical to consider potential impacts over the entire lifespan of the fish (Alami-Durante and Rouel, 2006). For instance, elevated temperatures during early life stages may induce male heavily skewed sex ratios (e.g. for for E. seabass) or skeletal abnormalities which may negatively affect production later on (Arfuso et al., 2017; Sfakianakis et al., 2013).

Due to the many uncertainties in climate modelling as well as to limitations on our knowledge regarding the biological effects close to the edges of the species thermal tolerance range, it is challenging to forecast the long term effects of global warming on farmed fish. Yet, some modelling studies exist for the Mediterranean regions which offer useful insights for the future. Using a bioenergetics modelling approach, Stavrakidis-Zachou et al. (2021) simulated potential effects on growth performance and farm profitability under RCP45 and RCP85 scenarios for E. seabass and meagre, also considering the effects of extreme weather events and a number of husbandry parameters. Their simulations suggest that while fish indeed may slightly benefit from the higher future temperatures in terms of growth, the benefits will be largely offset by the negative effects of extreme event**s** like marine heatwaves and storms. They also proposed that such events may cause substantial mortalities, escapees and losses in biomass which will have implications to farm profits ranging from mild to detrimental depending on the various scenarios. The same authors also suggest, that shifts in management practices such as the time of stocking, the selection of inshore or offshore locations for farming, and the choice of target market size may offer impactful adaptation solutions. Furthermore, the above simulations were integrated into a free access computer-based Decision Support System (DSS), along with other climate relevant data such as a risk and opportunity analysis and economic information for aquaculture farms in Greece (Stavrakidis-Zachou et al., 2018, 2021. While this tool does not expand to the whole EMME area, it still offers useful means of assessing alternative climate and production scenarios for one of the many producing countries, and thus, provides insights on future climate impacts according to the severity that the users assign to various climate threats. On another modelling study, Sarà et al. (2018) predicted the shift in the sustainability trade-offs of finfish farming in the Mediterranean under climate change. In particular, they demonstrated that climate change will have detrimental effects on the environmental sustainability of fish farming and also that there will be significant trade offs between environmental costs and benefits in the future which will vary widely under various spatiotemporal scales. While the forecasting of the above studies is limited to a few species and areas, the methodology appears promising for expanding predictions to other important aquaculture finfish and regions such as the Red Sea and the Arabian Sea.

Regarding the impacts of other climate stressors on aquaculture, the available information appears scarce. For acidification, the lower future pH in the EMME is expected to affect calcifying organisms, resulting in reduced calcification rates and shell dissolution, thus, posing threats to bivalve farming (Gazeau et al., 2007; Rosa et al., 2012). However, elevated CO_2 concentrations seem to affect adult fish minimally (Pope et al., 2014), and according to Lacoue-Labarthe et al. (2016) the most commonly farmed species in the EMME region will be able to withstand the projected CO_2 concentrations in the near future. While some mild physiological responses may be recorded, it has been shown that even under the most pessimistic IPCC scenarios, the larvae and fingerlings of E. seabass (which are generally less resilient than adults) will not exhibit significant alterations of gene expression, survival, and growth (Crespel et al., 2017) depending on the species however, other species may be more vulnerable during the early developmental stages. Following the increasing of water temperatures, the frequency and intensity of eutrophication and occurrence of Harmful Algal Blooms (HABs) are expected to be increased. While there is an inherent uncertainty in forecasting such events for the EMME region (Wells et al., 2015; Aleynik et al., 2016), their ramification for aquaculture under climate change may be causing severe events of hypoxia, toxicity, gill irritation, disease, and mass mortalities in reared fish populations as has been shown in the Sea of Oman and the Western Arabian Sea (Harrison et al., 2017). Uncertainties also exist for the future impacts of changes in salinity as well as in the dissolved oxygen. In particular, the latter presents a stressor of critical interest for fish farming. While it is challenging to model long terms changes, future projections for the EM are optimistic that the area will remain fully oxygenated by year 2100 even under the most adverse scenarios (Powley et al., 2016). However, due to the fact that oxygen solubility decreases with temperature increase, the presence of marine heatwaves, other localized events, and algal blooms, especially around farming areas where the oxygen demand is substantially higher, may exacerbate potential hypoxic events. Such hypoxic events may in turn result in reduced fish appetite, growth retardation (Thetmeyer et al., 1999; Pérez-Jiménez et al., 2012) and even mass mortalities which can have severe ramifications for the industry. Another aspect of CV&C that may have important consequences for finfish farming in the region is diseases. Disease outbreaks have traditionally been the main bottleneck in aquaculture, accounting for economic losses of billions of dollars every year (Meyer, 1991). Elevated temperatures affect both the physiology of the fish, often rendering them more susceptible to disease (Magnadóttir, 2006) but also promote the growth rates of pathogens ranging from bacteria, and viruses to multicellular parasites (Burge et al., 2014; Lafferty et al., 2015). Consequently**,** global warming is expected to exacerbate disease outbreaks, especially around aquaculture sites where fish are kept in high stocking densities. These outbreaks not only have huge financial implications for farming but also pose potential threats for humans as some pathogens found in the EMME regions such as bacteria *Photobacterium damselae* and *Mycobacterium marinum* have been known to have zoonotic potential (Lima dos Santos and Howgate, 2011; Gauthier, 2015). In their review, Cascarano et al. (2021) reported that many of the pathogens afflicting the populations of the main Mediterranean aquaculture fish have temperature thresholds significantly higher than their host. Consequently, as temperatures continue to increase causing fish welfare to deteriorate, pathogens will thrive, potentially increasing the frequency and severity of disease outbreaks.

Overall, CV&C is expected to impact finfish aquaculture in the EMME in a multitude of ways. Positive effects may be expected, such as increased growth rates, particularly during the winters which will now be milder allowing larger seasonal windows for growth while others such as extreme weather events and outspread of diseases may be detrimental for production. It is important to note that the optimum temperatures for the main species currently being farmed in the area lie between 22-28^{o}C while the tolerance range for survival seems to be a conserved trait among them ranging from 32-34^{o}C (Person-Le Ruyet et al., 2004; Claireaux et al., 2006; Dülger et al., 2012; Kır et al., 2017; Kır, 2020; Islam et al., 2020; Stavrakidis-Zachou et al., 2021, 2022). Considering that summer temperatures already reach 28-30^{o}C in certain parts of the EMME (Shaltout and Omstedt, 2014; Sakalli, 2017), it is evident that the species will progressively have to reside in temperatures outside their optimal range. Since these species can tolerate even higher temperatures during acute warming events, their survivability may not be threatened by temperature alone in the near future (Kır et al., 2017;

Stavrakidis-Zachou et al., 2021, 2022). However, it should be taken into account that the synergistic effect of temperature with other drivers such as dissolved oxygen, acidification, HABs, and salinity may substantially reduce those tolerance thresholds. Moreover, what will be largely impacted is the profitability of farming. Studies on E. seabass, g. seabream, and meagre have shown that rearing in temperatures exceeding the optimum range result in physiological stress, and progressively lower growth performance which eventually diminishes to zero once the upper biological thresholds are reached (Antonopoulou et al., 2020; Feidantsis et al., 2021; Stavrakidis-Zachou et al., 2021, 2022). By extension, prolonged exposure of fish in these conditions is correlated with lower production volumes and concomitant increase of operational costs related to low conversion efficiency (low Feed Conversion Ratio), and higher expenditure on disease prevention and treatment. While the impacts of climate change on EMME aquaculture are multifaceted, carry inherent uncertainties, and more research is required, the use of forecasting models and other tools such as DSS, offer useful means of evaluating potential future scenarios and constructing adaptation strategies.

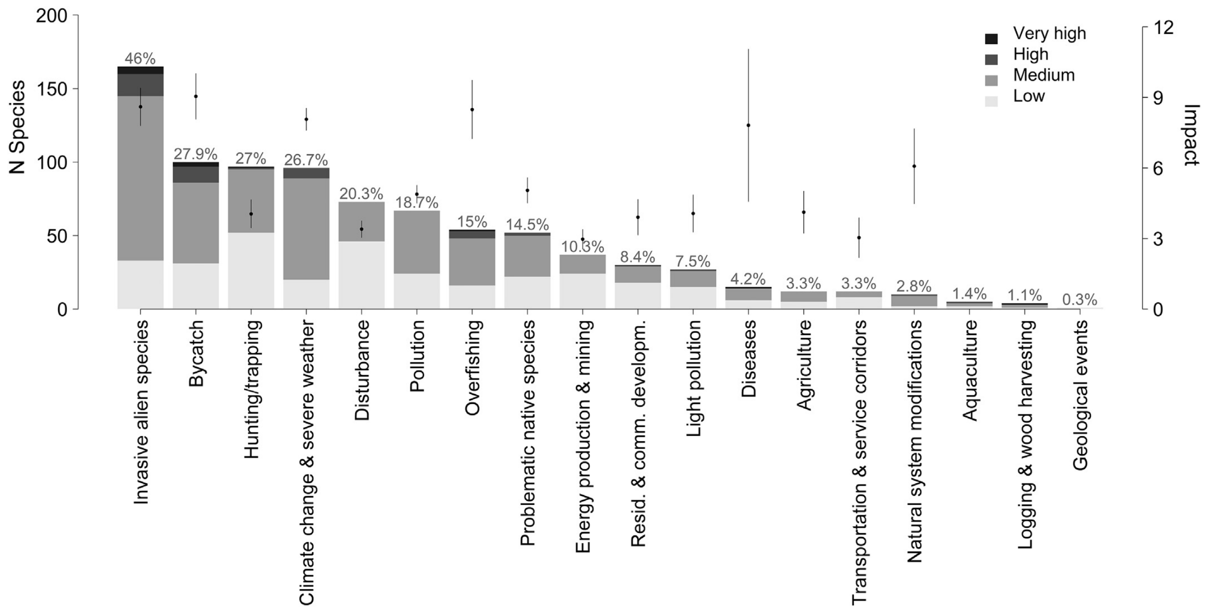
3.7 Marine birds

Seabird species are facing increased challenges in the form of invasive predators on their breeding sites, by-catch mortality by fisheries gear as well as climate change and severe weather conditions. It is worthwhile to mention that climate change/severe weather at present constitutes one of the top three threats to seabirds in terms of number of species affected (27% of the total number of seabird species) and average impact (Dias et al., 2019; Figure 35). That specific threat was also found persistent during the last two decades by comparing the outcome of relevant studies (Croxall et al., 2012; Dias et al., 2019).

Many seabird species are affected by several threats, which may produce cumulative impacts. Effects of climate change on seabirds are often difficult to disentangle from other threats for their conservation such as depletion of food sources due to overfishing by fishery industry (Grémillet and Boulinier 2009; Sydeman et al., 2012). Changes in ectoparasite and associated vector-borne pathogen distribution can also be expected with variations in climate conditions (Uhart et al., 2018). Consequently, it is difficult to understand the complex interactions between seabirds, oceanographic conditions, prey abundance-availability, fishery activities and diseases.

Numerous studies have shown that CC impact on seabirds involve direct and indirect effects. Most of them are focused on indirect effects trying to identify strong evidence linking long-term oceanographic and climatic changes to seabird populations through changes in the structure and functioning of marine, insular and terrestrial ecosystems eventually affecting food availability, predation, survival rates and breeding success, while other studies highlighted more direct impacts through loss of breeding habitat, alteration of foraging areas, disruption of their migratory pathways thermoregulation costs and large-scale breeding failure or mass mortality (wrecks) during the winter due to particular extreme weather events (Jentsch et al., 2007; Ramirez et al., 2016; McClelland et al., 2018; Rodriguez et al., 2019).

FIGURE 35. Ongoing threats to all seabird species (ordered by the number of species affected). Left y axis: total number of species affected; Right y axis: average impact ± SE. Values at bars indicate the percentage of species affected (n=359) (from Dias et al., 2019)



The MS, a highly dynamic system influenced by different oceanographic parameters (primary productivity, SST, sea level anomaly, seafloor depth, etc.) and human activities (e.g. fisheries), may constrain prey availability for top marine predators ultimately affecting their foraging behaviour (FAO 2016; Piroddi et al., 2017). For example, marine productivity plays a crucial role for the foraging behaviour of seabirds and the adoption of a relevant strategy throughout their breeding cycle (Weimerskirch 2007; Cecere et al., 2014). The MS is also characterized by evident eastward decline in primary production and increase of SST (Coll et al., 2010) affecting the productivity at low trophic levels (e.g. phytoplankton and zooplankton), and thus the foraging success of top predators such as marine birds (Peck et al., 2004; Erwin and Congdon 2007; Ramos et al., 2013; Weeks et al., 2013). Nevertheless, the Greek Seas are known to host a significant network of breeding and foraging sites for marine birds (Fric et al., 2012; Thanou 2013; Zakkak et al., 2017; Karris et al., 2017, 2018a; Xirouchakis et al., 2017).

It is expected that low food availability around seabird colonies in the EM will force breeders to perform a high proportion of long trips in their effort to reach the most profitable areas for food provision to chicks but also for their own energy demands (Cecere et al., 2014). Additionally, possible negative effects on fish stocks due to climate change may decrease the availability of fishery discards to scavenging seabird species. For instance, the most abundant seabirds in the Ionian Sea are Scopoli's Shearwater (*Calonectris diormedea*), Yellow-legged Gull (*Larus michahellis*), Yelkouan Shearwater (*Puffinus yelkouan*), and the Mediterranean Shag (*Gulosus aristotelis desmarestii*), and they are all known to scavenge regularly or infrequently (Bicknell et al., 2013; Karris et al., 2018b), while Audouin's gull (*Ichthyaetus audouinii*) exhibits scavenging behaviour in the Aegean Sea (Fric et al., 2012). Bottom trawler fishery operations in the Ionian Sea was found to provide significant amounts of benthopelagic prey species to shearwaters during their pre-laying period in spring (Karris, 2014; Karris et al., 2018b). This alternative food supply can be characterised as normally unavailable due to the foraging ecology of Scopoli's Shearwater and may also be affected by climate warming as it was recently found in a transition zone between Atlantic and Arctic waters (Emblemsvåg, 2022). Consequently, changes on demersal trawling (Ionian Sea) discard composition and quantity due to climate change may affect the population dynamics of local colonies and specifically that of the Strofades population which hosts the largest colony of Greece (Karris et al., 2017).

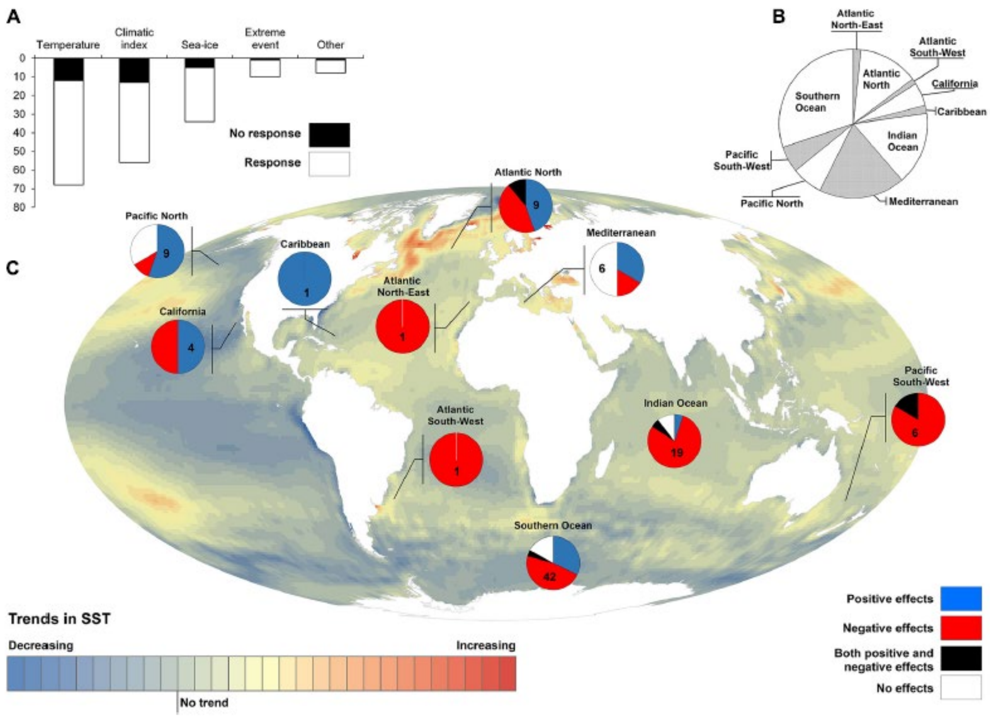
Breeding performance of colonial seabirds in the EM can be also affected by global-scale climate phenomena such as El Niño/La Niña, Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO), through the effects on abiotic factors including SST, precipitation, and storm frequency (Cane, 1983; Ottersen, 2001). More specifically, the connection of extreme

ENSO events to the tropical North Atlantic can affect the productivity of marine ecosystems and the availability of fish stocks, with negative consequences for seabird populations (Grosbois and Thompson, 2005; Casselman et al., 2023). Indeed, a relevant study showed that La Niña phenomenon is associated with reduced survival levels of Scopoli's Shearwater in the wintering grounds and a subsequent impact on the breeding success in a central Mediterranean population (Boano et al., 2010). Nevertheless, some studies have shown no impact or even positive relationships between increasing temperatures and petrels-shearwaters vital rates or abundance. The latter was also observed in Mediterranean basin as described by Rodriguez et al. (2019) (Figure 36).

Another aspect of possible detrimental impact of climate change/severe weather could be the inundation of breeding colonies on islands and islets due to sea level rise and/or severe rainfall storms (Dias et al., 2019). This threat could be of significant importance for coastal birds such as Mediterranean Shag which is distributed solely in the Mediterranean and the Black Sea in over 400 colonies (Bazin and Imbert, 2012) but also for pelagic species such as petrels and shearwaters that nest in low lying coastal zone (Karris et al., 2024), and may pose the local populations at risk during the next decades.

Dias et al. (2019) showed that the majority of seabirds affected by climate change/severe weather conditions are also affected by other threats, namely by-catch incidental mortality, overfishing as well as hunting/trapping. This indicates the importance of evaluating (e.g. Karris et al., 2013) and addressing effectively these additional threats so as to compensate for the possible negative impacts of climate change in the EM. Additionally, effective conservation measurements and assessments at local scale need fundamental knowledge (e.g. breeding success, breeding phenology, migration pattern and foraging strategy) which may be used as baseline data for the evaluation of possible effects of climate change on seabirds in the EM. Therefore, a long-term research effort should be dedicated to that fundamental knowledge in order to test the consequences of climate warming on seabirds.

FIGURE 36. Reported seabird responses to climate driven environmental changes. In total 64 studies were compiled, reporting up to 176 cases in which petrel and shearwater species responded (any kind of response, 144) or not (32) to environmental features such as air or sea temperatures, large-scale climatic indexes, sea-level or extreme weather events (A). These responses were grouped geographically to elucidate the spatial heterogeneity in the distribution of reported responses (B). Responses that could be directly interpreted as a benefit or a threat for seabirds (e.g. changes in breeding performance or survival rates; but not in breeding phenology or distribution) when facing climate driven environmental changes (e.g. increasing temperatures and extreme weather events or decreasing extents of sea-ice; but not large-scale climatic indices) were selected and grouped geographically to show the spatially explicit effects of climate change on petrel and shearwater populations; colored background represents the pixel-basis long-term (1983–2014) trend in sea surface temperature (SST) (Ramírez et al., 2017) (C) (from Rodriguez et al., 2019)



3.8 Exposure in metals

Both, temperature rise and seawater acidification could trigger biological responses in marine organisms related to their growth, metabolism / vital rates, immune defense, fertilization success, as well as contaminants uptake and regulation (Gazeau et al., 2014; Sezer et al., 2020 and references therein; Szalaj et al., 2017). The potential impact of ocean acidification (OA) on marine organisms, and their ability to adapt, will determine future marine biodiversity and ecosystem functions. In the future ocean, marine life will have to face acidification simultaneously with other anthropogenic stressors such as elevated pollution mainly at the coastal zone and especially by metals (Pascal et al., 2010; Vizzini et al., 2013; Nardi et al., 2018; Giuliani et al., 2020). Metal pollution could be a significant threat due to industrial and urban activities concentrated in the Mediterranean coastal area. Although most trace metals are essential nutrients for organisms, increased concentrations in the marine environment could pose a risk to marine life while food web interrelations could biomagnify the risk of metal contamination. Taking into consideration the additional risk of the 'mercury anomaly' in the Mediterranean (Cossa and Coquery, 2005) enriched with large deposits of cinnabar (HgS), marine organisms are susceptible to mercury accumulation as well (Girolametti et al., 2023).

Acidity plays a significant role on metal solubility and speciation in seawater (Millero et al., 2009) and subsequently in metal bioavailability and uptake by marine organisms (Zeng et al., 2015). It is anticipated that changes in seawater chemistry resulting from OA may impact the toxicity of both waterborne and dietary metals. Additionally, the adaptation of organisms to the new climatic conditions, including OA, is expected to impact their physiology and metabolic requirements (Ivanina and Sokolova, 2015). The OA effects are species specific due to the different biology of the organisms (Lewis et al., 2016; Wilson-McNeal et al., 2020 and references therein). The reproduction process and success are considered more vulnerable to OA (Byrne et al., 2010) and even more to multi-stressor exposure to OA and metal pollution (Dorey et al., 2018; Caetano et al., 2021).

It has already been shown that OA and warming could affect both metal (Ag, Cd, Zn) permeability properties of the eggshell and the embryonic metabolism of the cuttlefish *Sepia officinalis* (Lacoue-Labarthe et al., 2009) as metal accumulation in the eggs and embryos of the squid *Loligo vulgaris* (Lacoue- Labarthe et al., 2011). The acidic environment increases the solubility of metals from sediments affecting the mobility of metals within sediments and their subsequent bioaccumulation by clams (Lopez et al., 2010). Additionally, metal accumulation by mussels could be increased under the combined exposure to elevated partial pressure of carbon dioxide (pCO_2 and the consequent seawater pH decrease), and temperature while it has been shown that OA alone does not pose a threat to elevated metal bioaccumulation (Romero-Freire et al., 2020).

Recently, Qu et al. (2021), Thangal et al. (2023) and Zheng et al. (2023) explored the toxicological consequences of Cu exposure in mussels, Cd exposure in crabs and Cu exposure in octopuses respectively, under different OA scenarios. It should be noted, that EM people traditionally consume all the above species which are abundant in the coastal zone of the region and available in the fish market; in addition, these species have been widely used as indicators in marine pollution research and could therefore be used as model organisms for multi-stressor metal exposure studies. In the above studies, physiological, cellular and biochemical biomarkers were evaluated under the aforementioned multi-stressor conditions, indicating that OA can affect metal toxicity, thus presenting an additional risk to marine species and ecosystems' integrity. More specifically, Qu et al. (2021) found that exposure only to OA did not significantly affect the vital rates of clearance and respiration. In the same experiments, oxidative stress biomarkers were activated to protect mussels by both the metallic exposure and OA, although the antioxidant defense mechanisms were not efficient enough to completely protect the organisms and finally an increase of lipid peroxidation was also recorded after the exposure to free radicals. The final step in the previous experiment was a quite long depuration period (56 days) during which mussels showed signs of recovery and an improved ability to cope with the combined exposure to OA and Cu (Qu et al., 2021). Crabs exposed to Cd under OA conditions showed a decrease in growth, molting, in the major biological molecules concentration and activation of the oxidative defense system of the organisms while elevated oxidative damage was recorded as well; additionally, Cd toxicity in crabs was increased due to the potential synergistic interaction of OA and metal exposure (Thangal et al., 2023). Cu exposure and OA, synergistically reduced growth and food intake in octopuses while oxidative damage after Cu exposure was higher due to OA (Zheng et al., 2023). The combined effect of metal exposure and OA altered the transcriptomic profiles (transmembrane transport, mitochondrial, and protein and DNA damages), the microbial community structure within octopuses' intestines, and Cu toxicity though octopuses showed to be well acclimatized when exposed at decreased pH only (Zheng et al., 2023). The toxicity of copper in mussels and sea urchins in the near future OA was investigated by Lewis et al. (2016) who showed that DNA-damage in both species was greater when the animals were metal exposed under OA conditions. Sartori et al. (2023) presented a 20years timeseries (from early 2000 to early 2020) of the Copper EC50 (concentration effect at the 50% level) on a natural sea urchin population. The effects examined on larval development (including deformities of the arms and abnormalities in the gut formation of the plutei), showed a sharp decrease in the EC50 timeseries from the years 2016-2017 and onwards (Sartori et al., 2023).

Copper EC50 values after 2016 were negatively correlated with surface pCO_2 and temperature and positively correlated with pH and dissolved oxygen (Sartori et al., 2023). The authors explained these results taking into account that the warmest period in Europe began in 2015 (Lopez, 2021).

As the potential pH decrease in the Mediterranean Sea is higher than that of the adjacent Atlantic Ocean (Schneider et al., 2007), it is crucial to investigate the potential effects of OA on EM dominant species exposed to chronic metal pollution in coastal zone. Such studies might be constantly expanding to include cultivated or endangered species. For example, in the EM, cultivated mussel landings are significant at the European level. The main coastal areas with mussel cultures in Greece are located in the northern part of the country while regions with lower carrying capacity are distributed along the Aegean and Ionian Seas (Theodorou et al., 2011). Furthermore, shellfish farming is considered a 'carbon sink' with low greenhouse gas (GHG) emissions and has the credit of being a 'climate positive' food product (Bertolini et al., 2023 and references therein). Consequently, the growth and risks of this economically important and environmentally friendly activity under the ongoing climate change in the sensitive EM environment should be considered accordingly. Seafood, an important component of the so-called Mediterranean diet, is recommended for frequent consumption due to its health benefits (EU, 2023). Indeed, seafood safety and the nutritional value of the edible marine species under climate change are of major concern especially under the synergistic effects of OA and temperature increase (Lemasson et al., 2019).

3.9 Knowledge gaps

Reviews using meta-analytical methodologies have indicated specific knowledge gaps which are either correlated to specific species or taxonomic groups, or to specific eco-physiological processes that need to be studied further. For example, Padilla-Gamiño et al. (2022) indicated that crustaceans as a group are less studied regarding the effects of acidification on their reproduction, even though these species constitute a large proportion of the economically important fisheries. Specific reproduction traits such as mating behaviour and determination of gender balance have not been sufficiently studied.

Experimental studies on multi-generational, multiple stressor and species interactions need to be performed in order to better clarify complex ecosystem-level changes and to identify how these changes might affect ecosystem services under futue conditions also at a community level (Cattano et al., 2018). Long-lasting experiments can allow investigation of the acclimatization capability to climate change conditions and thus to produce more relevant data for predicting long-term consequences. In addition, longer term experiments involving multiple generations might also enlighten potential adaptation abilities of some species under climate change condition (Cattano et al., 2018).

Investigation of climate change effects under laboratory experimental conditions may have some implications in the understanding and assessment of the impacts on the life traits of marine organisms. It is obvious that climate change is not restricted only to ocean acidification and increase of temperature in the seawater, but a series of other forms of destruction will also occur in parallel such as hypoxia for example. Therefore, controlled experiments combining multi-stressors are more favourable and reliable to describe the "big picture" of future scenarios. However, controlled experiments test rather environmental tolerances instead of behavioural preferences which are free to occur in the natural environment (Pankhurst and Munday, 2011). Finally, with few exceptions, the ecological impact of invasive species on the native Mediterranean biota have not been scientifically studied (Galil, 2023).

3.10 Conclusions

3.10.1 Main conclusion and perspective

The introduction of invasive alien species appears to be the major direct driver of biodiversity alteration in the EMME region (and finally throughout Mediterranean), intensified mainly by climate change but also by pollution, habitat loss, and other human-induced disturbances. The Suez Canal is the main pathway and its successive enlargements have raised concern over increasing propagule pressure. It is now widely believed that "If we do not understand and mitigate the ecological risks associated with the expansion of the Suez Canal, the integrity of a large part of the Mediterranean ecosystem could be exposed in an unbelievable threat".

In fact, the Egyptian government is in a position to reduce future introductions. In 2021 Egypt issued tenders for 17 new desalination plants adding 2.8 million m^3 daily capacity, and plans to increase to 6.4 million m^3 by 2050; the hypersaline brine effluent will establish a formidable salinity barrier if discharged into the canal, recreating the Bitter Lakes (Galil, 2023). Construction of locks would decrease the transit of current-borne propagules. Commemorative stamps issued by Egypt on the occasion of the inauguration of the "New Suez Canal" depict a pair of locks. The Suez Canal Authority ought to turn this image into reality, for the sake of the Mediterranean and its inhabitants (Galil, 2023).

The above action, along with both, other management actions in order to avoid the arrival of additional species, and measures in order to lighten up the impacts of NIS-IAS on biodiversity, ecosystem services and health, are the necessary next steps for attempting mitigation.

3.10.2 Conclusive remarks (ecological impacts)

Benthic communities

- Degradation of macroalgal communities and sublittoral reef communities.
- Biodiversity alteration of shallow marine habitats.
- Species disappearance.
- Changes in habitat suitability.
- Coral bleaching.
- Decreased coral reef growth.
- Decline of large corals.
- Coral reefs in the northern RS amy be among the last standing against climate change.
- Physiological thresholds of Persian Gulf corals are higher than elsewhere, allowing them to survive in the Gulf's extreme temperatures.
- Mass mortality events.
- Loss of ecological functions
- Habitat loss and degradation.

Plankton communities

- Decreased contribution to biological carbon sequestration.

- Shifts in geographical range, and body size decrease.
- Rapid changes in coccolithophore communities.
- Different components of the pelagic food web may respond discordantly to future climatic changes.
- Change in distributional patterns.
- Alteration of abundance and phenology.
- The impact of interplay, between warming and alterations in ecological status, on plankton has been reported in the Saronikos Gulf.
- Climate-driven hydrological changes control zooplankton dynamics.
- Potential for future colonization events driven by climate-induced disruptions in circulation barriers.
- Further OA increases in the Mediterranean Sea, will drive ongoing reductions in marine biogenic calcification.
- MHWs have pronounced impacts on the Mediterranean plankton food web.
- Heatwaves affect phytoplankton quality.
- Concerning primary productivity, an increase is projected in the EM, contrasting a decrease in ME.

Marine fisheries

- 2,8 - 12,1% decrease of potential fisheries production by 2050.
- Overfishing, higher exposure to warming, arrival of non-indigenous species, and an overall lower adaptive capacity increase the Mediterranean fisheries vulnerability.
- Sardine and anchovy in the north Aegean Sea reacted negatively to the temperature increase.
- Environment suitability for valuable commercial cephalopods is decreasing in the Mediterranean.
- The bulk of increase in catch and biomass, projected in the next years, would be located in the southeastern Mediterranean, characterised by an increase of thermophilic and/or exotic, of smaller size and of low trophic level species, as well as on a drastic decrease of generally large-sized species, some of them of great commercial interest.

- Small pelagic populations appear to be more vulnerable.
- Several fish species tend to reach maturity at a smaller size in warmer waters.
- Red Sea total catch increased until the mid-2000s when it started to decline apparently due to resource depletion.
- Oxygen depletion, acidification and overfishing have already impacted the resources, in ME.
- Continuous decreasing in the total annual catches of iconic commercial species such as groupers and emperors, in ME.
- A decline in many priority fish species and local extinctions in ME is expected.

Aquaculture

- The actual impact of the identified threats will largely depend on the ability and flexibility of the industry for mitigation and adaptation.
- As the effect of CC on growth is stage-specific, potential impacts over the entire lifespan should be considered.
- Fish may benefit from the ocean warming in terms of growth; however the benefits will be largely offset by the negative effects of extreme events causing substantial mortalities, escapees and losses in biomass.
- HABS under CC can cause severe events of hypoxia, toxicity, gill irritation, disease, and mass mortalities in reared fish populations.
- As global warming continues triggering fish welfare deterioration, pathogens will thrive, potentially increasing the frequency and severity of disease outbreaks.
- Synergistic effect of temperature with other drivers such as dissolved oxygen, acidification, HABs, salinity is expected to substantially reduce tolerance thresholds.
- The profitability of farming will be largely impacted.

Marine birds

- Climate change/severe weather constitutes one of the top three threats to seabirds in terms of number of species affected (27% of the total number of species).

- Changes in ectoparasite and associated vector-borne pathogen distribution can be associated with variations in climate conditions.
- Negative effects on fish stocks due to climate change may decrease the availability of fishery discards to scavenging seabird species; constrain of prey availability ultimately affects the foraging behaviour.
- Changes on demersal trawling (Ionian Sea) discard composition and quantity due to climate change may affect the population dynamics of local colonies and specifically that of the Strofades population.
- A possible impact of climate change is expected to be the inundation of breeding colonies on islands and islets due to sea level rise and/or severe rainfall storms.
- For pelagic species such as petrels and shearwaters that nest in low lying coastal zones, and may pose the local populations at risk during the next decades.

Exposure in metals

- Acidity plays a significant role on metal solubility and speciation in seawater and subsequently in metal bioavailability and uptake by marine organisms.
- The acidic environment increases the solubility of metals from sediments affecting the mobility of metals within sediments and their subsequent bioaccumulation by clams.
- Crabs exposed to Cd under OA conditions showed a decrease in growth, moulting and major biological molecules concentration.
- Cu exposure and OA, synergistically reduced growth and food intake in octopuses.
- DNA-damage in mussel and sea urchin was greater when the animals were metal exposed under OA conditions than under metal alone.
- Temperature has been also found to increase sea urchin vulnerability in metal exposure.

4 Carrying Capacity and Assessment of tourism sector of the EMME

4.1 Introduction

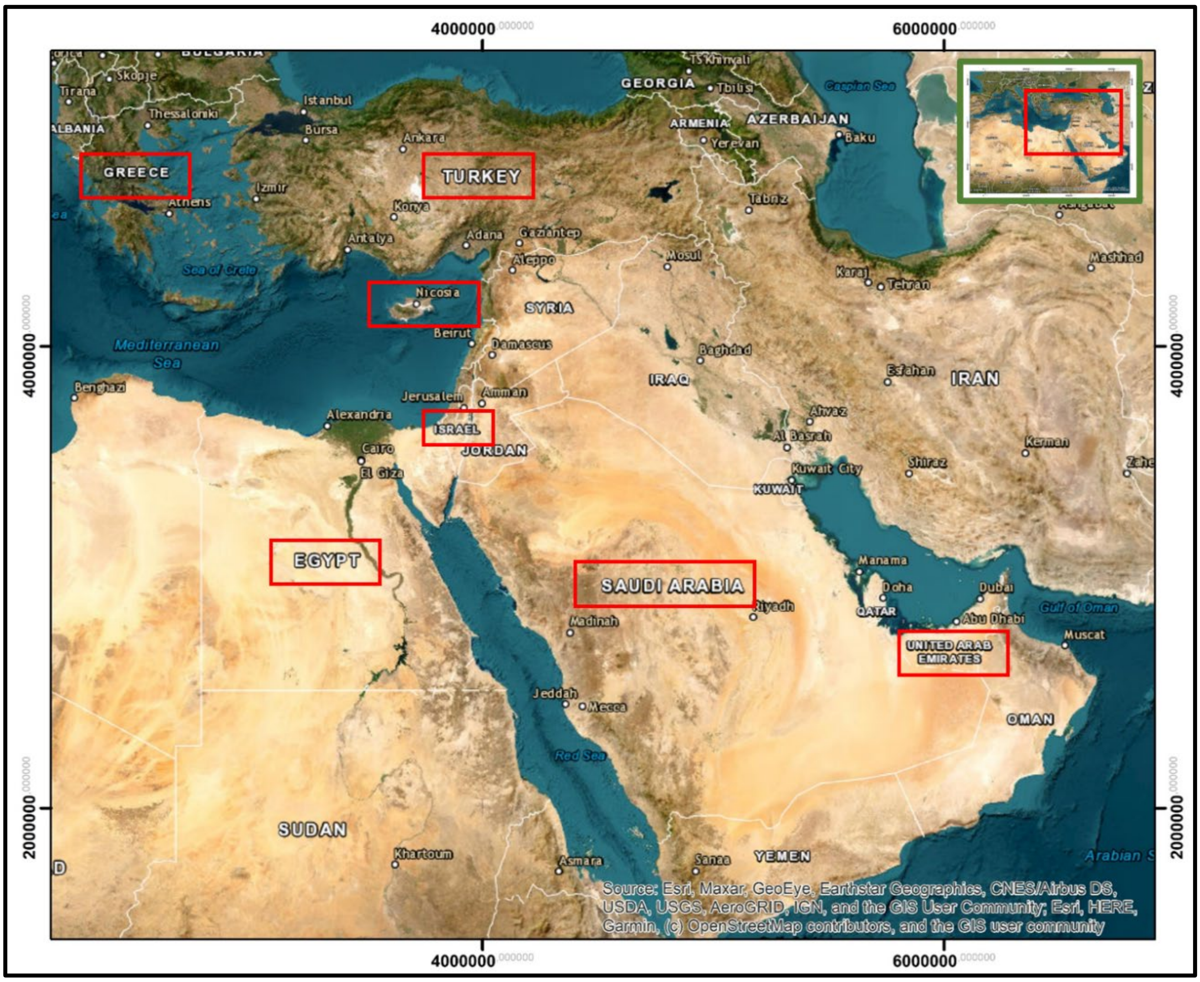
The concept of sustainable tourism development is considered of great importance in decision-making strategies. Consequently, it requires the calculation of the Carrying Capacity of an area based on specially selected indicators. Such quantification constitutes a valuable tool for assessing the potential negative or positive effects of East Mediterranean, which should be studied physically, socially, and economically. Therefore, they must be defined as a totality of such variables, considering the different regional characteristics (Briassoulis, 2001). Unlike other destinations in this area, Greece relies mainly on the tourism economic sector; consequently, considerable research has been conducted to maintain one of the most valuable products, as the main occupation is closely related to the tourist industry. Additionally, tourism contributes 34% of the total GDP (INSETTE, 2024). Based on the points mentioned above, the primary goal is to ensure the long-term viability of the tourist sector, as it has contributed significantly to the national income over time (Prokopiou et al., 2018). The calculation the Carrying Capacity for the tourist sector includes quantitative and qualitative variables. The latest Gross National Product (GNP) surveys indicate that the offered tourism services will need to be more appealing and environmentally friendly in the near future to attract more investments and maintain their leading position in the Greek economy (Vandarakis et al., 2019, 2021). In the rest of the countries, the tourism sector is crucial, but it is not as important as in Greece. For example, Turkey's GDP relies on a percentage of 12.5%, Cyprus 13.5%, UAE 12.0%, Egypt 8.1%, Saudi Arabia 11.5%, and for Israel, that information is Not Available (N/A).

In the last few decades, researchers have been developing, testing, and implementing tools to maintain sustainability by measuring tourism Carrying Capacity (Karagiannis and Thomakos, 2020; Panousi and Petrakos, 2021). According to the World Tourism Organization, Carrying Capacity is defined as "the maximum number of tourists who may visit a destination at the same time without affecting the economic, physical and social environment and not to limit the satisfaction of tourists" (Pearce, 1995; Butler, 1997; UNEP-PAP/RAC, 1997; Saveriades, 2000; Fokiali et al., 2005; Tselentis et al., 2006; Klaric et al., 2007). For this reason, the researchers soon realised that tourism has many aspects, so they changed their studies from an economically based perspective to a multivariable one. These studies consider the economic, environmental, and social impacts. As a result, calculating carrying capacity is crucial, as the benefits of tourism without proper planning can be detrimental, affecting the destination's attractiveness and competitiveness. Hence, the destination will be overloaded, tourism quality will be endangered, and any benefits from tourism flow will be diminished (Karagiannis and Thomakos, 2020).

Consequently, over the last 20 years, tourism standards have been striving to meet the social requirements for improved environmental quality, employing innovative environmental practices and leveraging the region's cultural specificities to benefit its tourist development. To determine the optimum tourist load for a particular area, the World Tourism Organisation (WTO, 2004) published a guidebook featuring a comprehensive set of indicators for sustainable tourism growth. Similarly, UNEP-WTO (2005) recommended a guide that includes policies and indicator tools based on real-world cases collected worldwide. The European Commission (2006) also published a methodological manual for assessing the sustainable development of tourism (Vandarakis et al., 2019, 2023; Karagiannis and Thomakos, 2020).

In the present research, a set of fifteen (15) most representative indicators was proposed based on the national and international literature in the quantification process of Carrying Capacity, tailored to the characteristics of this particular study area and the availability of data. Since there are no or insufficient environmental data, the number of tourists concentrated in a specific area (such as solid waste production and wastewater production) can lead to environmental stress. This will serve as a logical, indirect indicator to embed the environmental impact of tourism in the results and conclusions. The main objective is to cover all the physical-ecological, social-demographic and political-financial aspects, delineating and describing the present state of the Carrying Capacity for tourism in the EMME (Fig. 37). The results of this study could contribute for the recommendation of the best practices possible to the local administration, the decision makers and the stakeholders aiming its sustainable development.

FIGURE 37. Location map of the countries of the EMME region considered in this study



4.2 Area of concern

Geography and Coastal Orientation

Many countries in the region exhibit strong coastal identities, particularly Greece, Cyprus, and Turkey. Greece has one of the longest coastlines in the world (approx. 13,676 km), owing to its deeply indented shores and numerous islands (Kizos and Iosifides, 2007). This fragmentation contributes to significant regional diversity and underpins a tourism model centered on island destinations, maritime heritage and coastal resorts (Tsartas, 2003; Vandarakis et al., 2023). Similarly, Cyprus's strategic location in the Eastern Mediterranean has historically influenced its geopolitical significance and modern tourism development, particularly along its southern coastline (Sharpley, 2003). Turkey's peninsular form and dual Euro-pean-Asian location grant it both Aegean and Black Sea coastlines, fostering coastal urbanization and a thriving “sun-and-sea” tourism industry (Tosun and Jenkins, 1996).

Desert and Arid Landscapes

Contrastingly, countries such as Egypt, UAE, and Saudi Arabia are dominated by arid and semi-arid landscapes, which significantly influence settlement patterns and tourism strategies. Egypt's geography is defined by the Nile River, a lifeline cutting through the arid Sahara, creating a narrow band of fertile land (Hassan, 1997). The Red Sea coast supports a growing resort-based tourism industry (e.g., Sharm El Sheikh, Hurghada), blending marine ecology with desert aesthetics. The UAE and Saudi Arabia are characterised by vast desert interiors (e.g., the Rub' al Khali), punctuated by coastal urban centres such as Dubai, Abu Dhabi, and Jeddah. These countries have adopted large-scale infrastructure development to mitigate the limitations of arid environments and diversify their tourism offerings (Gössling and Hall, 2006; Gössling et al., 2012).

Mountainous and Rift Valley Regions

Israel's topography is marked by diverse features ranging from coastal plains to the Jordan Rift Valley, with the Dead Sea representing the Earth's lowest point on land. This geographic complexity underlies its eco-tourism, pilgrimage, and wellness industries (Collins-Kreiner, 2010). Turkey and Greece also feature significant mountainous areas, such as the Taurus, Pontic, and Pindus ranges, which influence regional climate variation and promote inland tourism, including hiking and thermal spas (Tsiotas and Polyzos, 2018).

Urbanization and Environmental Constraints

Rapid urbanization in the UAE and Israel has prompted adaptive planning responses to climate extremes, sea-level rise, and limited freshwater resources (Elgendy, 2020). Coastal reclamation and the creation of artificial islands in the Gulf exemplify how geography is reshaped to meet economic and demographic pressures. Conversely, Greece and Cyprus face challenges from the seasonal pressures of tourism on small island ecosystems and infrastructure.

Cross-Cutting Themes

Across all these countries, geography is a fundamental determinant of land use, transportation networks, disaster risk, and tourism carrying capacity. Geographical Information Systems (GIS) and remote sensing have become increasingly important for managing spatial development and monitoring environmental change in these regions (UNWTO, 2022).

4.3 Literature review

Recently, carrying capacity has been considered a multidisciplinary approach to tourism sustainability as part of the planning process. Furthermore, it is a crucial aspect of sustainable tourism development and is often used to specify limitations for tourist use and measure the impacts at each destination. Tourism carrying Capacity (TCC) refers not only to the number of tourists but also to the capability of the local community to manage tourism flows (Vandarakis et al., 2019; Karagiannis and Thomakos, 2020).

Buttler (1980) demonstrated the cycle of a tourist destination and described the distinctive stages that follow its development process, aiming to plan and manage tourism assets. O'Reilly (1986) recommended that Tourism Carrying Capacity applies not only to the maximum limit of visitors but also to the maximum rate of growth, above which it is harmful. Martin and Uysal (1990) described the link between carrying Capacity and tourism lifecycle and suggested policy implications. McElroy (2005) and McElroy and de Albuquerque (1998) proposed a five-fold system: to construct a simple index of tourism penetration and to apply this index to a sample of twenty (20) small Caribbean islands in order to group them into subsets based on levels of tourism penetration; to present four case studies that describe the different characteristics of each island at various levels of tourism penetration; and to highlight the policy implications of such indicator. Blancas et al. (2010) introduced a new synthetic indicator to simplify the measurement of sustainability and facilitate comparative analysis of rankings. This measurement was obtained by applying a procedure that minimised the number of subjective decisions made by the analyst, utilizing an innovative two-stage aggregation methodology based on principal component analysis. As mentioned earlier, the indicator was applied to Spanish coastal destinations, and the results serve as a guideline for tourism planning. Zacarias et al. (2011), based on the Tourism Carrying Capacity Assessment combined with the PAOT (People At One Time) approach, explore the area of Praia de Faro, attempting to assess the optimum number of people that can be accommodated without degrading the surrounding ecological, social, and cultural environment. Jurando et al. (2012)

established a methodology to assess the growth limits of tourist destinations, which was subsequently applied to the management and planning of an open tourist resort. The limits to growth are established using a mathematical formulation (i.e., multicriteria analyses based on the reference point methodology) that applies synthetic indicators to two scenarios: weak and strong sustainability. De Lucia et al. (2019) consider one of Italy's most visited tourist destinations (Puglia) and use quantitative (i.e., inferential and text mining) and qualitative (i.e., survey) approaches. The main results indicate that socioeconomic and environmental factors have a positive influence on residents' perceptions of tourism as a driver of sustainable development. Furthermore, the spatial dimensions of the territories in Puglia, as perceived through local indigenous knowledge, are key elements in the attractiveness of its destinations to tourists. Additionally, Coccosis and Koutsopoulou (2020) and Parpairis (2017) present a framework that measures and monitors sustainability at the local level by introducing a three-tier system of indicators. The framework effectively incorporates the diverse types of tourism activities and the unique characteristics of Mediterranean coastal tourist destinations, while also facilitating comparisons among them.

International organisations, such as the WTO, OECD, UN, UNESCO, and the EC, have increased their awareness of the sustainability of the tourism sector and its significant impact on communities. The Secretary-General of the WTO Zurab Pololikashvili, addressed to the European Committee on the 19th of February 2020, mentioning that "Making the tourism sector as a key part in the EU Agenda and as we face up to the biggest challenge of our lifetimes in the climate emergency, we must make sure tourism's potential to contribute to the European Green Deal is fully realized. The tourism sector should use its unique dynamic to lead the response to the climate emergency and ensure responsible growth" (Karagiannis and Thomakos, 2020).

In Greece, recent studies aim to calculate the Carrying Capacity of various destinations using various indicators based on the framework proposed by national and international literature. Tselentis et al. (2006) used, for the cases of Kos and Rhodes islands, a set of selected parameters/indicators such as tourist arrivals related to the local population, during high and low season, seasonal population, airport and port arrivals, beach impact factor, natural environment and garbage and waste management upon the availability of the data. Tselentis et al. (2012) applied the principles of coastal environmental management to the central

Aegean Sea islands via the carrying capacity assessment methodology, developing environmental performance indicators necessary for formulating a novel sustainable development policy proposal for Greek tourism. Prokopiou et al. (2018) were based on three axes of Carrying Capacity calculation: tourist development, economic and social assessments, and environmental assessment. Varelas and Belias (2019) calculated and analyzed the limits and prospects of tourism development as they are approached and evaluated through the methodological tool of the carrying capacity assessment on a local scale.

Moreover, Vagiona and Palloglou (2021) developed and implemented an integrated indicator-based system covering different Tourism Carrying Capacity (TCC) components. The indicator-based method was applied to the island of Milos (Greece). Twenty indicators were selected to contribute to the final system of TCC calculation. The study was focused on an island (Milos) with a tourism-based economy.

Studies cluster around two desert tourism foci: (a) the archaeological zones of the Nile Valley and (b) the Red Sea Riviera. El-Barmelgy (2016) demonstrates that excessive visitation accelerates stone erosion at the Giza Pyramids, suggesting a Real Carrying Capacity (RCC) that integrates daily visitor quotas with micro-climatic controls within the monuments. Along the Red Sea, El Bastawesy et al. (2008) adapt Coccosis' (1996) PCC-RCC-ECC model, integrating coral-reef health indices, beach width, and resort water demand. Their scenario analysis demonstrates that reef degradation occurs once overnight density exceeds ~3,000 beds km^{-1} of shoreline.

TCC work in the UAE pivots on resource-based limits rather than physical space. Al-Sulayyim and El Ansari (2019) couple visitor flows with per-capita energy, desalinated-water and solid-waste coefficients to gauge Environmental Carrying Capacity (ECC) for desert-safari corridors outside Dubai. GIS-remote-sensing studies (Hafiz and Abdurrahman, 2021) map land-surface-temperature "hot spots" and dune erosion to establish spatial caps on off-road vehicle tourism. Findings suggest that even low visitor volumes can exceed thermal thresholds during the summer months, underscoring the need for seasonally variable limits.

Tourism in Saudi Arabia is expanding rapidly under the Vision 2030 initiative. Al-Sulayyim et al. (2022) report that megaprojects, such as NEOM, embed TCC within strategic environmental assessments, utilising water-balance modelling, biodiversity offsets, and carbon budgets as proxies for visitor limits. While quantitative caps are rarely disclosed, preliminary estimates for the AlUla cultural landscape set an upper bound of ~1.5 million visitors yr^{-1} to preserve fragile sandstone formations and archaeological integrity.

In the Negev Desert, Cohen et al. (2009) fuse ecological sensitivity mapping with visitor stagnation curves for Ein Gedi and Ramon Crater. Their hybrid PCC–social carrying capacity framework shows that perceived crowding becomes critical long before ecological stress is detectable, implying that management should prioritise dispersal and time-slot reservations even at moderate volumes. Israel's park authorities now supplement ecological indicators with visitor-satisfaction surveys to refine permissible carrying capacity.

The aforementioned techniques were used to assess TCC/CCA and can be adapted for use in other tourist destinations with diverse landscapes, such as those in the present research.

4.4 Methodology

Carrying Capacity Assessment (CCA) is the most common technique used for the estimation of tourism assessment and management (González, and De Lázaro., 2013; Vandarakis et al., 2019, 2023). The analysis of CCA in the field of tourism globally has included, over the recent years, measurable physical and ecological-environmental parameters as well as demographic and socio-cultural factors that are not easy to be quantified (UNEP-PAP/RAC, 1997; Klaric et al., 2003; Fokiali et al., 2005; Tselentis et al., 2006; Navarro Jurado et al., 2012; Tselentis et al., 2012). This can be achieved mainly through increasing or restricting economic measures (such as tax policy and the construction of large-scale public infrastructure systems) and the handling and utilisation of the CCA, especially in developed countries of the Mediterranean, to which these guidelines are primarily addressed. The general context for quantifying the CCA for the Mediterranean Tourism sector is also based on these three sets of parameters. Additionally, the relationship between the parameters is crucial for the overall framework of the CCA calculation, which is implemented through an Integrated Coastal Area Management (ICAM) program for each country.

For the EMME region, the research approach is based on the quantification, analysis, and evaluation of WTO (2004) and UNEP-PAP/RAC (1997), which have been enriched and customised according to various researchers. Precisely, the methodology (indicators) proposed by Alghamdi, et al. (2022), Coccosis and Koutsopoulou (2020), Karagiannis and

Thomakos (2020), Vandarakis et al. (2019), Varelas and Belias (2019), Al-Sulayyim and El Ansari (2019), Prokopiou et al. (2014; 2018), Tselentis et al. (2006; 2012), Cohen et al. (2009) and Briassoulis (2001), is thought to be the most indicative methodology based on the conceptualization of CCA, the regional reality and the availability of the information concerning the different characteristics (Table 9).

Relevant carrying capacity indicators have been selected and categorised according to global and regional context: 1. physical-ecological, 2. social-demographic, and 3. political-financial. It is highly topical to develop and integrate such indicators into the planning process of the Eastern Mediterranean tourism industry, specifically the island tourism sector, which countries with extended coastlines and islands rely heavily on. It is believed that, through this process, realistic and sustainable scenarios for tourist development can be proposed for such areas (Gersmehl, 2005; Gersmehl and Gersmehl, 2006; Tselentis, et al., 2006). Therefore, the Carrying Capacity of Tourism for the EMME region has been calculated through fifteen (15) indicators and their thresholds (Table 10).

The data collected in the present study/chapter is mainly related to population structure (permanent residents, non-residents, overnight stays, domestic/international arrivals, seasonal population, etc.), to the physical characteristics (geomorphology of the area, the total length of the coastal area, environmental quality, infrastructures, etc.), the economic/financial situation (Contribution of tourism to the country's GDP, available beds, and the number of tourists arrived in each country per peak day, etc). The available data was quantified by applying the appropriate equations proposed by national and international studies. They are provided and explained thoroughly in Tables 9 and 10, along with their thresholds, in Table 11. Following the statistical analysis of the data, potential scenarios for sustainable development in the EMME region can be proposed.

TABLE 9. Selected variables/indicators and their description, used to calculate the Carrying Capacity in the EMME region based on the importance, the implementation and the availability of the data

Indexes/Variables			
Physical – ecological Indexes	**Tourist Operation Index-TOI (V1)**	$\frac{\text{Total Beds}}{\text{Population}} \text{ x } 100$	It offers useful conclusions regarding the degree to which the tourism industry is developed
	Tourism Density Index (TDI) (V2)	$\frac{\text{Total beds x } 100}{\text{Resident population x total Area}}$	If this number is higher than others, phenomena of "over-tourism" are present, while in the opposite case, phenomena of "under tourism"
	Tourism Intensity Index (TII) (V3)	$\frac{\text{Beds}}{\text{Population}}$	This index determines the true capability of the main regional market
	Tourism Tolerance Population Index (TTPI) (V4)	$\frac{\text{Number of tourists per peak day}}{\text{Population}}$	Indicates whether the number of tourists fluctuates in such levels so as not to exceed the limits of its Carrying Capacity each tourist destination concerning the resident population
	Tourism Pressure Index (TPrI) (V5)	$\frac{\text{Tourists per peak day}}{\text{Area}}$	Indicates whether the number of tourists fluctuates in such levels so as not to exceed the limits of its each tourist destination's Carrying Capacity concerning a specific area
	Tourists/Beds per km of beach (V13)	$\frac{\text{Beds}}{\text{Total length of beaches (km)}}$	It demonstrates the tourist burden of the users on the beach
	People-users of beach in peak day per m of beach (V14)	$\frac{\text{Residents} + \text{beds} + \text{cruises}}{\text{Total length of beaches } (m)}$	It demonstrates the total number of people / users on the beach
	Tourism Concentration Index (TConI) (Ha) (V9)	$\frac{\text{Total Overnight stays}}{\text{Area}}$	It demonstrates the will of the visitors to stay in a specific area
Social – Demographic Indexes	**Tourism Penetration Index (TPenI) (V6-7)**	$\frac{\text{Overnight stays non} - \text{Domestic } (\mathit{or\ Domestic}) \text{ x } 100}{\text{Resident Population x } 360}$	It expresses the level of development as a tourist destination
	Tourism Attractiveness Index (TAI) (V8)	$\frac{\text{Total International Arrivals}}{\text{Total Domestic Arrivals}}$	It presents the ratio of the number of arrivals of the foreign tourists in a destination to the domestic equivalent
	Total Arrivals to a Specific Area (km^2) Index (V11)	$\frac{\text{Total Arrivals}}{\text{Area}}$	It demonstrates the will of the visitors to visit a specific area
	Tourism Overnight Stays Index (TOSI) (V10)	$\frac{\text{Total Overnight Stays}}{\text{Resident population}}$	It demonstrates the total time of tourist stays in a specific area and the possible pressure on the local population
Political-Financial Indexes	**Contribution of tourism to the region's GDP (V15)**	Single value (2019)	It demonstrates the contribution of the tourist industry in this specific Region
	Total beds per Area (km^2) (V12)	$\frac{\text{Total Beds}}{\text{Area}}$	It demonstrates the tourist development/ economic revenues in a specific area

TABLE 10. Methodological approach with the corresponding bibliography

Index Name	Bibliographic References
Tourist Operation Index – TOI (V1)	Butler, 1980; Coccosis and Parpairis, 1996; Navarro Jurado et al., 2012; Tselentis et al., 2012; Coccosis and Koutsopoulou, 2020; De Lucia et al., 2020; Vagiona and Palloglou, 2021; Vandarakis et al., 2023;
Tourism Density Index – TDI (V2)	Navarro Jurado et al., 2012; Varelas and Belias, 2019; Vandarakis et al., 2023
Tourism Intensity Index – TII (V3)	Butler, 1980; McElroy and De Albuquerque, 1998; Blancas et al., 2010; Navarro Jurado et al., 2012; Varelas and Belias, 2019
Tourism Tolerance Population Index – TTPI (V4)	Butler, 1980; Varelas and Belias, 2019; Vandarakis et al., 2023
Tourism Pressure Index – TPrI (V5)	Prokopiou et al., 2014; Varelas and Belias, 2019; Vandarakis et al., 2019
Tourists/Beds per km of beach (V13)	Blancas et al., 2010
People-users of beach in peak day per m of beach (V14)	Coccosis and Parpairis, 1996; Capocchi et al., 2019; Coccosis and Koutsopoulou, 2020; Vandarakis et al., 2023
Tourism Concentration Index (TConI) (Ha) (V9)	Tselentis et al., 2012
Tourism Penetration Index – TPenI (V6-7)	McElroy, 2005; Navarro Jurado et al., 2012
Tourism Attractiveness Index – TAI (V8)	O'Reilly, 1986; Saveriades, 2000; Vandarakis et al., 2021
Total Arrivals to a Specific Area (V11)	Tselentis et al., 2012
Tourism Overnight Stays Index – TOSI (V10)	Briassoulis, 2001; Vandarakis et al., 2023
Contribution of tourism to GDP (V15)	Saveriades, 2000; Panousi and Petrakos, 2021; Alghamdi et al., 2022; WTTC, 2023
Total beds per Area (km^2) (V12)	Capocchi et al., 2019; Saveriades, 2000

4.5 Results

4.5.1 Socio-Demographic and Physical data for the calculation of CCA in the EMME region

Based on the investigation of the available data acquired (in many cases the researchers faced unavailability of specific data) from INSETE, (2022); Ktimatologio.gov.gr; www.statistics.gr; www.mintour.gov.gr; fcsc.gov.ae; economy.ae; dubaidet.gov.ae; dct.gov.ae; tuik.gov.tr; kultur.gov.tr; cystat.gov.cy; tourism.gov.cy; capmas.gov.eg; tourism.gov.eg; stats.gov.sa; mt.gov.sa; cbs.gov.il; tourism.gov.il, it is easily detected that Cyprus and Israel exhibit high tourism-per-resident and bed-per-area ratios. Greece and Egypt have more land and coastline, offering more dilution capacity. Saudi Arabia is experiencing a rise in domestic tourism, thanks to its large land reserves. UAE features extremely high hotel density and tourism volumes in a small geographic footprint (Table 12).

TABLE 11. Thresholds of CCA indicators, provided by national/international literature

Thresholds of CCA indicators		
TOI (V1)	**>500**	Excessive/intensive tourism development
	100-500	Almost exclusive tourism development
	40-100	Main growth relative to other sectors
	10-40	Important but not main growth
	4-10	Small or very small tourism growth
TII (V3)	**3**	High level of tourist services, exceeding tourist carrying Capacity
	1-3	Satisfactory level of tourism services, growth potential
	<1	Low level of tourism services, significant growth potential
TTPI (V6)	**>2**	Exceeding tourist Carrying Capacity, control of tourist arrivals
	2	Significant point of exceeding Carrying Capacity, control of tourist arrivals
	1.5	Satisfactory level of tourism, need of control of tourist arrivals
	1	Low number of tourists, thus, greater number of tourists can be received
People-users / m of beach (V7) and (V9)	**0**	No danger for environmental degradation
	1	Existence of pressure
	2	Existence of significant pressure
Tourism Concentration Indicator (V10)	**>9.58**	Highest risk
	=6.31-9.58	High risk
	=4.50-6.30	Medium risk
	=3.18-4.49	Low risk
	<3.18	Lowest risk
Tourism Attractiveness Indicator (V12)	**0-1**	Preferable to domestic tourists
	>1	Preferable to international tourists
Overnight to residents indicator (V14)	**>9**	High level of tourist services
	=6-9	Satisfactory level of tourist services
	6<	Low level of tourist services

Specifically, according to geographical characteristics and coastal access, considering the geographical scale and access to coastlines, which are the key determinants of tourism development capacity. Greece exhibits the first-longest coastline among the surveyed countries, measuring approximately 13676 km, which is remarkable given its modest land area (131957 km²). This extensive maritime boundary encompasses numerous islands and peninsulas, making Greece a premier destination for coastal and island tourism. Turkey, with a coastline of 7.2 km meters, ranks second, followed by Saudi Arabia (2.64 km) and UAE (1.32 km), highlighting significant opportunities for beach and cruise tourism (Table 12.

In terms of land area, Saudi Arabia dominates the region with 2,149,690 km², offering substantial spatial capacity for future tourism infrastructure. Egypt (1,010,408 km²) and Turkey (783,562 km²) also have extensive territories, while Israel (22,072 km²) and UAE (83,600 km²) are smaller being spatially constrained. Greece, despite its relatively small area, maximises its coastal advantages to support dense and dispersed tourism flows (Table 12).

Accommodation availability, as measured by the total number of beds, reflects the maturity and scale of each country's tourism infrastructure. Turkey reports an extraordinarily high capacity of 195 million beds - likely inclusive of a broad definition of lodging facilities - while Greece maintains a strong infrastructure with 937,088 beds, proportionally significant relative to its population and land area. Saudi Arabia (886,400 beds), Egypt (445,000 beds), and UAE (433,932 beds) follow closely, demonstrating the presence of large-scale hotel and resort developments. Israel, with 112,000 beds, caters to a more regionally focused market with compact urban tourism hubs (Table 12).

Additionally, cruise tourism must be taken into account, as it varies significantly across the dataset. Greece and Israel are the only countries with reported cruise traffic - 1,316,662 and 114,000 passengers, respectively - signalling their roles as important cruise hubs in the Mediterranean. The absence of cruise traffic data from other countries may point to either limited cruise infrastructure or data unavailability (Table 12).

The Tourists per Peak Day metric provides insight into seasonal tourism pressures. Turkey (135.45 million) and Egypt (123.9 million) record the highest peak day values, suggesting intense seasonal fluctuations. Saudi Arabia also experiences significant pressure (63.4 million), due in part to religious tourism. Greece, although smaller in area, records a substantial 25.75 million tourists per peak day, highlighting the intense seasonal use of its spatial and ecological resources, particularly on the islands. The UAE and Israel show relatively lower but still considerable values (26.69 million and 14.6 million, respectively) (Table 12).

Tourist behaviour and particularly the volume of overnight stays, helps assess infrastructure usage and destination performance. Greece reported 71.3 million international overnight stays and 6.82 million domestic stays in 2021, totalling 78.1 million stays, illustrating its dependence on international tourism. Saudi Arabia recorded an impressive 495 million domestic overnight stays, driven by internal religious pilgrimages, while data for other countries were limited or missing (Table 12).

The number of domestic arrivals was available only for Greece (2.93 million) and Saudi Arabia (81.9 million), reinforcing Saudi Arabia's role in fostering robust internal travel. In contrast, Greece exhibits a balance between domestic and international flows, with international arrivals reaching 15.27 million, highlighting its global appeal. Turkey receives the highest number of international arrivals (50.45 million), followed by Saudi Arabia (27.4 million), UAE (16.79 million), Egypt (14.9 million), and Israel (4.9 million). Greece, with 15.27 million, ranks mid-range, but relative to its population size (10.48 million), this reflects a high per capita tourist influx (Table 12).

Population data contextualize the pressure placed on national infrastructure. Egypt has the largest population (109 million), while UAE and Israel have smaller populations (under 10 million). Countries like Greece and UAE experience high tourism-to-resident ratios, emphasizing the need for well-managed carrying capacity strategies (Table 12).

4.5.2 Results of the calculation of the appropriate Indicators for the estimation of the tourist impact on the EMME region

This section presents a comparative analysis of tourism carrying capacity across selected countries—namely, the United Arab Emirates (UAE), Egypt, Israel, Turkey, and Cyprus—based on standardised, index-based metrics. These indicators offer a multidimensional evaluation of tourism's spatial intensity, infrastructural stress, socio-environmental tolerance, and economic dependence. The analysis is based on established metrics such as the Tourism Operational Index (TOI), Tourism Density Index (TDI), and Tourism Pressure Index (TPrI), which collectively inform policy-making in sustainable destination management (Table 13).

TABLE 12. Socio-Demographic and Physical data for the calculation of CCA such as Coastal Length, Area, Total beds/tourists/beds, Cruise traffic, Tourists per peak day, Overnight stays for Greek and non-Greek tourists, Total Overnight stays, Domestic Arrivals (by airplane), International Arrivals (by airplane) and Total resident population of the Islands of South Aegean Region. The color palette is selected from the Lowest (green) to the Highest (red) value

S/N	1	2	3	4	5	6	7
Region	Saudi Arabia	UAE	Egypt	Israel	Turkey	Cyprus	Greece
Coastal Length (m)	2640000	1318000	245000	273000	7200000	648000	13676000
Area (km^2)	2149690	83600	1010408	22072	783562	9251	131957
Total Beds	886400	433932	445000	112000	1740000	85000	937088
Cruise traffic	0	0	0	114000	0	0	1316662
Tourists per peak day	63400000	26690000	123900000	14600000	135450000	1200000	25754690
Overnight stays international	0	0	0	0	0	0	71307798
Overnight stays domestic	495000000	0	0	0	0	0	6824373
Total Overnight stays (2021)	0	0	0	16000000	0	0	78132171
Domestic Arrivals	81900000	0	0	0	0	674000	2934902
International arrivals	27400000	16790000	14900000	4900000	50450000	0	15272203
Resident Population	36000000	9900000	109000000	9700000	85000000	1200000	10482487

Tourism Operational Index (TOI) and Destination Intensity

The Tourism Operational Index (TOI) is a synthetic indicator reflecting the efficiency and maturity of tourism operations in a country. Cyprus demonstrates the highest operational efficiency, with a TOI of 7.08, followed by the UAE (4.38), Turkey (2.05), and Israel (1.15). In contrast, Egypt lags behind at 0.41, indicating relatively underdeveloped tourism operations or systemic inefficiencies. Complementing this, the Tourism Intensity Index (TII) measures tourism activity in relation to the national population. Again, Cyprus leads with a TII of 0.07, followed by UAE (0.044) and Turkey (0.02), suggesting a high intensity of tourist presence in these countries. In contrast, Egypt exhibits a notably low TII (0.004), which reflects its growth potential but also indicates relatively low per capita tourist activity (Table 13).

Spatial Stress Indicators: Density, Pressure, and Concentration

The Tourism Density Index (TDI) reflects the number of tourists per unit of area. Values are generally low across the board, with Cyprus again reporting the highest density (0.000766), followed by UAE and Israel (0.000052). Turkey and Egypt display minimal densities (0.000003 and 0.0, respectively), possibly due to larger land areas diluting tourism intensity per square kilometer. The Tourism Pressure Index (TPrI) provides an integrated measure of physical and infrastructural pressure. Israel records the highest TPrI (0.66), indicating considerable stress on infrastructure, likely due to high urban density and limited space. UAE and Turkey follow with 0.32 and 0.17, respectively. Egypt and Cyprus exhibit moderate pressure levels despite having fewer tourists, suggesting that limited infrastructure may be a contributing factor. The Tourism Concentration Index (TCI)—defined as total overnight stays per hectare—is only recorded for Israel (7.25), implying an exceptionally high spatial concentration of tourist stays and, therefore, pressure on localised areas (Table 13).

Socio-Cultural Sustainability: Tolerance and Penetration Indices

The Tourism Tolerance Index (TTPI) reflects the capacity of the host community and governance structures to accommodate tourism. The UAE scores the highest (2.70), followed by Turkey (1.59) and Israel (1.51), while Egypt scores relatively low (1.14). Notably, Cyprus is assigned a tolerance index of 1, potentially reflecting community limits to mass tourism despite high operational capacity. Tourism Penetration Indices (TPenI) for both domestic and international markets are largely reported as zero across countries, possibly due to data limitations or low tourism market integration relative to GDP or social structures. This limitation restricts direct interpretation but implies an underrepresentation of tourism in some national economies, particularly Egypt and Israel (Table 13).

Environmental Impact and Infrastructure Load

The Beds per Area Index provides a proxy for lodging infrastructure intensity. Cyprus leads with 9.19 beds per km², indicating a densely developed hospitality sector. UAE (5.19) and Israel (5.07) also exhibit high levels of accommodation infrastructure. In contrast, Egypt has only 0.44 beds per km², indicating underdevelopment or a dispersed infrastructure. In terms of Beds per km of Coastline, Egypt (1.82) leads, highlighting a concentrated coastline tourism model, followed by Israel (0.41), the UAE (0.33), and Turkey (0.24). This indicator reflects environmental exposure, particularly in ecologically sensitive beach zones. The Beach Environmental Impact Index (people per meter of beach) is a direct measure of overcrowding and potential degradation. Egypt exhibits an alarming value (505.7 people/m), far exceeding that of all other countries and indicating severe pressure on coastal ecosystems. Israel follows at 53.48, and UAE at 20.25, indicating moderate pressure. Turkey (18.8) and Cyprus (1.85) reflect relatively better-managed or less intensely used beach environments (Table 13).

Economic Contribution: Tourism GDP Share

The Tourism GDP (%) metric highlights the direct economic importance of tourism. Cyprus reports the highest share (13.5%), followed by Turkey (12.5%) and UAE (12%). Egypt, despite its significant cultural heritage and tourism appeal, registers only 8.1%, which may reflect either low sectoral integration or structural barriers. Data for Israel is missing, which hinders conclusive assessment (Table 13).

4.6 Discussion

Estimating the Carrying Capacity is a practical and internationally tested tool for identifying potential areas at risk due to uncontrolled tourist growth. Its main goal is to contribute to decision-makers, stakeholders, and local administration by selecting suitable variables based on data availability and area characteristics. The analysis of the physical, social-demographic, and economic characteristics of the EMME region insular receives the most significant number of tourists in terms of total tourist accommodation and food service (INSETE, 2022; Ktimatologio.gov.gr; www.statistics.gr; www.mintour.gov.gr; fcsc.gov.ae; economy.ae; dubaidet.gov.ae; dct.gov.ae; tuik.gov.tr; kultur.gov.tr; cystat.gov.cy; tourism.gov.cy; capmas.gov.eg; tourism.gov.eg; stats.gov.sa; mt.gov.sa; cbs.gov.il; tourism.gov.il).

TABLE 13. Results of the calculated indicators/variables estimating the Carrying Capacity for the EMME region. The classification of variables V1, V3, V4, V8, V9 and V10 was scaled according to national and international thresholds. The remaining variables had been classified from low (green) to high (red)

Region	Indexes	Saudi Arabia	UAE	Egypt	Israel	Turkey	Cyprus	Greece
Tourism Operational Index	TOI (V1)	2.46	4.38	0.41	1.15	2.05	7.08	8.94
Tourism Density Index	TDI (V2)	0.000001	0.0001	0.0000004	0.0001	0.0000	0.0008	0.0001
Tourism Intensity Index	TII (V3)	0.02	0.04	0.00	0.01	0.02	0.07	0.09
	TII-scale	1.50	2.00	1.50	1.50	1.50	1.00	1.00
Tourism Tolerance Operation Index	TTPI (V4)	1.76	2.70	1.14	1.51	1.59	1.00	2.46
Tourism Pressure Index-(Gazis)	TPrI (V5)	0.03	0.32	0.12	0.66	0.17	0.13	0.20
Tourism Penetration Index	TPenI Domestic (V6)	3.82	0.00	0.00	0.00	0.00	0.00	0.18
	TPenI International (V7)	0.00	0.00	0.00	0.00	0.00	0.00	1.89
Tourism Attractiveness Index	TAI (V8)	0.33	0.00	0.00	0.00	0.00	0.00	5.20
Tourism Concentration Index- Total overnights/ha	TCI (V9)	0.00	0.00	0.00	7.25	0.00	0.00	5.92
Total overnights/residents	TNRI (V10)	0.00	0.00	0.00	1.65	0.00	0.00	7.45
Total Arrivals / km^2	TArI (V11)	50.84	200.84	14.75	222.00	64.39	72.86	137.98
Beds per Area km^3	(V12)	0.41	5.19	0.44	5.07	2.22	9.19	7.10
Beds per km of beach	(V13)	0.34	0.33	1.82	0.41	0.24	0.13	0.07
Indicator of beach environmental impact (people/m of beach)*	(V14)	24.02	20.25	505.71	53.48	18.81	1.85	1.88
Country's Tourism GDP	(V15)	11.50	12.00	8.10	N/A	12.50	13.50	34.00

The fifteen selected indicators effectively describe and delineate the present situation of the tourism industry and its pros and cons for the EMME region. The lack of diverse information (especially environmental) from state agencies must be highlighted. Although indirect environmental impacts, based on the concentration of tourists in a specific area (solid waste production, wastewater production, and management), must be taken into account by stakeholders and the local administration. Therefore, they can be implemented in areas similar to those of many countries, with a significant augmented tourism sector and millions of visitors per year, especially in the EMME.

This study offers valuable insights into the causes and consequences of overtourism in host destinations, highlighting the proper strategies that policymakers and stakeholders should adopt for environmentally friendly and sustainable growth. Nevertheless, the unregulated growth of tourism (tourists per peak day/area) can contribute to significant environmental degradation, since limited or no data is available. However, all these factors are rapidly spreading and irrevocably changing tourism destinations, as well as the rate at which this transformation is being realised. Meanwhile, effective tourism planning and management are becoming increasingly necessary.

Incorporating Carrying Capacity Assessment (CCA) into the tourism and management planning process proved to be absolutely necessary. The Carrying Capacity included a set of specific indicators to determine the best scenarios and management practices for tourism development in a particular area, taking into account its distinctive characteristics. It should be used as guidelines for laying out tourism development and management plans at all levels. Furthermore, the results of calculating the appropriate indicators can lead to various conclusions. This cross-country assessment underscores distinct typologies of tourism development.

In general, the countries with significant environmental impact from over tourism, according to its specific characteristics are Cyprus, Israel and Greece (especially some Greek islands). They present severe saturation risk, international reliance and coastal ecological stress. In a better situation are the UAE which have High spatial bed density, Urban resource strain and large cruise/tourist volumes. All these factors must be taken into account to preserve the physical and ecological beauty of the country. Finally, Turkey, Egypt, and Saudi Arabia present opportunities; thus, they still exhibit moderate intensity levels, room for managed expansion, and potential to avoid overdependence if balanced. Specifically, Cyprus is characterised by high operational efficiency, spatial intensity, and infrastructure density, yet it maintains a relatively low environmental impact, suggesting effective governance and planning.

The UAE combines high operational performance with moderate spatial pressure and strong resilience in tourism. Israel shows high spatial and environmental pressure, necessitating targeted interventions for sustainable visitor dispersal and infrastructure resilience. Turkey presents a middle-ground with scalable infrastructure and moderate pressures, showing potential for balanced growth. Egypt reveals structural underperformance, despite its high tourism potential, as indicated by low indices across all categories, with a disproportionately high environmental impact, particularly on beaches.

In summary, Turkey and Greece are heavily reliant on Coastal and International Tourism. They present extensive coastlines and well-developed accommodation networks, which sustain large volumes of international arrivals. Their main challenge lies in managing seasonal overload and protecting fragile coastal and island ecosystems. Saudi Arabia and Egypt can be characterised as giants in domestic and religious tourism. These countries attract large domestic tourism flows, particularly for cultural or religious purposes. Infrastructure must strike a balance between internal mobility and heritage preservation. The remaining countries (UAE, Israel) operate in spatially constrained environments, focusing on high-value, niche, or religious tourism. They face unique challenges related to urban density, resource use, and geopolitical sensitivity.

This analysis supports the need for country-specific strategies grounded in composite indicators. Integrating these indices into national tourism policies can help address over-tourism, guide infrastructure investment, and ensure environmental sustainability across the Mediterranean and Middle East. They reflect trends noted in WTTC (2023) - GDP reliance indicators- , UNEP-WTO (2005) carrying capacity indicators, strategic warnings from Panousi and Petrakos (2021) on regional economic over-dependence, and synthesis and policy implications.

4.7 Conclusions

The spread of tourist arrivals aims to prevent the studied islands from being overexploitation, mainly in areas that have already overcome their carrying capacity. In such areas, the primary environmental pressure is applied to the littoral areas of the countries, as all of the aforementioned research sites have extensive coastlines, where millions of tourists are concentrated daily. Consequently, the coastal areas must be protected, as they are used intensively in the Eastern Mediterranean and Gulf Regions. Therefore, designing and implementing a tourism development plan that takes into account local particularities is necessary. Following the path of sustainability, modern strategies for promoting and growing tourism should be applied in an ecological, social, and financial multidimensional framework, in order not only to protect the natural wealth of a region but also to achieve various types of tourism throughout the year. This solution will be facilitated by extending the tourist season, as high temperatures are present throughout the year due to the local climatic regime, which is influenced by global climate change.

Apart from the natural environment, tourism development should follow various axes, including cultural, sports, diving, sport fishing, medical, luxury, sea tourism (yachting), and conferences, among others. Moreover, communities must monitor the number of tourists during spe-cific periods or in some geographic regions to compare and note patterns of change. Furthermore, additional studies in this area are needed to assess resident attitudes, satisfaction, and perceptions of tourism development using subjective indicators. The evaluation of implementation using both objective and subjective indica-tors will help create a robust monitoring system. Following the UN directives for tourism development until 2030, this study contributes to the Sustainable Development Goals. Since tourism is one of the fastest-growing economic sectors, especially in this region, it can play a significant role (Capocchi et al., 2019). Based on these directives, this specific area's fifteen (15) indicators were selected as the most representative. The calculation of CCA involves numerous choices based on various aspects of Carrying Capacity due to Physical, Ecological, and Demographic differences in the study area. Thus, in this study, these particular indicators accurately reflect the current state of Carrying Capacity in the multi-dimensional Eastern Mediterranean and Gulf Regions. The data highlight the diverse socio-demographic and spatial conditions that influence tourism development in the Eastern Mediterranean and Gulf Regions. While Greece exemplifies a model of dense, coastally dependent international tourism, Saudi Arabia and Egypt demonstrate high domestic tourism demand. The UAE and Israel serve as examples of compact tourism economies with specialized offerings, whereas Turkey represents a hybrid model with vast capacity and international appeal.

Ultimately, to ensure sustainable development, each country must tailor its tourism strategies to its unique spatial resources, demographic profile, and environmental thresholds, particularly in light of the increasing stress of climate change and geopolitical shifts. To achieve sustainable tourism policies, developing a new tourism model must be based on respect for tourist resources and the environment. Additionally, the determination of protection zones for cultural heritage and natural resources (based on the Natura 2000) is necessary to limit or prohibit the possibility of construction and, consequently, potential landscape degradation. The high quality of the services provided, in terms of human resources and infrastructure, combined with the environmental and natural advantages of the South Aegean Region, gives the area a significant lead over its competitors, according to statistical evidence from INSETE (2024). Additionally, by applying visitor caps and timed access in peak areas, promote domestic tourism and cultural resilience, monitor spatial saturation in real-time using GIS, diversify product offerings in high-risk areas, and develop tourism zones in underutilised or low-pressure areas

It is necessary, therefore, to have a concerted effort by the state and local administration to adopt alternative tourist models aiming in sustainability.

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