Drivers and their interactions

2

Coordinating Lead Authors:
Murat BELIVERMIS *(Türkiye)*, **Dario CAMUFFO** *(Italy)*

Lead Authors:
Nuno CAIOLA *(Spain)*, **Claudio FERRARI** *(Italy)*, **Nadia MHAMMDI** *(Morocco)*, **Estela ROMERO** *(Spain)*, **Claudia WOLFF** *(Germany)*

Contributing Authors:
Vincenzo ASERO *(Italy)*, **Sana BEN ISMAIL** *(Tunisia)*, **Cem DALYAN** *(Türkiye)*, **Hamouda DAKHLAOUI** *(Tunisia)*, **Lena REIMANN** *(The Netherlands)*, **Alessio TEI** *(Italy)*, **Matteo VACCHI** *(Italy)*, **Antonio della VALLE** *(Italy)*

This document should be cited as:
Belivermis, M., Camuffo, D., Caiola, N., Ferrari, C., Mhammdi, N., Romero, E., Wolff, C., 2024: Drivers and their Interactions. In: *Climate and Environmental Coastal Risks in the Mediterranean.* [Djoundourian, S., Lionello, P., Llasat, M.C., Guiot, J., Cramer, W., Driouech, F., Gattacceca, J.C., Marini, K. (eds.)]. MedECC Reports. MedECC Secretariat, Marseille, France, pp. 71-130, doi: 10.5281/zenodo.15096232

2

Chapter 2
Drivers and their interactions

Executive summary **73**

2.1 Introduction **76**

2.2 Climate and geological driver **76**
- 2.2.1 Air temperature **76**
- 2.2.2 Precipitation **78**
- 2.2.3 Atmospheric circulation **79**
- 2.2.4 Cyclones affecting Mediterranean coasts **80**
- 2.2.5 Sea water temperature, salinity and acidification **83**
- 2.2.6 Net hydrological balance: evaporation, precipitation and river runoff **85**
- 2.2.7 Sea level rise and (permanent) coastal submersion **86**
- 2.2.8 Natural and anthropic land subsidence across the Mediterranean coast **87**
- 2.2.9 Geohazards **89**

2.3 Biological driver **93**
- 2.3.1 Non-indigenous species **93**
- 2.3.2 Changes in the limits of species distribution **94**
- 2.3.3 Jellyfish blooms **95**

2.4 Pollution drivers **97**
- 2.4.1 Nutrients **97**
- 2.4.2 Trace metals **98**
- 2.4.3 Persistent organic pollutants (POPs) **100**
- 2.4.4 Plastics **101**
- 2.4.5 Emerging pollutants **102**
- 2.4.6 Air pollution **103**

2.5 Social and economic drivers **104**
- 2.5.1 Current and future population and urban development trends across the coastal region **104**
- 2.5.2 The economic use of the coast **105**

2.6 Final remarks **110**

References **112**

Information about authors **129**

Executive Summary

This chapter provides a comprehensive overview of the main natural and socio-economic drivers affecting the Mediterranean coasts. These drivers are of different origins and nature, including atmospheric, marine, terrestrial, biological, pollution-related, and socio-economic factors.

They contribute to phenomena such as coastal flooding, changes in ecosystem services, utilisation and exploitation of marine and coastal resources, degradation of natural and built infrastructure, among others, which impact the lives and livelihoods of the large and densely populated coastal areas and the proximate urban areas that depend heavily on marine and coastal resources. Some drivers are linked to climate change (exacerbated by human activities), while others are partially or entirely of anthropogenic origin (e.g. air and water pollution, tourism, urbanisation, socio-economic development). The situation can become complex as these drivers occur in temporal sequence, jointly, or in synergy. This chapter introduces the drivers, while their impacts are be considered in subsequent chapters.

Climate and geological drivers

Coastal air is warming. At the beginning of the 2020s, the near-surface air temperature of the Mediterranean region is +1.5°C warmer than in the 1850–1900 preindustrial period *(high confidence).* On the Mediterranean coasts, referring to the 1850–1900 period, there is *high confidence* that the projected increase in air temperature will be +1.6°C to +2.7°C for the medium term and +1.6°C to +3°C for the long term for the SSP1-2.6 low emission scenario *(very likely)* and values up to +2.3°C to +3.6°C for the medium term, and +4.2°C to +6.8°C for the long term, for the SSP5-8.5 very high emission scenario *(very likely)*. {2.2.1}

Coastal waters are warming. Since the preindustrial period, the surface temperature of the Mediterranean water has been rising with a long-term positive trend of about +0.86°C per century. This trend is not constant but is characterised by a multidecadal periodicity (~70 years) superimposed on it *(high confidence)*. {2.2.1}. Since the 1980s, satellite data has shown that the warming rate of the sea surface is spatially inhomogeneous, ranging between +0.29°C and +0.44°C per decade, and is stronger in the eastern Mediterranean. In addition, over the last two decades, the mean frequency of marine heat waves (MHW) has increased by +40%, and the duration by +15% *(high confidence)*. {2.2.5}

Significant warming is expected in the surface waters of the Mediterranean Sea *(virtually certain)*. Compared to the end of the 20th century, the annual mean basin sea surface temperature is expected to increase by +0.6°C to +1.3°C before the mid-21st century and by +2.7°C to +3.8°C at the end of the 21st century period for the pessimistic RCP8.5 scenario, and by +1.1°C to +2.1°C for the medium RCP4.5 scenario *(high confidence)*. {2.2.5}

Sea level is rising. Sea level changes have long been documented with instrumental and non-instrumental data. The pre-instrumental period is known from proxy data, tide gauges started in 1871, and satellite altimetry started in 1992. The rise rate increases over time, and the longest reconstructed series, for example Venice's seven century long record, shows an exponential trend *(observation evidence)*. {2.2.7}

The Mediterranean Sea level is projected to rise further during the coming decades and centuries *(high confidence)*, *likely* reaching +0.28 m to +0.55 m for shared socioeconomic pathways (SSP1-1.9) and +0.63 m to +1.01 m for SSP5-8.5 in 2100 (relative to 1995–2014) *(medium confidence)*. The process is irreversible at the scale of centuries to millennia *(high confidence)*. {2.2.7}

Land subsidence increases coastal submersion. Relative sea level is determined by the sum of the mean sea level and vertical land movements (i.e. negative subsidence and positive uplift). Relative sea level rise increases especially in areas affected by significant land subsidence. The situation across the European coasts has been documented by studies and especially satellite data (Copernicus Sentinel) since 2016, and the most affected areas are the coastal region of the Adriatic Sea and the Po Delta in Italy, Thessaloniki in Greece, and some small islands *(high confidence)*. The non-

European coasts on the eastern and southern Mediterranean are less documented, except for Mejerda near Tunis, and the eastern Nile Delta in Egypt *(high confidence).* Land subsidence is mainly determined by geological factors, but it may be increased by human activities, such as extraction of water, gases, or building load. In certain areas, subsidence may reach values of the order of -10 mm yr^{-1} *(observation evidence).* {2.2.8}

For the combined effect of sea level rise and subsidence, the risk of coastal floods will increase in low-lying areas that constitute 37% of the Mediterranean coastline *(high confidence)*. {2.2.4}

Saltwater intrusion in rivers, estuaries, and coastal aquifers will *likely* increase, affecting groundwater resources, river discharges, the use of coastal areas, and the most extensive wetlands that are found in relation to the major Mediterranean rivers *(high confidence)*. {2.2.4}

The main drivers of storm surges and coastal floods in the Mediterranean region vary by season. In the cold season, the penetration of Atlantic fronts, or low-pressure areas developing over the Mediterranean, may generate storm surges and exceptionally deep coastal floods, high wind waves and other phenomena such as flash floods that are potentially dangerous to people, the environment, and the whole coastal area *(high confidence).* {2.2.4}. In the warm season, increasing aridity or intense precipitation combined with occasional high intensity precipitation events will *likely* constitute the main challenges *(medium confidence).* {2.2.2}

Water salinity and acidity are related to water temperature. Not only temperature, but water salinity and acidity will also be affected, with *likely* impacts on the terrestrial and marine environment. Acidification is projected to continue *(virtually certain)* with a pH decrease of up to –0.46 unit in a high emission scenario *(medium confidence)*. {2.2.5}

Future reduced precipitation, associated with increased evaporation will lead to a decline in runoff in the Mediterranean region and fresh water supply. Droughts are projected to become more severe, more frequent and longer under moderate emission scenarios, and strongly enhanced under severe emission scenarios *(high confidence)* {2.2.6}

Biological drivers

With over a thousand non-indigenous species, the Mediterranean, which is a major invasion hotspot *(virtually certain)* is the most heavily invaded marine region in the world. Non-indigenous species outcompete indigenous species, causing regional biodiversity shifts and altering ecosystem functions and services *(high confidence).* The Suez Canal has provided the most important entrance for non-native species in the Mediterranean. At present, other pathways such as shipping vectors and the aquarium trade are responsible for a considerably higher number of the non-indigenous species that have been introduced. {2.3.1}

The Mediterranean is warming faster than other seas, becoming increasingly suitable to be colonised and invaded by organisms of tropical origin. The effect of global warming is therefore contributing to species colonisation through the Strait of Gibraltar, but also to the dispersal of these and truly non-indigenous species within the Mediterranean. Moreover, species are changing their life-history traits and patterns due to warming, which can lead to a loss of competitive abilities to cope with the effects of biological drivers, especially those caused by biological invasions. {2.3.2}

Recent studies show an increase in the frequency of jellyfish blooms in the Mediterranean Sea *(medium confidence).* There is some evidence that this is occurring due to eutrophication and other human-induced stressors, such as global warming *(medium confidence).* {2.3.3}

Pollution drivers

There is *robust evidence* that the high fluxes of nutrients transported by air, surface water, and groundwater to Mediterranean coasts are related to agricultural practices and urban and industrial uses. Nutrient fluxes are expected to decrease in the north due to the implementation of environmental regulations, but nutrient increases are expected in the south as a result of urban development and agricultural intensification *(high confidence).* Submarine groundwater discharge inputs, which lag a few decades behind agricultural inputs, can contribute to sustained nutrient increases in the coming years and compromise water quality *(medium confidence).* The overall projected changes in land-derived nutrients will contribute to widening the current nutrient imbalance in coastal ecosystems, increasing the availability of N relative to P and ultimately exacerbating eutrophication problems *(high agreement)*. {2.4.1}

Concentrations of certain persistent organic pollutants (POPs), such as polychlorinated biphenyl (PCBs) and dichlorodiphenyltrichloroethane (DDT), will *very likely* continue to decline in the Mediterranean coasts due to regulations *(medium confidence).* Concentrations of emerging pollutants, such as pharmaceuticals and personal care products, will not show a downward trend due to emerging industries and socioeconomic change *(medium confidence).* {2.4}

The amount of plastic pollution along Mediterranean coasts has remained steady for the past two decades *(medium confidence).* Annual plastic leakage into the Mediterranean coastal area is *likely* to reach 500,000 tonnes by 2040 if annual plastic production continues to grow at a rate of 4% and waste management is not radically improved. In the scenario of 1% annual growth in plastic production and improved waste management, the leakage is *likely* to decrease by 2040 *(medium confidence).* {2.4.4}

Given the high concentrations of plastics, trace elements and emerging pollutants in the Mediterranean Sea, their co-occurrence with seawater warming, acidification, and deoxygenation is *likely* to rise along the Mediterranean shores *(high confidence).* {2.2.5; 2.4}

Social and economic drivers

The Mediterranean countries have higher urbanisation rates than the rest of the world. Currently, two out of three people live in urban regions *(medium confidence).* In the past, socio-economic growth in the Mediterranean coastal region has been quite rapid and spatially diversified, leading to significant climate-related coastal exposure in all Mediterranean countries *(high confidence).* Under all socio-economic projections, the total population of the Mediterranean coastal region will continue to grow faster than the inland population *(medium confidence).* The coastal regions of the Mediterranean Middle East and Maghreb countries are anticipated to have the highest exposure to sea-level rise due to their projected coastal population growth. {2.5.1}

Climate change, with increasing sea level rise and storm frequency, will negatively impact port structures and operations *(high confidence).* Climate change will *likely* affect coastal sustainable development. On the one hand, energy related infrastructure will become widespread, impacting land use and pollution levels. On the other hand, the distribution of sediments over the coastal regions will be highly affected by environmental changes *(high confidence).* {2.5.2}

The Mediterranean coast is the world's leading tourism destination, and the past projections included very optimistic development *(high confidence).* However, the COVID-19 pandemic and the growing geopolitical conflicts caused a very severe decline (up to 80%) and the whole sector is suffering from uncertainties *(low confidence).* {2.5.2}

With the increasing use of freshwater and the expected increase of aridity, desalination for drinking water, livestock and agricultural use is important and it is *very likely* that it will continue to gain importance on the coast of Algeria, Egypt, Israel, Italy, Malta, and Spain. {2.5.2.3}

The catch potential of fish and invertebrates on the eastern and southern Mediterranean coasts is projected to decline and even to become extinct under the most pessimistic scenario (RCP8.5). Some species will be included in the Red List of the International Union for Conservation of Nature (IUCN) and others are expected to become extinct *(very high confidence).* {2.5.2.4}

2

2.1 Introduction

A driver is any natural or human-induced factor that directly or indirectly causes a change in a system (IPCC 2021a). Most drivers, especially those related to climate change, pollution, or human activities, have been presented and discussed in the latest IPCC AR6 report of the Working Group I (IPCC 2021b) and the MedECC First Mediterranean Assessment Report (MAR1, MedECC 2020). This Chapter is mainly grounded on them, but with some updating and additional items. Drivers may operate singularly, or in conjunction, and may generate negative feedback loops, where drivers can be either the cause or consequence of changes. The aim is to summarise the key drivers that govern the coastal climate, the sea level, and the coastal ecosystem of the Mediterranean, and are a prerequisite to understanding what is explained in the next Chapters. This Chapter considers a comprehensive set of drivers relevant for coastal communities, with special attention to projections and their potential synergisms with other natural or anthropic drivers. The spatial and temporal combination of concurrent drivers and/or meteorological conditions may amplify each other and lead to even greater secondary impacts with unprecedented social, ecological and economic consequences (Bevacqua et al. 2021; Xoplaki et al. 2023).

The identification of drivers helps to identify critical issues, predict changes and hazards, and assess risks *(Chapter 3).* On this basis, it will be possible to adopt measures to reduce potential damage to ecosystems and human systems, or to adapt them to climate change *(Chapter 4),* as well as to plan sustainable development pathways *(Chapter 5).* Therefore, the presentation of the drivers, their long-term trends, and related future scenarios, has been organised to produce a comprehensive overview.

2.2 Climate and geological drivers

2.2.1 Air temperature

There is robust evidence that the Mediterranean region has significantly warmed basin-wide. The annual mean temperature of the air in the Mediterranean region is +1.54°C higher than the 1860-1890 preindustrial level for land and sea areas, that is +0.4°C more than the global average *(observed data)* (Cherif et al. 2020). The Mediterranean Sea's surface temperature has been

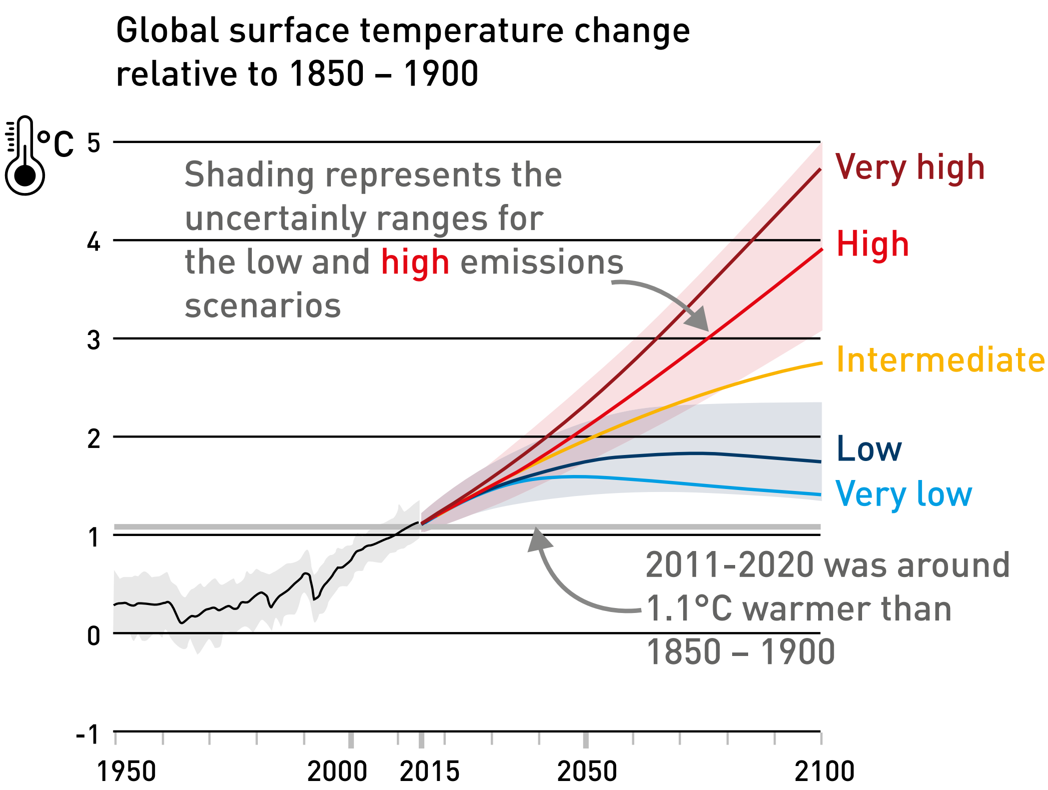


Figure 2.1 | Projected global surface temperature change relative to 1850 – 1900. Source: IPCC (2023).

characterised by a long-term positive trend of about +0.86°C per century since the preindustrial period *(observed data),* in conjunction with a multidecadal periodicity (~70 years) (Axaopoulos and Sofianos 2010; Rivetti et al. 2017; Darmaraki et al. 2019a; Pastor et al. 2020).

Over the 20th century, climate reconstructions, ground-based observations, reanalysis and remote-sensing datasets all corroborate the transition to warmer conditions, and that warming has accelerated during the last decades, with significant positive trends of the order of +0.1°C to +0.5°C per decade (Lionello and Scarascia 2018; Bilbao et al. 2019). All studies, and IPCC (2021b) as well, present a strong consensus that present-day warming is robust throughout the Mediterranean region *(high confidence),* although the extent and level of significance of the observed temperature trends along the Mediterranean coast vary, depending on geographical position, type of data, season, and period of analysis. Air and sea temperature and their extremes are *likely* to continue to increase more than the global average *(high confidence)* (Boberg and Christensen 2012). The projected annual mean warming on land at the end of the century is in the range of +0.9°C to +5.6°C compared to the last two decades of the 20th century, depending on the emission scenario *(high confidence)* (Boberg and Christensen 2012; Cos et al. 2022). According to map from MedECC (2020) and IPCC (2023), the most severe warming will *likely* occur on the mountain and the coastal areas of the easternmost Mediterranean Sea, for example Egypt, Israel, Lebanon, and Syria *(high confidence).*

The Mediterranean Basin is among the most responsive regions to global (Seneviratne et al. 2021). In the future, widespread warming will *almost certainly* occur in the Mediterranean in the 21st century *(high confidence).* There are strong indications and a general consensus that regional warming will continue faster than the global average and at the end of the century it will exceed the global mean value by +20% on an annual basis and +50% in summer *(high confidence).* According to projections for the RCP8.5 scenario[21], summer daily maximum temperature is expected to increase up to +7°C by the end of the 21st century in comparison with the recent past (Lelieveld et al. 2016; Lionello and Scarascia 2018; Bilbao et al. 2019). As shown in *Chapter 1*, *Table 1.1*, making reference to the 1850–1900 period, for the Mediterranean coasts, the IPCC interactive Atlas (Gutiérrez et al. 2021) projected a temperature increase of +1.6°C to +2.7°C for the medium term, and +1.6°C to +3°C for the long term, for the SSP1-2.6 low emissions scenario *(very likely)* and values up to +2.3°C to +3.6°C for the medium term, and +4.2°C to +6.8°C for the long term, for the SSP5-8.5 very high emissions scenario *(very likely).*[22]

Unusual and persistent hot weather is expressed in terms of heat waves[23] (HW). Projected changes in extreme temperature indicators suggest that both the frequency and the severity of heat waves will increase *(very high confidence).*

Daytime temperatures are expected to increase more than night-time temperatures, indicating an increase in the amplitude of the daily temperature range. The minimum temperature of the day is recorded at the end of the night, and a day in which the minimum temperature exceeds 20°C is said to have a tropical night[24] (TN). The number of TNs has increased over most Mediterranean locations including Iberia, North Africa, Italy, Malta, Greece, Anatolia, and the Levant *(very high confidence).* The number of TNs *will likely* increase by more than +60% in these parts of the Mediterranean. The increase

21 Representative Concentration Pathways (RCP) are greenhouse gas concentration trajectories (not emissions) used for the 5th phase of the Coupled Model Intercomparison Project (CMIP5) and labelled in line with a possible range of radiative forcing values in the year 2100: 2.6, 4.5, 6.0, and 8.5 W m^{-2} respectively. These correspond to one stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0), and one scenario with very high GHG emissions (RCP8.5).

22 Shared Socioeconomic Pathways (SSP) are cited as defined in IPCC AR6 based on future greenhouse gases (GHG) emissions, labelled after the SSP narrative and associated radiative forcing values in the year 2100 (1.9, 2.6, 4.5, 7.0, and 8.5 W m^{-2}). SSP1-1.9 - very low GHG emissions and SSP1-2.6 – low GHG emissions (CO_2 emissions reduce to net zero in the 2050s), SSP2-4.5 – intermediate GHG emissions (CO_2 emissions remain around current levels until 2050, then falling but not reaching net zero by 2100), SSP3-7.0 – high GHG emissions, and SSP5-8.5 – very high GHG emissions (CO_2 emissions roughly double from current levels by 2100 and 2050, respectively).

23 A heat wave (HW) is broadly defined as a 'marked warming of the air, or the invasion of very warm air, over a large area; it usually lasts from a few days to a few weeks' by the International Meteorological Vocabulary (WMO 1992) and more recently as 'a period of abnormally hot weather, often defined with reference to a relative temperature threshold, lasting from two days to months' (IPCC 2021) and 'a period of marked and unusually hot weather persisting for at least two consecutive days' (WMO 2023).

24 Tropical night (TN) is defined as a 'night in which the air temperature does not fall below 20°C' (WMO et al. 2009).

in high temperature extremes will especially occur in summer, with +4°C global warming. Almost all nights will be warm and there will be no cold days *(medium confidence)* (Lionello and Scarascia 2020). Satellite investigations made on cities of the Iberian Peninsula have found no evidence that the effect of urban heat islands on the coasts is more enhanced than inland, but that the result may change with the characteristics of the cities, i.e. the choice of the case studies *(low confidence)* (Hidalgo García et al. 2022).

An unusually high and persistent sea water temperature is expressed in terms of marine heat waves[25] (MHW). In response to increasing greenhouse gas forcing, MHW are projected to further increase in frequency, duration, spatial extent and intensity (maximum temperature) *(very high confidence).* Climate models project increases in the frequency of MHW by 2081–2100, relative to 1850–1900, by approximately 20 times under RCP2.6 and 50 times under RCP8.5 *(medium confidence)* (IPCC 2023). More particularly, MHW are expected to become stronger and more intense under RCP4.5 and RCP8.5 than RCP2.6. By 2100 and under RCP8.5, simulations project at least one long-lasting MHW every year, up to three months longer, about 4 times more intense and 42 times more severe than present-day events. They are expected to occur from June to October and to affect the entire basin at peak *(medium confidence).* Until the mid-21st century, MHW characteristics are estimated to increase independently of the choice of the emission scenario, the influence of which becomes more evident by the end of the period. Further analysis reveals different climate change responses in certain configurations, more *likely* linked to their driving global climate model rather than to the individual model biases *(low confidence)* (Darmaraki et al. 2019a).

2.2.2 Precipitation

The synthesis made by IPCC (2023) is that precipitation will *likely* decrease in most areas by −4 to −22%, depending on the emission scenario *(medium confidence).* Rainfall extremes will *likely* increase in the northern part of the Mediterranean coast, as well as in Sicily, where a significant increasing trend has been observed *(high confidence)* (Treppiedi et al. 2021). Analysis of long-term rainfall time series showed statistically significant increasing trends in short duration precipitation occurrence, and rainfall rates, suggesting a possible future scenario with a more frequent exceedance of threshold triggering values, and an increase of landslide risk *(high confidence)* (Roccati et al. 2020). Droughts will become more prevalent in many areas, especially in the easternmost and southern Mediterranean coasts *(high confidence)* (MedECC 2020; UNEP/MAP and Plan Bleu 2020; Ali et al. 2022).

Across the Mediterranean, observed precipitation trends show pronounced spatial variability, increasing or decreasing depending on the time period and season considered. Several studies have assessed changes in interannual variability of precipitation, but the extent and the pattern of precipitation decreases widely vary across models, even with contrasting trends *(low confidence)* (Peña-Angulo et al. 2020; Vicente-Serrano et al. 2021). Model projections suggest that global warming will further increase the existing difference in intensity of precipitation and hydrological extremes between northern and southern Mediterranean areas *(high confidence).* The projected increase in dry spell length is greater in the southern than in the northern Mediterranean *(medium confidence)* (Lionello and Scarascia 2020). In the total annual budget, the contribution of extreme daily rainfall is projected to increase throughout the Mediterranean region. This increase is expected to be strongest in North Africa and particularly in the Maghreb region *(high confidence)* (Zittis et al. 2021). A robust and significant precipitation decline is projected over large parts of the region during summer by the end of the century and for the high emission scenario (−49% to −16% for CMIP6 (Coupled Model Intercomparison Project Phase 6[26]) and −47% to −22% for CMIP5) *(high confidence)* (Cos et al. 2022). Future projections made by Zittis et al. (2021) indicate a strong northern/southern Mediterranean gradient, with significant, decreasing

25 Marine heat wave (MHW) is defined as a 'period of five or more days in which ocean temperatures are above the 90th percentile, that is in the top 10% of recorded figures for that region at that time of year' (WMO 2023) as well as 'a period during which water temperature is abnormally warm for the time of the year relative to historical temperatures, with that extreme warmth persisting for days to months.' (IPCC 2021).

26 https://wcrp-cmip.org/

trends in the magnitude of daily precipitation extremes in the south and the Maghreb region (up to −10 mm decade^{-1}) and less profound, increasing trends in the north *(high confidence).*

At a local scale, the extreme rainfall trend can increase by a factor of 2 compared to the regional assessment. In the future climate, characterised by an increase of about 2°C in global temperature, extreme daily rainfall (95th percentile) is expected to increase by about +10% relative to the current level *(medium confidence).* This is the same order of magnitude as the increase observed at regional scale in the recent past (Molinié et al. 2016). The 100-year extremes have no specific trend or preferential areas *(medium confidence)* (Peña-Angulo et al. 2020; Vicente-Serrano et al. 2021). The contribution of the wettest day per year to the annual total precipitation is expected to increase (+5% to +30%) throughout the whole Mediterranean region. The 50-year daily precipitation extremes are projected to strongly increase (up to +100%) throughout the whole region *(medium confidence)* (Zittis et al. 2021). IPCC (2023) specifies that there is low agreement on heavy precipitation change across the Mediterranean *(low confidence).*

2.2.3 Atmospheric circulation

The proximity to the Atlantic and Indian Oceans and the surrounding massive land areas, places the Mediterranean area at the crossroads of many global climate patterns and processes of tropical and extratropical origin. The projected expansion of the Hadley Cell will shift the mid-latitude westerlies and storm tracks northward, thus reducing storminess *(medium/high confidence)* (D'Agostino et al. 2020) and precipitation *(medium confidence).* The Mediterranean could be influenced by additional local circulation anomalies, leading to pronounced changes in precipitation patterns *(medium confidence)* (D'Agostino and Lionello 2020).

Winds and wind waves

Surface wind speeds and their changes across different temporal and spatial scales are governed by driving and drag forces, whose individual contributions are difficult to estimate and disentangle. In addition, observation-based studies of winds across the Mediterranean are less frequent than for other meteorological variables. Wintertime large-scale circulation has exhibited a long-term trend toward increased sea-level pressure and anticyclonic circulation over the Mediterranean, with multi-decadal variability *(very high confidence).* During summer, a possible decline in sea-level pressure over North Africa and the southern Mediterranean is expected *(medium confidence).* In most regions, wind trends have been found to be non-monotonic over the past decades, which complicates the identification of clear long-term patterns *(very low confidence).*

Despite the uncertainties in future projections, there is a general agreement for a limited wind speed reduction across most of the Mediterranean, with the exception of the Aegean Sea and northeastern land areas *(medium confidence),* while changes in the local winds may have more complex responses involved, depending on the changes in their underlying feedbacks. Over the western Mediterranean, Mistral wind is projected to have small changes, and Tramontane a significant decrease in frequency. Over the Adriatic Sea, in winter, the occurrence of Bora wind is projected to increase in frequency, while the frequency of Sirocco is expected to decrease. Over the Aegean Sea, Etesian winds are expected to increase in speed *(high confidence)* (Belušić Vozila et al. 2019; Dafka et al. 2019; Ezber 2019).

Since sea waves are primarily driven by winds, high waves are present across most of the Mediterranean Sea and tend to reach the highest values where strong winds combine with long fetches. Wind waves are driven by wind and continue their motion by inertia, until they break on a coast exposed to the wind, thus causing coastal erosion. Compared to the Atlantic, in the Mediterranean Sea, the mean wave heights (1 m to 1.5 m) are lower, and the periods (5 s to 6 s) shorter, with relevant spatial variability due to the complex orography and coastline surrounding the basin *(high confidence)* (Menendez et al. 2014).

The coasts most exposed to the risk of high waves are mainly located in the central and western Mediterranean, and in particular the Gulf of Lion, on the southern coast of France, where the effect is most pronounced (Patlakas et al. 2021). It has been evaluated that 71.4% of the Mediterranean coast is exposed to significant wave heights that have a 100-year return period higher than 5 m, and

22.4% of the coast to waves higher than 9 m. These values increase for islands, where 93.2% of the coast is exposed to significant wave heights higher than 5 m and 30% higher than 9 m *(medium confidence)* (Toomey et al. 2022).

The highest waves (5 m to 6 m) extend from the Gulf of Lion to the southwestern Sardinia through the Balearic Sea and are sustained southwards approaching the Algerian coast *(high confidence)* (Lionello et al. 2017). They result from northerly winds dominant in the western Mediterranean Sea (Mistral or Tramontana) that become stronger due to orographic channelling, and act over a large area, breaking on the northern and western coasts of Corsica, Sardinia, and Balearic Islands. In the Ionian Sea, the northerly Mistral wind is still the main cause of high waves (4 m to 5 m) that will break on the eastern coasts of Greece and northern Africa. In the Aegean and Levantine Seas, high waves (4 m to 5 m) are caused by the northerly Bora winds (affecting the western coasts), prevalent in winter, and the northerly Etesian winds (affecting the southern coasts), prevalent in summer. In general, northerly winds are responsible for most high waves in the Mediterranean Sea *(high confidence)* (Obermann-Hellhund et al. 2018; Dafka et al. 2019; Ezber 2019). Model projections suggest that future changes in waves will be determined by changes in the wind field over the Mediterranean Sea *(high confidence).* A number of studies point towards a generalised reduction of the mean significant wave height field over a large portion of the Mediterranean Sea, especially in winter *(high confidence)* (Hueging et al. 2013; Tobin et al. 2015; Moemken et al. 2018). For all the Mediterranean Sea, during spring, the projected changes of wave directional spectra present an overall robust decrease in the predominant wave systems, in agreement with previous studies depicting a decrease in the significant wave height. Nonetheless, a robust increase in other less energetic frequencies and directions is observed for both mid-century and end-of-century conditions throughout the Mediterranean Basin *(medium-high confidence)* (Lira-Loarca and Besio 2022).

Extreme waves are expected to decrease in number and intensity, although there is no consensus on whether very large extreme events, associated with very strong winds, would also decrease *(low confidence).* A simulation done with a set of seven models under emission scenario RCP8.5 across the Mediterranean Basin has shown, on average, a decreasing trend of significant wave height and mean period, while the wave directions may be characterised by a slight eastward shift *(medium confidence)* (De Leo et al. 2021).

2.2.4 Cyclones affecting Mediterranean coasts

Certain hazards may occur occasionally, independently from other challenges, or may occur in temporal sequence, or may operate synergistically. Their combination and clustering may constitute a hazard greater than the sum of the individual contributions, and Mediterranean cyclones are a typical example. The sea level rise driven by climate change, combined with changes in storminess, will *likely* lead to increased clustering of storm surges, waves, and high sea levels, further exacerbating the impacts of flooding and erosion (Fox-Kemper et al. 2021). The Mediterranean is one of the main cyclogenetic areas of the world, and Mediterranean cyclones are related to a number of effects, for example episodic events affecting sea level anomalies, or generating meteotsunamis, high waves, and flooding (see *Chapter 3*).

2.2.4.1 Cyclogenetic activity

The northwestern Mediterranean, North Africa, and the north shore of the Levantine Basin are the areas most affected by cyclogenetic activity (Miglietta 2019). When cyclogenesis occurs in the western Mediterranean, either positive or negative sea level anomalies[27] may be generated. Atlantic cyclones mainly produce positive anomalies in the western Mediterranean. Cyclogenesis in the eastern Mediterranean generates positive sea level anomalies on the easternmost Mediterranean coast. Cyclogenesis over North Africa generates positive anomalies on the African coast and negative anomalies on the eastern Mediterranean and northern Aegean coasts (Lionello et al. 2019). High correlations between deep depressions and sea level

27 Elevations above sea level (i.e. increase) are positive and elevations below sea level (i.e. decrease) are negative.

anomalies have been observed in several parts of the northern Mediterranean coasts (Gulfs of Valencia and Lions, Ligurian and northern Adriatic Seas). They are followed by mid-latitude areas around Corsica, Sardinia, the mid-zonal Italian Peninsula and the Adriatic, and the northern Aegean Sea. The influence of deep depressions on storm surges is lower for Sicily, southern Italy, Peloponnese, Crete, the southern Aegean archipelago, and Alboran Sea *(high confidence)* (Makris et al. 2023).

2.2.4.2 Mediterranean cyclones

Long-term changes, at interannual and longer timescales, in extreme sea levels are primarily driven by changes in mean sea level (Woodworth et al. 2019). However, variations in extreme sea levels unrelated to mean sea level variability have also been identified in tide gauge records at an hourly scale (Wahl and Chambers 2015; Marcos and Woodworth 2017) and been linked to storminess and changes in storminess (Pérez Gómez et al. 2022). Mediterranean cyclones are responsible for severe surges, but flooding frequency and flooding water depth depend on a complex combination of factors including coastal morphology, vertical land motions and local sea level. The local sea level may be amplified by waves, wind, intense precipitation, currents and other factors. In the Mediterranean, higher values are found in the northern Adriatic (between 150 cm and 200 cm) while in the rest of the region they vary between 20 cm and 60 cm (Marcos et al. 2009). If the corresponding annual mean level is extracted from the extreme sea levels, a reduction in trends at most stations is obtained, which leads to the conclusion that much of the change in the extremes is due to a change in the mean sea level *(high confidence)* (Menéndez and Woodworth 2010). The future sea level rise will *very likely* become the dominant factor for an increased frequency and intensity of coastal floods (Camuffo et al. 2017; Lionello et al. 2017; Vousdoukas et al. 2017; Soto-Navarro et al. 2020; Camuffo 2022a, 2022b, 2023; Reale et al. 2022). The highest sea surface elevations are found on the coasts of the northern Adriatic Sea (caused by storm surges induced by south-easterly wind setup effect) and in regions with wide shallow continental shelves (Gulf of Gabes, Syrte, Nile delta, Gulf of Lion, and the Spanish eastern coasts) that favour wind and wave setup *(high confidence)* (Toomey et al. 2022). The rise in frequency of concurrent extremes in precipitation and meteorological tides is particularly evident for coasts in the northern Mediterranean *(high confidence)* (Bevacqua et al. 2020). Steric expansion and storminess are shown to be contrasting factors; in the next decades, wave and storm surge maxima will decrease while the thermosteric expansion will increase the mean sea level. To a large extent, these two effects will offset each other, so that their superposition will increase/decrease the maximum water level along two comparable fractions of the coastline (about 15% to 20%) by the mid-21st century *(medium confidence)* (Lionello et al. 2017). However, at a multi-decadal timescale, there is an offset of −10 cm per century between observed and modelled thermosteric sea level over the historical period and modelled thermosteric sea level over this century for the same rate of change in global temperature. The mass addition across the Gibraltar Strait to the Mediterranean Sea will *likely* become the dominant factor and determine an increase in the maximum water level along most of the coast *(medium confidence)* (Lionello et al 2017). Analyses of tide gauge data have revealed an increase in the magnitude and duration of extreme sea levels in the region in recent decades, caused by the rise in the relative mean sea level *(very high confidence)* (Lionello et al. 2021; Zanchettin et al. 2021; Camuffo 2022a, 2022b, 2024).

Although the number of cyclones has *likely* decreased, this reduction is not statistically significant (Romera et al. 2017; González-Alemán et al. 2019). The projected changes in cyclone hazards toward the late 21st century show a limited agreement in terms of magnitude and even sign of the projected changes along most of the coastal regions *(low confidence)* (Toomey et al. 2022).

Future projections under the RCP8.5 scenario, estimate that the Alboran Sea, the Gulfs of Gabes, Alexandretta, and the Aegean Sea's coasts will be further increasingly influenced by deep depressions *(medium confidence)*. A general consensus is that deep depressions and storm surges would probably cause mid-to-high sea elevations on the Aegean Sea, Ionian Sea, Gulf of Lions, Valencia, Gabes; the highest will be reached on the northern Adriatic and the Ligurian Sea. In the coastal regions of northern Italy, however, intense local wind forcing (i.e. Sirocco) might play a more significant role in the formation of high storm surges *(high confidence)* (Makris et al. 2023).

The predicted northward shift of storm tracks will cause a decreasing trend in storminess *(medium confidence)*, especially over areas where the main driving factor of extreme events is the atmospheric pressure pattern over the Mediterranean, and its dynamics (D'Agostino et al. 2017; Grise et al. 2019). The extreme sea surface elevations are predicted to increase in several Mediterranean sub-regions, such as the southern Adriatic, Balearic and Tyrrhenian Seas. In the Aegean Sea, low-pressure systems are predicted to be the main drivers of high surges, while in the Adriatic Sea, high surges will be *likely* driven by adverse wind conditions *(medium confidence)* (Androulidakis et al. 2015).

For a moderate-emission scenario (RCP4.5), the magnitude of 1-in-100-year water height values on the northern Adriatic coast is projected to increase by +12 cm to +17 cm by 2050 and +24 cm to 56 cm by 2100. Local subsidence (which is not included in the above estimates) will further contribute to the future increase in extreme water heights. On the northern Adriatic coast, for a high-emission scenario (RCP8.5), with respect to present levels, these values are projected to increase by +26 cm to +35 cm by 2050 and by +53 cm to +171 cm by 2100 and are subject to continue increasing thereafter *(medium confidence)* (Lionello et al. 2021)

Medicanes

A sub-group of hybrid depressions of extratropical cyclogenesis is constituted of so-called medicanes, that is Mediterranean hurricanes or tropical-like cyclones. The highest waves induced by medicanes are found in the central and the southwest part of the western Mediterranean, while the greatest storm surges are found in the Adriatic Sea and regions characterised by wide and gently sloping continental shelves (Toomey et al. 2022). In Sicily, coastal flooding due to medicanes is more frequent than flooding caused by other storms (Scicchitano et al. 2021). In the recent past, no strong trends have been identified *(medium confidence).* The projected effect of climate change on medicanes indicates a decreased frequency and a tendency toward a moderate increase in intensity *(medium confidence)* (Gaertner et al. 2007; E. Romero et al. 2013; R. Romero and Emanuel 2013; Tous and Romero 2013; Cavicchia et al. 2014; Walsh et al. 2014; Romera et al. 2017; González-Alemán et al. 2019; Toomey et al. 2022).

2.2.4.3 Meteotsunamis

Meteotsunamis are atmospherically induced destructive long waves in the tsunami frequency band, formed by storm systems moving rapidly across the sea, such as a squall line, and their development depends on several factors such as the intensity, direction and speed of the disturbance as it travels over the sea. The initial meteorological forcing may be related to atmospheric gravity waves, frontal passages, squalls, pressure jumps, and other types of atmospheric disturbances. On many occasions the forcing, being of mesoscale nature, has been related to some favourable synoptic pattern, which has been clearly established (Ramis and Jansà 1983; Monserrat et al. 1991). The atmospheric source normally generates barotropic ocean waves in the open ocean which after being amplified near the coast through some resonance mechanism (Proudman, Greenspan, shelf, harbour) can affect coasts in a similar damaging way as seismic tsunamis. However, due to the resonance mechanism required, their catastrophic effects are restricted to some specific bays and inlets (Monserrat et al. 2006).

Meteotsunamis have been traditionally studied much more in the Mediterranean than in the rest of the world. This is surely related to the micro-tidal nature of most of the Mediterranean Sea (e.g. Tsimplis et al. 1995). Due to the small tides, coastal infrastructures along the Mediterranean are generally not adapted to accommodate large sea level changes and meteotsunami damages and flooding are potentially worse in the Mediterranean in comparison to other macro-tidal coasts of the world (*see Chapter 3, Section 3.2.4.2*).

It seems that no significant changes in meteotsunamis are projected under RCP2.6 and RCP4.5 scenarios. However, they are *likely* to increase in RCP8.5, where the increase matches the spring–summer season when meteotsunamis reach their maximum intensity *(medium confidence)* (Vilibić et al. 2018 2021).

2.2.4.4 Cyclonic precipitation

On the coasts, the intense precipitation that on some occasions is associated with cyclones, may generate flash floods of low-lying areas, coastal erosion, raging torrents, or invade the urbanised areas causing a significant loss of human lives (see *Chapter 3, Section 3.2.3*).

The origin and track of cyclones producing intense precipitation differ in different areas. For the end of the 21st century, models project an overall weakening of the systems crossing the Mediterranean region, and in particular a robust decrease in the number and intensity of cyclones crossing the central part of Italy, Tyrrhenian Sea, parts of the Anatolian Peninsula, Balkan area and North Africa. A significant increase in cyclone-related precipitation and wind intensity in the central part of the Mediterranean region is also expected *(medium confidence).* Over most of the Mediterranean, the decrease in accumulated precipitation in winter will be driven by the decrease in the number of cyclones crossing the area and will be only partially compensated by the increase in the intensity of the rainy events associated with each cyclone. In the eastern Mediterranean, the drier conditions observed in winter will be driven by both the decrease in the number of cyclones and the intensity of each rainy event *(medium confidence)* (Reale et al. 2022a). Conversely, models predict an opposite change in precipitation and wind intensity in the south-eastern part of the region. Both signals are spatially coincident with the decrease of the number of cyclones. In winter, an overall decrease in total accumulated precipitation over most of the Mediterranean region is expected. For the end of the 21st century, models are consistent in predicting a decrease in the number and an overall weakening of cyclones moving across the Mediterranean *(high confidence),* but the magnitude of the projected changes varies considerably across models, especially over the Ionian Sea and Iberian Peninsula *(low confidence)* (Reale et al. 2022a).

2.2.5 Sea water temperature, salinity, and acidification

2.2.5.1 Sea water temperature

The water temperature of the Mediterranean Sea is unevenly distributed, with the higher temperature values on the easternmost side and North Africa. Direct observations and numerical simulations show that the Mediterranean waters are becoming warmer *(very high confidence).*

Satellite data since the 1980s show spatially inhomogeneous warming rates of the sea surface between +0.29°C and +0.44°C per decade, stronger in the eastern Mediterranean, and that over the last two decades, mean MHW frequency increased by +40%, and duration increased by +15% *(high confidence)* (CEAM 2019, 2021; Darmaraki et al. 2019a; Pisano et al. 2020; Ibrahim et al. 2021). Sea surface warming has not been uniform, but mostly bimodal with stronger trends in the eastern Mediterranean (Adriatic, Aegean, Levantine and North-East Ionian Seas), while a spot in the Ionian Sea has warmed 50% less than the Mediterranean average (Dell'Aquila et al. 2018). In the Mediterranean Sea, periods of abnormally warm sea surface, also called 'marine heat waves' have become more frequent, more intense, spatially more extended and more severe over recent decades (Oliver et al. 2018; Darmaraki et al. 2019a).

Model projections suggest significant warming of the surface waters of the Mediterranean Sea *(very high confidence)* (Alexander et al. 2018; Darmaraki et al. 2019b). The warming rate depends on both the temporal horizon and the greenhouse gas emission scenario *(very high confidence).* For the large thermal inertia of water, sea warming will generally remain below that of the air over the surrounding land *(high confidence),* probably causing an increase in land-sea temperature contrast. Compared to the end of the 20th century, the annual mean basin sea surface temperature is expected to increase from +0.6°C to +1.3°C before the mid-21st century, and from +2.7°C to +3.8°C at the end of the 21st century period under the pessimistic RCP8.5 scenario and from +1.1°C to +2.1°C for the medium RCP4.5 scenario *(medium confidence)* (Darmaraki et al. 2019b). Future warming will be roughly homogeneous in space *(medium confidence)* with the Balearic Sea, the north Ionian Sea, the north-eastern Levantine Sea and the Adriatic Sea identified as potential hotspots of maximum warming *(low confidence).* At the end of the 21st century, water masses deeper than 600 m may warm between +0.03°C and +1.38°C (Soto-Navarro et al. 2020). Warming is not projected to be constant all year round. Stronger warming is expected in summer and weaker warming in winter, resulting in a substantial increase in warm extremes and a weaker decrease in cold extremes *(medium* to *high confidence)* (Alexander et al. 2018; Darmaraki et al. 2019b; Soto-Navarro et al. 2020).

2.2.5.2 Salinity

Coastal gradients of soil salinity are established from the seashore to inland areas, and vascular plant richness and diversity are influenced by the distance from the sea. Soil salinity is strongly affected by the type of soil and habitat, which is average at the rocky coasts and negligible at the sandy shores (Maccioni et al. 2021).

An increase in salinity has been projected in both the RCP4.5 and RCP8.5 scenarios in the intermediate layer at the basin scale and in both the eastern and western sub-basins of the Mediterranean. The variation in salinity is strongly dependent on the emission scenario, with more intense anomalies — both negative and positive — obtained under RCP8.5 conditions *(medium confidence).* For example, the salinity in the surface layer at basin scale and in the eastern Mediterranean is characterised by a decrease between 2020 and 2050 followed by a constant increase until the end of the 21st century. Conversely, after 2050, the western basin shows a freshening of the surface layer with respect to the beginning of the century (Soto-Navarro et al. 2020; Reale et al. 2022b). Direct observations and numerical simulations show that deep Mediterranean waters are becoming saltier *(high confidence).* The future evolution of sea surface salinity of the Mediterranean Sea remains largely uncertain as its sign of change *(very low confidence).* Any change will *likely* be spatially and temporally inhomogeneous due to the primary role of the river and near-Atlantic freshwater inputs *(medium confidence)* (Soto-Navarro et al. 2020).

Across the Strait of Gibraltar, near-Atlantic warming will *likely* increase the net transport of water mass and heat towards the Mediterranean Sea. However, the future evolution of the net salt transport across the strait is unclear, because it depends on the salinity change in the near-Atlantic Ocean surface layer entering the Mediterranean Sea. Consequently, it is unclear whether the salt transport from the Atlantic will increase or decrease *(low confidence)* (Soto-Navarro et al. 2020).

For the surface waters of the Mediterranean, model projections suggest that, for the end of the 21st century, basin-scale surface salinity anomalies range from −0.18 psu to +0.16 psu for the pessimistic RCP8.5 scenario and from −0.25 psu to +0.25 psu for the RCP4.5 scenario. However, a surface salinity increase in the eastern Mediterranean Basin is more *likely* than not, whereas the western basin is highly uncertain. For the deeper layers, the rates of warming and salinity changes are very uncertain. At the end of the 21st century, the salinity of water masses deeper than 600 m may increase or decrease with a large uncertainty range, depending on the model (−0.05 psu to +0.51 psu) *(low confidence)* (Soto-Navarro et al. 2020).

2.2.5.3 Acidification and deoxygenation

Excessive nutrient discharges and associated microbial bloom are the main reasons for coastal hypoxia and acidification. Extremely high pCO_2 values have been reported as a result of algal bloom, eutrophication and mucilage in hypoxic coastal areas, which may further exacerbate the increased pCO_2 levels induced by anthropogenic CO_2 emissions. The Mediterranean is vulnerable on the northern coasts to eutrophication and associated coastal acidification due to the excessive loads of nutrients from sewage effluents, river fluxes, agriculture and aquaculture fertilisers, and industrial facilities (Karydis and Kitsiou 2012; Kapsenberg et al. 2017).demonstrated a pH decline in seawater (−0.0028 ± 0.0003 pH_T y^{-1}) on the northwestern coast in the long term, which is more rapid than open oceans. On the other hand, there is a growing trend in nutrient input along the eastern and southern Mediterranean coasts (see *Section 2.4.1*), which will exacerbate the coastal acidification on the eastern and southern coasts *(medium confidence).*

The change in pH is well correlated with dissolved inorganic carbon. Human-caused CO_2 on the sea surface results in an increase in seawater H+ ions, and a decline in carbonate ion concentration. Due to this phenomenon called ocean acidification, the acidity in surface seawater has increased by about +30% (i.e. −0.10 to −0.15 decrease in pH) since the industrial revolution. Average in situ pH decline is −0.002-unit y^{-1} in world oceans (IPCC 2023), similar to the Mediterranean Sea (Solidoro et al. 2022).

Several studies have reported a significant decline in the pH of the Mediterranean Sea over the last few decades (e.g. Touratier and Goyet 2011; Palmiéri et al. 2015; Flecha et al. 2019; Solidoro et al. 2022). The decrease of pH is between −0.055 and −0.156 pH unit in surface seawater since the industrial revolution indicates that all Mediterranean Sea waters are already acidified (Hassoun et al. 2015). Wimart-Rousseau et al. (2021) reported a significant annual decrease in the surface seawater pH_T (−0.0024 ± 0.0004 pH unit) in the northwestern Levantine Basin. Since pH trends offshore and on the coast are similar in the Mediterranean Sea, acidification is projected to continue both offshore and on the coast (virtually certain) (Seneviratne et al. 2021; Hassoun et al. 2022). pH will decrease between −0.25 and −0.46 pH units in Mediterranean surface waters by the end of this century compared to the pre-industrial era in high CO_2 emission scenarios *(medium confidence)* (Goyet et al. 2016; Hassoun et al. 2022; Solidoro et al. 2022).

Due to diminishing oxygen solubility with rising temperatures, as well as increased water column stratification and eutrophication events, global warming may exacerbate hypoxia in coastal environments. There have been a few reports of oxygen depletion in the Mediterranean Sea, mostly in the area south of Cyprus and the Balearic Islands (EEA 2022b). Approximately 21% of the Mediterranean Sea suffers from hypoxia (2.3% hypoxic: <2 mg oxygen L^{-1}, 18.3% moderate hypoxic: 2–6 mg oxygen L^{-1}) (EEA 2022b). The increasing trend in warming, nutrient discharges and associated eutrophication is *likely* to expand the extent and intensity of hypoxia in Mediterranean coasts (Reale et al. 2022b).

Projections made for the middle and end of the 21st century under RCP4.5 and RCP8.5 predict changes in the dissolved nutrient contents of the euphotic and intermediate layers of the basin, net primary production, phytoplankton respiration and carbon stock (including phytoplankton, zooplankton, bacterial biomass and particulate organic matter). The projections show uniform surface and subsurface deoxygenation driven by the warming of the water column and by the increase in ecosystem respiration as well as an acidification signal in the upper water column linked to the increase in the dissolved inorganic carbon content of the water column due to CO_2 absorption from the atmosphere and the increase in respiration. The projected changes are smaller near the Strait of Gibraltar (with a maximum decrease of −0.3% under RCP4.5 and −1.2% under RCP8.5) for the exchanges with the Atlantic, and stronger on the eastern Mediterranean coast (with a maximum decrease of −1.2% under RCP4.5 and −3.1% under RCP8.5) *(medium confidence)* (Reale et al. 2022b).

2.2.6 Net hydrological balance: evaporation, precipitation, and river runoff

Overall, the net surface water loss (i.e. the evaporation minus the precipitation over the sea) has increased over most of the Mediterranean surface, mainly due to a decrease in precipitation during the period 1960–1990 and strong evaporation increase since the mid-seventies due to local warming (Sevault et al. 2014; Mariotti et al. 2015; Skliris et al. 2018). Furthermore, the freshwater discharge due to the river runoff has decreased (Lutz et al. 2016; Suárez-Almiñana et al. 2017). An increase in net Gibraltar water flux to compensate for the overall increase in freshwater loss has been derived (Fenoglio-Marc et al. 2013). On the coasts of the easternmost Mediterranean and northern Africa the balance is negative and requires irrigation to mitigate drought and aridity (FAO et al. 2022).

Positive multi-decadal evapotranspiration trends in Mediterranean have been found by several authors (Miralles et al. 2014; Zhang et al. 2016; Zhan et al. 2019), as a consequence of increases in transpiration and interception components, counterbalanced by decreasing soil evaporation *(very high confidence).*

Water stress refers to freshwater withdrawals in proportion to available freshwater resources, taking into account environmental water requirements (the minimum amount of water required to maintain freshwater and estuarine ecosystems and their functioning included in the calculation). A regional-scale investigation conducted for the Mediterranean Basin (Milano et al. 2013) highlighted that 112 million people experience water shortage conditions. The most vulnerable regions are southern Spain, Libya, Tunisia, and the south-eastern Mediterranean (Israel, Lebanon, State of Palestine, and Syrian Arab Republic). By 2050, 236 million people are expected to be living under water shortage *(high confidence).* Severe water stress situations could be mitigated in Albania, Greece and Türkiye but efficiency improvements alone would not be able to reduce water stress in Spain and the southern Mediterranean (UNEP/MAP and Plan Bleu 2020).

In the future, an increase in the net surface water loss by the sea is expected due to a decrease in precipitation and in river runoff and an increase in evaporation *(high confidence)* (Sanchez-Gomez et al.

2009; Elguindi et al. 2011; Dubois et al. 2012; Planton et al. 2012; Adloff et al. 2015; Mariotti et al. 2015). Widespread increase of evaporative demand and a decrease in precipitation explain the drying of the Mediterranean region during recent decades *(high confidence)* (Spinoni et al. 2015, 2017; Gudmundsson and Seneviratne 2016; Stagge et al. 2017; Caloiero et al. 2018; Seneviratne et al. 2021; Ali et al. 2022). Droughts are projected to become more severe, more frequent and longer under moderate emission scenarios, and strongly enhanced under severe emission scenarios *(high confidence)* (Hertig and Tramblay 2017; Lehner et al. 2017; Ruosteenoja et al. 2018; Spinoni et al. 2018; Grillakis 2019; Lionello and Scarascia 2020; Seneviratne et al. 2021).

Several studies show that a combination of reduced precipitation, associated with increased evaporation, will affect the hydrological balance, leading to a decline in water availability, river runoff, and low flows in most locations of the Mediterranean region *(high confidence)* (Droogers et al. 2012; Mariotti et al. 2015; Marx et al. 2018; Thober et al. 2018; Dakhlaoui et al. 2020 2022; Yeste et al. 2021; Ali et al. 2022). River runoff and low flows are expected to decline by –12% to –15% or more *(medium confidence)* (Ali et al. 2022). In North Africa, surface water availability is projected to be reduced by –5% to –40% in 2030–2065 and by –7% to –55% in 2066–2095 from 1976–2005 (Tramblay et al. 2018), with decreases in runoff by –10% to –63% by mid-century in Morocco and Tunisia *(medium confidence)* (Marchane et al. 2017; Dakhlaoui et al. 2020).

2.2.7 Sea level rise and (permanent) coastal submersion

In the recent period, in which Global Sea Level has been monitored by satellite altimetry (1993–2023), in the decade 2013–2022 the rising rate has been +4.68 mm yr^{-1}, which is twice the rate in 1993–2002 at +2.27 mm yr^{-1} *(observed data)* (Cazenave and Moreira 2022). Sea level change is the combination of several processes, including vertical tectonics, glacio–hydro–isostatic signals associated with the last glacial cycle, and changes in ocean volume driven by climate changes. The coastal sea-level, and its change, can substantially differ from open sea-level because near the coast, small-scale processes are combined with the global mean and regional sea-level components (Woodworth et al. 2019). In addition, in many coastal zones, vertical land motions caused by ground subsidence amplify the climate-related sea level rise (SLR) (Wöppelmann and Marcos 2016). The trend is compounded by local effects and interannual and decadal variability that can temporarily mask SLR. During the 20th century, coastal tide gauges around the Mediterranean have recorded SLRs ranging from +0.68 ± 0.37 mm yr^{-1} in Split Rt Marjana to +2.53 ± 0.14 mm yr^{-1} in Venice, both on the northern side of the Adriatic Sea. These different SLRs are explained by vertical land movements. The other stations of the Adriatic Sea show high correlation between them (Pérez Gómez et al. 2022).

The SLR of the Mediterranean has been monitored with 240 tide gauges. The longest series of data, i.e. longer than one century, has been collected by four tide gauges in the Mediterranean (i.e. Trieste and Venice (Italy), Bakar (Croatia), and Marseille (France)) and three in the Black Sea (i.e. Poti, Tuapse, and Sevastopol). The data from all the tide gauge stations have been collected and analysed. (Pérez Gómez et al. 2022). Venice constitutes the longest time series, combining instrumental and proxy data, dating back to 1350. It has been obtained combining tide gauge records (1871 to present) with proxies (i.e. paintings showing the original level of the algae belt, submersion of doors and water stairs of buildings). The observed time series *(Figure 2.2)* shows a continuous increasing trend with +130 cm total rise over 667 years; the initial rate was +1 mm yr^{-1} in 1350, and nowadays (in 2017) it is +3.3 mm yr^{-1} *(observed data)* (Camuffo et al. 2017; Camuffo 2021, 2022a, 2022b). However, it must be specified that around 1mm yr^{-1} is due to local land subsidence. The Venice dataset can be interpolated at the same confidence level by an exponential (that is mathematically representative of sea level rise, rate, and acceleration over time) or a parabola[28] (that gives the rise over time, and the average acceleration over the whole period) (Camuffo et al. 2017; Camuffo 2022a, 2022b). An increasing trend over the past 1000 years is consistent with the multiproxy analysis

28 The quadratic coefficient of the parabola represents ½ of the average acceleration over the whole period. Future projections are based on the trend extrapolation method, which constitutes the projection of a highly inertial system (Camuffo 2022b).

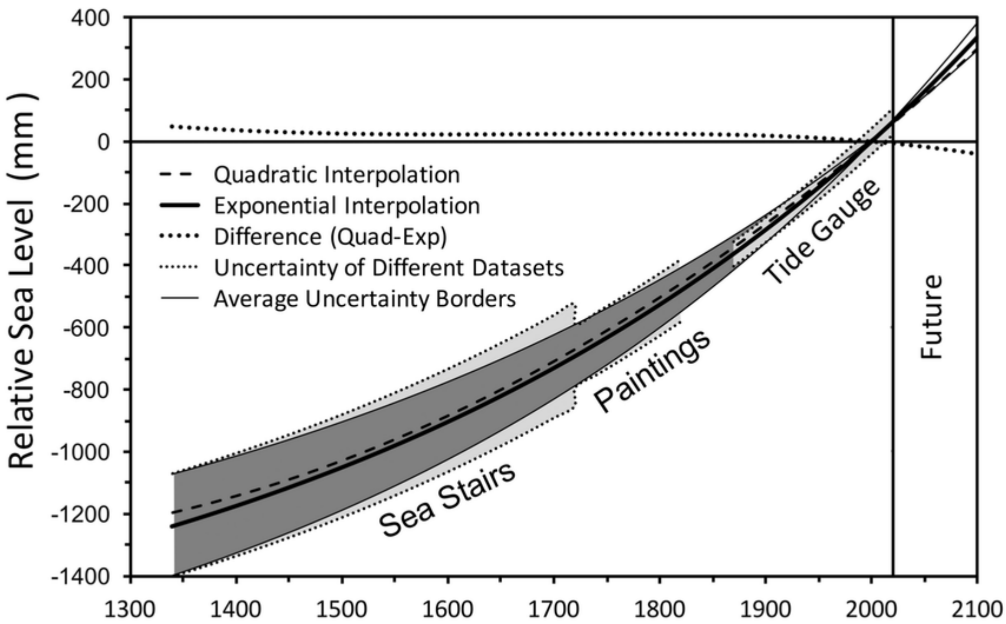


Figure 2.2 | Exponential trend of the relative sea level rise in Venice. Data sources include observations from tide gauge record (1871–2021), Canaletto, Bellotto and Veronese paintings (18th century and 1571) and submersion of the sea stairs used as a proxy (1350–1750). Uncertainties are specified in the legend. The future is based on the trend extrapolation method, which constitutes the projection of a highly inertial system (Camuffo 2022b).

concerning the Gulf of Venice obtained by Kaniewski et al. (2021, 2024). Regional projections including the local and regional processes affecting relative SLR trends in Venice (i.e. local land subsidence), predict the *likely* range of relative SLR by 2100 to range between +32 cm and +62 cm above the end of the 20th century level for the RCP2.6 scenario, and between +58 cm and +110 cm for the RCP8.5 scenario (Zanchettin et al. 2021).

It is virtually certain that global mean sea level will continue to rise over the 21st century. Relative to 1995-2014, the *likely* global mean sea level rise by 2100 is +0.28 m to 0.55 m under the very low emissions scenario (SSP1-1.9); +0.32 m to +0.62 m under the low emissions scenario (SSP1-2.6); +0.44 m to +0.76 m under the intermediate emissions scenario (SSP2-4.5); and +0.63 m to +1.01 m under the very high emissions scenario (SSP5-8.5), and by 2150 is +0.37 m to 0.86 m under the very low scenario (SSP1-1.9); +0.46 m to +0.99 m under the low scenario (SSP1-2.6); +0.66 m to +1.33 m under the intermediate scenario (SSP2-4.5), and +0.98 to +1.88 m under the very high scenario (SSP5-8.5) *(medium confidence)* (Oppenheimer et al. 2019; IPCC 2023). Accounting for low-likelihood, high-impact outcomes of climate change on sea level rise leads to high-end estimates up to +2.5 m by 2100 and +7m by 2150, depending on the triggering of acceleration processes such as Antarctic marine-based ice-shelves disaggregation (Arias et al. 2021). Model projections suggest that stabilising temperature does not stabilise the sea level but, rather, the rate of sea level rise (Oppenheimer et al. 2019).

2.2.8 Natural and anthropic land subsidence across the Mediterranean coast

Subsidence is a common cause of amplified relative sea-level rise, flooding, and erosion in coastal environments. In the past it has increased and may significantly continue to increase the impacts of sea-level rise in the coming decades (Nicholls et al. 2021; Spada and Melini 2022). In the Mediterranean, coastal subsidence is influenced by crustal movements driven by glacial isostatic adjustment (GIA) and tectonic activity as well as by the compaction of Holocene sediments, notably in the coastal plains and in large deltas (Rovere et al. 2016). Negative land-level changes are driven by tectonic subsidence and natural sediment compaction, often accelerated by anthropic withdrawal of underground fluids (water, oil and gas, as well as drainage of organic soils) (Tosi et al. 2013; Calabrese et al. 2021). In some cases, vertical land movements are driven by localised anthropic activity. The long-term knowledge of vertical land movements is limited to some sites where geological or geodetical surveys have been carried out.

Figure 2.3 shows the vertical land motions detected across Europe during the 2018–2022 period, using Interferometric Synthetic Aperture Radar (InSAR) data from the Sentinel satellites, provided by the Copernicus European Ground Motion Service (EGMS). The coast most affected by land subsidence is on the Italian side of the northern Adriatic from Grado to Rimini, reaching the maximum rate of –8 mm yr^{-1} on the delta of the Po River. In the northern Adriatic, observed and predicted changes can lead to severe coastal submersions and increased saltwater inland in the near future (Kaniewski et al. 2021). The InSAR data may be compared with literature. In the historical centre of Venice, the average value in the literature is –1 mm yr^{-1} (Zanchettin et al. 2021), about 50% of InSAR, while in the lagoon, major subsidence rates have affected the northern sector (–3 mm yr^{-1} to –4 mm yr^{-1}) (Tosi et al. 2018). The Arno and Po deltas have been evaluated at –10 mm yr^{-1} and –7 mm yr^{-1}, respectively (Besset et al. 2017).

In southern Italy, in the Volturno plain, InSAR satellite data defined average subsidence rates at –3 mm yr^{-1} (Di Paola et al. 2021) while in the coastal plain of Catania, rates ranging from –6 to –12 mm yr^{-1} have been calculated (Anzidei et al. 2021).

In the Ebro (Spain) and Rhône (France) deltas, vertical rates of –2 mm yr^{-1} and –1.4 mm yr^{-1} have been evaluated respectively (Besset et al. 2017).

InSAR data show that there are other sites with high subsidence rates, especially islands (e.g. Ischia and Aeolian Islands, Italy; Symi, Greece) and very localised portions of the coast. Positive uplifts are visible in Greece and the Aegean Sea (Samos, Cyclades Island) but are irregularly distributed over space and over time, even with alternating positive and negative vertical motions, conditioned by the complex tectonic and anthropogenic interactions of the area. In Crete, the western side is uprising, and the eastern sinking (Mourtzas et al. 2015). Major subsidence rates have been observed near Thessaloniki and next to the coastline, reaching rates of –35 mm yr^{-1}, related to the intensive mining and overexploitation of aquifers and reach dangerous values near the sites of such anthropic activity (Svigkas et al. 2016; Loupasakis 2020). Sometimes, ruptures of the crust and rebound may cause opposite local effects, that is land uplift (Loupasakis 2020).

In the southern portion of the Mediterranean Basin, subsidence rates up to –10 mm yr^{-1} have affected

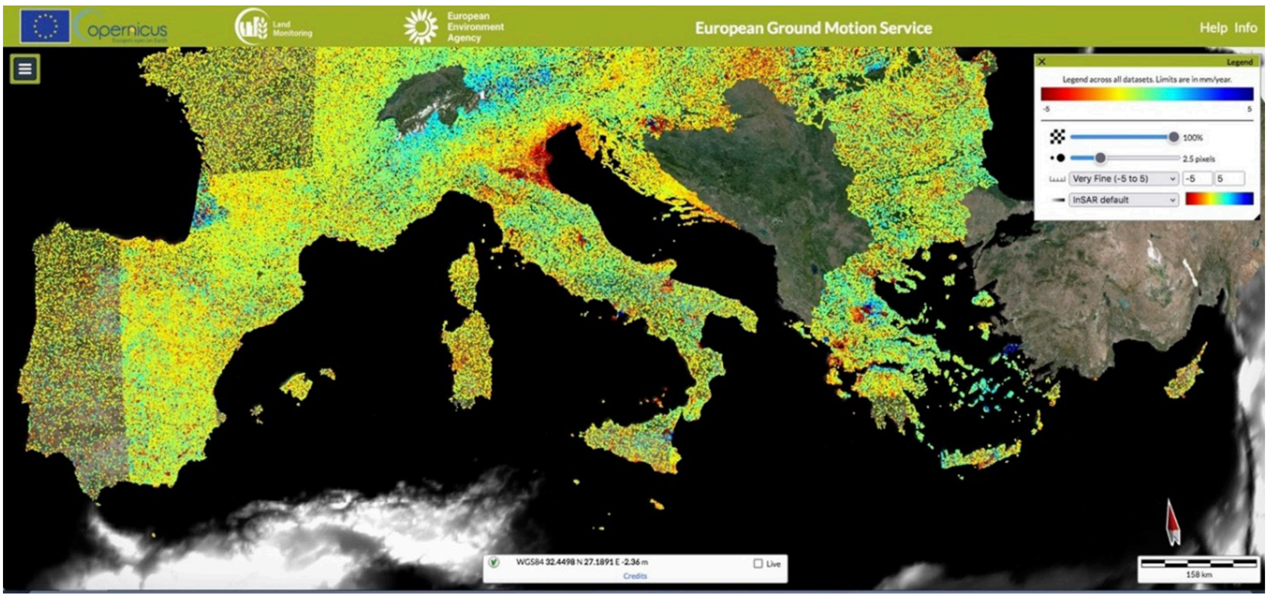


Figure 2.3 | Vertical ground motions over the European coasts of the Mediterranean. InSAR Satellite, Copernicus, European Ground Motion Service data. Period: 2018–2022. https://egms.land.copernicus.eu/

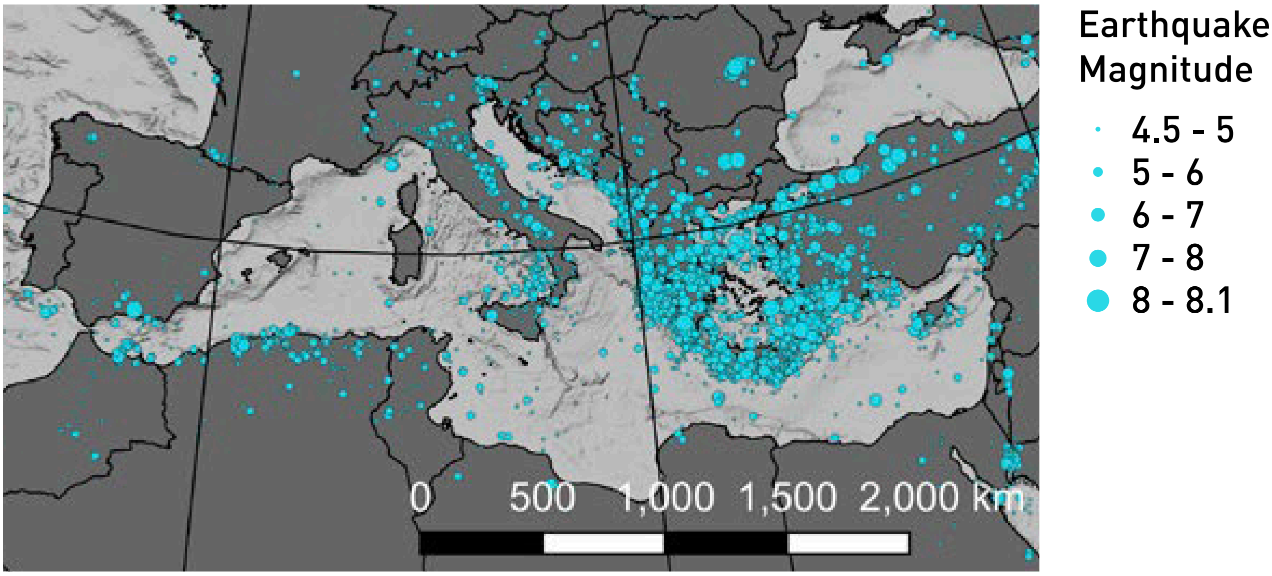


Figure 2.4 | Earthquakes with epicentres M_w>4.4 affecting Europe and the Mediterranean area. Source: Kopp et al. (2021).

the Nile delta (Egypt), and the Medjerda coastal plain (Tunisia) (Besset et al. 2017; Saleh and Becker 2019). Lower subsidence rates of −3 mm yr^{-1} were observed at the Moulouya river mouth (Morocco) (Besset et al. 2017).

In the Black Sea, data are only available for the Danube delta (Romania) which show long-term subsidence rates of −1.5 mm yr^{-1} (Besset et al. 2017).

2.2.9 Geohazards

A geohazard is a geological condition which is – or has the potential to develop into - a situation leading to damage or uncontrolled risk. The major marine geohazards are earthquakes, volcanoes, tsunamis, submarine mass movements, fluid activity and its manifestations, migrating bedforms, human induced and technological hazards (Kopp et al. 2021). Geohazards may have a direct impact on the coast or may generate tsunamis that reach the coast with destructive effects. This section highlights only a few of the major coastal geohazards. Even though the events reported in this section have occurred in the past there is currently no way to predict when similar events will occur in the future using available technology. Other marine geohazards such as liquefaction, active faults, gas seepages, and migrating bedforms are not shown because no standard mapping of these features exists for the Mediterranean Sea (Kopp et al. 2021).

2.2.9.1 Earthquakes

An earthquake manifests in the sudden movement of the Earth's surface, resulting from an abrupt release of energy by the rupture of faults in the crust and upper mantle of the Earth. Earthquakes are among the most damaging geohazards, frequently causing devastating loss of lives, assets and infrastructure, especially in densely populated areas. Earthquakes are the most commonly cited cause of offshore slope failure, especially in seismically active regions with high mountain ranges close to the coast (e.g. Alboran Sea, Ligurian Sea, Calabria region, eastern Sicily, Aegean Sea) which can experience large earthquakes. A collapse of transport infrastructure can be expected either due to ground shaking, landslides or tsunamis (Kopp et al. 2021). A catalogue of the earthquakes that have affected Italy and the Mediterranean area has been published by Guidoboni et al. (2018, 2019).

The Mediterranean Sea, located at the African–Eurasian plate boundary, is subject to strong earthquakes because of its active geology (mainly in Algeria, Italy, Greece, and Türkiye), while two of the five largest volcanic eruptions ever recorded on Earth (Campi Flegrei, Italy 40,000 BCE and Santorini 1600 BCE) occurred in the Tyrrhenian and Aegean Sea. The Mediterranean seafloor is characterised by countless mass movement processes, including submarine landslides, debris avalanches and large turbidity flows. Steep continental slopes fed by mountain-supplied rivers are prone to seabed instability and, because of high sedimentation rates and the retrogressive evolution of the canyon heads that often reach the coast, small landslides are ubiquitous (CIESM 2011).

The largest and most destructive subduction zone earthquake with the moment magnitude M_w>8 occurred in 365 CE offshore of Crete Island (Shaw et al. 2008). Offshore of Crete, it caused an instantaneous uplift of western Crete by more than +6 m and triggered a catastrophic tsunami that impacted nearly all coastal areas around the eastern Mediterranean Sea.

Coastal Earthquakes with epicentres with a Moment Magnitude of M_w >4.5 are shown in *Figure 2.4.*

2.2.9.2 Volcanoes

Volcanoes may form at, or near, the margins of tectonic plates where magma reaches the surface, or over hotspots, i.e. over deep magma sources located in the Earth's lower mantle. In the sea, volcanoes may be completely submerged or grow large enough to form islands or coastal volcanoes, many of which have been inhabited since prehistoric times to benefit from the fertile soils.

The most hazardous Mediterranean volcanoes are shown in *Figure 2.5.* The central and western Mediterranean include Mount Etna, Vesuvius, Ischia, Campi Flegrei in the Gulf of Naples, Stromboli and Vulcano in the Aeolian Islands, Pantelleria Island and Ferdinandea volcano. These rank amongst the world's most active volcanoes. Mount Etna and Vesuvius have been designated as Decade Volcanoes by the United Nations, worthy of close study in light of their potentially large, destructive eruptions and proximity to densely populated areas. In the Tyrrhenian Sea, the Marsili Seamount is active with eruptions; possible flank collapses would generate tsunamis affecting the whole southern Tyrrhenian Sea (Teresita et al. 2019). In the eastern Mediterranean, the main marine seismogenic zones are the Calabrian, Hellenic and Cyprus arcs and the North Anatolian Fault, all of which are recurrent sources of tsunamis. The Hellenic Arc creates large earthquakes commonly associated with large tsunamis. The major geohazards in the northern Aegean Sea and the Sea of Marmara originate from the activity of the North Anatolian Fault: the major boundary between the Eurasian and Anatolian-Aegean plates.

2.2.9.3 Submarine landslides

Submarine landslides are a broad term for indicating the phenomena of failure of near-seabed sediments under the effect of gravity. This occurs due to the combination of stresses applied to the seabed with the ensuing environmental conditions that might cause sediment weakening (Scarselli 2020). Submarine landslides may have several negative consequences, for example: triggering tsunamis, causing the collapse

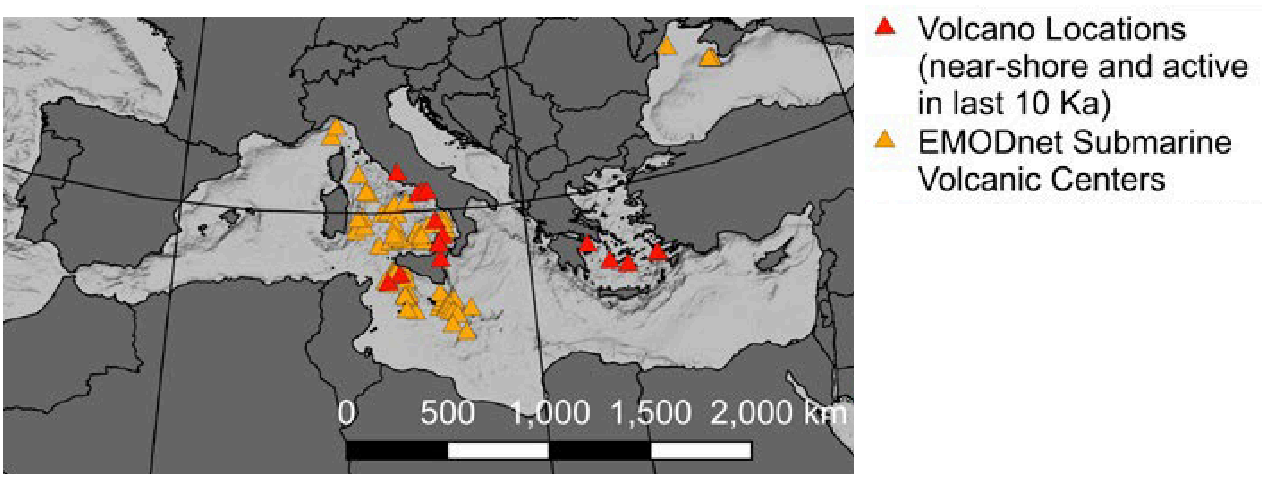


Figure 2.5 | Location of mapped submarine, island and nearshore volcanoes (red when active). Other volcanic sites that were active less recently or lie too far from shorelines to represent a marine hazard are excluded. Source: Kopp et al. (2021).

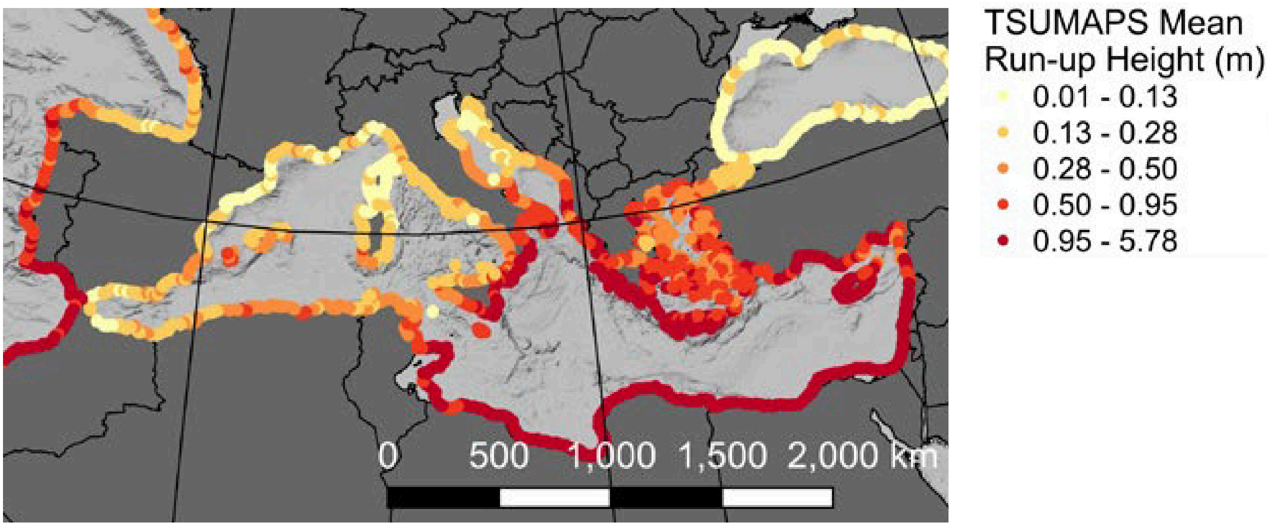


Figure 2.6 | Coastal hazard from seismically induced tsunamis. The mean run-up height (m) was calculated by Basili et al. (2021). Tsunamis induced by landslides are not considered. Source: Kopp et al. (2021).

of coastal areas into the sea; destroying seabed infrastructure; mobilising huge amounts of seafloor material; breaking submarine pipes and cables.

The pattern of landslide-generated tsunamis is more radial than in the case of earthquake sources, and displays different properties, e.g. they are more affected by frequency dispersion, lower tsunami celerity, shorter wavelength and faster wave amplitude attenuation. These factors limit the far-field propagation of tsunamis. However, in places where submarine landslides occur along coastal slopes, the distance to the coastline, and hence the propagation time, is often too short to allow coastal populations to be alerted and evacuated (Rodriguez et al. 2017).

In the Mediterranean Sea, Urgeles and Camerlenghi (2013) reported 696 submarine landslides covering 18% of the seafloor. Their distribution has higher density near the major deltaic wedges, while tectonically active margins are characterised by relatively small failures. In the Mediterranean Sea, small submarine landslides occur every year, while those with volumes larger than 10 km^3 have a return period of 1000 years (Urgeles and Camerlenghi 2013). Except for a number of studies in the Mediterranean (Camerlenghi et al. 2010; Urgeles and Camerlenghi 2013) and in the northern part of the Alboran Basin (Casas et al. 2011; Alonso et al. 2014), most of the submarine landslide geometries and chronologies are yet to be described, and their causal factor are still poorly known (d'Acremont et al. 2022).

2.2.9.4 Tsunamis

A tsunami is a succession of waves of extremely long wavelength, that move the whole column of water from sea floor to the surface, generated by a powerful, underwater disturbance that causes a sudden displacement of a large volume of water from the sea floor (Kopp et al. 2021). Tsunamis may be triggered by earthquakes, volcanic eruptions, submarine landslides, and onshore landslides in which large volumes of debris fall into the water (USGS 2006).

The European GITEC-TWO tsunami catalogue (Tinti et al. 2001) contains 94 reliably assessed earthquake-generated tsunami events during the last 2500 years (Sørensen et al. 2012). Another catalogue including 135 past tsunamis in the Mediterranean has been compiled by Marriner et al. (2017). A map of coastal hazards from seismically induced tsunamis is shown in *Figure 2.6*. The mean run-up height (m) has been calculated using the Probabilistic TSUnami Hazard MAPS for European Coastlines[29] (Basili et al. 2021).

29 https://tsumaps-neam.eu/

In the historical and recent period, several tsunamis have been generated by earthquakes. The most famous tsunamis occurred in 365 CE and 1303 CE in the Hellenic Arc, and the third in 1908, in the Messina Strait (Sicily, Italy). Messina was also previously hit in 1783. The vulnerability of Lampedusa Island and the Messina Strait has been recently simulated with 3D flooding maps (Distefano et al. 2022). Other devastating tsunamis occurred in 373 BCE and 1748 in the Gulf of Corinth (Greece). The most recent destructive tsunamis occurred in the Aegean Sea in 1956 with runup heights reaching +25 m (Papazachos et al. 1985) and northern Algeria in 2003 with runup heights up to +2 m in the Balearic Islands (Alasset et al. 2006). All the above tsunamis were generated by a strong earthquake (Soloviev et al. 2000; Papadopoulos and Fokaefs 2005).

Other tsunamis were generated by volcanic eruptions, such as the eruption of the Thera Volcano (Santorini Island) in the southern Aegean Sea around 1600–1650 BCE, followed by a remarkably strong tsunami (Friedrich et al. 2006). This event has been cited as contributing to the destruction of the Minoan civilization (Soloviev 2000).

2.3 Biological drivers

2.3.1 Non-indigenous species

Species that establish viable populations outside their native ranges can become powerful biological agents of change, causing significant negative effects on human livelihoods and biodiversity (Simberloff et al. 2013; Bacher et al. 2018; IPBES 2019; Shackleton et al. 2019). This problem is set to increase, as the prevalence of these organisms continues to rise worldwide (Seebens et al. 2017). Non-indigenous species are not the only examples of biological drivers. There are other organisms that, despite not having been introduced by humans into a new environment, can colonise areas beyond their natural distribution ranges due to human-induced factors, becoming invasive and causing ecological and economic disruptions.

According to the International Union for Conservation of Nature , non-indigenous species — often called alien, exotic, introduced, non-native or non-indigenous — are plants and animals that have been intentionally or unintentionally introduced, established populations and spread into the wild in the new host region. Moreover, when these species become invasive, they negatively impact native biodiversity, ecosystem services and human well-being.

Non-indigenous species are one of the major agents of coastal biodiversity change, and mostly climate drivers interact to support their spread and colonisation success *(high confidence)* (Iacarella et al. 2020; MedECC 2020; Cooley et al. 2022). They have the potential to displace native species, destroy native genotypes, alter habitats and community structures, alter food web network structure and ecosystem processes, prevent the delivery of ecosystem services and can act as vectors of pathogens and parasites (Grosholz 2002; Perrings et al. 2002; Wallentinus and Nyberg 2007; Molnar et al. 2008; Vilà et al. 2010). As seen in the Mediterranean, non-indigenous species outcompete indigenous species, causing regional biodiversity shifts and altering ecosystem functions and services *(high confidence)* (e.g. Caiola and Sostoa 2005; Mannino et al. 2017; Bianchi et al. 2019; Hall-Spencer and Harvey 2019; Verdura et al. 2019; Cherif et al. 2020; García-Gómez et al. 2020; Dimitriadis et al. 2021).

The Suez Canal has provided the most important entrance for non-native species in the Mediterranean. Through this man-made passage, hundreds of Red Sea species have reached the Mediterranean since it opened in 1869 (Galil et al. 2017; Zenetos et al. 2017). At present, other pathways such as shipping vectors and the aquarium trade are responsible for a considerably higher number of non-indigenous species introduced (Zenetos and Galanidi 2020).

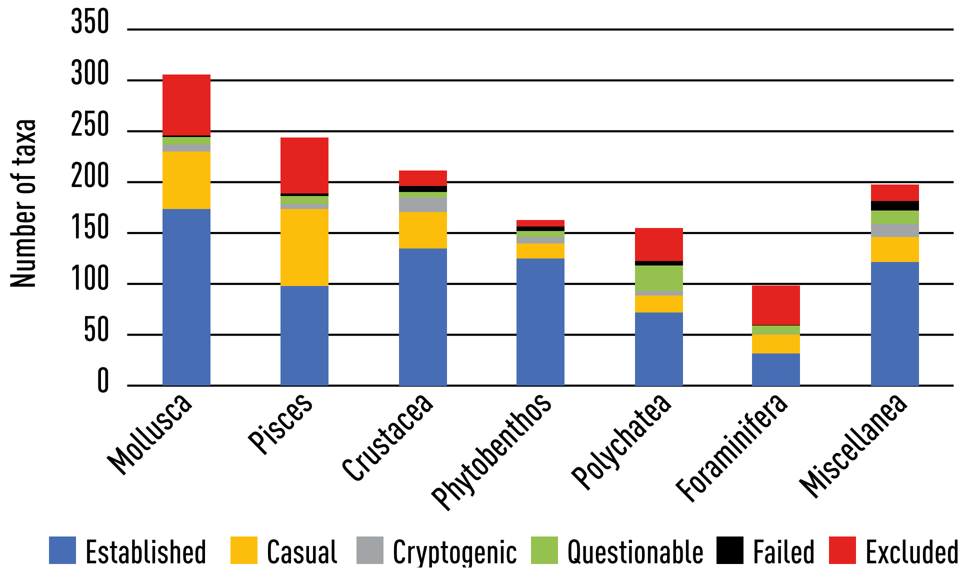


Figure 2.7 | Status of non-indigenous species in the Mediterranean Sea according to their taxa and introduction stages. Source: Zenetos et al. (2022).

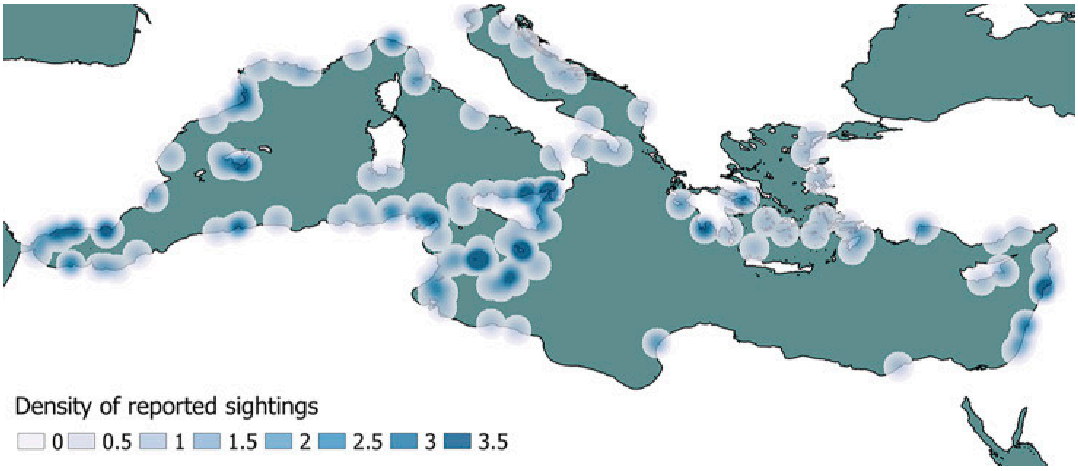


Figure 2.8 | Heat map showing the cumulative density of reported sightings of fish of Atlantic origin (radius = 70 km). These fishes are believed to have entered the Mediterranean through the Strait of Gibraltar without direct human assistance. Source: Azzurro et al. (2022b).

Several of these organisms have established large, permanent populations in the eastern Mediterranean and are spreading westwards. The main introduction pathways of non-indigenous species in other Mediterranean coastal and transitional ecosystems such as estuaries or coastal lagoons are accidental introductions from aquaculture facilities (e.g. Caiola and Sostoa 2005), aquarium species trade (e.g. Hamza et al. 2022) and boats' ballast waters (e.g. Gollasch et al. 2019) and biofouling on recreational vessels (Ulman et al. 2019).

With over a thousand non-indigenous species, the eastern Mediterranean, which is a major invasion hotspot (virtually certain) (Edelist et al. 2013), is the most heavily invaded marine region in the world (Zenetos and Galanidi 2020; Golani et al. 2021; Azzurro et al. 2022a) and suffers from continuous invasion of exotic species (Azzurro, Smeraldo, Minelli, et al. 2022). Non-indigenous species in the Mediterranean coasts began to occupy depths below 200 m (Dalyan et al. 2012). However, it should be noted that most of the reported non-indigenous species in the Mediterranean Sea are coastal species *(Figure 2.7)*, probably because the depth of the Suez Canal (24 m) creates a geographic isolation that limits the passage of deep-sea species. Moreover, shallow coastal ecosystems are more accessible and have been more studied and monitored than the open sea *(Figure 2.8)*. Wetlands, saltmarshes, seagrass beds and sandy beaches are some of the Mediterranean coastal ecosystems with the highest potential of services delivery that interact via non-indigenous species. Moreover, these and other Mediterranean ecosystems are very rich in species and endemism (Coll et al. 2010; Lejeusne et al. 2010).

2.3.2 Changes in the limits of species distribution

Native species will be affected by ocean warming. Some species are changing their life-history traits and patterns which can lead to a loss of competitive abilities to cope with the effects of biological drivers, especially those caused by biological invasions (Cooley et al. 2022; Chatzimentor et al. 2023). As the Mediterranean warms, conditions at the edge of the species' distribution will become warmer. If temperatures reach higher values than the maximum thermal tolerance of the species, local native populations can undergo a gradual decline in performance and a decreasing population size, *very likely* resulting in a range contraction. On the other hand, thermophilic species will show faster dispersal rates and population size increase *(high confidence)* (Azzurro 2008). Assessed future scenarios of marine ecosystem conditions in the eastern Mediterranean showed significant increases of non-indigenous species of the benthic and pelagic macrofauna while native species and vulnerable species decreased *(very high confidence)* (Corrales et al. 2018).

The construction of the Aswan Dam in 1969 caused a drastic reduction of the Nile outflow and, therefore, the freshwater barrier between the Red Sea and the Mediterranean disappeared, increasing the entry of non-indigenous species. The increase in temperature experienced in the last decades also reduces the water inflow to the eastern Mediterranean and increases salinity. The increase in both sea surface temperature and salinity (Theocharis et al. 1999) indicates that the physico-chemical conditions of the eastern Mediterranean have changed in favour of thermophilic species. The waters coming from the Red Sea into the Mediterranean are rich in pelagic eggs and larvae. The survival rates of these eggs and larvae, which have lower ecological tolerance (Downie et al. 2020) than adults, increase due to the similarity of the Red Sea and eastern Mediterranean environments. It is *extremely likely* that the situation will be effective in the population formation process of non-indigenous species in the Mediterranean. Moreover, hydrographic changes triggered by high seawater temperature have increasingly been caused by the expansion of thermophilic biota into the central and western basins of the Mediterranean *(very high confidence)* (Occhipinti-Ambrogi and Galil 2010).

In some cases, non-indigenous species act invasively, and they are listed together with "true" exotic species (Golani et al. 2021). Regardless of where these species came from, understanding the spatial and temporal dynamics of their "invasion" would be helpful to assess the transformation of the Mediterranean biota, which some authors have referred to as 'tropicalisation' or 'Mediterranisation' (Quignard and Tomasini 2000; Bianchi and Morri 2003).

The Mediterranean is warming faster than other seas (Vargas-Yáñez et al. 2008; Schroeder et al. 2016), becoming increasingly suitable to be colonised and invaded by organisms of tropical origin. The effect of global warming is therefore contributing to species colonisation through the Strait of Gibraltar, but also to the dispersal of these and truly non-indigenous species within the Mediterranean.

The Strait of Gibraltar provides a natural connection between the Atlantic and the Mediterranean and enables the passage of species between the two water bodies. Since the Late Miocene, Atlantic species form the main framework of the Mediterranean biota. A heat map showing the cumulative density of reported sightings of fish of Atlantic origin, which are thought to have entered the Mediterranean through the Strait of Gibraltar, without direct human assistance, is given in *Figure 2.8.* A clear geographical pattern is visible with the distribution of records strongly skewed toward the west, indicating the continuous entry of new species from the Atlantic and their expansion towards the east.

There is an exponential dynamic of Atlantic fish entering the Mediterranean between the 1950–2021 period (Azzurro, Smeraldo, Minelli, et al. 2022). Moreover, the expansion of these neo-native species increased exponentially by the mid–1990s and 2000, coinciding with the observed shift in the sea surface temperature of the Mediterranean. Due to global warming, the Mediterranean is becoming increasingly apt to be colonised and invaded by organisms of tropical origin that are expanding their distribution ranges *(high confidence)*. Warming will alter the distribution of invasive subtropical species *(high confidence)* (Cooley et al. 2022; IPCC 2022).

2.3.3 Jellyfish blooms

Although jellyfish blooms are natural events in marine ecosystems, their intensity and recurrence in the last decades have increased significantly (Purcell et al. 2007; Molinero et al. 2008) particularly in coastal waters and semi-enclosed basins (Brotz and Pauly 2012; Brotz et al. 2012). These events are usually very conspicuous and reports of human problems with jellyfish have increased worldwide and have captured public attention[30] (e.g. stinging swimmers, interference with fishing, aquaculture and power plant operations) (B. Carpenter 2004).

According to the Jellywatch Program of the Mediterranean science commission (CIESM) there are a total of 23 main species of jellyfish occurring on the coasts of the Mediterranean and Black Seas that can potentially develop bloom events[31]. Of these, there are nine species of major concern either

30 https://www.naturalhistorymag.com/naturenet/08995/the-blob

31 https://ciesm.org/gis/JW/build/JellyBlooms.php

because of the magnitude of the blooms or due to the impacts they may cause (Boero 2013). Five of these species are native to the Mediterranean and the other others are non-indigenous.

Although in some areas, jellyfish have not shown any increase or have even declined (Brotz 2011), there is a general perception of an increase in global jellyfish abundance, with blooms being recorded in different seas across the planet (e.g. Boero et al. 2008; Brotz et al. 2012; Purcell 2012; Condon et al. 2013; Canepa et al. 2014). There is some evidence that jellyfish may benefit from eutrophication and other human induced stressors, such as global warming *(medium confidence)* (Purcell et al. 2007). However, many authors suggest that there is not enough evidence to support an increase in jellyfish blooms because the results from studies on this issue are not based on long time-series data on jellyfish populations (Brotz et al. 2012; Canepa et al. 2014). Nevertheless, recent studies show an increase in the frequency of these blooms in the Mediterranean Sea *(medium confidence)* (Báez et al. 2022).

2.4 Pollution drivers

The majority of pollution in the Mediterranean is caused by land, followed by air and shipping pollution (MedECC 2020). Land-based pollution is essentially made up of point-source pollution such as domestic and industrial effluents and diffuse pollution consisting of the drainage of irrigation water, which carries substances used in agriculture such as fertilisers, pesticides and herbicides as well as storm water runoff from urban areas carrying toxic pollutants from hydrocarbon residues. The Mediterranean Sea has some moderately polluted coasts due to coastal squeeze, intense industrialisation, uncontrolled discharges of municipal and industrial wastewater, river inputs and low seawater circulation (Trincardi et al. 2023).

2.4.1 Nutrients

The input of nutrients, mainly nitrogen (N) and phosphorus (P), is one of the major factors that drives phytoplankton communities. The availability of nutrients and their relative proportions determine algal growth and biomass, and it also determines community composition (Moore et al. 2013).

The Mediterranean is an oligotrophic sea widely recognised as phosphorus-limited (Siokou-Frangou et al. 2010; Álvarez et al. 2023). Nutrient concentrations decrease from the west to the east, and mean values in surface waters may be as low as 0.5 μM for nitrate and 0.01 μM for phosphate in the most oligotrophic eastern region, with substantial nutrient imbalances (Pujo-Pay et al. 2011; Lazzari et al. 2016). Despite the general oligotrophic conditions offshore, there are coastal regions where nutrient concentrations can be very high *(Figure 2.9).* In the north, the largest inputs occur in the Gulf of Lion, the Adriatic, and the northern Aegean Sea (Karydis and Kitsiou 2012; Cozzi et al. 2018; Viaroli et al. 2018). In the southern and south-eastern Mediterranean, the Gulf of Gabès and the Nile-Levantine basin are critical nutrient hotspots, with high concentrations of phosphate, nitrate, and ammonia (e.g. Drira et al. 2016; Kateb et al. 2018; Dorgham et al. 2019; Champagne et al. 2021). Nutrient enrichment of coastal waters occurs via rivers and streams, atmospheric deposition, and submarine groundwater discharge (SGD). River inputs are estimated at 1.9–2.6 Tg N yr^{-1} and 0.11–0.12 Tg P yr^{-1} (Malagó et al. 2019; E. Romero et al. 2021), and basin-wide atmospheric inputs account for 1.3 Tg N yr^{-1} and 0.004 Tg P yr^{-1} (Kanakidou et al. 2020), with a predominant role in the south. The contribution of SGD, for years completely overlooked in nutrient budgets, is now recognised as an essential input, particularly for N (Santos et al. 2021). Rodellas et al. (2015) estimated that SGD could contribute up to 2.6 Tg N yr^{-1} and 0.02 Tg P yr^{-1} to the Mediterranean Sea, hence comparable to fluvial and atmospheric inputs.

There is *robust evidence* that the high fluxes of nutrients transported by air, surface waters and groundwaters to Mediterranean coastal seas are related to agricultural practices and urban and industrial uses. Intensive agriculture and livestock farming, which rely on the massive use of synthetic fertilisers, manure and imported feed, are responsible for heavy N and P pollution (Billen et al. 2011; Viaroli et al. 2018; E. Romero et al. 2021; Lassaletta et al. 2021). Urban areas and industrial facilities are also important sources of N and P, especially in the southern Mediterranean, where the population is increasing rapidly, environmental regulations are less restrictive, and wastewater treatment plants have yet to be widely implemented (Powley et al. 2016; Morsy et al. 2020).

High nutrient loads in coastal areas can lead to a large increase in phytoplankton growth and biomass, resulting in eutrophication. Eutrophication can trigger acidification, hypoxia or anoxia, episodes of massive mucilage formation and harmful algal blooms (HABs). Coastal eutrophication is already an issue of medium or important significance in 13 Mediterranean countries (MedECC 2020). Before 1980, HABs were rarely documented in the Mediterranean Sea. Since then, adverse events and several toxic episodes have been reported in different coastal regions, and harmful phytoplankton species have become dominant in many coastal locations on the northern and southern coasts (Tsikoti and Genitsaris 2021; Zingone et al. 2021; Ligorini et al. 2022). HABs and toxic events are expected to increase in magnitude, frequency, and geographical distribution due to global warming and anthropogenic pressures *(high agreement)* (Hallegraeff 2010; Glibert 2017). This is a serious threat, notably in semi-enclosed bays and estuaries, coastal lagoons and deltas with high productivity and that are close to highly populated areas.

Changes in the stoichiometry of nutrient inputs (N/P ratio) are also crucial to consider when addressing the state of coastal waters, as nutrient imbalances can induce changes in planktonic communities and promote HAB proliferation, as can high nutrient loads (Justić et al. 1995; Glibert 2017). The median N/P of Mediterranean river exports during the 2000–2010 period was 44 (E. Romero et al. 2021), well above the Redfield N/P value of 16. Moreover, a steady increase in N/P ratios has been described in many rivers worldwide (Beusen et al. 2016; Ibáñez and Peñuelas 2019), and the Mediterranean is no exception to this global trend. Aerial and SGD inputs could further exacerbate these elevated N/P ratios (Rodellas et al. 2015; Kanakidou et al. 2020).

Nutrient (N, P) flows from rivers to coastal areas have decreased in most parts of the northern Mediterranean for the past decades (Ludwig et al. 2010; E. Romero et al. 2013) and there is *high agreement* that they may further decrease in the coming years following the implementation of European environmental regulations (Grizzetti et al. 2021). However, river nutrient exports have increased in southern and eastern Mediterranean regions, and growing trends are expected in the future if urban development and agricultural intensification continue at the current pace *(high confidence)* (Ludwig et al. 2010; Powley et al. 2018; UNEP/MAP and Plan Bleu 2020). Atmospheric N deposition is projected to increase only slightly (4%), while airborne soluble P fluxes may decrease by 34% compared to current values (Kanakidou et al. 2020). The discharge of N from SGD will increase in the north and the south in the years to come *(medium confidence)* (Powley et al. 2018).

Finally, nutrient pollution in coastal waters may be enhanced through several processes. Projections suggest that climate change, in interaction with other drivers (mainly demographic and socio-economic developments including unsustainable agricultural practices), is *likely* to impact most of the Mediterranean Basin through increased water scarcity *(high confidence).* Water scarcity challenges water quality because lower flows reduce the dilution capacity of streams and aquifers. Warming and increased seawater temperatures can also trigger mucilage outbreaks (Schiaparelli et al. 2007). Nutrient pollution will also suffer from the loss and degradation of ecosystems that act as natural nutrient buffers. Upstream, projections point at changes in freshwater communities and a decrease in biological processes like nutrient uptake, primary production, or decomposition *(medium confidence).* Downstream, alterations to coastal ecosystems (lagoons, deltas, salt marshes, etc.) directly affect the transfers to the sea. Wetlands, for instance, act as traps of nutrients before they reach coastal areas. Half of the wetland area has been lost or degraded since 1970, and this trend is expected to continue *(high confidence)* (Perennou et al. 2020).

2.4.2 Trace metals

Metal trace elements such as cadmium (Cd), chromium (Cr), lead (Pb), mercury (Hg), nickel (Ni), and zinc (Zn) are naturally occurring in the Earth's crust (Navarro-Pedreño et al. 2008). Some metals, such as Cd, Hg, and Pb, and metalloids, such as arsenic (As), are not essential for living things and are toxic even in minute concentrations. In addition to these trace elements of major concern, Technology-Critical Elements (TCEs) such as platinum (Pt), tellurium (Te), germanium (Ge), lanthanum (La), and gallium (Ga) have been released from emerging technology and introduced into Mediterranean coasts (Abdou et al. 2019; Romero-Freire et al. 2019) There is increased evidence that human activities have increased trace metal concentrations on Mediterranean coasts (Belivermiș et al. 2016; Tovar-Sánchez et al. 2016; Cherif et al. 2020). There is *high confidence* that urban and industrial wastewaters, atmospheric deposition and run-off from metal-contaminated sites constitute the major sources of trace metals in coastal areas (Cherif et al. 2020; Trincardi et al. 2023).

Lead, mercury, and cadmium hotspots were essentially located on the north-central and south-eastern shores of the Mediterranean Basin (Cherif et al. 2020). The main sector contributing to the release of heavy metals in southern Mediterranean countries is the manufacturing of refined petroleum products. For the Balkans and Türkiye, the main contributing sectors are petroleum products refining, and the manufacturing of cement. For the Mediterranean EU countries, the principal sector is energy production responsible for the release of heavy metals (EEA-UNEP/MAP 2021). In the western Mediterranean coastal waters, high Cd, Hg, Ni, and Pb levels were reported in the Alborán Sea, north-western Mediterranean, Tyrrhenian Sea, North Africa, respectively, while the rest of the western Mediterranean displayed moderate metal pollution

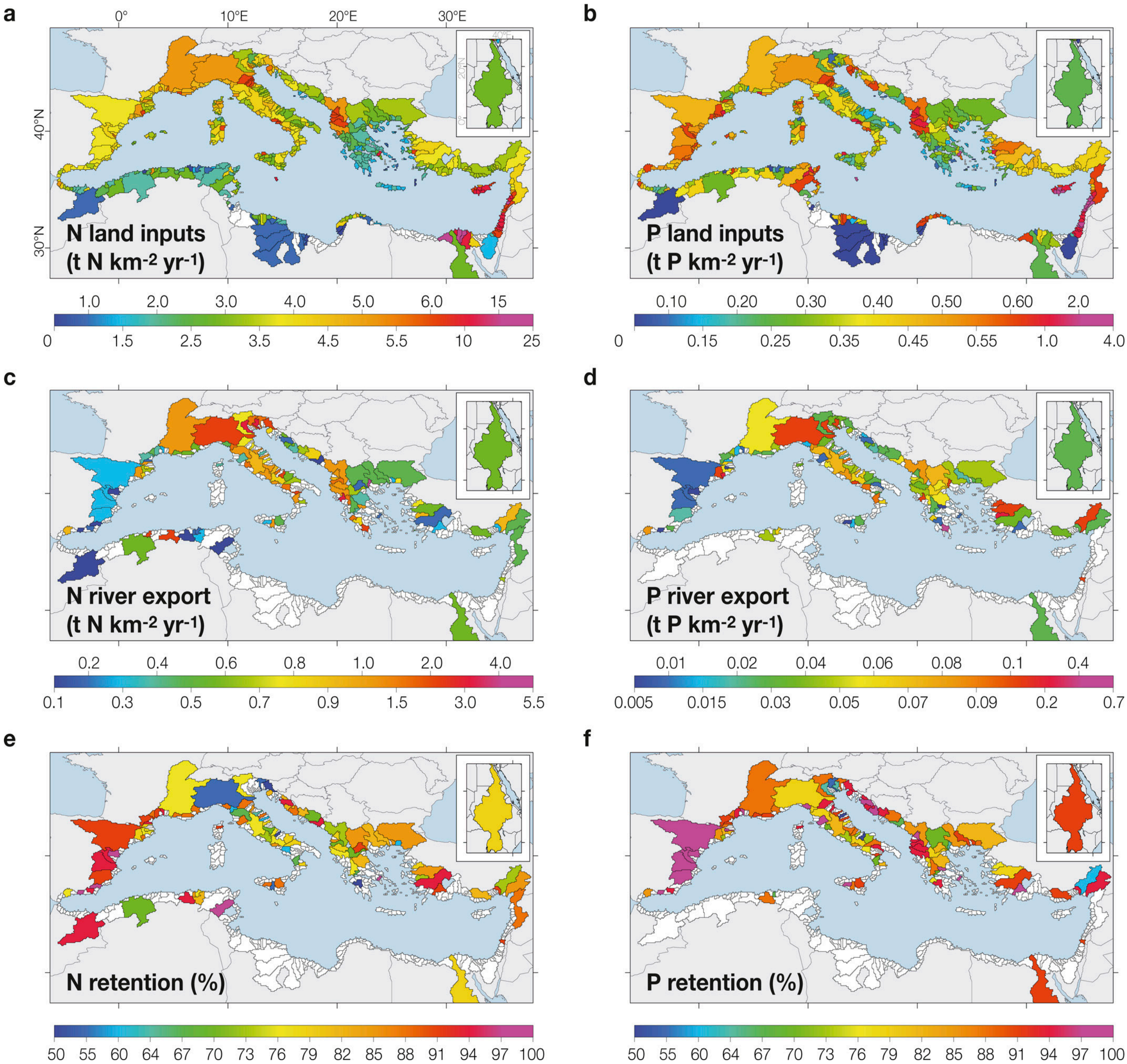


Figure 2.9 | Total land inputs and river exports of N (on the left column) and P (on the right column) into the Mediterranean Sea. a-b: spatial variability of land inputs within the basins (data at 5 arc min resolution); c-d: land inputs averaged per river basin; e-f: river exports averaged per river basin. About 10-25% of all N land inputs and 8-12% of P inputs are directly exported by rivers to coastal seas. Modified from E. Romero et al. (2021).

(Benedicto et al. 2011). On the eastern Mediterranean coasts, the highest concentrations of metals were reached in the pollution hotspots, heavily impacted by human activities. For instance, the highest Cu, Pb, and Zn concentrations were detected in the sediment samples of Alexandria harbour (Egypt) while the highest As, Cd, Cu, Hg, Pb, and Zn concentrations were detected in the sediment samples of Priolo, Gela, Taranto and Crotone (Italy) (Lipizer et al. 2022).

Hg concentrations in many Mediterranean top-predatory fish exceed European Union regulatory thresholds. MeHg (methylated mercury) is bio-magnified in marine food webs more efficiently compared to Hg. MeHg concentrations are twice as high in the waters of the western Mediterranean compared to the eastern Mediterranean *(high confidence),* and higher in marine food in the west compared to the east *(high confidence)* (Cossa et al. 2022).

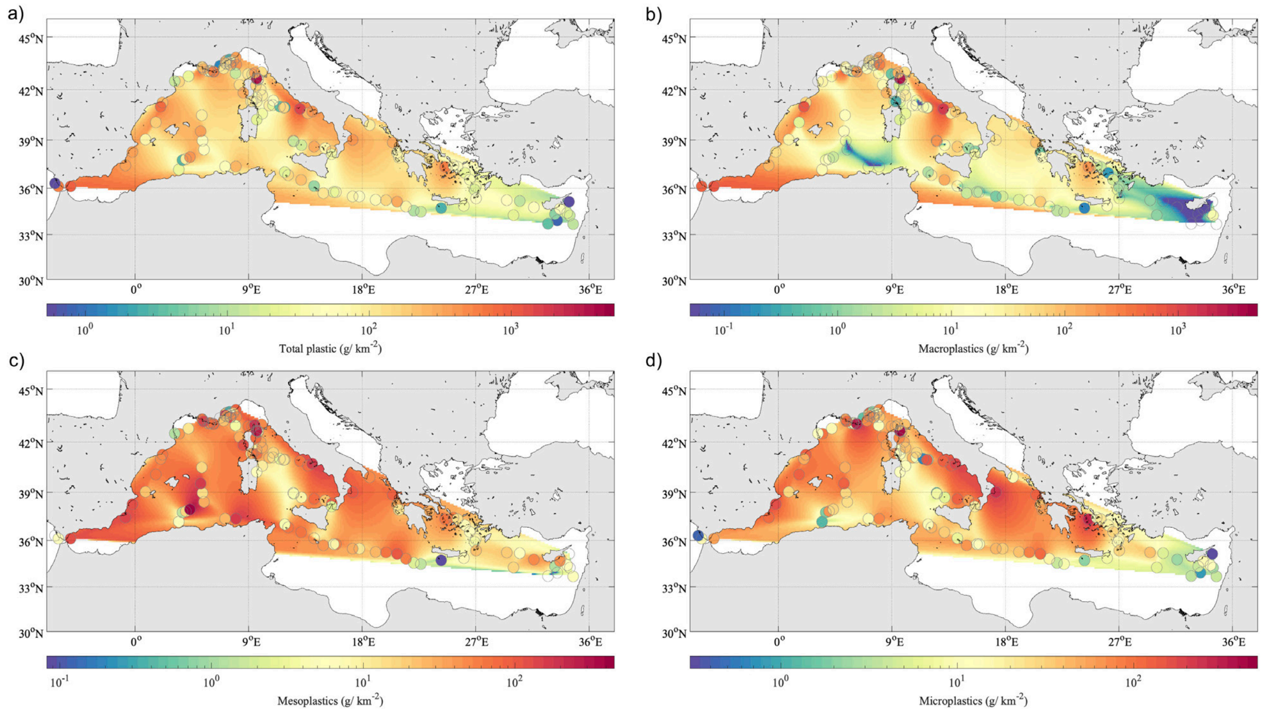


Figure 2.10 | The mass concentrations of floating plastic debris (g km^{-2}) in the Mediterranean Sea. a) total mass concentration, b) macroplastics (>20 mm) c) mesoplastics (between 5 and 20 mm), d) microplastics (<5 mm). Source: Pedrotti et al. (2022).

Levels of Cd, Hg, and Pb in coastal waters show a more or less acceptable environmental status, assessed from bivalves and fish against Background Assessment Concentrations (BAC) and Environmental Assessment Criteria (EAC). In 10% of the stations, Pb levels in mussels were above the maximum concentrations set by the European Commission (EC 2006). For Hg, 53% of the sediment stations assessed are above the Effects Range Low value developed by the US Environmental Protection Agency as sediment quality guidelines, used to protect against potential adverse biological effects on organisms (UNEP/MAP 2017; UNEP/MAP and Plan Bleu 2020).

In summary, for EU countries in the Mediterranean, trends in the release of Cd, Hg and Pb indicate a general decrease (EEA 2021, 2022) *(high confidence).* There is strong evidence that metal concentrations decreased in the northern Mediterranean thanks to regulatory measures *(high confidence)* (Santos-Echeandía et al. 2021; Tavoloni et al. 2021). However, temporal increment trends were reported in some coastal areas, such as Venice (Italy) (Morabito et al. 2018) and the Nile Delta (Egypt) (Mandour et al. 2021).

2.4.3 Persistent organic pollutants (POPs)

Persistent organic pollutants (POPs) are a group of organic compounds that have bioaccumulation potential and toxic properties and persist in the environment. Because of their persistence, these chemicals can be transported through rivers and estuaries and reach coasts and open seas. POPs include pesticides such as dichlorodiphenyltrichloroethane (DDT), industrial chemicals such as polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs) (Merhaby et al. 2019; Cherif et al. 2020). There is increased evidence that the Mediterranean Sea is one of the hotspots of POPs in the world (UN 2021).

Industrial discharges, combustion of organic compounds of natural and/or anthropogenic origin and oil spills are the primary sources of POPs (Merhaby et al. 2019; Kılıç et al. 2023). Maritime accidents can lead to chemical pollution (Ülker et al. 2022). Shipping is one of the main sources of oil pollution on Mediterranean coasts. About 90% of tanker spills in the Mediterranean Sea occur near coastlines. In the east, the Levantine Sea coast is the hotspot of oil pollution *(medium confidence)* (Polinov et al. 2021) due to regional political instability and extensive coastal oil facilities.

The Ebro and Rhone rivers that flow into the north-western Mediterranean are the primary vectors for contamination by POPs (Marsili et al. 2018). Accordingly, POP levels in the north-western Mediterranean coasts are higher compared to the eastern and southern coasts (Marsili et al. 2018). Most of the Mediterranean countries had no published data regarding the concentration of polychlorinated biphenyls (PCBs) on their coasts. There is increased evidence that Italy, France, Spain and Egypt were flagged as the countries most polluted Mediterranean with PAHs and PCBs (Merhaby et al. 2019; Trincardi et al. 2023). The highest PAH and PCB levels are around the harbour and industrial areas, as in the case of Lazaret Bay (France), Naples Bay (Italy), and the Gulf of Taranto (Italy) (Di Leo et al. 2014; Merhaby et al. 2019).

Overall, the levels of POPs, specifically polychlorinated dibenzodioxins (PCDD), polychlorinated dibenzofuran (PCDF) and volatile organic compounds (VOCs) have generally declined on the Mediterranean coasts *(high confidence)* (EEA-UNEP/MAP 2021). Levels of most POPs on the coast will *likely* decline with the improvement of wastewater treatment and the banning of certain compounds (Piante and Ody 2015) as in the case of DDT (Combi et al. 2020; Trincardi et al. 2023) and PCBs (Marsili et al. 2018; Combi et al. 2020; Kılıç et al. 2023). Despite the general decreasing trend in POP levels on the Mediterranean coasts, there is a growing trend in maritime transport, port activity and the production of offshore gas and oil in the Mediterranean Sea (Piante and Ody 2015), which release POPs.

2.4.4 Plastics

Disposal of manufactured and processed solid waste in the marine environment, known as marine litter, is one of the major threats to Mediterranean coasts (Boucher and Billard 2020; Cherif et al. 2020; UNEP/MAP and Plan Bleu 2020). Plastics account for up to 82% of observed litter, 95–100% of total floating marine litter and more than 50% of seabed marine litter in the Mediterranean Sea (UNEP/MAP and Plan Bleu 2020; González-Fernández et al. 2021). Floating plastics squeeze along the coasts due to human activities (tourism, fishing activities, industrial and municipal wastewater) and the unique hydrodynamics of the semi-enclosed Mediterranean Basin (Trincardi et al. 2023).

There is increased evidence that the Mediterranean Sea is one of the areas most polluted with plastics across the globe due to its high coastal population density and its connection with populated rivers coasts (Boucher and Billard 2020; Cherif et al. 2020; UN 2021). In the Mediterranean, 67% of all the plastic particles crossing the land-source buffer zones remain on the coasts (Baudena et al. 2022). According to models, predicted plastic fluxes are highest in the following coastal areas of the Mediterranean: Mersin (Türkiye), Tel-Aviv (Israel), Syria, Algiers (Algeria), Barcelona (Spain), Bizerte (Tunisia), Alexandria (Egypt), and the Po delta (Italy). The models also showed that daily plastic debris flux on the coastline (kg km^{-1}) is the highest in Türkiye's Cilicia region (Mersin) followed by Barcelona and Tel-Aviv (Liubartseva et al. 2018; Baudena et al. 2022). Italy (12.6 kT y^{-1}) and Türkiye (12.1 kT y^{-1}) accumulate the most coastline plastic debris each year due to the length of their coastlines and the elevated plastic leakage in coastal waters *(high confidence)* (Liubartseva et al. 2018; González-Fernández et al. 2021; Baudena et al. 2022).

Contrary to the models, floating mega debris (>30 cm) is more significant in the west and the centre of the Mediterranean compared to the east (Lambert et al. 2020). Accordingly, macroplastics (>20 mm), mesoplastics (between 5 and 20 mm), and microplastics (<5 mm) concentrations are higher in the west and the centre compared to the east (Pedrotti et al. 2022). For instance, surface water plastic debris levels are high ($> 5 \times 10^5$ items km^{-2}) in coastal areas from Nice to Toulon (Ligurian Sea), north-eastern Sicily, Messina Channel, and Naples coasts (Tyrrhenian Sea), the Gulf of Taranto (Ionian Sea), and the Saronic Gulf (Aegean Sea), while levels are low ($<1.6 \times 10^4$ items km^{-2}) in Sicily, southern Crete (Ionian Sea), and southern and eastern Cyprus (Levantine Sea) *(Figure 2.10)*.

In summary, the amount of plastic along Mediterranean coasts has remained steady for the past two decades *(medium confidence)* (UN 2021). Annual plastic leakage into the Mediterranean coastal area is as high as 230,000–260,000 tonnes (Cózar et al. 2015; Suaria et al. 2016; Boucher and Billard

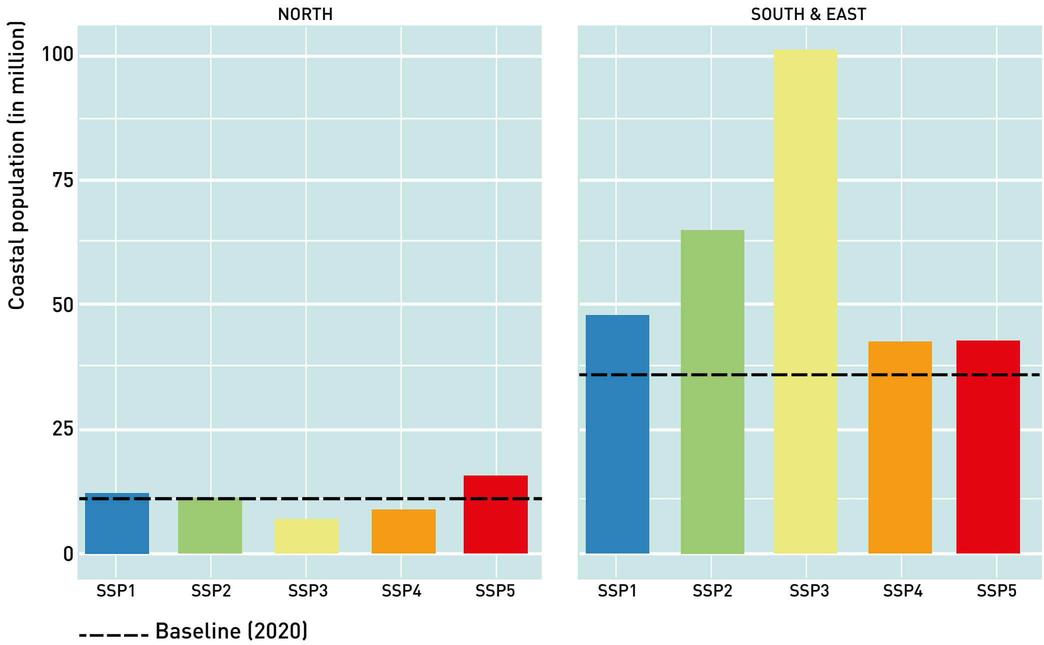


Figure 2.11 | Mediterranean coastal population in each SSP and geographical region in 2100 compared to 2010. (Coastal = LECZ based on MERIT, population in 2010 is based on Global Human Settlement Population Grid; GHS-POP). Please note different scales of the y–axes. Source: Reimann et al. (2021).

2020), and it is *likely* to reach 500,000 tonnes by 2040 if both annual plastic production continues to grow at a rate of 4% and waste management is not radically improved (Boucher and Bilard 2020). In the scenario of 1% annual growth in plastic production, improved waste management and implementing regulations limiting single-use plastic, leakage is *very likely* to decrease by 2040 (Boucher and Bilard 2020).

2.4.5 Emerging pollutants

The term 'emerging pollutants' (EPs) refers to a diverse group of thousands of chemicals and xenobiotics, the biological effects of which are not well-known and whose existence in the environment has only recently been studied and monitored (Cherif et al. 2020; Antunes et al. 2021; Chacón et al. 2022). These chemicals are found in personal care products (cosmetics, etc.), household detergents, flame retardants, plastic additives, pesticides, and pharmaceuticals (painkillers, antibiotics, and antidepressants) that are products of cutting-edge technology (UNEP/MAP and Plan Bleu 2020; Chacón et al. 2022). Runoff and seepage from landfills, pesticides, fertilizers, hospital discharges, industrial and urban wastewater all release EPs into the coastal environment (Li 2014). The low geographical variability of EPs in the Mediterranean Sea suggests that they emanate from diffuse pollution sources such as runoff from agricultural areas (Brumovský et al. 2017). Among the wide variety of EPs, PPCPs (pharmaceutical and personal care products) are those that are the most concentrated in the three river basins in the Mediterranean Sea. In these basins, urban discharges are the primary source of pharmaceuticals like ibuprofen. Pesticide-like chemicals are associated with agricultural activity, while PFOS (perfluorooctane sulfonic acid) are associated with industrial facilities in Mediterranean coasts (Köck-Schulmeyer et al. 2021). On Mediterranean coasts, the levels of pharmaceuticals ranged from 100 to 10,000 or even 100,000 ng L^{-1} in sewage waters, dropping to 1 to 10,000 ng L^{-1} in rivers and not detected to 3000 ng L^{-1} in coastal seawater. Among the 43 drugs, pharmaceuticals highlighted thirteen compounds that are cause for concern in Mediterranean coasts, such as antibiotics and anti-inflammatories (Desbiolles et al. 2018). Anti-inflammatories and antibiotics are the most dominant types of PPCPs in the eastern and southern Mediterranean (Ouda et al. 2021).

EPs, such as pharmaceuticals and personal care products, are expected to increase on the Mediterranean coasts due to socioeconomic changes and emerging industries *(medium confidence)*. The northern Mediterranean coasts are polluted with EPs more severely than the south due to the abundance of point sources on the northern coast *(medium confidence).* However, EP levels are elevated in the rivers of some Mediterranean countries, such as Israel, Spain, Tunisia, Türkiye, and Palestine *(low confidence)* (Wilkinson et al. 2022). Active pharmaceutical ingredients are elevated due to the discharge of untreated sewage in Tunisia and Palestine *(low confidence)* (Wilkinson et al. 2022).

2.4.6 Air pollution

Energy consumption, road transport, shipping emissions and the manufacturing and extractive industries are the main sources of air particulate matter in the northern and eastern Mediterranean (Cherif et al. 2020). There is *high confidence* that air quality on Mediterranean coasts is negatively affected by airborne particulate matter ($PM_{2.5}$–PM_{10}; particulate matter diameters of 2.5 and 10 microns or less, respectively) and gases from northern and eastern Europe, desert dust from the Sahara and surrounding arid regions, biomass burning (forest fires), in addition to local pollution sources such as ports, vehicular traffic, industrial and residential heating (Dulac et al. 2022; Perrone et al. 2022).

Air pollution monitoring and related data are scarce in the southern and eastern Mediterranean (except for Greece and Türkiye) compared to the north *(high confidence)*. Having said that the data is scarce in the southern Mediterranean, the highest concentrations of particulate matter and benzo[a]pyrene (a carcinogenic organic pollutant) were reported in central eastern Europe and Italy due primarily to the burning of solid fuels for domestic heating and their use in industry. In 2020, some Italian and Turkish coastal areas showed $PM_{2.5}$ and PM_{10} concentrations higher than EU limit values. PM concentrations in certain coasts of the southern Mediterranean are much higher than the EU and World Health Organization (WHO) limit values *(low confidence)* (Naidja et al. 2018). Emissions from road traffic, resuspension of road dust and natural contributions (i.e. dust from the Saharan Desert) are principal sources of air particles on southern Mediterranean coasts (Naidja et al. 2018).

The eastern Mediterranean and the Middle East are characterised by high background tropospheric ozone concentrations *(high confidence)* (Lelieveld et al. 2002; Georgiou et al. 2022). Ozone levels were lower in 2019–2021 than in previous years, but still high in central Europe and some Mediterranean coastal areas such as the Turkish coasts *(medium confidence).* Concentrations of NO_2 and Benzo[a] pyrene (BaP) are higher on the Greek and Italian coasts, respectively, than the limit value set by the EU *(medium confidence)* (EEA 2021 2022a). Cyprus faces challenges with the exceedance of air quality limits and compliance with European regulatory standards *(medium confidence)* (Georgiou et al. 2022).

15% of global shipping activity and around 18% of global crude oil shipments take place in the Mediterranean Sea (A. Carpenter and Kostianoy 2018). Luxury cruise ships emit up to 18-, 10-, and 4-times higher SO_x than all of the passenger vehicles (including cars) respectively in Spain, Italy, and Greece, the top cruise ship polluted countries in Europe (T&E 2019). However, shipping in many coastal areas of the Mediterranean Sea caused less O_3 and NO_2 release than those of the North and Baltic Seas since shipping lanes are typically further from the coast in the Mediterranean Sea (Fink et al. 2023). Shipping contributions to $PM_{2.5}$ or PM_{10} emissions (between 0.2% and 14%) are greater in the Mediterranean area compared to northern Europe (Contini and Merico 2021). Among the world's harbours (mostly European harbours), Taranto (Italy) has the highest PM_{10} concentrations (Sorte et al. 2020).

In summary, emissions of all key air pollutants in Mediterranean EU countries have been declining since 2005 *(high confidence).* Emissions of sulphur dioxide and nitrogen oxides have fallen by 76% and 36%, respectively, since 2005. $PM_{2.5}$–PM_{10} emissions fell by 29% and 27% respectively, since 2005 across the northern and eastern Mediterranean (EEA 2021 2022a). However, the release and levels of air pollutants will increase *more likely than* not on some Mediterranean coasts due to the upward trend in wildfires (Ruffault et al. 2020), port activity, maritime transport, offshore gas and oil production (Piante and Ody 2015; Doussin 2023).

2.5 Social and economic drivers

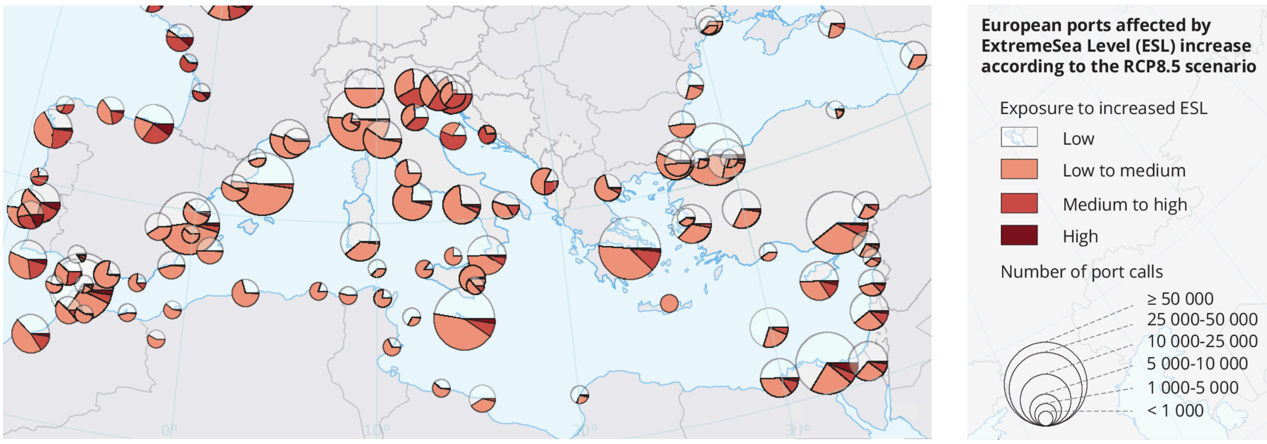
2.5.1 Current and future population and urban development trends across the coastal region

Mediterranean countries are currently home to more than 540 million people, with a high concentration of urban settlements and infrastructure near the coast (Ali et al. 2022). Mediterranean communities have adapted their lifestyles to the historically stable coastline due to non-dynamic water levels, unique to the Mediterranean due to its low-energy wave conditions (Vafeidis et al. 2020). Consequently, about one-third of the Mediterranean population currently lives in close proximity to the coast (UNEP/MAP and Plan Bleu 2020). The Mediterranean Low Elevation Coastal Zone (LECZ, areas below 10 m) hosted more than 41.8 million people (share 8.9%) in 2010 (Reimann et al. 2018). Southern and eastern Mediterranean countries face a higher risk of climate-related coastal exposure, primarily due to higher urban population density, which is three orders of magnitude higher compared to the north (Reimann et al. 2021).

The future population in the Mediterranean coastal region is projected to increase under all socio-economic scenarios, leading to significant exposure to sea-level rise and coastal hazards in the north, south, and east (see *Figure 2.11*). In the northern Mediterranean, Shared Socioeconomic Pathway (SSP) 5 leads to the highest coastal population growth (15.2 million), whereas a reduction to 6.5 million is anticipated under SSP3 by the end of the century. In contrast, the southern and eastern Mediterranean are expected to see the greatest population increase under SSP3 (over 100 million), with the lowest coastal population increase under SSP5 (42.7 million) (see *Figure 2.11*) (Reimann et al. 2021).

At the country level, Egypt, Libya, Morocco and Tunisia are currently most exposed to sea-level rise due to their extensive coastal floodplains and large coastal populations *(medium confidence)* (Adams et al. 2014; Ali et al. 2022). According to Neumann et al. (2015), Egypt is the country with the largest population in the LECZ along the Mediterranean coast (26 million; constituting 38% of its total population). In 2000, the Nile Delta's population density was 1075 people km^{-2}, comparable to the population density of Japan or Bangladesh in the LECZ. This population density is projected to increase to 1902 people km^{-2} by 2030 and 2681 people km^{-2} by 2060 (Neumann et al. 2015). In contrast, the lowest total LECZ population is observed in EU candidate countries, namely Bosnia and Herzegovina, Montenegro, Albania and Türkiye (Reimann et al. 2018).

Additionally, urban expansion and the associated concentration of wealth production are increasing



Note: the map illustrates the secondary effects of the disruption of European port operations as a result of a projected increase of ESL until 2100. It is based on information on connections of container ports. The size of the pies represent the total number of connections or port calls and the coloured pieces of the pies represent the part of the total connections to ports exposed to different levels of ESL increased.

Figure 2.12 | Container ports affected by the projected extreme sea level increase according to the RCP8.5 scenario until 2100. Source: Christodoulou et al. (2019).

more rapidly in low-lying coastal regions than inland worldwide (Seto et al. 2011). Mediterranean countries, with their large and increasing urban population (dos Santos et al. 2020), are experiencing rapid coastal urbanisation. This trend increases exposure of human settlements and infrastructure to sea-level rise and its associated hazards (UNEP/MAP and Plan Bleu 2020). Two-third of the Mediterranean population already lives in urban areas, which is higher than the global average (dos Santos et al. 2020). The UN Human Settlements Program projects that by 2050, the urban population in the northern Mediterranean will grow from 140 million in 2005 to about 170 million, and in the south and east, from 151 million in 2005 to over 300 million (UNEP/MAP 2016). Wolff et al. (2020) project increased urban expansion in the coastal floodplain across all regions (including 10 northern Mediterranean countries and Türkiye) by 2100, leading to a substantial increase in coastal exposure. For example, under the SSP5 scenario, urban areas are expected to increases by 67% (2075 km²) in Italy, 104% (2331 km²) in France (considering only the Mediterranean coast), and 86% (691 km²) in Greece within the extended LECZ (E-LECZ, referring to the area below 20 meter elevation that is hydrologically connected to the sea) between 2012 and 2100. Furthermore, tourism drives coastal urban development in the Mediterranean, with over 360 million international tourist arrivals annually, mainly concentrated in coastal zones, which represents nearly one-third of global tourism (UNWTO 2019).

In summary, the Mediterranean coastal region is characterised by rapid and spatially diverse socioeconomic development, mainly influenced by demographic trends and human settlement patterns *(high confidence)* (Vafeidis et al. 2020; Reimann et al. 2021).

2.5.2 The economic use of the coast

2.5.2.1 Seaports, tourism and cruising

Global environmental change exacerbates existing challenges for the population living around the Mediterranean Sea, through climate change, land use changes, increasing urbanisation and tourism and increased energy demand. Tourism will *likely* be affected by climate change through reduced thermal comfort, degradation of natural resources, including freshwater availability, and coastal erosion due to sea level rise and urban development. The net economic effect on tourism will depend on the country and the season. In the Mediterranean, tourist activity is at its highest in summer, coinciding with peak demands from irrigated agriculture which may create tensions regarding water availability *likely* to be exacerbated in the future due to climate change *(high confidence)* (Toth et al. 2018). Northern Mediterranean regions could experience climate-induced tourism revenue decreases of up to –0.45% of gross domestic product per year by 2100 *(medium confidence)* (dos Santos et al. 2020).

The Mediterranean coastal regions are characterised by high socio-cultural wealth resulting from the enormous cultural and socioeconomic diversity around the basin, which is an important cultural, economic and/or heritage asset for the economy (e.g. tourism) and society (dos Santos et al. 2020) (dos Santos et al. 2020). There is a development gap between the northern, southern, and eastern countries in terms of economic growth, income, population growth and education (UNEP/MAP 2016). War and social unrest are examples of pressing problems in several eastern and southern Mediterranean countries that may exacerbate this development gap and therefore have the potential to further reduce adaptive capacity to coastal hazards (Vafeidis et al. 2020). Another example is the European debt crisis, which has weakened the economic sectors and the labour market in northern Mediterranean countries. In addition, other societal challenges such as corruption, demographic change, poverty, social imbalances and/or inequalities are related to economic growth and have a strong influence on the overall adaptive capacity of the Mediterranean region (dos Santos et al. 2020). In summary, the Mediterranean coastal region is characterised by rapid and spatially diverse socioeconomic development, mainly related to demographic trends and human settlement patterns *(high confidence)* (Vafeidis et al. 2020).

The projected climate change will have a number of consequences affecting seaports. Sea level rise (SLR) will cause diffuse shoreline retreat that will depend on the local morphology and will be worsened by local land subsidence. Seaports will be at risk of flooding, therefore reducing their activity *(high confidence)* (see *Figure 2.12*). In port facilities, SLR will put all the infrastructure located too close to the actual sea level at risk of regular and permanent inundation. Changing the water

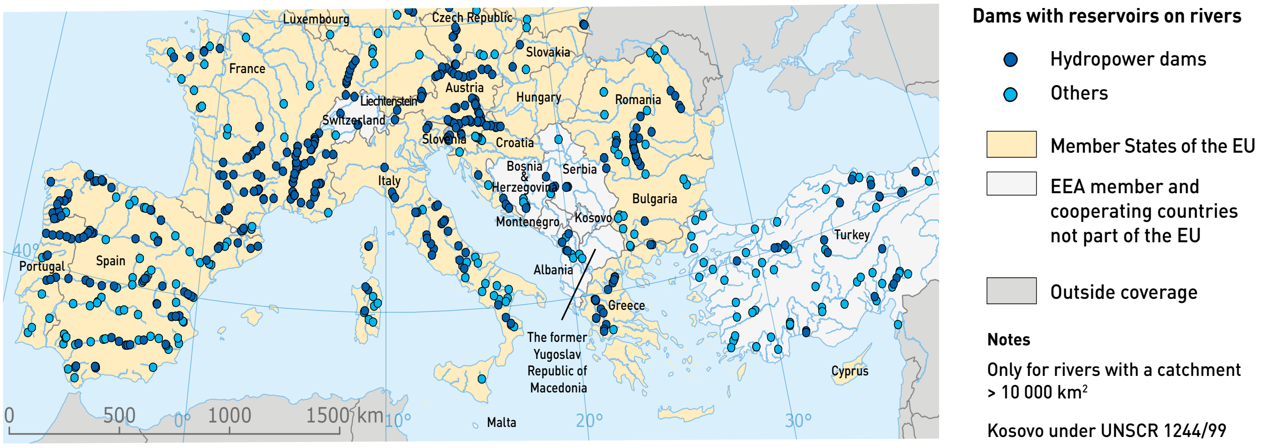


Figure 2.13 | Map of dams in Europe only for rivers with catchment areas greater than 10,000 km². Source: EEA (2016). https://www.eea.europa.eu/en/analysis/maps-and-charts/dams-with-reservoirs-on-rivers

shelf, waves will change the propagation pattern and the way they penetrate into ports. Port infrastructure and/or cargo will be exposed to higher risk of damage. Sand and mud will *likely* increase sedimentation in ports and navigation channels, requiring frequent dredging. Ports will face increased construction and maintenance costs *(high confidence)* (Christodoulou and Demirel 2018; Christodoulou et al. 2019; EMSA 2021). This situation will affect all ports, either for shipping containers or tourism *(high confidence).*

Coastal tourism covers maritime tourism and includes accommodation, transport and other expenditures. The Mediterranean is the world's leading tourism destination in terms of both international and domestic tourism for numerous advantages over other cruising areas, due to its variety of cultural and nature-based-tourism, people, languages, history, gastronomy and the mild climate, even in winter (EC 2022). In addition, the Mediterranean Sea is also a well-known destination for recreational boating (González-Alemán 2020).

Over half of the EU's tourist accommodation establishments are located in coastal areas. Cruise infrastructure remains located on the northern shore: 75% of Mediterranean ports are on the northern coast, while 9% of ports are in Türkiye and Cyprus; and 7% in North Africa; the rest on the eastern Mediterranean side (Plan Bleu 2022).

However, the COVID-19 pandemic and growing geopolitical conflicts are increasing threats for the tourism industry globally, and particularly in the Mediterranean. The tourism sector suffered an 80% decline that will be felt for years to come, with wide uncertainty, and scarce and fragmented knowledge on the current state and path of the sector (EC 2022).

In their efforts to stay competitive, cruise companies introduce continuous innovations, such as new port destinations. Because of this continuous growth, a number of countries think of cruises as key products for tourism development. Some port organisations and local authorities have even decided to build new terminal infrastructure (Kasimati and Asero 2021).

In general, cruise tourism is seen as unsustainable. When big ships arrive at small destinations, this normally has a big impact on the lives of local communities. The biggest problem with cruise tourism is that it generates negative impacts on the environment and may cause overtourism due to the many visitors, who stay only a short amount of time (Asero and Skonieczny 2018). Another drawback is related to the carbon footprint and waste from packaging (e.g. water and beverage packaging) left by passengers who visit ports and other localities on cruise ships (Paiano et al. 2020). However, the cruise industry is slowly responding to the growing demand for sustainability by leading the way in responsible tourism, investing in new ships, and pursuing the goal of net carbon neutral cruising by 2050 (CLIA 2022).

2.5.2.2 Oil and gas extraction and exploration, dams and sediment supply to coastal areas

Oil and gas

In the Mediterranean, the locations with the majority of oil and gas exploration and exploitation activities lie in the eastern Mediterranean Sea, and the eastern coast of Italy in the Adriatic Sea. Drilling wells for offshore production are located in the waters off Egypt, Greece, Italy, Libya, Spain and Tunisia, and along the coasts of Cyprus, Egypt, Israel, Lebanon, and Palestine (A. Carpenter and Kostianoy 2018). Energy industries are intensive consumers of coastal areas. While renewable energies pose specific challenges in terms of logistics, oil and gas industries generate a series of issues in terms of exploration, resource exploitation, and product transportation. Different countries within the Mediterranean Basin manage concessions and royalties in different ways, with most exploitation areas (i.e. coastal regions with at least one offshore platform) located in the eastern side of the Mediterranean Sea. In contrast with other world regions (e.g. Gulf of Mexico, North Sea, Caspian Sea), decommissioning has not been a major issue yet, with main exploitation projects still ongoing and not creating conflicts between local authorities and oil and gas companies (Liaropoulos et al. 2019). Despite this, countries outside the EU do not usually have a specific policy related to decommissioning, arising issues in terms of life-cycle assessments of main exploitation sites and related social and environmental impact.

Another peculiarity of the Mediterranean Basin is connected to the sea conditions that allow companies to enjoy lower costs (and less operational challenges) than in other markets, making many Mediterranean exploitation areas quite competitive with respect to other offshore fields.

Sediments supply and erosion of coastal areas

Throughout the world, coastal areas are constantly threatened by a complex balance between sedimentation and erosion. This problem is the result of multiple factors, which can be divided into three large groups: (1) factors related to climate, e.g. sea level rise, storm, coastal waves, marine currents; (2) factors related to the morphology and quality of the sediment that makes up the beach, as well as to the shoreline morphology (i.e. shoreline orientation), (3) factors generated by the anthropogenic structures and activities that exist in the area (Pagán et al. 2018; López-Olmedilla et al. 2022; Toledo et al. 2022).

In Europe, it is estimated that around 20,000 km of coastline, accounting for 20% of its entire length, have coastal erosion problems (EC 2004). These areas are particularly vulnerable to both human activities and the effects of global warming *(very high confidence).*

Considering sediments and dams, it is worth noticing that the Mediterranean drainage basin incorporates more than 160 rivers, most of which are small and distributed across the European side of the Mediterranean. Poulos and Collins (2002) highlighted how 'suspended sediment contributes some two-thirds of the load, with the remaining third supplied by the combined dissolved and bed-load components'. It has been highlighted that about 46% of the total length of the Mediterranean coastline has been formed by sediment deposition and many Mediterranean deltas have progressed in recent times *(high confidence)* (Poulos and Collins 2002; Anthony 2014, 2019).

Dams within the Mediterranean region have affected river sediments. Most of them are far from the sea but directly influence watersheds. These investments have led to a reduction in the sediment supply to approximately –50% of the potential (natural) sediment supply, directly impacting coastal lands and their composition, especially in the North African area *(high confidence)* (Poulos and Collins 2002).

The sediments supplied by the River Nile have been cut off by dams, sea level rise, marked shelf subsidence, and regional climate changes, which have altered the amounts and components of sediments *(high confidence)* (Frihy and Stanley 2023).

On the European side, the location of dams and their impact on the environment are monitored by the European Environment Agency (EEA 2016) (see *Figure 2.13*) which focuses on understanding their value as water reservoirs and the impact of sediments on coastal development. Within this framework, the European Rivers Network monitors the impact of dams on river ecosystems, highlighting the different effects in the long run with respect to the short run, in terms of sediment balance, need for renovation, and coastal impact of river flows.

Projections of sandy beach erosion due to sea-level rise are affected by large uncertainties. A variance-based global sensitivity analysis indicates that the uncertainty associated with the choice of geophysical datasets can contribute up to 45% (26%) of the variance in coastal land loss projections for Europe by 2050 (2100) *(low confidence)* (Athanasiou et al. 2020).

2.5.2.3 Seawater desalination

The ongoing decrease in precipitation and increase in average annual temperatures include smaller effective meteoric contribution, lower discharge of rivers and higher evapotranspiration. In the coastal areas, this causes a general deterioration of water quality in aquifers due to freshwater salinisation *(high confidence)* (Re and Zuppi 2011). Desalination for drinking water, livestock or agricultural use is gaining importance on islands and in coastal cities with limited water resources. In the Mediterranean, the largest producers of freshwater through desalination are Malta, Algeria, Egypt, Israel, Italy, and Spain. In the Middle East and North Africa, the production of desalinated seawater is projected to be thirteen times higher in 2040 than 2014 *(high confidence)* (FAO 2016; UNEP/MAP and Plan Bleu 2020). Seawater desalination requires a large amount of energy and produces brine potentially impacting the marine ecosystem if not properly managed (Pistocchi, et al. 2020). At the same time, it represents a reliable and constant supply of freshwater in water-scarce regions. Its relatively high cost appears to be increasingly accepted as the costs of conventional water supply (including impacts on ecosystems caused by freshwater abstractions and greenhouse gas emissions) due to pumping, storage and freshwater treatment needs increase. The Mediterranean already has a relatively high share of water supplies provided by desalination, with the European Mediterranean coast alone featuring close to 9 million m^3 day^{-1} in desalination capacity mostly concentrated in Spain and, to a lesser extent, Italy and other countries (EC et al. 2022), accounting for almost 10% of the global capacity. As a hotspot of climate change, projected to face increasingly severe water scarcity, Mediterranean countries *will likely* need to build several new plants in coastal areas throughout the region *(high confidence).* This fact is related to significant greenhouse gas emissions unless sufficient plants able to function with renewable energy sources are designed *(high confidence)* (Ganora et al. 2019; Pistocchi et al. 2020b). Benefits increase when coupling desalination with water reuse *(high confidence)* (Pistocchi et al. 2020b). The Middle East and North Africa (MENA) region is the most water scarce region of the world. High population growth rates, urbanisation and industrialisation, coupled with limited availability of natural potable water resources are leading to serious deficits of freshwater in many parts of the MENA region. Freshwater sources in the MENA region are being continuously over-exploited and increased use of desalinated seawater is unavoidable in order to maintain a reasonable level of water supply *(high confidence).* However, conventional large-scale desalination is cost-prohibitive and energy-intensive, and not viable for poor countries in the MENA region due to increasing costs of fossil fuels. In addition, the environmental impacts of desalination are considered critical on account of emissions from energy consumption and discharge of brine into the sea (*high confidence).*

2.5.2.4 Aquaculture and fisheries

Fishery is an activity involving the harvesting of fish. It may involve capture of wild fish or raising fish through aquaculture (FAO 2023). Aquaculture is based on the cultivation of fish, crustaceans, molluscs, algae and aquatic plants of value in sheltered coastal or offshore waters, as well as in proximity to rivers, ponds, lakes, canals and especially deltas. These activities are currently impacted mostly by overfishing and coastal development, but climate change and acidification may play an important role in the future. Both capture fisheries and aquaculture depend on natural ecosystems. Capture fisheries, in particular, depend on the status of fisheries resources, while aquaculture depends on water quality and the appropriate spatial conditions to carry out these activities. Impacts include fishing itself, but also climate change, pollution, and the appearance and expansion of non-indigenous species. The upward trend in aquaculture production has been driven primarily by increased production in Egypt and Türkiye, followed by Greece, Italy, Spain, France, and Tunisia (UNEP/MAP and Plan Bleu 2020). For fisheries, the most seriously overexploited priority species in the Mediterranean is the European hake, which – due to its presence in most trawl fisheries – shows an average overexploitation rate 5.8 times higher than the target *(high confidence).* For aquaculture, more than 100 species (finfish, shellfish, crustaceans, and algae) are currently cultivated within a wide range of environments and farming systems (UNEP/MAP and Plan Bleu 2020). Mediterranean countries import more fish products than they export as a result of increasing demand for seafood. Despite being major exporters, France, Italy, and Spain are the countries with the highest trade deficits for seafood. There are no quantitative estimates on the impact of climate change on future seafood production in the Mediterranean region, but ocean acidification and warming will *very likely* impact an already-stressed fishing sector *(very high confidence)* (UNEP/MAP and Plan Bleu 2020). By 2040–2059, compared to 1991–2010, more than 20% of fish and invertebrates currently fished in the eastern Mediterranean are projected to become locally extinct under the most pessimistic scenario (RCP8.5) *(very high confidence)* (Jones and Cheung 2015; Cheung et al. 2016). By 2070–2099, forty-five species are expected to qualify for the Red List of the International Union for Conservation of Nature (IUCN) and fourteen are expected to become extinct *(very high confidence)* (Ben Rais Lasram et al. 2010). The maximum catch potential on the southern coast of the Mediterranean Sea is projected to decline by more than 20% by the 2050s with respect to the 1990s under RCP8.5 *(high confidence)* (Cheung et al. 2016).

2.6 Final remarks

Climate change, sea level rise and local land subsidence expose large portions of coasts to risk of permanent submersion, or to the impact of episodic floods driven by adverse meteorological conditions, sometimes worsened by certain anthropic activities *(very high confidence)*. This situation suggests that specific studies should be carried out for planning, or to decide on coastal use and development.

The dramatic and unexpected events of recent years (e.g. the COVID–19 pandemic, the socio-political events that have given rise to new wars, the increased costs of fuels and energy, and recently a devastating earthquake) have negatively influenced many forecasts related to free trade, tourism, development, industry, agriculture, commerce, and several other sectors. This has created a margin of uncertainty that is not easily determinable, not even as regards its duration.

Regarding pollution and biological drivers, comprehensive data sets including all coasts of the Mediterranean are very scarce *(very high confidence)* due to unequal socio-economic structures of the countries across the Mediterranean, political instability and lack of international cooperation. Furthermore, each part of the Mediterranean coast is polluted to varied degrees, and no limit and/or threshold levels of pollutants are approved by all Mediterranean countries *(high confidence).* Large-scale periodic and standardised pollution and biological monitoring campaigns (including all Mediterranean countries) are needed to develop more solid data, reveal the current status and project future scenarios. Capacity building, technology and knowledge transfer among the Mediterranean countries can enhance our understanding of pollution and biological drivers. Setting standard applications for the treatment of municipal and industrial wastewater is *likely* to decrease pollution on Mediterranean coasts.

References

Abdou M., Schäfer J., Hu R., Gil-Díaz T., Garnier C., Brach-Papa C., Chiffoleau J. F., Charmasson S., Giner F., Dutruch L., and Blanc G. (2019). Platinum in sediments and mussels from the northwestern Mediterranean coast: Temporal and spatial aspects. *Chemosphere, 215.* doi: 10.1016/j.chemosphere.2018.10.011

Adams, S., Aich, V., Albrecht, T., Baarsch, F., Boit, A., Canales Trujillo, N., Cartsburg, M., Coumou, D., Eden, A., Fader, M., Hare, B., Hoff, H., Jobbins, G., Jones, L., Kit, O., Krummenauer, L., Langerwisch, F., Le Masson, V., Ludi, E., Marcus, R., ... World Bank. (2014). *Turn down the heat: Confronting the new climate normal (Vol. 2 of 5): Main report.* World Bank Group. http://documents.worldbank.org/curated/en/317301468242098870

Adloff F., Somot S., Sevault F., Jordà G., Aznar R., Déqué M., Herrmann M., Marcos M., Dubois C., Padorno E., Alvarez-Fanjul E., and Gomis D. (2015). Mediterranean Sea response to climate change in an ensemble of twenty first century scenarios. *Climate Dynamics, 45*(9–10), 2775–2802. doi: 10.1007/s00382-015-2507-3

Alasset P. J., Hébert H., Maouche S., Calbini V., and Meghraoui M. (2006). The tsunami induced by the 2003 Zemmouri earthquake (MW = 6.9, Algeria): Modelling and results. *Geophysical Journal International, 166*(1), 213–226. doi: 10.1111/J.1365-246x.2006.02912.x

Alexander M. A., Scott J. D., Friedland K. D., Mills K. E., Nye J. A., Pershing A. J., and Thomas A. C. (2018). Projected sea surface temperatures over the 21st century: Changes in the mean, variability and extremes for large marine ecosystem regions of Northern Oceans. *Elementa: Science of the Anthropocene, 6.* doi: 10.1525/elementa.191

Ali E., Cramer W., Carnicer J., Georgopoulou E., Hilmi N. J. M., Le Cozannet G., and Lionello P. (2022). Cross-Chapter Paper 4: Mediterranean Region. In H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, & B. Rama (Eds.), *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 2233–2272. doi: 10.1017/9781009325844.021

Alonso B., Ercilla G., Garcia M., Vázquez J. T., Juan C., Casas D., Estrada F., D´Acremont E., Gorini Ch., El Moumni B., and Farran M. (2014). Quaternary Mass-Transport Deposits on the North-Eastern Alboran Seamounts (SW Mediterranean Sea). In S. Krastel, J.-H. Behrmann, D. Völker, M. Stipp, C. Berndt, R. Urgeles, J. Chaytor, K. Huhn, M. Strasser, & C. B. Harbitz (Eds.), *Submarine Mass Movements and Their Consequences: 6th International Symposium* (pp. 561–570). Springer, Cham. doi: 10.1007/978-3-319-00972-8_50

Álvarez M., Catalá T. S., Civitarese G., Coppola L., Hassoun A. E. R., Ibello V., Lazzari P., Lefevre D., Macías D., Santinelli C., and Ulses C. (2023). Mediterranean Sea general biogeochemistry. In *Oceanography of the Mediterranean Sea* (pp. 387–451). Elsevier. doi: 10.1016/b978-0-12-823692-5.00004-2

Androulidakis Y. S., Kombiadou K. D., Makris C. V, Baltikas V. N., and Krestenitis Y. N. (2015). Storm surges in the Mediterranean Sea: Variability and trends under future climatic conditions. *Dynamics of Atmospheres and Oceans, 71,* 56–82. doi: 10.1016/j.dynatmoce.2015.06.001

Anthony E. J. (2014). The Human influence on the Mediterranean coast over the last 200 years: a brief appraisal from a geomorphological perspective. *Géomorphologie : Relief, Processus, Environnement, 20(3)*, 219–226. doi: 10.4000/geomorphologie.10654

Anthony E. J. (2019). *Beach Erosion* (C. W. Finkl & C. Makowski, Eds.; pp. 234–246). doi: 10.1007/978-3-319-93806-6_33

Antunes E., Vuppaladadiyam A. K., Sarmah A. K., Varsha S. S. V, Pant K. K., Tiwari B., and Pandey A. (2021). Application of biochar for emerging contaminant mitigation. In *Advances in Chemical Pollution, Environmental Management and Protection* (Vol. 7, pp. 65–91). Elsevier. https://linkinghub.elsevier.com/retrieve/pii/S2468928921000034

Anzidei M., Scicchitano G., Scardino G., Bignami C., Tolomei C., Vecchio A., Serpelloni E., De Santis V., Monaco C., Milella M., Piscitelli A., and Mastronuzzi G. (2021). Relative Sea-Level Rise Scenario for 2100 along the Coast of South Eastern Sicily (Italy) by InSAR Data, Satellite Images and High-Resolution Topography. *Remote Sensing, 13*(6), 1108. doi: 10.3390/rs13061108

Arias P. A., Rojas M., Sillmann J., Barimalala R., Berger S., Dentener F. J., Dereczynski C., Eyring V., Fischer E., Gutierrez J. M., Hamdi R., Kossin J., Krakovska S., Ngo-Duc T., Otto F., Sathyendranath S., Seneviratne S. I., von Schuckmann K., and Zaehle S. (2021). Technical Summary. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (Eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 33–144. doi: 10.1017/9781009157896.002

Asero V., and Skonieczny S. (2018). Cruise Tourism and Sustainability in the Mediterranean. Destination Venice. In L. Butowski (Ed.), *Mobilities, Tourism and Travel Behavior - Contexts and Boundaries.* InTech. doi: 10.5772/intechopen.71459

Athanasiou, P., van Dongeren, A., Giardino, A., Vousdoukas, M. I., Ranasinghe, R., & Kwadijk, J. (2020). Uncertainties in projections of sandy beach erosion due to sea level rise: an analysis at the European scale. *Scientific Reports, 10*(1), 11895. doi: 10.1038/s41598-020-68576-0

Axaopoulos P., and Sofianos S. (2010). Long Term Variability of Sea Surface Temperature in Mediterranean Sea. *AIP Conference Proceedings, 1203*(1), 899–904. doi: 10.1063/1.3322579

Azzurro E. (2008). The advance of thermophilic fishes in the Mediterranean Sea: overview and methodological questions. In *CIESM workshop monographs.* Vol. 35. CIESM, Monaco. https://www.ciesm.org/online/monographs/35/WM_35_39_45.pdf

Azzurro E., Smeraldo S., and D'Amen M. (2022a). Spatio-temporal dynamics of exotic fish species in the Mediterranean Sea: Over a century of invasion reconstructed. *Global Change Biology, 28*(21), 6268–6279. doi: 10.1111/gcb.16362

Azzurro E., Smeraldo S., Minelli A., and D'Amen M. (2022b). ORMEF: a Mediterranean database of exotic fish records. *Scientific Data, 9*(1), 363. doi: 10.1038/s41597-022-01487-z

Báez J. C., Pennino M. G., Albo-Puigserver M., Coll M., Giraldez A., and Bellido J. M. (2022). Effects of environmental conditions and jellyfish blooms on small pelagic fish and fisheries from the Western Mediterranean Sea. *Estuarine, Coastal and Shelf Science, 264*, 107699. doi: 10.1016/j.ecss.2021.107699

Basili R., Brizuela B., Herrero A., Iqbal S., Lorito S., Maesano F. E., Murphy S., Perfetti P., Romano F., Scala A., Selva J., Taroni M., Tiberti M. M., Thio H. K., Tonini R., Volpe M., Glimsdal S., Harbitz C. B., Løvholt F., ... Zaytsev A. (2021). The Making of the NEAM Tsunami Hazard Model 2018 (NEAMTHM18). *Frontiers in Earth Science, 8*, 616594. doi: 10.3389/feart.2020.616594

Baudena A., Ser-Giacomi E., Jalón-Rojas I., Galgani F., and Pedrotti M. L. (2022). The streaming of plastic in the Mediterranean Sea. *Nature Communications, 13*(1), 2981. doi: 10.1038/s41467-022-30572-5

Belivermiş M., Kılıç Ö., and Çotuk Y. (2016). Assessment of metal concentrations in indigenous and caged mussels *(Mytilus galloprovincialis)* on entire Turkish coastline. *Chemosphere, 144*, 1980–1987. doi: 10.1016/j.chemosphere.2015.10.098

Belušić Vozila A., Güttler I., Ahrens B., Obermann-Hellhund A., and Telišman Prtenjak M. (2019). Wind Over the Adriatic Region in CORDEX Climate Change Scenarios. *Journal of Geophysical Research: Atmospheres, 124*(1), 110–130. doi: 10.1029/2018jd028552

Ben Rais Lasram F., Guilhaumon F., Albouy C., Somot S., Thuiller W., and Mouillot D. (2010). The Mediterranean Sea as a 'cul-de-sac' for endemic fishes facing climate change. *Global Change Biology, 16*(12), 3233–3245. doi: 10.1111/j.1365-2486.2010.02224.x

Benedicto J., Andral B., Martínez-Gómez C., Guitart C., Deudero S., Cento A., Scarpato A., Caixach J., Benbrahim S., Chouba L., Boulahdid M., and Galgani F. (2011). A large scale survey of trace metal levels in coastal waters of the Western Mediterranean basin using caged mussels (Mytilus galloprovincialis). *Journal of Environmental Monitoring, 13*(5). doi: 10.1039/c0em00725k

Besset M., Anthony E. J., and Sabatier F. (2017). River delta shoreline reworking and erosion in the Mediterranean and Black Seas: The potential roles of fluvial sediment starvation and other factors. *Elementa, 5*. doi: 10.1525/elementa.139/112409

Beusen A. H. W., Bouwman A. F., Beek L. P. H. Van, Mogollón J. M., and Middelburg J. J. (2016). Global riverine N and P transport to ocean increased during the 20th century despite increased retention along the aquatic continuum. *Biogeosciences, 13*(8). doi: 10.5194/bg-13-2441-2016

Bevacqua E., De Michele C., Manning C., Couasnon A., Ribeiro A. F. S., Ramos A. M., Vignotto E., Bastos A., Blesić S., Durante F., Hillier J., Oliveira S. C., Pinto J. G., Ragno E., Rivoire P., Saunders K., van der Wiel K., Wu W., Zhang T., and Zscheischler J. (2021). Guidelines for Studying Diverse Types of Compound Weather and Climate Events. *Earth's Future, 9*(11). doi: 10.1029/2021ef002340

Bevacqua E., Vousdoukas M. I., Zappa G., Hodges K., Shepherd T. G., Maraun D., Mentaschi L., and Feyen L. (2020). More meteorological events that drive compound coastal flooding are projected under climate change. *Communications Earth & Environment, 1*(1), 47. doi: 10.1038/s43247-020-00044-z

Bianchi C. N., Azzola A., Bertolino M., Betti F., Bo M., Cattaneo-Vietti R., Cocito S., Montefalcone M., Morri C., Oprandi A., Peirano A., and Bavestrello G. (2019). Consequences of the marine climate and ecosystem shift of the 1980-90s on the Ligurian Sea biodiversity (NW Mediterranean). *The European Zoological Journal, 86(1), 458*–487. doi: 10.1080/24750263.2019.1687765

Bianchi C. N., and Morri C. (2003). Global sea warming and "tropicalization" of the Mediterranean Sea: biogeographic and ecological aspects. Biogeographia – *The Journal of Integrative Biogeography, 24*(1). doi: 10.21426/b6110129

Bilbao J., Román R., and De Miguel A. (2019). Temporal and Spatial Variability in Surface Air Temperature and Diurnal Temperature Range in Spain over the Period 1950–2011. *Climate, 7*(1), 16. doi: 10.3390/cli7010016

Billen G., Silvestre M., Grizzetti B., Leip A., Garnier J., Voss M., Howarth R., Bouraoui F., Lepistö A., Kortelainen P., Johnes P., Curtis C., Humborg C., Smedberg E., Kaste Ø., Ganeshram R., Beusen A., and Lancelot C. (2011). Nitrogen flows from European regional watersheds to coastal marine waters. *The European Nitrogen Assessment,* 271–297. doi: 10.1017/CBO9780511976988.016

Boberg F., and Christensen J. H. (2012). Overestimation of Mediterranean summer temperature projections due to model deficiencies. *Nature Climate Change, 2*(6), 433–436. doi: 10.1038/nclimate1454

Boero F. (2013). Review of jellyfish blooms in the Mediterranean and Black Sea. In *United Nations Human Settlements Programme (UN-Habitat): Addis Ababa, Ethiopia. (2021).* FAO, Rome, Italy. https://openknowledge.fao.org/handle/20.500.14283/i3169e

Boero F., Bouillon J., Gravili C., Miglietta M., Parsons T., and Piraino S. (2008). Gelatinous plankton: irregularities rule the world (sometimes). *Marine Ecology Progress Series, 356*, 299–310. doi: 10.3354/meps07368

Boucher, J. & Bilard, G. (2020). *The Mediterranean: Mare plasticum.* Gland, Switzerland: IUCN. x+62 pp. https://portals.iucn.org/library/sites/library/files/documents/2020-030-En.pdf

Brotz L. (2011). *Changing jellyfish populations : trends in large marine ecosystems.* doi: 10.14288/1.0053266

Brotz L., Cheung W. W. L., Kleisner K., Pakhomov E., and Pauly D. (2012). Increasing jellyfish populations: trends in Large Marine Ecosystems. In J. Purcell, H. Mianzan, & J. R. Frost (Eds.), *Jellyfish Blooms IV* (pp. 3–20). Springer Netherlands. https://link.springer.com/10.1007/978-94-007-5316-7_2

Brotz L., and Pauly D. (2012). Jellyfish populations in the Mediterranean Sea. *Acta Adriatica, 53*(2), 213–232. https://acta.izor.hr/ojs/index.php/acta/article/view/322

Brumovský M., Bečanová J., Kohoutek J., Borghini M., and Nizzetto L. (2017). Contaminants of emerging concern in the open sea waters of the Western Mediterranean. *Environmental Pollution, 229*. doi: 10.1016/j.envpol.2017.07.082

Caiola N., and Sostoa A. (2005). Possible reasons for the decline of two native toothcarps in the Iberian Peninsula: evidence of competition with the introduced Eastern mosquitofish. *Journal of Applied Ichthyology, 21*(4), 358–363. doi: 10.1111/j.1439-0426.2005.00684.x

Calabrese A., Luciani P., and Perini L. (2021). *A review of impact of subsidence induced by gas exploitation on costal erosion in Emilia Romagna, Italy. 62*, 279–300. doi: 10.4430/bgta0356

Caloiero T., Caloiero P., and Frustaci F. (2018). Long-term precipitation trend analysis in Europe and in the Mediterranean basin. *Water and Environment Journal, 32*(3), 433–445. doi: 10.1111/wej.12346

Caloiero T., Veltri S., Caloiero P., and Frustaci F. (2018). Drought Analysis in Europe and in the Mediterranean Basin Using the Standardized Precipitation Index. *Water 2018, Vol. 10, Page 1043,* 10(8). doi: 10.3390/w10081043

Camerlenghi A., Urgeles R., and Fantoni L. (2010). A Database on Submarine Landslides of the Mediterranean Sea. In D. C. Mosher, R. C. Shipp, L. Moscardelli, J. D. Chaytor, C. D. P. Baxter, H. J. Lee, & R. Urgeles (Eds.), *Submarine Mass Movements and Their Consequences* (pp. 503–513). Springer Netherlands. http://link.springer.com/10.1007/978-90-481-3071-9_41

Camuffo D. (2021). Four centuries of documentary sources concerning the sea level rise in Venice. *Climatic Change, 167*(3–4), 54. doi: 10.1007/s10584-021-03196-9

Camuffo D. (2022a). A discussion on sea level rise, rate and acceleration. Venice as a case study. *Environmental Earth Sciences, 81*(13), 349. doi: 10.1007/s12665-022-10482-x

Camuffo D. (2022b). Historical Documents as Proxy Data in Venice and Its Marine Environment. *Oxford Research Encyclopedia of Climate Science*. doi: 10.1093/acrefore/9780190228620.013.875

Camuffo D. (2023). The Treatise on Waters by Cornaro (1560) and a quantitative assessment of the historical sea surges "Acqua Alta" in Venice. *Climatic Change, 176*(3), 18. doi: 10.1007/s10584-023-03492-6

Camuffo D., Bertolin C., and Schenal P. (2017). A novel proxy and the sea level rise in Venice, Italy, from 1350 to 2014. *Climatic Change, 143*(1–2), 73–86. doi: 10.1007/s10584-017-1991-3

Canepa A., Fuentes V., Sabatés A., Piraino S., Boero F., and Gili J.-M. (2014). Pelagia noctiluca in the Mediterranean Sea. In K. A. Pitt & C. H. Lucas (Eds.), *Jellyfish Blooms* (pp. 237–266). Springer, Dordrecht doi: 10.1007/978-94-007-7015-7_11

Carpenter A., and Kostianoy A. G. (2018). Oil Pollution in the Mediterranean Sea: Part I. The International Context. In A. Carpenter & A. G. Kostianoy (Eds.), *The Handbook of Environmental Chemistry* (Vol. 83). Springer Cham. doi: 10.1007/978-3-030-12236-2

Carpenter B. (2004). Feeling the sting. *U.S. News & World Report, 137*(5), 68–69. https://pubmed.ncbi.nlm.nih.gov/15352737/

Casas D., Ercilla G., Yenes M., Estrada F., Alonso B., García M., and Somoza L. (2011). The Baraza Slide: Model and dynamics. *Marine Geophysical Research, 32*(1), 245–256. doi: 10.1007/s11001-011-9132-2

Cavicchia L., von Storch H., and Gualdi S. (2014). Mediterranean Tropical-Like Cyclones in Present and Future Climate. *Journal of Climate, 27*(19), 7493–7501. doi: 10.1175/jcli-d-14-00339.1

Cazenave A., and Moreira L. (2022). Contemporary sea-level changes from global to local scales: A review. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 478*(2261). doi: 10.1098/rspa.2022.0049

CEAM (2019). *Mediterranean Sea Surface Temperature report (Spring 2019).* Meteorology and Pollutant Dynamics Area. Fundación CEAM. 2019. doi: 10.13140/rg.2.2.35354.08648

CEAM (2021). *Mediterranean Sea Surface Temperature report (Summer 2021).* Meteorology and Pollutant Dynamics Area. Fundación CEAM. doi: 10.13140/rg.2.2.27205.99048

Chacón L., Reyes L., Rivera-Montero L., and Barrantes K. (2022). Transport, fate, and bioavailability of emerging pollutants in soil, sediment, and wastewater treatment plants: Potential environmental impacts. *Emerging Contaminants in the Environment: Challenges and Sustainable Practices* (pp 111-136). doi: 10.1016/B978-0-323-85160-2.00020-2

Champagne P., Dorgham M. M., Liang S., Favreau G., and Shaaban N. A. (2021). Time series relationships between chlorophyll-a, physicochemical parameters, and nutrients in the Eastern Harbour of Alexandria, Egypt. *Environmental Monitoring and Assessment, 193*(12), 1–15. doi: 10.1007/s10661-021-09604-y

Chatzimentor A., Doxa A., Katsanevakis S., and Mazaris A. D. (2023). Are Mediterranean marine threatened species at high risk by climate change? *Global Change Biology, 29*(7). doi: 10.1111/gcb.16577

Cherif S., Doblas-Miranda E., Lionello P., Borrego C., Giorgi F., Iglesias A., Jebari S., Mahmoudi E., Moriondo M., Pringault O., Rilov G., Somot S., Tsikliras A., Vila M., and Zittis G. (2020). Drivers of change. In W. Cramer, J. Guiot, & K. Marini (Eds.), *Climate and Environmental Change in the Mediterranean Basin–Current Situation and Risks for the Future. First Mediterranean Assessment Report.* Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, pp. 59-180. doi: 10.5281/zenodo.7100601

Cheung W. W. L., Jones M. C., Reygondeau G., Stock C. A., Lam V. W. Y., and Frölicher T. L. (2016). Structural uncertainty in projecting global fisheries catches under climate change. *Ecological Modelling, 325,* 57–66. doi: 10.1016/j.ecolmodel.2015.12.018

Christodoulou A., Christidis P., and Demirel H. (2019). Sea-level rise in ports: a wider focus on impacts. *Maritime Economics & Logistics, 21*(4), 482–496. doi: 10.1057/s41278-018-0114-z

Christodoulou A., and Demirel H. (2018). Impacts of climate change on transport - A focus on airports, seaports and inland waterways. In *Publications Office of the European Union, Lubembourg.* doi: 10.2760/378464

CIESM (2011). Marine Geohazards in the Mediterranean: an overview. In F. Briand (Ed.), *Marine geohazards in the Mediterranean. N° 42 in CIESMWorkshop Monographs. CIESM, Monaco,* 192 pp. https://www.researchgate.net/publication/272164711_Marine_Geohazards_in_the_Mediterranean_an_overview

CLIA (2022). *State of the cruise industry. Outlook.* https://cruising.org/sites/default/files/2025-03/CLIA-State-Of-The-Cruise-Industry-2022_updated.pdf

Coll M., Piroddi C., Steenbeek J., Kaschner K., Ben Rais Lasram F., Aguzzi J., Ballesteros E., Bianchi C. N., Corbera J., Dailianis T., Danovaro R., Estrada M., Froglia C., Galil B. S., Gasol J. M., Gertwagen R., Gil J., Guilhaumon F., Kesner-Reyes K., … Voultsiadou E. (2010). The Biodiversity of the Mediterranean Sea: Estimates, Patterns, and Threats. *PLoS ONE, 5(8),* e11842. doi: 10.1371/journal.pone.0011842

Combi T., Pintado-Herrera M. G., Lara-Martín P. A., Lopes-Rocha M., Miserocchi S., Langone L., and Guerra R. (2020). Historical sedimentary deposition and flux of PAHs, PCBs and DDTs in sediment cores from the western Adriatic Sea. *Chemosphere, 241.* doi: 10.1016/j.chemosphere.2019.125029

Condon R. H., Duarte C. M., Pitt K. A., Robinson K. L., Lucas C. H., Sutherland K. R., Mianzan H. W., Bogeberg M., Purcell J. E., Decker M. B., Uye S., Madin L. P., Brodeur R. D., Haddock S. H. D., Malej A., Parry G. D., Eriksen E., Quiñones J., Acha M., … Graham W. M. (2013). Recurrent jellyfish blooms are a consequence of global oscillations. *Proceedings of the National Academy of Sciences, 110*(3), 1000–1005. doi: 10.1073/pnas.1210920110

Contini D., and Merico E. (2021). Recent advances in studying air quality and health effects of shipping emissions. *Atmosphere, 12*(1). doi: 10.3390/atmos12010092

Cooley, S., D. Schoeman, L. Bopp, P. Boyd, S. Donner, D.Y. Ghebrehiwet, S.-I. Ito, W. Kiessling, P. Martinetto, E. Ojea, M.-F. Racault, B. Rost, and M. Skern-Mauritzen, 2022: Oceans and Coastal Ecosystems and Their Services. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability.* Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 379–550. doi: 10.1017/9781009325844.005

Corrales X., Coll M., Ofir E., Heymans J. J., Steenbeek J., Goren M., Edelist D., and Gal G. (2018). Future scenarios of marine resources and ecosystem conditions in the Eastern Mediterranean under the impacts of fishing, alien species and sea warming. *Scientific Reports, 8*(1), 14284. doi: 10.1038/s41598-018-32666-x

Cos J., Doblas-Reyes F., Jury M., Marcos R., Bretonnière P. A., and Samsó M. (2022). The Mediterranean climate change hotspot in the CMIP5 and CMIP6 projections. *Earth System Dynamics, 13*(1), 321–340. doi: 10.5194/esd-13-321-2022

Cossa D., Knoery J., B-naru D., Harmelin-Vivien M., Sonke J. E., Hedgecock I. M., Bravo A. G., Rosati G., Canu D., Horvat M., Sprovieri F., Pirrone N., and Heimbürger-Boavida L. E. (2022). Mediterranean Mercury Assessment 2022: An Updated Budget, Health Consequences, and Research Perspectives. *Environmental Science and Technology, 56*(7). doi: 10.1021/acs.est.1c03044

Cózar A., Sanz-Martín M., Martí E., González-Gordillo J. I., Ubeda B., Gálvez J. Á., Irigoien X., and Duarte C. M. (2015). Plastic Accumulation in the Mediterranean Sea. *PLOS ONE, 10*(4), e0121762. doi: 10.1371/journal.pone.0121762

d'Acremont E., Lafuerza S., Rabaute A., Lafosse M., Jollivet Castelot M., Gorini C., Alonso B., Ercilla G., Vazquez J. T., Vandorpe T., Juan C., Migeon S., Ceramicola S., Lopez-Gonzalez N., Rodriguez M., El Moumni B., Benmarha O., and Ammar A. (2022). Distribution and origin of submarine landslides in the active margin of the southern Alboran Sea (Western Mediterranean Sea). *Marine Geology, 445*, 106739. doi: 10.1016/j.margeo.2022.106739

Dafka S., Toreti A., Zanis P., Xoplaki E., and Luterbacher J. (2019). Twenty-First-Century Changes in the Eastern Mediterranean Etesians and Associated Midlatitude Atmospheric Circulation. *Journal of Geophysical Research: Atmospheres, 124*(23), 12741–12754. doi: 10.1029/2019jd031203

D'Agostino R., and Lionello P. (2020). The atmospheric moisture budget in the Mediterranean: Mechanisms for seasonal changes in the Last Glacial Maximum and future warming scenario. Quaternary Science Reviews, 241, 106392. doi: 10.1016/j.quascirev.2020.106392

D'Agostino R., Lionello P., Adam O., and Schneider T. (2017). Factors controlling Hadley circulation changes from the Last Glacial Maximum to the end of the 21st century. *Geophysical Research Letters, 44*(16), 8585–8591. doi: 10.1002/2017gl074533

D'Agostino R., Scambiati A. L., Jungclaus J., and Lionello P. (2020). Poleward Shift of Northern Subtropics in Winter: Time of Emergence of Zonal Versus Regional Signals. *Geophysical Research Letters, 47*(19). doi: 10.1029/2020gl089325

Dakhlaoui H., Hakala K., and Seibert J. (2022). Hydrological Impacts of Projected Climate Change on Northern Tunisian Headwater Catchments—An Ensemble Approach Addressing Uncertainties. In W. Leal Filho & E. Manolas (Eds.), *Climate Change in the Mediterranean and Middle Eastern Region* (pp. 499–519). Springer International Publishing. doi: 10.1007/s10113-020-01615-8

Dakhlaoui H., Seibert J., and Hakala K. (2020). Sensitivity of discharge projections to potential evapotranspiration estimation in Northern Tunisia. *Regional Environmental Change, 20*(2), 34. doi: 10.1007/s10113-020-01615-8

Dalyan C., Yemişken E., and Eryilmaz L. (2012). A new record of gaper (Champsodon capensis Regan, 1908) in the Mediterranean Sea. *Journal of Applied Ichthyology, 28*(5), 834. doi: 10.1111/J.1439-0426.2012.02019.x

Darmaraki S., Somot S., Sevault F., and Nabat P. (2019a). Past Variability of Mediterranean Sea Marine Heatwaves. *Geophysical Research Letters, 46*(16), 9813–9823. doi: 10.1029/2019gl082933

Darmaraki S., Somot S., Sevault F., Nabat P., Cabos Narvaez W. D., Cavicchia L., Djurdjevic V., Li L., Sannino G., and Sein D. V. (2019b). Future evolution of Marine Heatwaves in the Mediterranean Sea. *Climate Dynamics, 53*(3–4), 1371–1392. doi: 10.1007/s00382-019-04661-z

De Leo F., Besio G., and Mentaschi L. (2021). Trends and variability of ocean waves under RCP8.5 emission scenario in the Mediterranean Sea. *Ocean Dynamics, 71*(1), 97–117. doi: 10.1007/s10236-020-01419-8

Dell'Aquila A., Mariotti A., Bastin S., Calmanti S., Cavicchia L., Deque M., Djurdjevic V., Dominguez M., Gaertner M., and Gualdi S. (2018). Evaluation of simulated decadal variations over the Euro-Mediterranean region from ENSEMBLES to Med-CORDEX. *Climate Dynamics, 51*(3), 857–876. doi: 10.1007/s00382-016-3143-2

Desbiolles F., Malleret L., Tiliacos C., Wong-Wah-Chung P., and Laffont-Schwob I. (2018). Occurrence and ecotoxicological assessment of pharmaceuticals: Is there a risk for the Mediterranean aquatic environment? *Science of the Total Environment, 639*. doi: 10.1016/j.scitotenv.2018.04.351

Di Leo A., Annicchiarico C., Cardellicchio N., Giandomenico S., Conversano M., Castellano G., Basile F., Martinelli W., Scortichini G., and Spada L. (2014). Monitoring of PCDD/Fs and dioxin-like PCBs and seasonal variations in mussels from the Mar Grande and the Mar Piccolo of Taranto (Ionian Sea, Southern Italy). *Environmental Science and Pollution Research, 21*(23). doi: 10.1007/s11356-014-2495-6

Di Paola G., Rizzo A., Benassai G., Corrado G., Matano F., and Aucelli P. P. C. (2021). Sea-level rise impact and future scenarios of inundation risk along the coastal plains in Campania (Italy). *Environmental Earth Sciences, 80*(17), 608. doi: 10.1007/s12665-021-09884-0

Dimitriadis C., Fournari-Konstantinidou I., Sourbès L., Koutsoubas D., and Katsanevakis S. (2021). Long Term Interactions of Native and Invasive Species in a Marine Protected Area Suggest Complex Cascading Effects Challenging Conservation Outcomes. *Diversity, 13*(2), 71. doi: 10.3390/d13020071

Distefano S., Baldassini N., Barbagallo V., Borzì L., D'Andrea N. M., Urso S., and Di Stefano A. (2022). 3D Flooding Maps as Response to Tsunami Events: Applications in the Central Sicilian Channel (Southern Italy). *Journal of Marine Science and Engineering 2022, Vol. 10, Page 1953, 10*(12), 1953. doi: 10.3390/jmse10121953

Dorgham M., El-Tohamy W., Qin J., Abdel-Aziz N., and Ghobashy A. (2019). Water quality assessment of the Nile Delta Coast, south eastern Mediterranean, Egypt. *Egyptian Journal of Aquatic Biology and Fisheries, 23*(3), 151–169. doi: 10.21608/ejabf.2019.45019

dos Santos M., Moncada S., Elia A., Grillakis M., and Hilmi N. (2020). Society: Development. In W. Cramer, J. Guiot, & K. Marini (Eds.), *Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future. First Mediterranean Assessment Report.* Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, pp. 469-492. doi: 10.5281/zenodo.7101111

Doussin J.-F. (2023). The Mediterranean Atmosphere Under Anthropogenic Pressures. In *Atmospheric Chemistry in the Mediterranean Region.* doi: 10.1007/978-3-031-12741-0_4

Downie A. T., Illing B., Faria A. M., and Rummer J. L. (2020). Swimming performance of marine fish larvae: review of a universal trait under ecological and environmental pressure. *Reviews in Fish Biology and Fisheries, 30*(1), 93–108. doi: 10.1007/s11160-019-09592-w

Drira Z., Kmiha-Megdiche S., Sahnoun H., Hammami A., Allouche N., Tedetti M., and Ayadi H. (2016). Assessment of anthropogenic inputs in the surface waters of the southern coastal area of Sfax during spring (Tunisia, Southern Mediterranean Sea). *Marine Pollution Bulletin, 104*(1–2). doi: 10.1016/j.marpolbul.2016.01.035

Droogers P., Immerzeel W. W., Terink W., Hoogeveen J., Bierkens M. F. P., Van Beek L. P. H., and Debele B. (2012). Water resources trends in Middle East and North Africa towards 2050. *Hydrology and Earth System Sciences, 16*(9), 3101–3114. doi: 10.5194/hess-16-3101-2012

Dubois C., Somot S., Calmanti S., Carillo A., Déqué M., Dell'Aquilla A., Elizalde A., Gualdi S., Jacob D., L'Hévéder B., Li L., Oddo P., Sannino G., Scoccimarro E., and Sevault F. (2012). Future projections of the surface heat and water budgets of the Mediterranean Sea in an ensemble of coupled atmosphere–ocean regional climate models. *Climate Dynamics, 39*(7–8), 1859–1884. doi: 10.1007/s00382-011-1261-4

Dulac F., Sauvage S., and Hamonou E. (2022). Atmospheric chemistry in the Mediterranean region. In *Atmospheric Chemistry in the Mediterranean Region (Vol. 2).* doi: 10.1007/978-3-030-82385-6

EC (2004). Part I—Major Findings and Policy Recommendations of the EUROSION Project. Living With Coastal Erosion in Europe: Sediment and Space for Sustainability. Official Publications of the European Communities, Luxembourg, 57. http://www.eurosion.org/reports-online/reports.html

EC (2006). *Commission Regulation (EC) No 1881/2006 of 19 December 2006 setting maximum levels for certain contaminants in foodstuffs.* Official Journal of the European Union, L 364, 5–24. https://eur-lex.europa.eu/eli/reg/2006/1881

EC: Directorate-General for Maritime Affairs and Fisheries, Addamo A. M., Calvo Santos A., Guillén J., and Guillén J., N. S. et al. (2022). *The EU blue economy report 2022.* Publications Office of the European Union. doi: 10.2771/793264

Edelist D., Rilov G., Golani D., Carlton J. T., and Spanier E. (2013). Restructuring the Sea: profound shifts in the world's most invaded marine ecosystem. *Diversity and Distributions, 19*(1), 69–77. doi: 10.1111/ddi.12002

EEA (2016). Dams on larger rivers in Europe, available at https://www.eea.europa.eu/data-and-maps/figures/dams-with-reservoirs-on-rivers

EEA (2021). Sources and emissions of air pollutants in Europe - European Environment Agency. European Environmental Agency. https://www.eea.europa.eu/publications/air-quality-in-europe-2021/sources-and-emissions-of-air

EEA (2022a). *Air quality in Europe 2022.* European Environmental Agency doi: 10.2800/488115

EEA (2022b). *Oxygen concentrations in coastal and marine waters surrounding Europe.* https://www.eea.europa.eu/ims/oxygen-concentrations-in-coastal-and

EEA-UNEP/MAP (2021). *Technical assessment of progress towards a cleaner Mediterranean Monitoring and reporting results for Horizon 2020 regional initiative.* Publications Office of the European Union. https://data.europa.eu/doi/10.2800/898759

Elguindi N., Somot S., Déqué M., and Ludwig W. (2011). Climate change evolution of the hydrological balance of the Mediterranean, Black and Caspian Seas: impact of climate model resolution. *Climate Dynamics, 36*(1–2), 205–228. doi: 10.1007/s00382-009-0715-4

EMSA (2021). *European Maritime Transport Environmental Report 2021.* Luxembourg: Publications Office of the European Union, 2019. https://www.emsa.europa.eu/emter-2021.html

Ezber Y. (2019). Assessment of the changes in the Etesians in the EURO-CORDEX regional model projections. *International Journal of Climatology, 39*(3), 1213–1229. doi: 10.1002/joc.5872

FAO (2016). Livestock contribution to food security in the Near East and North Africa. *FAO regional conference for the Near East, 33rd Session,* Beirut, Lebanon, 18-22 April 2016. https://openknowledge.fao.org/server/api/core/bitstreams/78b4f304-b687-4069-a5de-21f6c25d31ed/content

FAO (2023). Fisheries Glossary. In *Fisheries and Aquaculture.* [online] https://www.fao.org/fishery/en/collection/glossary_fisheries

FAO, IFAD, UNICEF, WFP, and WHO (2022). *The State of the World's Land and Water Resources for Food and Agriculture 2021 – Systems at breaking point. Main report.* Rome, FAO. doi: 10.4060/cb9910en

Fenoglio-Marc L., Mariotti A., Sannino G., Meyssignac B., Carillo A., Struglia M. V, and Rixen M. (2013). Decadal variability of net water flux at the Mediterranean Sea Gibraltar Strait. *Global and Planetary Change, 100*, 1–10. doi: 10.1016/j.gloplacha.2012.08.007

Fink L., Karl M., Matthias V., Oppo S., Kranenburg R., Kuenen J., Moldanova J., Jutterstrom S., Jalkanen J. P., and Majamaki E. (2023). Potential impact of shipping on air pollution in the Mediterranean region - A multimodel evaluation: Comparison of photooxidants NO_2 and O_3. *Atmospheric Chemistry and Physics, 23*(3). doi: 10.5194/acp-23-1825-2023

Flecha S., Pérez F. F., Murata A., Makaoui A., and Huertas I. E. (2019). Decadal acidification in Atlantic and Mediterranean water masses exchanging at the Strait of Gibraltar. *Scientific Reports, 9*(1), 15533. doi: 10.1038/s41598-019-52084-x

Fox-Kemper B., Hewitt H. T., Xiao C., Aðalgeirsdóttir G., Drijfhout S. S., Edwards T. L., Golledge N. R., Hemer M., Kopp R. E., Krinner G., Mix A., Notz D., Nowicki S., Nurhati I. S., Ruiz L., Sallée J.-B., Slangen A. B. A., and Yu Y. (2021). Ocean, cryosphere, and sea level change. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, Ö. Yelekçi, R. Yu, & B. Zhou (Eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1211–1362. doi: 10.1017/9781009157896.011

Friedrich W. L., Kromer B., Friedrich M., Heinemeier J., Pfeiffer T., and Talamo S. (2006). Santorini Eruption Radiocarbon Dated to 1627-1600 B.C. *Science, 312*(5773), 548. doi: 10.1126/science.1125087

Frihy O. E., and Stanley J.-D. (2023). The Modern Nile Delta Continental Shelf, with an Evolving Record of Relict Deposits Displaced and Altered by Sediment Dynamics. *Geographies, 3*(3), 416–445. doi: 10.3390/geographies3030022

Gaertner M. A., Jacob D., Gil V., Domínguez M., Padorno E., Sánchez E., and Castro M. (2007). Tropical cyclones over the Mediterranean Sea in climate change simulations. *Geophysical Research Letters, 34*(14), 14711. doi: 10.1029/2007gl029977

Galil B., Marchini A., Occhipinti-Ambrogi A., and Ojaveer H. (2017). The enlargement of the Suez Canal—Erythraean introductions and management challenges. *Management of Biological Invasions, 8*(2), 141–152. doi: 10.3391/mbi.2017.8.2.02

Ganora D., Dorati C., Huld T. A., Udias A., and Pistocchi A. (2019). An assessment of energy storage options for large-scale PV-RO desalination in the extended Mediterranean region. *Scientific Reports, 9*(1), 16234. doi: 10.1038/s41598-019-52582-y

García-Gómez J. C., Sempere-Valverde J., González A. R., Martínez-Chacón M., Olaya-Ponzone L., Sánchez-Moyano E., Ostalé-Valriberas E., and Megina C. (2020). From exotic to invasive in record time: The extreme impact of Rugulopteryx okamurae (Dictyotales, Ochrophyta) in the strait of Gibraltar. *Science of The Total Environment, 704*, 135408. doi: 10.1016/j.scitotenv.2019.135408

Georgiou G. K., Christoudias T., Proestos Y., Kushta J., Pikridas M., Sciare J., Savvides C., and Lelieveld J. (2022). Evaluation of WRF-Chem model (v3.9.1.1) real-Time air quality forecasts over the Eastern Mediterranean. *Geoscientific Model Development, 15*(10). doi: 10.5194/gmd-15-4129-2022

Glibert P. M. (2017). Eutrophication, harmful algae and biodiversity — Challenging paradigms in a world of complex nutrient changes. *Marine Pollution Bulletin, 124*(2). doi: 10.1016/j.marpolbul.2017.04.027

Golani D., Azzurro E., Dulčić J., Massutí E., and Orsi-Relini L. (2021). *Atlas of Exotic Fishes in the Mediterranean Sea* (F. Briand, Ed.). CIESM Publishers, Paris, Monaco.

Gollasch S., Hewitt C. L., Bailey S., and David M. (2019). Introductions and transfers of species by ballast water in the Adriatic Sea. *Marine Pollution Bulletin, 147*, 8–15. doi: 10.1016/j.marpolbul.2018.08.054

González-Alemán J. J., Pascale S., Gutierrez-Fernandez J., Murakami H., Gaertner M. A., and Vecchi G. A. (2019). Potential Increase in Hazard From Mediterranean Hurricane Activity With Global Warming. *Geophysical Research Letters, 46*(3), 1754–1764. doi: 10.1029/2018gl081253

González-Fernández D., Cózar A., Hanke G., Viejo J., Morales-Caselles C., Bakiu R., Barceló D., Bessa F., Bruge A., Cabrera M., Castro-Jiménez J., Constant M., Crosti R., Galletti Y., Kideys A. E., Machitadze N., Pereira de Brito J., Pogojeva M., Ratola N., ... Tourgeli M. (2021). Floating macrolitter leaked from Europe into the ocean. *Nature Sustainability, 4*(6). doi: 10.1038/s41893-021-00722-6

Goyet C., Hassoun A., Gemayel E., Touratier F., Abboud-Abi Saab M., and Guglielmi V. (2016). Thermodynamic Forecasts of the Mediterranean Sea Acidification. *Mediterranean Marine Science, 17*(2), 508. doi: 10.12681/mms.1487

Grillakis M. G. (2019). Increase in severe and extreme soil moisture droughts for Europe under climate change. *Science of The Total Environment, 660*, 1245–1255. doi: 10.1016/j.scitotenv.2019.01.001

Grise K. M., Davis S. M., Simpson I. R., Waugh D. W., Fu Q., Allen R. J., Rosenlof K. H., Ummenhofer C. C., Karnauskas K. B., Maycock A. C., Quan X.-W., Birner T., and Staten P. W. (2019). Recent Tropical Expansion: Natural Variability or Forced Response? *Journal of Climate, 32*(5), 1551–1571. doi: 10.1175/jcli-d-18-0444.1

Grosholz E. (2002). Ecological and evolutionary consequences of coastal invasions. In *Trends in Ecology and Evolution, 17*(1), 22-27. doi: 10.1016/S0169-5347(01)02358-8

Gudmundsson L., and Seneviratne S. I. (2016). Anthropogenic climate change affects meteorological drought risk in Europe. *Environmental Research Letters, 11*(4). doi: 10.1088/1748-9326/11/4/044005

Guidoboni E., Ferrari G., Mariotti D., Comastri A., Tarabusi G., Sgattoni G., and Valensise G. (2018). Historical earthquake data from the CFTI5Med catalogue [dataset publication series]. *PANGAEA*. doi: 10.1594/pangaea.896754

Guidoboni E., Ferrari G., Tarabusi G., Sgattoni G., Comastri A., Mariotti D., Ciuccarelli C., Bianchi M. G., and Valensise G. (2019). CFTI5Med, the new release of the catalogue of strong earthquakes in Italy and in the Mediterranean area. *Scientific Data, 6*(1), 80. doi: 10.1038/s41597-019-0091-9

Gutiérrez J. M., Jones R. G., G.T. Narisma G. T., Alves L. M., Amjad M., Gorodetskaya I. V., Grose M., Klutse N. A. B., Krakovska S., Li J., Martínez-Castro D., Mearns L. O., Mernild S. H., Ngo-Duc T., van den Hurk B., and Yoon J.-H. (2021). Atlas. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (Eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1927–2058. doi: 10.1017/9781009157896.021

Hallegraeff G. M. (2010). Ocean Climate Change, Phytoplankton Community Responses, and Harmful Algal Blooms: A Formidable Predictive Challenge. *Journal of Phycology, 46*(2), 220–235. doi: 10.1111/j.1529-8817.2010.00815.x

Hall-Spencer J. M., and Harvey B. P. (2019). Ocean acidification impacts on coastal ecosystem services due to habitat degradation. *Emerging Topics in Life Sciences, 3*(2), 197–206. doi: 10.1042/etls20180117

Hassoun A. E. R., Bantelman A., Canu D., Comeau S., Galdies C., Gattuso J.-P., Giani M., Grelaud M., Hendriks I. E., Ibello V., Idrissi M., Krasakopoulou E., Shaltout N., Solidoro C., Swarzenski P. W., and Ziveri P. (2022). Ocean acidification research in the Mediterranean Sea: Status, trends and next steps. *Frontiers in Marine Science, 9*. doi: 10.3389/fmars.2022.892670

Hertig E., and Tramblay Y. (2017). Regional downscaling of Mediterranean droughts under past and future climatic conditions. *Global and Planetary Change, 151*, 36–48. doi: 10.1016/j.gloplacha.2016.10.015

Hidalgo García D., Arco Díaz J., Martín Martín A., and Gómez Cobos E. (2022). Spatiotemporal Analysis of Urban Thermal Effects Caused by Heat Waves through Remote Sensing. *Sustainability, 14*(19), 12262. doi: 10.3390/su141912262

Hueging H., Haas R., Born K., Jacob D., and Pinto J. G. (2013). Regional Changes in Wind Energy Potential over Europe Using Regional Climate Model Ensemble Projections. *Journal of Applied Meteorology and Climatology, 52*(4), 903–917. doi: 10.1175/jamc-d-12-086.1

Iacarella J. C., Lyons D. A., Burke L., Davidson I. C., Therriault T. W., Dunham A., and DiBacco C. (2020). Climate change and vessel traffic create networks of invasion in marine protected areas. *Journal of Applied Ecology, 57*(9), 1793–1805. doi: 10.1111/1365-2664.13652

Ibáñez C., and Peñuelas J. (2019). Changing nutrients, changing rivers. *Science, 365*(6454), 637–638. doi: 10.1126/science.aay2723

Ibrahim O., Mohamed B., and Nagy H. (2021). Spatial Variability and Trends of Marine Heat Waves in the Eastern Mediterranean Sea over 39 Years. *Journal of Marine Science and Engineering, 9*(6), 643. doi: 10.3390/jmse9060643

IPBES (2019). *Global assessment report on biodiversity and ecosystem services* (E. S. Brondizio, J. Settele, S. Díaz, & H. T. Ngo, Eds.). IPBES secretariat, Bonn, Germany. 1148 pages. doi: 10.5281/zenodo.3831673

IPCC (2021a). Annex VII: Glossary [Matthews, J.B.R., V. Möller, R. van Diemen, J.S. Fuglestvedt, V. Masson-Delmotte, C. Méndez, S. Semenov, A. Reisinger (eds.)]. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & and B. Zhou (Eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 2215–2256. doi: 10.1017/9781009157896.022

IPCC (2021b). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou, Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. doi: 10.1017/9781009157896

IPCC (2022). *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, & B. Rama, Eds.). Cambridge University Press. Cambridge, UK and New York, NY, USA, 3056 pp. doi: 10.1017/9781009325844

IPCC (2023). *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Core Writing Team, H. Lee, & J. Romero, Eds.). IPCC, Geneva, Switzerland, pp. 35-115. doi: 10.59327/IPCC/AR6-9789291691647

Jones M. C., and Cheung W. W. L. (2015). Multi-model ensemble projections of climate change effects on global marine biodiversity. *ICES Journal of Marine Science*, *72*(3), 741–752. doi: 10.1093/icesjms/fsu172

Justić D., Rabalais N. N., Turner R. E., and Dortch Q. (1995). Changes in nutrient structure of river-dominated coastal waters: Stoichiometric nutrient balance and its consequences. *Estuarine, Coastal and Shelf Science*, *40*(3). doi: 10.1016/S0272-7714(05)80014-9

Kanakidou M., Myriokefalitakis S., and Tsagkaraki M. (2020). Atmospheric inputs of nutrients to the Mediterranean Sea. *Deep Sea Research Part II: Topical Studies in Oceanography*, *171*, 104606. doi: 10.1016/j.dsr2.2019.06.014

Kaniewski D., Marriner N., Cheddadi R., Morhange C., Vacchi M., Rovere A., Faivre S., Otto T., Luce F., Carre M. B., Benčić G., and Van Campo E. (2021). Coastal submersions in the north-eastern Adriatic during the last 5200 years. *Global and Planetary Change*, *204*. doi: 10.1016/j.gloplacha.2021.103570

Kaniewski D., Marriner N., Vacchi M., Camuffo D., Bivolaru A., Sarti G., Bertoni D., Diatta L., Markakis N., Martella A., Otto T., Luce F., Calaon D., Cottica D., and Morhange C. (2024). Holocene Sea-level impacts on Venice Lagoon's coastal wetlands. *Global and Planetary Change*, *236*. doi: 10.1016/j.gloplacha.2024.104426

Kapsenberg L., Alliouane S., Gazeau F., Mousseau L., and Gattuso J.-P. (2017). Coastal ocean acidification and increasing total alkalinity in the northwestern Mediterranean Sea. *Ocean Science*, *13*(3), 411–426. doi: 10.5194/os-13-411-2017

Karydis M., and Kitsiou D. (2012). Eutrophication and environmental policy in the Mediterranean Sea: a review. *Environmental Monitoring and Assessment*, *184*(8), 4931–4984. doi: 10.1007/s10661-011-2313-2

Kasimati E., and Asero V. (2021). Cruise Tourism, Gender and Sustainability. In M. Valeri & V. Katsoni (Eds.), Gender and Tourism (pp. 37–53). Emerald Publishing Limited. doi: 10.1108/978-1-80117-322-320211003

Kateb A. El, Stalder C., Rüggeberg A., Neururer C., Spangenberg J. E., and Spezzaferri S. (2018). Impact of industrial phosphate waste discharge on the marine environment in the Gulf of Gabes (Tunisia). *PLOS ONE*, *13*(5), e0197731. doi: 10.1371/journal.pone.0197731

Kılıç S., Kılıç, Belivermiş M., and Ergül H. A. (2023). Chronology of PAH and PCB pollution using sediment core in the Golden Horn estuary (Sea of Marmara). *Marine Pollution Bulletin*, *187*. doi: 10.1016/j.marpolbul.2023.114570

Köck-Schulmeyer M., Ginebreda A., Petrovic M., Giulivo M., Aznar-Alemany Ò., Eljarrat E., Valle-Sistac J., Molins-Delgado D., Diaz-Cruz M. S., Monllor-Alcaraz L. S., Guillem-Argiles N., Martínez E., Miren L. de A., Llorca M., Farré M., Peña J. M., Mandaric L., Pérez S., Majone B., … Barceló D. (2021). Priority and emerging organic microcontaminants in three Mediterranean river basins: Occurrence, spatial distribution, and identification of river basin specific pollutants. *Science of the Total Environment*, *754*. doi: 10.1016/j.scitotenv.2020.142344

Kopp H., Chiocci F. L., Berndt C., Çağatay M. N., Ferreira T., Fortes C. J. E. M., Gràcia E., González Vega A., Kopf A. J., Sørensen M. B., Sultan N., and Yeo I. A. (2021). *Marine geohazards: Safeguarding society and the Blue Economy from a hidden threat* (A. Muñiz Piniella, P. Kellett, R. van den Brand, B. Alexander, A. Rodríguez Perez, J. Van Elslander, & J. J. Heymans, Eds.). Position Paper 26 of the European Marine Board, Ostend, Belgium. 100 pages. doi: 10.5281/zenodo.5591938

Lambert C., Authier M., Dorémus G., Laran S., Panigada S., Spitz J., Van Canneyt O., and Ridoux V. (2020). Setting the scene for Mediterranean litterscape management: The first basin-scale quantification and mapping of floating marine debris. *Environmental Pollution*, *263*. doi: 10.1016/j.envpol.2020.114430

Lassaletta L., Sanz-Cobena A., Aguilera E., Quemada M., Billen G., Bondeau A., Cayuela M. L., Cramer W., Eekhout J. P. C., Garnier J., Grizzetti B., Intrigliolo D. S., Ramos M. R., Romero E., Vallejo A., and Gimeno B. S. (2021). Nitrogen dynamics in cropping systems under Mediterranean climate: a systemic analysis. *Environmental Research Letters*, *16*(7), 073002. doi: 10.1088/1748-9326/ac002c

Lehner F., Coats S., Stocker T. F., Pendergrass A. G., Sanderson B. M., Raible C. C., and Smerdon J. E. (2017). Projected drought risk in 1.5°C and 2°C warmer climates. *Geophysical Research Letters*, *44*(14), 7419–7428. doi: 10.1002/2017gl074117

Lejeusne C., Chevaldonné P., Pergent-Martini C., Boudouresque C. F., and Pérez T. (2010). Climate change effects on a miniature ocean: the highly diverse, highly impacted Mediterranean Sea. *Trends in Ecology & Evolution*, *25*(4), 250–260. doi:10.1016/j.tree.2009.10.009

Lelieveld J., Berresheim H., Borrmann S., Crutzen P. J., Dentener F. J., Fischer H., Feichter J., Flatau P. J., Heland J., Holzinger R., Korrmann R., Lawrence M. G., Levin Z., Markowicz K. M., Mihalopoulos N., Minikin A., Ramanathan V., De Reus M., Roelofs G. J., … Ziereis H. (2002). Global air pollution crossroads over the Mediterranean. *Science*, *298*(5594). doi: 10.1126/science.1075457

Lelieveld J., Proestos Y., Hadjinicolaou P., Tanarhte M., Tyrlis E., and Zittis G. (2016). Strongly increasing heat extremes in the Middle East and North Africa (MENA) in the 21st century. *Climatic Change*, *137*(1–2), 245–260. doi: 10.1007/s10584-016-1665-6

Li W. C. (2014). Occurrence, sources, and fate of pharmaceuticals in aquatic environment and soil. *Environmental Pollution*, *187*, 193–201. doi: 10.1016/j.envpol.2014.01.015

Liaropoulos A., Sapountzaki K., and Nivolianitou Z. (2019). Adopting risk governance in the offshore oil industry and in diverse cultural and geopolitical context: North Sea vs Eastern Mediterranean countries. *Safety Science*, *120*, 471–483. doi: 10.1016/j.ssci.2019.07.032

Ligorini V., Malet N., Garrido M., Derolez V., Amand M., Bec B., Cecchi P., and Pasqualini V. (2022). Phytoplankton dynamics and bloom events in oligotrophic Mediterranean lagoons: seasonal patterns but hazardous trends. *Hydrobiologia*, *849*(10), 2353–2375. doi: 10.1007/s10750-022-04874-0

Lionello P., Barriopedro D., Ferrarin C., Nicholls R. J., Orlić M., Raicich F., Reale M., Umgiesser G., Vousdoukas M., and Zanchettin D. (2021). Extreme floods of Venice: characteristics, dynamics, past and future evolution (review article). *Natural Hazards and Earth System Sciences*, *21*(8), 2705–2731. doi: 10.5194/nhess-21-2705-2021

Lionello P., Conte D., Marzo L., and Scarascia L. (2017). The contrasting effect of increasing mean sea level and decreasing storminess on the maximum water level during storms along the coast of the Mediterranean Sea in the mid 21st century. *Global and Planetary Change*, *151*, 80–91. doi: 10.1016/j.gloplacha.2016.06.012

Lionello P., Conte D., and Reale M. (2019). The effect of cyclones crossing the Mediterranean region on sea level anomalies on the Mediterranean Sea coast. *Natural Hazards and Earth System Sciences*, *19*(7), 1541–1564. doi: 10.5194/nhess-19-1541-2019

Lionello P., and Scarascia L. (2018). The relation between climate change in the Mediterranean region and global warming. *Regional Environmental Change*, *18*(5), 1481–1493. doi: 10.1007/s10113-018-1290-1

Lionello P., and Scarascia L. (2020). The relation of climate extremes with global warming in the Mediterranean region and its north versus south contrast. *Regional Environmental Change*, *20*(1), 31. doi: 10.1007/s10113-020-01610-z

Lipizer M., Berto D., Cermelj B., Fafandjel M., Formalewicz M., Hatzianestis I., Ilijanić N., Kaberi H., Kralj M., Matijevic S., Molina Jack M. E., Parinos C., Tronczynski J., and Giani M. (2022). Trace metals and polycyclic aromatic hydrocarbons in the Eastern Mediterranean sediments: Concentration ranges as a tool for quality control of large data collections. *Marine Pollution Bulletin*, *185*. doi: 10.1016/j.marpolbul.2022.114181

Lira-Loarca A., and Besio G. (2022). Future changes and seasonal variability of the directional wave spectra in the Mediterranean Sea for the 21st century. *Environmental Research Letters*, *17*(10), 104015. doi: 10.1088/1748-9326/ac8ec4

Liubartseva S., Coppini G., Lecci R., and Clementi E. (2018). Tracking plastics in the Mediterranean: 2D Lagrangian model. *Marine Pollution Bulletin*, *129*(1). doi: 10.1016/j.marpolbul.2018.02.019

López-Olmedilla L., Almeida L. P., de Figueiredo S. A., Fontán-Bouzas Á., Silva P. A., and Alcántara-Carrió J. (2022). Effect of alongshore sediment supply gradients on projected shoreline position under sea-level rise (northwestern Portuguese coast). *Estuarine, Coastal and Shelf Science*, *271*, 107876. doi: 10.1016/j.ecss.2022.107876

Loupasakis C. (2020). An overview of the land subsidence phenomena occurring in Greece, triggered by the overexploitation of the aquifers for irrigation and mining purposes. *Proceedings of the International Association of Hydrological Sciences*, *382*, 321–326. doi: 10.5194/piahs-382-321-2020

Ludwig W., Bouwman A. F., Dumont E., and Lespinas F. (2010). Water and nutrient fluxes from major Mediterranean and Black Sea rivers: Past and future trends and their implications for the basin-scale budgets. *Global Biogeochemical Cycles*, *24*(4). doi: 10.1029/2009gb003594

Lutz S. R., Mallucci S., Diamantini E., Majone B., Bellin A., and Merz R. (2016). Hydroclimatic and water quality trends across three Mediterranean river basins. *Science of The Total Environment*, *571*, 1392–1406. doi: 10.1016/j.scitotenv.2016.07.102

Maccioni A., Canopoli L., Cubeddu V., Cucca E., Dessena S., Morittu S., Filigheddu R., Padedda B. M., and Farris E. (2021). Gradients of salinity and plant community richness and diversity in two different Mediterranean coastal ecosystems in NW Sardinia. *Biodiversity Data Journal*, *9*, e71247. doi: 10.3897/bdj.9.e71247

Makris C. V., Tolika K., Baltikas V. N., Velikou K., and Krestenitis Y. N. (2023). The impact of climate change on the storm surges of the Mediterranean Sea: Coastal sea level responses to deep depression atmospheric systems. *Ocean Modelling*, *181*, 102149. doi: 10.1016/j.ocemod.2022.102149

Malagó A., Bouraoui F., Grizzetti B., and De Roo A. (2019). Modelling nutrient fluxes into the Mediterranean Sea. *Journal of Hydrology: Regional Studies*, *22*, 100592. doi: 10.1016/j.ejrh.2019.01.004

Mandour A., El-Sayed M. K., El-Gamal A. A., Khadr A. M., and Elshazly A. (2021). Temporal distribution of trace metals pollution load index in the Nile Delta coastal surface sediments. *Marine Pollution Bulletin*, *167*. doi: 10.1016/j.marpolbul.2021.112290

Mannino A. M., Balistreri P., and Deidun A. (2017). The Marine Biodiversity of the Mediterranean Sea in a Changing Climate: The Impact of Biological Invasions. In *Mediterranean Identities - Environment, Society, Culture*. InTech. doi: 10.5772/intechopen.69214

Marchane A., Tramblay Y., Hanich L., Ruelland D., and Jarlan L. (2017). Climate change impacts on surface water resources in the Rheraya catchment (High Atlas, Morocco). *Hydrological Sciences Journal*, *62*(6), 979–995. doi: 10.1080/02626667.2017.1283042

Marcos M., Tsimplis M. N., and Shaw A. G. P. (2009). Sea level extremes in southern Europe. *Journal of Geophysical Research*, *114*(C1), C01007. doi: 10.1029/2008jc004912

Marcos M., and Woodworth P. L. (2017). Spatiotemporal changes in extreme sea levels along the coasts of the North Atlantic and the Gulf of Mexico. *Journal of Geophysical Research: Oceans*, *122*(9), 7031–7048. doi: 10.1002/2017jc013065

Mariotti A., Pan Y., Zeng N., and Alessandri A. (2015). Long-term climate change in the Mediterranean region in the midst of decadal variability. *Climate Dynamics*, *44*, 1437–1456. doi: 10.1007/s00382-015-2487-3

Marriner N., Morhange C., Flaux C., and Carayon N. (2017). Harbors and Ports, Ancient. In A. S. Gilbert (Ed.), *Encyclopedia of Geoarchaeology* (pp. 382–403). Springer Netherlands. doi: 10.1007/978-1-4020-4409-0_119

Marsili L., Jiménez B., and Borrell A. (2018). Persistent Organic Pollutants in Cetaceans Living in a Hotspot Area: The Mediterranean Sea. In *Marine Mammal Ecotoxicology: Impacts of Multiple Stressors on Population Health*. doi: 10.1016/b978-0-12-812144-3.00007-3

Marx A., Kumar R., Thober S., Rakovec O., Wanders N., Zink M., Wood E. F., Pan M., Sheffield J., and Samaniego L. (2018). Climate change alters low flows in Europe under global warming of 1.5, 2, and 3 °C. *Hydrology and Earth System Sciences*, *22*(2), 1017–1032. doi: 10.5194/hess-22-1017-2018

MedECC (2020). *Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future. First Mediterranean Assessment Report* (W. Cramer, J. Guiot, & K. Marini, Eds.). Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, 632 pp. doi: 10.5281/zenodo.4768833

Menendez M., García-Díez M., Fita L., Fernández J., Méndez F. J., and Gutiérrez J. M. (2014). High-resolution sea wind hindcasts over the Mediterranean area. *Climate Dynamics*, *42*(7–8), 1857–1872. doi: 10.1007/s00382-013-1912-8

Menéndez M., and Woodworth P. L. (2010). Changes in extreme high water levels based on a quasi-global tide-gauge data set. *Journal of Geophysical Research: Oceans*, *115*(C10), 2009JC005997. doi: 10.1029/2009jc005997

Merhaby D., Rabodonirina S., Net S., Ouddane B., and Halwani J. (2019). Overview of sediments pollution by PAHs and PCBs in mediterranean basin: Transport, fate, occurrence, and distribution. *Marine Pollution Bulletin*, *149*. doi: 10.1016/j.marpolbul.2019.110646

Miglietta. (2019). Mediterranean Tropical-Like Cyclones (Medicanes). *Atmosphere*, *10*(4), 206. doi: 10.3390/atmos10040206

Milano M., Ruelland D., Fernandez S., Dezetter A., Fabre J., Servat E., Fritsch J.-M., Ardoin-Bardin S., and Thivet G. (2013). Current state of Mediterranean water resources and future trends under climatic and anthropogenic changes. *Hydrological Sciences Journal*, *58*(3), 498–518. doi: 10.1080/02626667.2013.774458

Miralles D. G., Van Den Berg M. J., Gash J. H., Parinussa R. M., De Jeu R. A. M., Beck H. E., Holmes T. R. H., Jiménez C., Verhoest N. E. C., Dorigo W. A., Teuling A. J., and Johannes Dolman A. (2014). El Niño–La Niña cycle and recent trends in continental evaporation. *Nature Climate Change*, *4*(2), 122–126. doi: 10.1038/nclimate2068

Moemken J., Reyers M., Feldmann H., and Pinto J. G. (2018). Future Changes of Wind Speed and Wind Energy Potentials in EURO-CORDEX Ensemble Simulations. *Journal of Geophysical Research: Atmospheres*, *123*(12), 6373–6389. doi: 10.1029/2018jd028473

Molinero J. C., Casini M., and Buecher E. (2008). The influence of the Atlantic and regional climate variability on the long-term changes in gelatinous carnivore populations in the northwestern Mediterranean. *Limnology and Oceanography*, *53*(4), 1456–1467. doi: 10.4319/lo.2008.53.4.1456

Molinié G., Déqué M., Coppola E., Blanchet J., and Neppel L. (2016). Sub-chapter 1.3.1. Heavy precipitation in the Mediterranean basin. In *The Mediterranean region under climate change* (pp. 107–114). IRD Éditions. doi: 10.4000/books.irdeditions.23121

Molnar J. L., Gamboa R. L., Revenga C., and Spalding M. D. (2008). Assessing the global threat of invasive species to marine biodiversity. *Frontiers in Ecology and the Environment*, *6*(9), 485–492. doi: 10.1890/070064

Monserrat S., Ibbetson A., and Thorpe A. (1991). Atmospheric gravity waves and the "Rissaga" phenomenon. *Quarterly Journal of the Royal Meteorological Society*, *117*(499), 553–570. doi: 10.1002/qj.49711749907

Monserrat S., Vilibić I., and Rabinovich A. B. (2006). Meteotsunamis: atmospherically induced destructive ocean waves in the tsunami frequency band. *Natural Hazards and Earth System Sciences*, *6*(6), 1035–1051. doi: 10.5194/nhess-6-1035-2006

Moore C. M., Mills M. M., Arrigo K. R., Berman-Frank I., Bopp L., Boyd P. W., Galbraith E. D., Geider R. J., Guieu C., Jaccard S. L., Jickells T. D., La Roche J., Lenton T. M., Mahowald N. M., Marañón E., Marinov I., Moore J. K., Nakatsuka T., Oschlies A., ... Ulloa O. (2013). Processes and patterns of oceanic nutrient limitation. *Nature Geoscience*, *6*(9), 701–710. doi: 10.1038/ngeo1765

Morabito E., Radaelli M., Corami F., Turetta C., Toscano G., and Capodaglio G. (2018). Temporal evolution of cadmium, copper and lead concentration in the Venice Lagoon water in relation with the speciation and dissolved/particulate partition. *Marine Pollution Bulletin*, *129*(2). doi: 10.1016/j.marpolbul.2017.10.043

Morsy K. M., Mishra A. K., and Galal M. M. (2020). Water Quality Assessment of the Nile Delta Lagoons. *Air, Soil and Water Research*, *13*. doi: 10.1177/1178622120963072

Mourtzas N., Kolaiti E., and Anzidei M. (2015). Vertical land movements and sea level changes along the coast of Crete (Greece) since Late Holocene. *Quaternary International*, 1–28. doi: 10.1016/j.quaint.2015.08.008

Naidja L., Ali-Khodja H., and Khardi S. (2018). Sources and levels of particulate matter in North African and Sub-Saharan cities: a literature review. *Environmental Science and Pollution Research*, *25*(13). doi: 10.1007/s11356-018-1715-x

Navarro-Pedreño J., Gómez Lucas I., Almendro-Candel M., and Melendez-Pastor I. (2008). Heavy metals in Mediterranean soils. *Soil Contamination Research Trends* (pp.161-176). Nova Science Publishers Inc. https://www.researchgate.net/publication/235935560_Heavy_metals_in_Mediterranean_soils

Neumann B., Vafeidis A. T., Zimmermann J., and Nicholls R. J. (2015). Future coastal population growth and exposure to sea-level rise and coastal flooding - A global assessment. *PLoS ONE*, *10*(3). doi: 10.1371/journal.pone.0118571

Nicholls R. J., Lincke D., Hinkel J., Brown S., Vafeidis A. T., Meyssignac B., Hanson S. E., Merkens J.-L., and Fang J. (2021). A global analysis of subsidence, relative sea-level change and coastal flood exposure. *Nature Climate Change*, *11*(4), 338–342. doi: 10.1038/s41558-021-00993-z

Obermann-Hellhund A., Conte D., Somot S., Torma C. Z., and Ahrens B. (2018). Mistral and Tramontane wind systems in climate simulations from 1950 to 2100. *Climate Dynamics*, *50*(1–2), 693–703. doi: 10.1007/s00382-017-3635-8

Occhipinti-Ambrogi A., and Galil B. (2010). Marine alien species as an aspect of global change. *Advances in Oceanography and Limnology*, *1*(1), 199–218. doi: 10.1080/19475721003743876

Oliver E. C. J., Donat M. G., Burrows M. T., Moore P. J., Smale D. A., Alexander L. V, Benthuysen J. A., Feng M., Sen Gupta A., Hobday A. J., Holbrook N. J., Perkins-Kirkpatrick S. E., Scannell H. A., Straub S. C., and Wernberg T. (2018). Longer and more frequent marine heatwaves over the past century. *Nature Communications*, *9*(1), 1324. doi: 10.1038/s41467-018-03732-9

Oppenheimer M., Glavovic B.C., Hinkel J., van de Wal R., Magnan A.K., Abd-Elgawad A., Cai R., Cifuentes-Jara M., DeConto R.M., Ghosh T., Hay J., Isla F., Marzeion B., Meyssignac B., and Sebesvari Z. (2019). Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, & N. M. Weyer (Eds.), *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 321–445. doi: 10.1017/9781009157964.006

Ouda M., Kadadou D., Swaidan B., Al-Othman A., Al-Asheh S., Banat F., and Hasan S. W. (2021). Emerging contaminants in the water bodies of the Middle East and North Africa (MENA): A critical review. *Science of the Total Environment*, *754*. doi: 10.1016/j.scitotenv.2020.142177

Pagán J. I., López M., López I., Tenza-Abril A. J., and Aragonés L. (2018). Causes of the different behaviour of the shoreline on beaches with similar characteristics. Study case of the San Juan and Guardamar del Segura beaches, Spain. *Science of The Total Environment*, *634*, 739–748. doi: 10.1016/j.scitotenv.2018.04.037

Paiano A., Crovella T., and Lagioia G. (2020). Managing sustainable practices in cruise tourism: the assessment of carbon footprint and waste of water and beverage packaging. *Tourism Management*, *77*, 104016. doi: 10.1016/j.tourman.2019.104016

Palmiéri J., Orr J. C., Dutay J.-C., Béranger K., Schneider A., Beuvier J., and Somot S. (2015). Simulated anthropogenic CO_2 storage and acidification of the Mediterranean Sea. *Biogeosciences*, *12*(3), 781–802. doi: 10.5194/bg-12-781-2015

Papazachos B. C., Koutitas Ch., Hatzidimitriou P. M., Karacostas B. G., and Papaioannou Ch. A. (1985). Source and short-distance propagation of the July 9, 1956 southern Aegean tsunami. *Marine Geology*, *65*(3–4), 343–351. doi: 10.1016/0025-3227(85)90064-7

Pastor F., Valiente J. A., and Khodayar S. (2020). A Warming Mediterranean: 38 Years of Increasing Sea Surface Temperature. *Remote Sensing*, *12*(17), 2687. doi: 10.3390/rs12172687

Patlakas P., Stathopoulos C., Tsalis C., and Kallos G. (2021). Wind and wave extremes associated with tropical-like cyclones in the Mediterranean basin. *International Journal of Climatology*, *41*(S1). doi: 10.1002/joc.6795

Pedrotti M. L., Lombard F., Baudena A., Galgani F., Elineau A., Petit S., Henry M., Troublé R., Reverdin G., Ser-Giacomi E., Kedzierski M., Boss E., and Gorsky G. (2022). An integrative assessment of the plastic debris load in the Mediterranean Sea. *Science of The Total Environment*, *838*, 155958. doi: 10.1016/j.scitotenv.2022.155958

Peña-Angulo D., Vicente-Serrano S. M., Domínguez-Castro F., Murphy C., Reig F., Tramblay Y., Trigo R. M., Luna M. Y., Turco M., Noguera I., Aznárez-Balta M., García-Herrera R., Tomas-Burguera M., and El Kenawy A. (2020). Long-term precipitation in Southwestern Europe reveals no clear trend attributable to anthropogenic forcing. *Environmental Research Letters*, *15*(9), 094070. doi: 10.1088/1748-9326/ab9c4f

Perennou C., Gaget E., Galewski T., Geijzendorffer I., and Guelmami A. (2020). Evolution of wetlands in Mediterranean region. In *Water Resources in the Mediterranean Region*. doi: 10.1016/b978-0-12-818086-0.00011-x

Pérez Gómez B., Vilibić I., Šepić J., Međugorac I., Ličer M., Testut L., Fraboul C., Marcos M., Abdellaoui H., Álvarez Fanjul E., Barbalić D., Casas B., Castaño-Tierno A., Čupić S., Drago A., Fraile M. A., Galliano D. A., Gauci A., Gloginja B., … Zodiatis G. (2022). Coastal sea level monitoring in the Mediterranean and Black seas. *Ocean Science*, *18*(4), 997–1053. doi: 10.5194/os-18-997-2022

Perrings C., Williamson M., Barbier E. B., Delfino D., Dalmazzone S., Shogren J., Simmons P., and Watkinson A. (2002). Biological invasion risks and the public good: An economic perspective. *Ecology and Society*, *6*(1). doi: 10.5751/es-00396-060101

Perrone M. R., Paladini F., Becagli S., Amore A., and Romano S. (2022). Daytime and nighttime chemical and optical properties of fine and coarse particles at a central Mediterranean coastal site. *Environmental Science and Pollution Research*, *29*(28). doi: 10.1007/s11356-021-18173-z

Piante C., Ody D.,2015. Blue Growth in the Mediterranean Sea: the Challenge of Good Environmental Status. *MedTrends Project*. WWF-France. 192 pages.

Pisano A., Marullo S., Artale V., Falcini F., Yang C., Leonelli F. E., Santoleri R., and Buongiorno Nardelli B. (2020). New Evidence of Mediterranean Climate Change and Variability from Sea Surface Temperature Observations. *Remote Sensing*, *12*(1), 132. doi: 10.3390/rs12010132

Pistocchi A., Bleninger T., Breyer C., Caldera U., Dorati C., Ganora D., Millán M. M., Paton C., Poullis D., Herrero F. S., Sapiano M., Semiat R., Sommariva C., Yuece S., and Zaragoza G. (2020a). Can seawater desalination be a win-win fix to our water cycle? *Water Research*, *182*, 115906. doi: 10.1016/j.watres.2020.115906

Pistocchi A., Bleninger T., and Dorati C. (2020b). Screening the hurdles to sea disposal of desalination brine around the Mediterranean. *Desalination*, *491*, 114570. doi: 10.1016/j.desal.2020.114570

Plan Bleu (2022). *State of Play of Tourism in the Mediterranean*. Interreg Med Sustainable Tourism Community project. https://planbleu.org/en/publications/state-of-play-of-tourism-in-the-mediterranean/

Planton S., Lionello P., Artale V., Aznar R., Carrillo A., Colin J., Congedi L., Dubois C., Elizalde A., Gualdi S., Hertig E., Jacobeit J., Jordà G., Li L., Mariotti A., Piani C., Ruti P., Sanchez-Gomez E., Sannino G., … Tsimplis M. (2012). The Climate of the Mediterranean Region in Future Climate Projections. In *The Climate of the Mediterranean Region* (pp. 449–502). Elsevier. doi: 10.1016/B978-0-12-416042-2.00008-2

Polinov S., Bookman R., and Levin N. (2021). Spatial and temporal assessment of oil spills in the Mediterranean Sea. *Marine Pollution Bulletin*, *167*. doi: 10.1016/j.marpolbul.2021.112338

Poulos S. E., and Collins M. B. (2002). Fluviatile sediment fluxes to the Mediterranean Sea: a quantitative approach and the influence of dams. *Geological Society, London, Special Publications*, *191*(1), 227–245. doi: 10.1144/gsl.sp.2002.191.01.16

Powley H. R., Dürr H. H., Lima A. T., Krom M. D., and Van Cappellen P. (2016). Direct Discharges of Domestic Wastewater are a Major Source of Phosphorus and Nitrogen to the Mediterranean Sea. *Environmental Science and Technology*, *50*(16), 8722–8730. doi: 10.1021/acs.est.6b01742

Powley H. R., Krom M. D., and Van Cappellen P. (2018). Phosphorus and nitrogen trajectories in the Mediterranean Sea (1950–2030): Diagnosing basin-wide anthropogenic nutrient enrichment. *Progress in Oceanography*, *162*, 257–270. doi: 10.1016/j.pocean.2018.03.003

Pujo-Pay M., Conan P., Oriol L., Cornet-Barthaux V., Falco C., Ghiglione J. F., Goyet C., Moutin T., and Prieur L. (2011). Integrated survey of elemental stoichiometry (C, N, P) from the western to eastern Mediterranean Sea. *Biogeosciences*, *8*(4). doi: 10.5194/bg-8-883-2011

Purcell J.E. (2012). Jellyfish and Ctenophore Blooms Coincide with Human Proliferations and Environmental Perturbations. *Annual Review of Marine Science*, *4*(1), 209–235. doi: 10.1146/annurev-marine-120709-142751

Purcell J.E., Uye S., and Lo W. (2007). Anthropogenic causes of jellyfish blooms and their direct consequences for humans: a review. *Marine Ecology Progress Series*, *350*, 153–174. doi: 10.3354/meps07093

Quignard, J.-P., & Tomasini, J. A. (2007). Mediterranean fish biodiversity. *Biologia Marina Mediterranea*, *7*(3), 1–66. http://publikationen.ub.uni-frankfurt.de/frontdoor/index/index/docId/16126

Ramis C., and Jansà A. (1983). Condiciones meteorológicas simultáneas a la aparición de oscilaciones del nivel del mar de amplitud extraordinaria en el Mediterráneo occidental. *Revista de Geofísica*, *39*, 35–42.

Re V., and Zuppi G. M. (2011). Influence of precipitation and deep saline groundwater on the hydrological systems of Mediterranean coastal plains: a general overview. *Hydrological Sciences Journal*, *56*(6), 966–980. doi: 10.1080/02626667.2011.597355

Reale M., Cabos Narvaez W. D., Cavicchia L., Conte D., Coppola E., Flaounas E., Giorgi F., Gualdi S., Hochman A., Li L., Lionello P., Podrascanin Z., Salon S., Sanchez-Gomez E., Scoccimarro E., Sein D. V, and Somot S. (2022a). Future projections of Mediterranean cyclone characteristics using the Med-CORDEX ensemble of coupled regional climate system models. *Climate Dynamics*, *58*(9–10), 2501–2524. doi: 10.1007/s00382-021-06018-x

Reale M., Cossarini G., Lazzari P., Lovato T., Bolzon G., Masina S., Solidoro C., and Salon S. (2022b). Acidification, deoxygenation, nutrient and biomasses decline in a warming Mediterranean Sea. *Biogeosciences*, *19*, 4035–4065. doi: 10.5194/bg-19-4035-2022

Reimann L., Jones B., Nikoletopoulos T., and Vafeidis A. T. (2021). Accounting for internal migration in spatial population projections - A gravity-based modeling approach using the Shared Socioeconomic Pathways. *Environmental Research Letters*, *16*(7). doi: 10.1088/1748-9326/ac0b66

Reimann L., Merkens J. L., and Vafeidis A. T. (2018). Regionalized Shared Socioeconomic Pathways: narratives and spatial population projections for the Mediterranean coastal zone. *Regional Environmental Change*, *18*(1). doi: 10.1007/s10113-017-1189-2

Rivetti I., Boero F., Fraschetti S., Zambianchi E., and Lionello P. (2017). Anomalies of the upper water column in the Mediterranean Sea. *Global and Planetary Change*, *151*, 68–79. doi: 10.1016/j.gloplacha.2016.03.001

Roccati A., Paliaga G., Luino F., Faccini F., and Turconi L. (2020). Rainfall Threshold for Shallow Landslides Initiation and Analysis of Long-Term Rainfall Trends in a Mediterranean Area. *Atmosphere*, *11*(12), 1367. doi: 10.3390/atmos11121367

Rodellas V., Garcia-Orellana J., Masqué P., Feldman M., Weinstein Y., and Boyle E. A. (2015). Submarine groundwater discharge as a major source of nutrients to the Mediterranean Sea. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(13), 3926–3930. doi: 10.1073/pnas.1419049112

Rodriguez M., Maleuvre C., Jollivet-Castelot M., d'Acremont E., Rabaute A., Lafosse M., Ercilla G., Vázquez J. T., Alonso B., Ammar A., and Gorini C. (2017). Tsunamigenic submarine landslides along the Xauen–Tofiño banks in the Alboran Sea (Western Mediterranean Sea). *Geophysical Journal International*, *209*(1), 266–281. doi: 10.1093/gji/ggx028

Romera R., Gaertner M. Á., Sánchez E., Domínguez M., González-Alemán J. J., and Miglietta M. M. (2017). Climate change projections of medicanes with a large multi-model ensemble of regional climate models. *Global and Planetary Change*, *151*, 134–143. doi: 10.1016/j.gloplacha.2016.10.008

Romero E., Garnier J., Lassaletta L., Billen G., Gendre R. Le, Riou P., and Cugier P. (2013). Large-scale patterns of river inputs in southwestern Europe: Seasonal and interannual variations and potential eutrophication effects at the coastal zone. *Biogeochemistry*, *113*(1–3). doi: 10.1007/s10533-012-9778-0

Romero E., Ludwig W., Sadaoui M., Lassaletta L., Bouwman A. F., Beusen A. H. W., Apeldoorn D. van, Sardans J., Janssens I. A., Ciais P., Obersteiner M., and Peñuelas J. (2021). The Mediterranean Region as a Paradigm of the Global Decoupling of N and P Between Soils and Freshwaters. *Global Biogeochemical Cycles*, *35*(3). doi: 10.1029/2020gb006874

Romero R., and Emanuel K. (2013). Medicane risk in a changing climate. *Journal of Geophysical Research: Atmospheres*, *118*(12), 5992–6001. doi: 10.1002/jgrd.50475

Romero-Freire A., Santos-Echeandía J., Neira P., and Cobelo-García A. (2019). Less-studied technology-critical elements (Nb, ta, ga, in, ge, te) in the marine environment: Review on their concentrations in water and organisms. *Frontiers in Marine Science*, *6*:532. doi: 10.3389/fmars.2019.00532

Rovere A., Stocchi P., and Vacchi M. (2016). Eustatic and Relative Sea Level Changes. *Current Climate Change Reports*, *2*(4), 221–231. doi: 10.1007/s40641-016-0045-7

Ruffault J., Curt T., Moron V., Trigo R. M., Mouillot F., Koutsias N., Pimont F., Martin-StPaul N., Barbero R., Dupuy J. L., Russo A., and Belhadj-Khedher C. (2020). Increased likelihood of heat-induced large wildfires in the Mediterranean Basin. *Scientific Reports*, *10*(1). doi: 10.1038/s41598-020-70069-z

Ruosteenoja K., Markkanen T., Venäläinen A., Räisänen P., and Peltola H. (2018). Seasonal soil moisture and drought occurrence in Europe in CMIP5 projections for the 21st century. *Climate Dynamics*, *50*(3–4), 1177–1192. doi: 10.1007/s00382-017-3671-4

Hamza H., Beya M. A., Bain A., de Wit R., and Klein J. (2022). First record of the invasive Asian date mussel Arcuatula senhousia (Benson, 1842) in El Mellah Lagoon (Southern coast of Algerian Basin, Western Mediterranean). *Bioinvasions Records*, *11*(3), 686–699. doi: 10.3391/bir.2022.11.3.05

Saleh M., and Becker M. (2019). New estimation of Nile Delta subsidence rates from InSAR and GPS analysis. *Environmental Earth Sciences*, *78*(1), 6. doi: 10.1007/s12665-018-8001-6

Sanchez-Gomez E., Somot S., and Mariotti A. (2009). Future changes in the Mediterranean water budget projected by an ensemble of regional climate models. *Geophysical Research Letters*, *36*(21), L21401. doi: 10.1029/2009gl040120

Santos I. R., Chen X., Lecher A. L., Sawyer A. H., Moosdorf N., Rodellas V., Tamborski J., Cho H. M., Dimova N., Sugimoto R., Bonaglia S., Li H., Hajati M. C., and Li L. (2021). Submarine groundwater discharge impacts on coastal nutrient biogeochemistry. *Nature Reviews Earth & Environment 2021 2:5*, *2*(5), 307–323. doi: 10.1038/s43017-021-00152-0

Santos-Echeandía J., Campillo J. A., Egea J. A., Guitart C., González C. J., Martínez-Gómez C., León V. M., Rodríguez-Puente C., and Benedicto J. (2021). The influence of natural vs anthropogenic factors on trace metal(loid) levels in the Mussel Watch programme: Two decades of monitoring in the Spanish Mediterranean sea. *Marine Environmental Research*, *169*. doi: 10.1016/j.marenvres.2021.105382

Scarselli N. (2020). Submarine landslides – architecture, controlling factors and environments. A summary. *Regional Geology and Tectonics: Volume 1: Principles of Geologic Analysis*, 417–439. doi: 10.1016/b978-0-444-64134-2.00015-8

Schiaparelli S., Castellano M., Povero P., Sartoni G., and Cattaneo-Vietti R. (2007). A benthic mucilage event in North-Western Mediterranean Sea and its possible relationships with the summer 2003 European heatwave: Short term effects on littoral rocky assemblages. *Marine Ecology*, *28*(3), 341-353. doi: 10.1111/j.1439-0485.2007.00155.x

Schroeder K., Chiggiato J., Bryden H. L., Borghini M., and Ben Ismail S. (2016). Abrupt climate shift in the Western Mediterranean Sea. *Scientific Reports*, *6*(1), 23009. doi: 10.1038/srep23009

Scicchitano G., Scardino G., Monaco C., Piscitelli A., Milella M., De Giosa F., and Mastronuzzi G. (2021). Comparing impact effects of common storms and Medicanes along the coast of south-eastern Sicily. *Marine Geology*, *439*, 106556. doi: 10.1016/j.margeo.2021.106556

Seebens H., Blackburn T. M., Dyer E. E., Genovesi P., Hulme P. E., Jeschke J. M., Pagad S., Pyšek P., Winter M., Arianoutsou M., Bacher S., Blasius B., Brundu G., Capinha C., Celesti-Grapow L., Dawson W., Dullinger S., Fuentes N., Jäger H., … Essl F. (2017). No saturation in the accumulation of alien species worldwide. *Nature Communications*, *8*(1), 14435. doi: 10.1038/ncomms14435

Seneviratne S. I., Zhang X., Adnan M., Badi W., Dereczynski C., Di Luca A., Ghosh S., Iskandar I., Kossin J., Lewis S., Otto F., Pinto I., Satoh M., Vicente-Serrano S. M., Wehner M., and Zhou B. (2021). Weather and Climate Extreme Events in a Changing Climate. In Masson-Delmotte V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (Eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1513–1766). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. doi: 10.1017/9781009157896.013

Seto K. C., Fragkias M., Güneralp B., and Reilly M. K. (2011). A meta-analysis of global urban land expansion. *PLoS ONE*, *6*(8) : e23777. doi: 10.1371/journal.pone.0023777

Sevault F., Somot S., Alias A., Dubois C., Lebeaupin-Brossier C., Nabat P., Adloff F., Déqué M., Decharme B., and Dé Qué M. (2014). A fully coupled Mediterranean regional climate system model: design and evaluation of the ocean component for the 1980–2012 period. *Tellus A: Dynamic Meteorology and Oceanography*, *66*(1), 23967. doi: 10.3402/tellusa.v66.23967

Shaw B., Ambraseys N. N., England P. C., Floyd M. A., Gorman G. J., Higham T. F. G., Jackson J. A., Nocquet J.-M., Pain C. C., and Piggott M. D. (2008). Eastern Mediterranean tectonics and tsunami hazard inferred from the AD 365 earthquake. *Nature Geoscience*, *1*(4), 268–276. doi: 10.1038/ngeo151

Simberloff D., Martin J.-L., Genovesi P., Maris V., Wardle D. A., Aronson J., Courchamp F., Galil B., García-Berthou E., Pascal M., Pyšek P., Sousa R., Tabacchi E., and Vilà M. (2013). Impacts of biological invasions: what's what and the way forward. *Trends in Ecology & Evolution*, *28*(1), 58–66. doi: 10.1016/j.tree.2012.07.013

Siokou-Frangou I., Christaki U., Mazzocchi M. G., Montresor M., Ribera D'Alcala M., Vaque D., and Zingone A. (2010). Plankton in the open mediterranean Sea: A review. *Biogeosciences*, *7*(5), 1543–1586. doi: 10.5194/bg-7-1543-2010

Skliris N., Zika J. D., Herold L., Josey S. A., and Marsh R. (2018). Mediterranean sea water budget long-term trend inferred from salinity observations. *Climate Dynamics*, *51*(7–8), 2857–2876. doi: 10.1007/s00382-017-4053-7

Solidoro C., Cossarini G., Lazzari P., Galli G., Bolzon G., Somot S., and Salon S. (2022). Modeling Carbon Budgets and Acidification in the Mediterranean Sea Ecosystem Under Contemporary and Future Climate. *Frontiers in Marine Science*, *8*. doi: 10.3389/fmars.2021.781522

Soloviev S. L., Solovieva O. N., Go C. N., Kim K. S., Shchetnikov N. A., Bonnin J., Levin B. W., Tinti S., and Papadopoulos G. A. (2000). Main Tsunamigenic Zones in the Mediterranean Sea. In J. Bonnin, B. W. Levin, S. Tinti, & G. A. Papadopoulos (Eds.), *Tsunamis in the Mediterranean Sea 2000 B.C.–2000 A.D.* (Vol. 13, pp. 1–15). Springer Netherlands. doi: 10.1007/978-94-015-9510-0_1

Sørensen M. B., Spada M., Babeyko A., Wiemer S., and Grünthal G. (2012). Probabilistic tsunami hazard in the Mediterranean Sea. *Journal of Geophysical Research: Solid Earth*, *117*(B1), 1305. doi:10.1029/2010jb008169

Sorte S., Rodrigues V., Borrego C., and Monteiro A. (2020). Impact of harbour activities on local air quality: A review. *Environmental Pollution*, *257*. doi: 10.1016/j.envpol.2019.113542

Soto-Navarro J., Jordá G., Amores A., Cabos W., Somot S., Sevault F., Macías D., Djurdjevic V., Sannino G., Li L., and Sein D. (2020). Evolution of Mediterranean Sea water properties under climate change scenarios in the Med-CORDEX ensemble. *Climate Dynamics*, *54*(3–4), 2135–2165. doi: 10.1007/s00382-019-05105-4

Spada G., and Melini D. (2022). New estimates of ongoing sea level change and land movements caused by Glacial Isostatic Adjustment in the Mediterranean region. *Geophysical Journal International*, *229*(2), 984–998. doi: 10.1093/gji/ggab508

Spinoni J., Naumann G., and Vogt J. V. (2017). Pan-European seasonal trends and recent changes of drought frequency and severity. *Global and Planetary Change*, *148*, 113–130. doi: 10.1016/j.gloplacha.2016.11.013

Spinoni J., Vogt J., Naumann G., Carrao H., and Barbosa P. (2015). Towards identifying areas at climatological risk of desertification using the Köppen-Geiger classification and FAO aridity index. *International Journal of Climatology*, *35*(9), 2210–2222. doi: 10.1002/joc.4124

Spinoni J., Vogt J. V., Naumann G., Barbosa P., and Dosio A. (2018). Will drought events become more frequent and severe in Europe? *International Journal of Climatology*, *38*(4), 1718–1736. doi: 10.1002/joc.5291

Stagge J. H., Kingston D. G., Tallaksen L. M., and Hannah D. M. (2017). Observed drought indices show increasing divergence across Europe. *Scientific Reports*, *7*(1), 14045. doi: 10.1038/s41598-017-14283-2

Suárez-Almiñana S., Pedro-Monzonís M., Paredes-Arquiola J., Andreu J., and Solera A. (2017). Linking Pan-European data to the local scale for decision making for global change and water scarcity within water resources planning and management. *Science of The Total Environment*, *603–604*, 126–139. doi: 10.1016/j.scitotenv.2017.05.259

Suaria G., Avio C. G., Mineo A., Lattin G. L., Magaldi M. G., Belmonte G., Moore C. J., Regoli F., and Aliani S. (2016). The Mediterranean Plastic Soup: synthetic polymers in Mediterranean surface waters. *Scientific Reports*, *6*(1), 37551. doi: 10.1038/srep37551

Svigkas N., Papoutsis I., Constantinos L., Tsangaratos P., Kiratzi A., and Kontoes C. H. (2016). Land subsidence rebound detected via multi-temporal InSAR and ground truth data in Kalochori and Sindos regions, Northern Greece. *Engineering Geology*, *209*, 175–186. doi: 10.1016/j.enggeo.2016.05.017

Tavoloni T., Miniero R., Bacchiocchi S., Brambilla G., Ciriaci M., Griffoni F., Palombo P., Stecconi T., Stramenga A., and Piersanti A. (2021). Heavy metal spatial and temporal trends (2008–2018) in clams and mussel from Adriatic Sea (Italy): Possible definition of forecasting models. *Marine Pollution Bulletin*, *163*. doi: 10.1016/j.marpolbul.2020.111865

Teresita G., Nicola M., Luca F., and Pierfrancesco C. (2019). Tsunami risk perception along the Tyrrhenian coasts of Southern Italy: the case of Marsili volcano. *Natural Hazards*, *97*(1), 437–454. doi: 10.1007/s11069-019-03652-x

Theocharis A., Nittis K., Kontoyiannis H., Papageorgiou E., and Balopoulos E. (1999). Climatic changes in the Aegean Sea influence the eastern Mediterranean thermohaline circulation (1986-1997). *Geophysical Research Letters*, *26*(11), 1617–1620. doi: 10.1029/1999gl900320

Thober S., Kumar R., Wanders N., Marx A., Pan M., Rakovec O., Samaniego L., Sheffield J., Wood E. F., and Zink M. (2018). Multi-model ensemble projections of European river floods and high flows at 1.5, 2-, and 3-degrees global warming. *Environmental Research Letters*, *13*(1), 014003. doi: 10.1088/1748-9326/aa9e35

Tinti S., Maramai A., and Graziani L. (2001). A new version of the European tsunami catalogue: updating and revision. *Natural Hazards and Earth System Sciences*, *1*, 255–262. doi: 10.5194/nhess-1-255-2001

Tobin I., Vautard R., Balog I., Bréon F.-M., Jerez S., Ruti P. M., Thais F., Vrac M., and Yiou P. (2015). Assessing climate change impacts on European wind energy from ENSEMBLES high-resolution climate projections. *Climatic Change*, *128*(1–2), 99–112. doi: 10.1007/s10584-014-1291-0

Toledo I., Ignacio Pagán J., López I., Aragonés L., Ignacio Pag an J., opez I. L., Aragon es Ignacio Toledo L., and Aragon es L. (2022). Causes of the different behaviour against erosion: Study case of the Benidorm Beaches (1956-2021). *Marine Georesources & Geotechnology, 41*(6), 648–661. doi: 10.1080/1064119x.2022.2084003

Toomey T., Amores A., Marcos M., Orfila A., and Romero R. (2022). Coastal Hazards of Tropical-Like Cyclones Over the Mediterranean Sea. *Journal of Geophysical Research: Oceans*, *127*(2). doi: 10.1029/2021jc017964

Tosi L., Da Lio C., Teatini P., and Strozzi T. (2018). Land Subsidence in Coastal Environments: Knowledge Advance in the Venice Coastland by TerraSAR-X PSI. *Remote Sensing 2018, Vol. 10, Page 1191*, *10*(8), 1191. doi: 10.3390/rs10081191

Tosi L., Teatini P., and Strozzi T. (2013). Natural versus anthropogenic subsidence of Venice. *Scientific Reports*, *3*(1), 2710. doi: 10.1038/srep02710

Toth E., Bragalli C., and Neri M. (2018). Assessing the significance of tourism and climate on residential water demand: Panel-data analysis and non-linear modelling of monthly water consumptions. *Environmental Modelling and Software*, *103*., 52-51. doi: 10.1016/j.envsoft.2018.01.011

Touratier F., and Goyet C. (2011). Impact of the Eastern Mediterranean Transient on the distribution of anthropogenic CO2 and first estimate of acidification for the Mediterranean Sea. *Deep Sea Research Part I: Oceanographic Research Papers*, *58*(1), 1–15. doi: 10.1016/j.dsr.2010.10.002

Tous M., and Romero R. (2013). Meteorological environments associated with medicane development. *International Journal of Climatology*, *33*, 1–14. doi: 10.1002/joc.3428

Tovar-Sánchez A., Basterretxea G., Omar M. Ben, Jordi A., Sánchez-Quiles D., Makhani M., Mouna D., Muya C., and Anglès S. (2016). Nutrients, trace metals and B-vitamin composition of the Moulouya River: A major North African river discharging into the Mediterranean Sea. *Estuarine, Coastal and Shelf Science*, *176*, 47–57. doi: 10.1016/j.ecss.2016.04.006

Tramblay Y., Jarlan L., Hanich L., and Somot S. (2018). Future Scenarios of Surface Water Resources Availability in North African Dams. *Water Resources Management*, *32*(4), 1291–1306. doi:10.1007/s11269-017-1870-8

Transport and Environment (2019). One Corporation to Pollute Them All. Luxury cruise air emissions in Europe. 2019 European Federation for Transport and Environment AISBL. https://www.transportenvironment.org/articles/one-corporation-pollute-them-all

Treppiedi D., Cipolla G., Francipane A., and Noto L. V. (2021). Detecting precipitation trend using a multiscale approach based on quantile regression over a Mediterranean area. *International Journal of Climatology*, *41*(13), 5938–5955. doi: 10.1002/joc.7161

Trincardi F., Francocci F., Pellegrini C., Ribera d'Alcalà M., and Sprovieri M. (2023). The Mediterranean Sea in the Anthropocene. In *Oceanography of the Mediterranean Sea* (pp. 501–553). Elsevier. doi: 10.1016/b978-0-12-823692-5.00013-3

Tsikoti C., and Genitsaris S. (2021). Review of Harmful Algal Blooms in the Coastal Mediterranean Sea, with a Focus on Greek Waters. *Diversity*, *13*(8), 396. doi: 10.3390/d13080396

Ülker D., Burak S., Balas L., and Çağlar N. (2022). Mathematical modelling of oil spill weathering processes for contingency planning in Izmit Bay. *Regional Studies in Marine Science*, *50*. doi: 10.1016/j.rsma.2021.102155

Ulman A., Ferrario J., Forcada A., Seebens H., Arvanitidis C., Occhipinti-Ambrogi A., and Marchini A. (2019). Alien species spreading via biofouling on recreational vessels in the Mediterranean Sea. *Journal of Applied Ecology*, *56*(12), 2620–2629. doi: 10.1111/1365-2664.13502

UN (2021). The Second World Ocean Assessment: World Ocean Assessment II - Volume I & II. In *The Second World Ocean Assessment*. United Nations. doi: 10.18356/9789216040062

UNEP/MAP (2016). *Mediterranean Strategy for Sustainable Development 2016-2025*. Valbonne. Plan Bleu, Regional Activity Centre. https://wedocs.unep.org/bitstream/handle/20.500.11822/7097/mssd_2016_2025_eng.pdf

UNEP/MAP (2017). *Mediterranean Quality Status Report*. Athens. https://www.unep.org/unepmap/resources/quality-status-report-mediterranean-med-qsr-2017

UNEP/MAP, and Plan Bleu (2020). *State of the Environment and Development in the Mediterranean*. Nairobi. https://planbleu.org/wp-content/uploads/2021/04/SoED_full-report.pdf

UNWTO (2019). *Yearbook of Tourism Statistics, Data 2013 – 2017, 2019 Edition*, UNWTO, Madrid. doi: 10.18111/9789284420414

Urgeles R., and Camerlenghi A. (2013). Submarine landslides of the Mediterranean Sea: Trigger mechanisms, dynamics, and frequency-magnitude distribution. *Journal of Geophysical Research: Earth Surface*, *118*(4), 2600–2618. doi: 10.1002/2013jf002720

USGS (2006). Tsunami Hazards—A National Threat. In *Fact Sheet 2006–3023*. U.S. Geological Survey. https://pubs.usgs.gov/fs/2006/3023/

Vafeidis A., Abdulla A., Bondeau A., Brotons L., Ludwig R., Portman M., Reimann L., Vousdoukas M., and Xoplaki E. (2020). Managing Future Risks and Building Socio-Ecological Resilience. In W. Cramer, J. Guiot, & K. Marini (Eds.), *Climate and Environmental change in the Mediterranean Basin - Current Situations and Risks for the Future*. Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, pp. 539-588. doi: 10.5281/zenodo.7101119

Vargas-Yáñez M., Jesús García M., Salat J., García-Martínez M. C., Pascual J., and Moya F. (2008). Warming trends and decadal variability in the Western Mediterranean shelf. *Global and Planetary Change*, *63*(2–3). doi: 10.1016/j.gloplacha.2007.09.001

Verdura J., Linares C., Ballesteros E., Coma R., Uriz M. J., Bensoussan N., and Cebrian E. (2019). Biodiversity loss in a Mediterranean ecosystem due to an extreme warming event unveils the role of an engineering gorgonian species. *Scientific Reports*, *9*(1), 5911. doi: 10.1038/s41598-019-41929-0

Viaroli P., Soana E., Pecora S., Laini A., Naldi M., Fano E. A., and Nizzoli D. (2018). Space and time variations of watershed N and P budgets and their relationships with reactive N and P loadings in a heavily impacted river basin (Po river, Northern Italy). *Science of The Total Environment*, *639*, 1574–1587. doi: 10.1016/j.scitotenv.2018.05.233

Vicente-Serrano S. M., Domínguez-Castro F., Murphy C., Hannaford J., Reig F., Peña-Angulo D., Tramblay Y., Trigo R. M., Mac Donald N., Luna M. Y., Mc Carthy M., Van Der Schrier G., Turco M., Camuffo D., Noguera I., García-Herrera R., Becherini F., Della Valle A., Tomas-Burguera M., and El Kenawy A. (2021). Long-term variability and trends in meteorological droughts in Western Europe (1851–2018). *International Journal of Climatology*, *41*(S1). doi: 10.1002/joc.6719

Vilibić I., Denamiel C., Zemunik P., and Monserrat S. (2021). The Mediterranean and Black Sea meteotsunamis: an overview. *Natural Hazards*, *106*(2), 1223–1267. doi: 10.1007/s11069-020-04306-z

Vilibić I., Šepić J., Dunić N., Sevault F., Monserrat S., and Jordà G. (2018). Proxy-Based Assessment of Strength and Frequency of Meteotsunamis in Future Climate. *Geophysical Research Letters*, *45*(19). doi: 10.1029/2018GL079566

Vousdoukas M. I., Mentaschi L., Voukouvalas E., Verlaan M., and Feyen L. (2017). Extreme sea levels on the rise along Europe's coasts. *Earth's Future*, *5*(3), 304–323. doi: 10.1002/2016ef000505

Wahl T., and Chambers D. P. (2015). Evidence for multidecadal variability in US extreme sea level records. *Journal of Geophysical Research: Oceans*, *120*(3), 1527–1544. doi: 10.1002/2014jc010443

Wallentinus I., and Nyberg C. D. (2007). Introduced marine organisms as habitat modifiers. *Marine Pollution Bulletin*, *55*(7–9). doi: 10.1016/j.marpolbul.2006.11.010

Walsh K., Giorgi F., and Coppola E. (2014). Mediterranean warm-core cyclones in a warmer world. *Climate Dynamics*, *42*(3–4), 1053–1066. doi: 10.1007/S00382-013-1723-y

Wilkinson J. L., Boxall A. B. A., Kolpin D. W., Leung K. M. Y., Lai R. W. S., Galban-Malag C., Adell A. D., Mondon J., Metian M., Marchant R. A., Bouzas-Monroy A., Cuni-Sanchez A., Coors A., Carriquiriborde P., Rojo M., Gordon C., Cara M., Moermond M., Luarte T., … Teta C. (2022). Pharmaceutical pollution of the world's rivers. *Proceedings of the National Academy of Sciences of the United States of America*, *119*(8). doi: 10.1073/pnas.2113947119

Wimart-Rousseau C., Wagener T., Álvarez M., Moutin T., Fourrier M., Coppola L., Niclas-Chirurgien L., Raimbault P., D'Ortenzio F., Durrieu de Madron X., Taillandier V., Dumas F., Conan P., Pujo-Pay M., and Lefèvre D. (2021). Seasonal and Interannual Variability of the CO2 System in the Eastern Mediterranean Sea: A Case Study in the North Western Levantine Basin. *Frontiers in Marine Science*, *8*. doi: 10.3389/fmars.2021.649246

WMO (1992). *International meteorological vocabulary* (WMO-No. 182). Secretariat of the World Meteorological Organization. https://library.wmo.int/idurl/4/35809

WMO (2023). *Guidelines on the Definition and Characterization of Extreme Weather and Climate Events. WMO-No. 1310*. WMO, Geneva, Switzerland.

WMO, Tank A., Zwiers F., and Zhang X. (2009). Guidelines on Analysis of Extremes in a Changing Climate in Support of Informed Decisions for Adaptation. WMO-TD No. 150. In *World Meteorological Organization*. WMO, Geneva, Switzerland. https://library.wmo.int/idurl/4/48826

Wolff C., Nikoletopoulos T., Hinkel J., and Vafeidis A. T. (2020). Future urban development exacerbates coastal exposure in the Mediterranean. *Scientific Reports*, *10*(1), 14420. doi: 10.1038/s41598-020-70928-9

Woodworth P. L., Melet A., Marcos M., Ray R. D., Wöppelmann G., Sasaki Y. N., Cirano M., Hibbert A., Huthnance J. M., Monserrat S., and Merrifield M. A. (2019). Forcing Factors Affecting Sea Level Changes at the Coast. *Surveys in Geophysics*, *40*(6), 1351–1397. doi: 10.1007/s10712-019-09531-1

Wöppelmann G., and Marcos M. (2016). Vertical land motion as a key to understanding sea level change and variability. *Reviews of Geophysics*, *54*(1), 64–92. doi: 10.1002/2015rg000502

Xoplaki E., Ellsäßer F., Grieger J., Nissen K. M., Pinto J., Augenstein M., Chen T.-C., Feldmann H., Friederichs P., Gliksman D., Goulier L., Haustein K., Heinke J., Jach L., Knutzen F., Kollet S., Luterbacher J., Luther N., Mohr S., … Wolf F. (2023). *Compound events in Germany in 2018: drivers and case studies*. doi: 10.5194/egusphere-2023-1460

Yeste P., Rosa-Cánovas J. J., Romero-Jiménez E., García-Valdecasas Ojeda M., Gámiz-Fortis S. R., Castro-Díez Y., and Esteban-Parra M. J. (2021). Projected hydrologic changes over the north of the Iberian Peninsula using a Euro-CORDEX multi-model ensemble. *Science of The Total Environment*, *777*, 146126. doi: 10.1016/j.scitotenv.2021.146126

Zanchettin D., Bruni S., Raicich F., Lionello P., Adloff F., Androsov A., Antonioli F., Artale V., Carminati E., Ferrarin C., Fofonova V., Nicholls R. J., Rubinetti S., Rubino A., Sannino G., Spada G., Thiéblemont R., Tsimplis M., Umgiesser G., … Zerbini S. (2021). Sea-level rise in Venice: historic and future trends (review article). *Natural Hazards and Earth System Sciences*, *21*(8), 2643–2678. doi: 10.5194/nhess-21-2643-2021

Zenetos A., Albano P. G., Garcia E. L., Stern N., Tsiamis K., and Galanidi M. (2022). Established non-indigenous species increased by 40% in 11 years in the Mediterranean Sea. *Mediterranean Marine Science*, *23*(1), 196–212. doi: 10.12681/mms.29106

Zenetos A., Çinar M. E., Crocetta F., Golani D., Rosso A., Servello G., Shenkar N., Turon X., and Verlaque M. (2017). Uncertainties and validation of alien species catalogues: The Mediterranean as an example. *Estuarine, Coastal and Shelf Science*, *191*, 171–187. doi: 10.1016/j.ecss.2017.03.031

Zenetos A., and Galanidi M. (2020). Mediterranean non-indigenous species at the start of the 2020s: recent changes. *Marine Biodiversity Records*, *13*(1), 10. doi: 10.1186/s41200-020-00191-4

Zhan S., Song C., Wang J., Sheng Y., and Quan J. (2019). A Global Assessment of Terrestrial Evapotranspiration Increase Due to Surface Water Area Change. *Earth's Future*, *7*(3), 266–282. doi: 10.1029/2018ef001066

Zhang L., Wu P., Zhou T., Roberts M. J., and Schiemann R. (2016). Added value of high resolution models in simulating global precipitation characteristics. *Atmospheric Science Letters*, *17*(12), 646–657. doi: 10.1002/asl.715

Zingone A., Escalera L., Aligizaki K., Fernández-Tejedor M., Ismael A., Montresor M., Mozetič P., Taș S., and Totti C. (2021). Toxic marine microalgae and noxious blooms in the Mediterranean Sea: A contribution to the Global HAB Status Report. *Harmful Algae*, *102*, 101843. doi: 10.1016/j.hal.2020.101843

Zittis G., Bruggeman A., and Lelieveld J. (2021). Revisiting future extreme precipitation trends in the Mediterranean. *Weather and Climate Extremes*, *34*, 100380. doi: 10.1016/j.wace.2021.100380

Information about the authors

Coordinating Lead Authors

Murat BELIVERMIS, Department of Biology, Faculty of Science, Istanbul University, *Istanbul, Türkiye*
Dario CAMUFFO, National Research Council of Italy (CNR), Institute of Atmospheric Sciences and Climate, *Padua, Italy*

Lead Authors

Nuno CAIOLA, Department of Climate Solutions and Ecosystem Services, Eurecat, *Amposta, Spain*
Claudio FERRARI, Department of Economics, University of Genoa, *Genoa, Italy*
Nadia MHAMMDI, Institut Scientifique, University Mohammed V of Rabat, *Rabat, Morocco*
Estela ROMERO, Global Ecology Unit, Centre for Ecological Research and Forestry Applications (CREAF), *Barcelona, Spain*
Claudia WOLFF, Institute of Geography, Kiel University, *Kiel, Germany*

Contributing Authors

Vincenzo ASERO, Department of Political and Social Sciences, University of Catania, *Catania, Italy*
Sana BEN ISMAIL, Institut National des Sciences et Technologies de la Mer, *Tunis, Tunisia*
Cem DALYAN, Department of Biology, Faculty of Science, Istanbul University, *Istanbul, Türkiye*
Hamouda DAKHLAOUI, University of Tunis El Manar, National Engineering School of Tunis, Laboratory of Modelling in Hydraulics and Environment, *Tunis, Tunisia* / University of Carthage, National School of Architecture and Urban Planning of Tunis, *Sidi Bou Said, Tunisia*
Lena REIMANN, Instituut voor Milieuvraagstukken (IVM) – Institute for Environmental Studies, Faculty of Science, Vrije Universiteit Amsterdam (VU), *Amsterdam, The Netherlands*
Alessio TEI, Department of Economics | DIEC, University of Genoa, *Genoa, Italy*
Matteo VACCHI, Department of Earth Sciences, University of Pisa, *Pisa, Italy*
Antonio della VALLE, Institute of Atmospheric Sciences and Climate, National Research Council of Italy (CNR-ISAC), *Padua, Italy*

ISBN: 978-2-493662-02-6
www.medecc.org
Enquiries: contact@medecc.org

MedECC
Mediterranean Experts on Climate and environmental Change